MAY 2017

M. Sc. in Civil Engineering

ABDUL RAZIQ HAKIMI

GAZIANTEP UNIVERSITY

GRADUATE SCHOOL OF

NATURAL & APPLIED SCIENCE

CONCRETE FILLED GLASS FIBER REINFORCED POLYMER (GFRP) SHORT COLUMN

M. Sc. THESIS

IN

CIVIL ENGINEERING

BY

ABDUL RAZIQ HAKIMI

MAY 2017

Concrete Filled Glass Fiber Reinforced Polymer (GFRP) Short Column

M.Sc. Thesis

in

Civil Engineering

University of Gaziantep

Supervisors

Prof. Dr. Abdulkadir ÇEVİK

Assist. Prof. Dr. Mehmet Eren GÜLŞAN

by

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MAY 2017

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GAZIANTEP UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCE
CIVIL ENGINEERING DEPARTMENT

Name of thesis: Concrete Filled Glass Fiber Reinforced Polymer (GFRP) Short Column

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Exam date: 26/ May/ 2017

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Abdul Raziq HAKIMI

ABSTRACT

CONCRETE FILLED GLASS FIBER REINFORCED POLYMER (GFRP) SHORT COLUMN

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M.Sc. in Civil Engineering

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May 2017

56 pages

This thesis presents experimental studies which investigate the mechanical behavior of glass fiber reinforced polymer (GFRP) tubes under axial compressive loading. The GFRP tubes were square in cross-section and filled with self-compacting concrete (SCC). A total number of ten specimens with major variables such as cross-section, length and compressive strength of SCC were tested in this experiment program. The column application of GFRP tubes in this study has found that concrete confinement by GFRP, significantly enhances the mechanical performance of columns under the axial compressive loading. In addition, the function of GFRP square tubes as permanent formwork can facilitate the construction process and provide better environmental protection for the concrete columns against acid and alkali. The GFRP square tube SCC-filled test results has showed an increase up to even 20 % in load carrying capacity of columns. The fracture and failure mechanism has been found to be brittle rather than ductile, this phenomenon was observed to be caused by brittle behavior of concrete core without the steel reinforcement. It has been noticed from the test results that ultimate axial strain hasn't been significantly affected by GFRP tubes confinement.

Key Words: Glass fiber, Polymer, Compressive strength, ultimate axial strain, Mechanical performance, Failure, column

ÖZET

BETON YERLEŞTIRILMIŞ CAM FİBER TAKVİYELİ POLİMER KISA KOLONLAR

HAKIMI, ABDUL RAZIQ

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Mayıs 2017

56 sayfa

Bu tez cam fiber takviyeli polimer tüplerin eksenel basınç yüklemesi altındaki mekanik davranışını araştıran deneysel araştırmaları sunmaktadır. Cam takviyeli polimer tüpler kare kesitlidir ve kendiliğinden yerleşen betonla doldurulmuştur. Bu deney programında kesit alanı, uzunluk ve kendiliğinden yerleşen betonun basınç mukavemeti gibi önemli değişkenler dikkate alınarak 10 adet numune test edilmiştir. Cam fiber takviyeli polimer tüplerin kolon uygulaması, betonun polimer tüp tarafından sargılanmasının kolonların eksenel basınç yüklemesi altındaki mekanik performansını önemli derecede geliştirdiğini ortaya çıkarmıştır. Ayrıca, cam fiber takviyeli polimer kare tüpler kalıcı bir kalıp olarak imalat sürecini kolaylaştırmakta ve kolonlar için asit ve alkaliye karşı daha iyi bir çevresel koruma sağlamaktadır. Kendiliğinden yerleşen betonla doldurulmuş cam fiber takviyeli kare tüplerin deney sonuçları yük taşıma kapasitesinde 20 %'e kadar artış olduğunu göstermektedir. Kırılma ve göçme mekanizmalarının sünek yerine kırılgan olduğu gözlemlenmiştir ve bu durumun çekirdekteki donatışız betonun kırılgan davranışından ötürü kaynaklandığı gözlemlenmiştir. Deney sonuçlarından maksimum eksenel birim yerdeğiştirmenin cam fiber takviyeli tüplerin sargılamasından önemli derecede etkilenmediği tespit edilmiştir.

Anahtar Kelimeler: Cam fiber, polimer, basınç mukavemeti, maksimum eksenel birim yerdeğiştirme, mekanik performans, göçme, kolon

To my family who have been always kind and source of inspiration for passion and love to me.

ACKNOWLEDGEMENT

I am deeply grateful of Professor Abdulkadir ÇEVİK, the civil engineering department head whose guidance and encouragement helped me to accomplish this scientific research on GFRP composites in structural engineering. I appreciate his support and feedback in lab work in providing the material and tools as well as technical comments.

My deep gratitude goes to Assist. Prof. Dr. Mehmet Eren GÜLŞAN, who always has been effective and kind consulter and supporter to all stage of my one-year research work in lab and academic affairs.

I am thankful and appreciate Mr. Ali Khalid HUSSEIN, Ph.D. student at engineering school of Gaziantep university, who was a good lab partner and assistant to me.

I deeply offer my gratefulness to all staff and students of engineering school, whom direct or indirect contribution in academic or administrative levels has been helpful to accomplishment of this research.

Here I once again express my deep gratefulness to my family who have always been encourager and supportive to my educational studies and efforts.

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CHAPTER 1

INTRODUCTION

1.1 General

The construction industry has experienced variety type of material, but predominant type used in large quantity are the steel and concrete. The ductile and brittle behavior of steel and concrete respectively has made them form a perfect composite used in construction. The deficiency of corrosiveness, high weight-to-strength ratio, difficulty in retrofitting…, encouraged the researchers to investigate the other material. During past few decades a composite material called Fiber-Reinforced-Polymer (FRP) which is made of fibers in a polymeric resin, has emerged and proved to be the lost material to confront the above mentioned deficiencies. The FRP composite growth aided by research and demonstration projects funded by private sector and governments around the world during the 1980s and through the 2000s [1], made it a common construction material which its usage expanded from few in 1980s to several thousand today [2].

FRP composite materials have emerged as an alternative to traditional materials used in repair and retrofitting. Due to their lightweight, noncorrosive, high tensile strength (ductile) behavior and tailorability, FRP materials have moved to new construction fields in composite columns structure members' application such as columns, beams, bridge trusts, piers and so on [3], [4].

One of FRP types made of E-glass fibers in polymeric resin, called "glass-fiber reinforced polymer" (GFRP), has emerged as new construction material for structural purposes. This text involves the investigation conducted on GFRP tubes filled with self-compacting concrete (SCC), for column application. The all above flexibility and efficiencies mentioned about FRP, is involving the GFRP as well, in addition the omitting of reinforced steel and usage of SCC instead of normal concrete, made this experiment as sensitive as valuable for future construction technology advances.

Major variable considered in this experiment were GFRP square tubes cross section (i.e. 100x100 mm and 75x75 mm), thickness of tubes (i.e. 4.0 mm and 6.0 mm), length of specimens (i.e. 300 mm and 600 mm) and normal and high strength concrete of 32 MPa and 50 MPa respectively. Total number of 10 specimens were used in this experiment program.

1.2 Thesis Objectives

The objectives of this research was to study the axial compressive strength of GFRP square tubes filled by SCC. In addition, it has been studied the failure mechanism of GFRP columns under axial load ranging beyond elastic state. Ductility and energy absorption of columns have been investigated and the result prevailed that GFRP increases the energy absorption capacity of columns by providing more ductile behavior due to the lateral confinement. The force-strain curves of GFRP columns have been analyzed and compared to draw reasonable conclusion based on tests output.

1.3 Thesis Outline

This thesis involves six chapters, named as Introduction, Literature Review, FRP Composite and Its Usage, Methodology, Result Discussion and Conclusion respectively. A brief overview has been written down in introduction to provide information about the FRP in general and GFRP in specific. Some technical terms which have been used in context, have been defined in this chapter as well. Chapter two covers a background reviews on topic. Moreover, the application of FRP composites in different engineering disciplines has been presented in chapter three. The experiment program and procedure written in chapter four. The chapters five and six involves result analysis and final conclusion respectively.

1.4 Definitions

1.4.1 Self-Compacting Concrete:

Concrete that is able to flow under its own weight and completely fill the formwork, even in the presence of dense reinforcement, without the need of any vibration, whilst maintaining homogeneity [5].

Admixture:

Material added during the mixing process of concrete in small quantities related to the mass of cement to modify the properties of fresh or hardened concrete.

Blinder:

The combined cement and hydraulic addition in a self-compacting concrete

Confined Flow ability (Passing Ability):

The ability of SCC to flow through tight openings such as spaces between steel reinforcing bars without segregation or blocking.

Powder (Fines):

Material of particle size smaller than 0,125 mm. It will also include this size fraction of the sand.

Mortar:

The fraction of the concrete comprising Paste plus those aggregates less than 4 mm.

Paste:

The fraction of the concrete comprising Powder plus water and air.

Segregation resistance:

The ability of SCC to remain homogeneous in composition during transport and placing.

Workability:

A measure of the ease by which fresh concrete can be placed and compacted: it is a complex combination of aspects of fluidity, cohesiveness, transportability, compactability and stickiness. [5]

1.4.2 Fiber-Reinforced Polymer

Fiber:

Slender and greatly elongated solid material, generally with a length at least 100 times its diameter, that has properties making it desirable for use as reinforcement.

Fiberglass:

Filament drawn from an inorganic fusion typically comprising silica-based material that has cooled without crystallizing. Types of glass fibers include alkali resistant (AR-glass), general purpose (E-glass), high strength (S-glass), and boron free (ECR-glass).

Fiber Carbon:

Fiber produced by heating organic precursor materials containing a substantial amount of carbon, such as rayon, polyacrylonitrile (PAN), or pitch in an inert environment and at temperatures of 2700 °F (1500 °C) or greater.

Fiber-reinforced Polymer (FRP):

A general term for a composite material comprising a polymer matrix reinforced with fibers in the form of fabric, mat, strands, or any other fiber form.

Glass Fiber-reinforced Polymer (GFRP):

A composite material comprising a polymer matrix reinforced with glass fiber cloth, mat, or strands [2].

Density:

FRP materials have densities ranging from 75 to 130 lb/ft3 (1.2 to 2.1 g/cm3), which is four to six times lower than that of steel (Table 1.1). The reduced density leads to lower transportation costs, reduces added dead load on the structure, and can ease handling of the materials on the project site [2].

Coefficient of thermal expansion:

The coefficients of thermal expansion of unidirectional FRP materials differ in the longitudinal and transverse directions, depending on the types of fiber, resin, and volume fraction of fiber (Table 2.2), [2].

Table 1.1 Typical densities of FRP materials, lb./ft3 (gr/cm3)

Steel	GFRP	CFRP	AFRP
490 (7.9)	75 to 130 (1.2 to 2.1)	90 to 100 (1.5 to 1.6)	75 to 90 (1.2 to 1.5)

Table 2.2 Typical coefficients of thermal expansion for FRP materials

	Coefficient of thermal expansion, x 10^{-6} /°F (x 10^{-6} /°C)		
Direction	GFRP	CFRP	AFRP
Longitudinal, α_L	3.3 to 5.6 (6 to 10)	-0.6 to 0 (-1 to 0)	-3.3 to -1.1 (-6 to -2)
Longitudinal, , α_T	10.4 to 12.6 (19 to 23)	12 to 27 (22 to 50)	33 to 44 (60 to 80)

CHAPTER 2

LITERATURE REVIEW

2.1 General

Since 1980s a new type of construction material has been added to conventional steel and concrete material of civil engineering, called Fiber Reinforced Polymer or Fiber Reinforced Plastic (FRP). First this technology was used for retrofitting the columns in Japan [2], and after then it showed to be a useful and effective material for different engineering purposes such as retrofitting of seismic structures, bridge decks and piers, strengthening the steel columns. FRPs which are made of fibers in polymeric resins are general in four types, such as Aramid FRP (AFRP), Carbon FRP (CFRP), Basalt FRP (BFRP) and Glass FRP (GFRP). All these types have been investigated during the last two decades, as a result nowadays FRP composites are going to be used as steel replacement in concrete providing flexural strength and environmental protection. FRP materials exhibit high tensile strength beside being lightweight and noncorrosive which are the basic challenges of conventional construction material. The GFRP which is the intent of this text has been used as bar in reinforced concrete because of its tensile strength and none corroding behavior, as well as tubes filled with concrete which is essential in protection of member against acids and humidity, as well as it facilities the construction process by omitting the formwork.

GFRP tubes low weight-to-strength ratio compared to steel has ductile behavior. Nowadays GFRP tubes are commercially available in vast variety of sizes [6]. GFRP tube distribution around the concrete core provides adequate reinforcement restrains for the member in case of lateral or eccentric loadings.

2.2 FRP Composites and Retrofitting

In 2014 Thomas Vincent & Ozbakkaloglu [7] investigated the slenderness of concrete-filled FRP tubes (CFFTs) under axial compressive loading. The experiment involved

18 aramid FRP (AFRP) tube with circular cross section filled with high-strength concrete (HSC). For all specimens a nominal diameter of 150mm was maintained while the height-to-diameter ratios where 1, 2, 3 and 5. Their work demonstrated decrease in axial strain as the slenderness on specimens increased specially the H/D ratio of 2 to 5 was found to be significant in the phenomenon. The H/D of 1 showed significantly higher strain and strength enhancements compared to H/D of 2 to 5 ratios. As a major achievement of their work, influence of slenderness on axial strength improvement of columns with H/D ratios of 2 and 5 was found to be negligible.

Similar to Vincent and Ozbakkaloglu work, In 2010 Jong-Hwa et al. [8] examined the mechanical performance of Reinforced Concrete Filled Fiber Reinforced Tube (RCFFT) as strut member of Prestressed Box Girder bridge. Their applied both compressive and flexural test to study both condition for composite strut of this type. In addition to RCFFT, concrete-filled FRP tubes (CFFT) were also used to improve the investigation process on confinement criteria. Based on their experimental outputs, an equation for ultimate compressive strength estimation of CFFT and RCFFT was proposed. In addition, the flexural performance of both CFFT and RCFFT due to reinforcement by FRP considered to be improved remarkably. As the major conclusion of their experiment the RCFFT strut members test result demonstrated that such as members can be used in real Prestressed Concrete Box Girder bridge and mentioned experiment would utilize the design work of such as member.

Moreover on retrofitting application of FRPs, M.Karbhari et al., 2000 [9] studied the use of FRP composites in renewal of civil structure in particular on pipelines and bridges. M.karbhari et al. research encountered the vast fields on civil infrastructures which FRP campsites are usable. Due to high overall durability, light weight, corrosion resistance and tailorability compared to conventional material FRP campsites seems to be the future design and research target. Meanwhile their large scale testing showed that FRP composites are costly and still has a long way to be implemented in large scale construction projects but because of simplicity in assemblage and crucial usage in replacement work and strengthening it is todays markets valuable constructions material.

The FRP application as a beam was studied by Ahmed Abouzied & Masmoudi, 2015 [10]. The rectangular beams with partially concrete-filled FRP tube (CFFT) with steel rebar and inner voids, were prepared as test specimen. The inner voids were provided by hollow circular or square FRP tube placed inside the rectangular filament-wound FRP tube, and shifted towards the tension zone (bottom of beam). In their experiment beside partially-CFFT, fully-CFFT and conventional steel-reinforced concrete (RC) beams having identical dimension were tested as well. The partially-CFFT strength-to-weight ratio exhibited 370% higher than the conventional RC beam, while the weight ratio of partially-CFFT to RC beams were 2/3. In addition, test showed that partially-CFFT beams are more ductile than RC ones in compression zone during the failure state. It was encountered that the inner void (provided by inner tube) cross section of circular shape has slightly better performance than the square ones. Their work involved the theoretical section analysis as well and was reported to be coincident with experiment result. The outstanding point of their experiment conclusion was the higher flexural strength with lighter weight of partially-CFFT beams compared to conventional RC beams, which dramatically effects the analysis and volumetric work of structure in general.

Jian C.Lim & Ozbakkaloglu, 2015 [11] studied the effect of concrete age on FRP-confined concrete members generally used in retrofitting of existing structures. The main purpose of their experiment was to investigate the influence of concrete age on compressive strength of FRP-confined columns. Therefore, they designed the experiment based on 36 specimens, half confined and the rest unconfined with identical dimension. These specimens where tested at 7 and 28 days. The pitfall of their work was the long term effect study, which they used the existing test result of FRP-confined concrete collected from pervious published papers. For the long term effect, age of 900 days for concrete was considered. Their findings showed that in long term FRP-confined concrete stress-strain behavior changes significantly and this phenomenon is more obvious at the transition zone of stress-strain curve. In addition, the short term effect of concrete age at FRP-confined concrete was found to be no significant.

During past decades the usage of concrete-filled steel tubes (CFT) as columns has been common and the inelastic outward local buckling at the ends of such as columns has been said to be the main challenge. As FRP composite material entered the cycle of construction material, many investigations carried out on the usage of retrofitting the CFTs to confront mentioned buckling challenge.

In 2016, Yu et al. [12], investigated the usage of FRP jackets/wraps for overpowering the local buckling of CFTs. For this purpose, they conducted experiment to study the FRP-confined CFT (CCFT) columns under both lateral and axial compression loadings. As the major parameters of their experiment, loading scenarios and FRP jacket's stiffness was selected. Their test result reflected the significant improvement in structural performance of CFT column under lateral loading, while FRP jacket applied at the end, and even this jacket could effectively delay and in a certain degree prevent outward local buckling. The cyclic lateral loading scenario was found to cause severe local deformation at the end of columns compared to the monotonic lateral loading. in addition, in was found the under cyclic loading FRP jackets may experience the rupture within the end region earlier then monotonic loading case.

Concerning the steel tube strengthening application of FRPs, Sundarraja & Prabhu, 2012 [13], studied the concrete-filled steel tube (CFST) section structural performance, bonded externally by Carbon FRP (CFRP) fabrics layers at horizontal strips. Their experiment CFRP characteristics such as the width and spacing of CFRP strips plus the number of its layers were the main parameters. The result was based on 30 specimens test which twenty-seven of them were bonded externally with 50mm width of CFRP wraps and the three reaming none bonded. The CFRP wraps spacing were set to 20mm, 30mm and 40mm. their test findings showed that externally bonding the CFST columns by CFRP strips, would increase the load carrying capacity and provides external confinement pressure effectively. In addition, it was noticed that CFRP strips bonding can delay the local buckling of CFST.

Moreover the seismic effects studies and need for strengthening and retrofitting the columns against the seismic cyclic loads, in 2014, Hu et al. [14], studied the CFST under compressive axial cyclic loading which is one of the way to simulate the seismic loading of such as columns. The tubes were wrapped by FRP strips at the bottom and also by additional steel tube segment to envelope the column. The experiment result showed that FRP strips has two advantage, first it provides additional confinement to the concrete core beside steel tube, and restrains the steel tube to confront its local buckling.

2.3 FRP Tubes

The FRP tubes technology was the second step of FRP growing process as construction material. Ozbakkaloglu & Vincent, 2014 [15] studied the Aramid Fiber Reinforced Polymer (AFRP) tube inner surface interaction with concrete. In his article the focusing concept was influence of FRP-to-concrete interface gap, caused by shrinkage, on axial compression behavior of FRP-confined concrete. Both normal and high strength concrete (NSC and HSC) were included in his work. The experiment result was based on 30 AFRP-confined concrete specimens, which six of them were monitored for long term shrinkage strain development and the remaining 24 specimens were tested under axial compression loading.

The possible separation of AFRP inner surface and concrete due to shrinkage was simulated by applying a gap up to 0.12mm in radial direction. As a result, the axial strain due to influence of applied gap was significant and increase in strain observed as gap enlarged, in contrary to axial strain, the axial strength enhancement found to be small due to enlargement of applied gap. The major point in this experiment was that the shrinkage strain causes a gap at interface of FRP tube and concrete core, which resulted in interface slip, meaning difference between axial deformation of concrete core and FRP tube.

Guades, et al., 2012 [16], investigated the FRP composite tubes under axial impact. Three major parameters of impactor's mass, number of impacts and incident energy was studied. Specimens were 100mm square FRP pultruded tubes, tested by axially impacting mass. The impacts range was set to 130 up to complete collapse by using a drop-weight type impactor. The height of release was set to be varied in order to produce incident energies in the range of 158 to 635 Joules. As their major finding the number of impacts was found to be the key factor at decreasing stage of incident energy, in addition, incident energy encountered to be the major damage factor at the lower number of impacts, causing the complete collapse of FRP tubes.

As the researches number on FRP tubes grew, the requirement to study the plastic state behavior of material was realized as well. Chung, et al., 2011 [17], studied the nonlinear failure behavior of concrete-filled FRP tubes (CFFT) structures. To study the nonlinearity in failure behavior they used the finite element analysis (FEM) modeling by introducing the layer shell element to represent the FRP tube and fiber beam element for concrete core. Beside FEM, CFFT specimens were tested as well. As the result of comparison between FEM output and experiment results, it was encountered that proposed finite element modeling is reasonable and can predict the initial cracking load level to certain acceptable level of accuracy. Also FEM showed to be accurate on predicting the yielding and ultimate load capacity of member as well.

Xie & Ozbakkaloglu, 2015 [18], studied basalt and carbon FRP tubes filled with concrete under axial compression load. The recycled concrete aggregate (RCA) were used in concrete. The FRP tubes were square and circular in cross section, hence they had experiment variable such as specimen cross-sectional shape, type of FRP, concrete strength and RCA replacement ratio. Total number of thirty-six specimens were included in their axial compression test. They found different interactions between their experimental parameters such compressive strength reduction and ultimate axial strain of FRP-confined concrete enhancement against the increase in RCA content of concrete core. In addition, it was noticed that RCA content increase causes reduction in hoop rupture strain of CFFTs. In comparing the FRP type and cross-sectional shape, it was found that carbon FRP (CFRP) tubes instead of basalt FRP (BFRP) tubes, and circular cross sectional instead of square one develops higher compressive strength, and as a result lower ultimate axial strain.

In 2013, Ozbakkaloglu [19], carried out an experiment to study the behavior of rectangular and square FRP tubes filled with ultrahigh-strength concrete (UHSC), under axial compression. The experiment involved 24 specimens with major parameters of cross-sectional aspect ratio, corner radius and amount of confinement. By using unidirectional carbon fiber sheets, the FRP tubes were manufactured. The UHSC of 108 MPa were used to fill the FRP tubes. The major achievement of his experiment was said to be the ductile behavior of square and rectangular FRP tubes while confined sufficiently. The test output also showed that increase in corner ratio and sectional aspect ratio approaches towards unity, enhances the confinement effectiveness of FRP tubes. It was also notice that UHSC are more sensitive than NSC to the effectiveness of confining tubes.

2.4 Glass Fiber-Reinforced Polymer (GFRP) tubes and bars

Fourth type of FRP (i.e. GFRP) has been studied during the last two decades as well and, in both usage scenarios (e.g. GFRP bars and Tubes) were investigated. The GFRP tube usage recently has sparked more attention of researchers due to its creditability in constructional industry.

In 2012, Zhou, et al. [20], studied the difference in durability of bonds between conventional steel reinforcing bars and GFRP bars in concrete subjected to various environmental conditions. Ninety pullout specimens with five different environmental conditioning media was included in experimental program. The goal was to study the bond strength of steel and GFRP bars with regard to concrete. It was found that environmental conditions such as tap water, alkaline and salt solutions have slight effect on bond strength of GFRP with concrete, even after the ninety days. While acid-chloride solutions proved to have significant effect on bond strength of GFRP. Comparing with steel bar, GFRP bars had similar bond strength in alkaline environment.

For all structures the dynamic analysis is essential and the behavior of elements under dynamic loading with application of FRPs was another field to be studied. Qasrawi, et al., 2015 [6], conducted a research on dynamic behavior of circular concrete-filled GFRP, (CFFTs) as column under impact loading. The main goal of their experiment was said to be the analysis and design procedure development for CFFTs under dynamic loadings such as seismic. Their experiment program involved six specimens which three were CFFTs and the remaining three without GFRP tubes but conventional RC columns with similar dimensions. GFRP tube application to columns, steel reinforcement ratio and the input kinetic energy. As the monotonic test result it was found that GFRP tube enhanced columns energy absorption by 487.5% which is interpreted as 112% increase in flexural capacity and maximum displacement. In the other hand the impact test result showed that steel reinforcement ratio increase from 1.2% to 2.4% resulted in specimens' energy absorbing capacity enhancement from 467% to 1223% compared the RC specimens. As the final output of their work a simplified design procedure of CFFTs under multiple impact loading was outlined by analyzing the experiment result in theory through nonlinear single degree of freedom model.

To study the ultimate load capacity of reinforced concrete-filled GFRP (RCFFTs) with circular cross-section, Wang et al. in 2016 [3], conducted a research on RCFFTs under compressive loading with eccentricity (20 and 40 mm). Four major variable were designed to be investigated such as GFRP tube thickness (4.5 and 6.0mm), eccentricity of axial loading, placement of I-Shape steel at the center of tube and longitudinal reinforcement of concrete core. The GFRP tube thickness proved to be significant and enhances the RCFFT ductility and ultimate load capacity when GFRP thickness is increased. I-shape steel at the core of columns showed to be ideal to increase the ductility and ultimate load capacity of RCFFT. As the noticeable point of their experiment result was the effeteness of GFRP tube on column's ductility and load carrying capacity under eccentric loading. The eccentricity was said to be crucial in decreasing load bearing capacity when it is increased.

S.Moghadassi, et al., 2012 [4], studied the usage of GFRP tube as a structural bracing specially for seismic retrofitting purpose. The GFRP tube as brace was considered with confined concrete core holding a steel member at the center for energy dissipation. The test showed that such as composite brace would result in stiffer structure and control of story floating which are the major challenges in seismic retrofitting. Beside the experimental test, a theoretical analysis by OpenSees package was done on parameters such as energy dissipation, ductility, stiffness and strength of bracings of three-story RC concrete frame. As their final findings it was noticed that composite brace such as GFRP tubes used in RC structures can effectively reduce the earthquake responses of structure without increasing the base shear demand.

CHAPTER 3

FRP COMPOSITE AND ITS USAGE

3.1 Constituent Material of FRPs

FRP composite are blended of high-strength fibers and resin which binds the fibers together to provide the stress and strain transfer between fibers, while fibers are the source of matter strength and stiffness. To gain full composite behavior, fiber’s sheet surfaces are coated with matrix. In some occasions two type fibers are combined such as carbon fiber usages to enhance the modulus, fatigue and strength performance of glass fiber reinforced polymers (GFRP).

The primary function of fiber usage in composite is to resist the major portion of applied load to composite systems. Nowadays a large spectrum of fibers is commercially available based on their strength and stiffness properties, and due to increasing demand of campsites in construction industry, it seems that the domain of variation in composites is widening. Typical FRP manufactured by composite industries are glass (E-glass & S-glass), aramid, carbon and basalt. In the following section all four mentioned above types are presented including with their technical and financial properties.

3.1.1 Glass fibers

The most common reinforcing fiber polymer used in composites are the glass fibers [21]. There is outstanding advantages of this material that makes it as predominant one of composites which are: low cost related to other types of FRPs, high tensile strength, low weight-to-strength ratio, chemical resistance such as resistance against corrosion and alkaline attacks and as final point, it possesses high temperature resistance. To be noticed there are disadvantage as well such as sensitivity to abrasion while handling, low tensile modulus, relatively low fatigue compared to other FRPs and brittleness [21]

Glass fibers are produced by fusing silicates with silica or with potash, lime, or various metallic oxides. The molten mass is passed through micro fine bushings and rapidly cooled to produce glass fiber filaments ranging in diameter from 5 to 24μm. These filaments are then drawn together into closely packed strands or loosely packed roving. During this process, the fibers are frequently covered with a coating, known as sizing, to minimize abrasion-related degradation of the filaments [21].

There are four types of glass composites which electrical glass (i.e. known as E-glass) and structural glass (i.e. known as S-glass) are the most common used fibers. The two left ones, chemical glass (C-glass) and alkali-resistant glass (i.e. known as AR-glass) are less used in FRP industry. Among all four above types, the E-glass is the most economical and widely used reinforcing polymer composite. Due to its efficient strength properties related to cost, the E-glass fiber dominates almost the 90% of all glass fiber used in reinforcing work [21]. Among all glass fibers S-glass has the highest tensile strength and it was originally developed for missile casing and aircraft industry, but because of its high cost and difficulty to produce the usage is mere. Typical properties of all four types composites (i.e. E-, S-, C- and AR-glass) are given in Table 3.1.

Table 3.1 Typical properties of glass fiber types [21]

Glass Type	Density	Tensile Strength		Modulus of elasticity		Dielectric constant	Elongation
	g/cm3	(MPa)	(ksi)	(GPa)	(ksi)	1 MHz @ 72℉	(%)
E-glass	2.60	3445	500	72.4	10,500	6.33	4.8
S-glass	2.49	4585	665	86.9	12,600	5.34	5.4
C-glass	2.56	3310	480	68.9	9,993	6.90	4.8
AR-glass	2.70	3241	470	73.1	10,602	8.10	4.4

3.1.2 Carbon Fibers

Carbon fibers with highest modulus of elasticity compared to the other types of reinforcing fibers, is the second major category of fibers used in composite industry. This type of composites has many boons, such as high tensile-strength-to-weight ratio, high fatigue strengths and high tensile-modulus-to-weight ratios. Apart from this, it has very low coefficient of linear thermal expansion even in some cases negative thermal expansion. The Carbon fibers experience almost zero expansion under the temperatures as high as 300 °C [21]. one of the most essential advantage of carbon fiber is the resistance against corrosion at temperature of below 400 °C, which is quite important in structural engineering discipline. Nevertheless, carbon fiber outstanding advantages, there are weak points as well such as high cost and low impact resistance which limits its usage in routine construction industry.

Although use of high-modulus carbon is not very common, these fibers (> 64,000 ksi or 440 GPa) have been used in a number of structures such as the London Underground subway system [21], one of the oldest and busiest underground railway networks in the world. High-modulus carbon fibers were successfully utilized to strengthen steel beams, cast iron struts, and girders. Table 3.2 compares some typical mechanical properties and costs of commercially available carbon fibers categorized by tensile modulus [21].

Table 3.2 Typical properties of commercially available carbon [21]

Grade	Tensile Modulus (Gpa)	Tensile Modulus (ksi)	Tensile Strength (Gpa)	Tensile Strength (ksi)	Country of Manufacturer	Manufacturer	Cost per Pound
Standard modulus (< 265 GPa) (also known as "high strength")							
AP38-500	228	33,000	3.4	500	Japan	Graphil	$16
AP38-600	228	33,000	4.1	600	Japan	Graphil	$24
AS2	228	33,000	2.8	400	USA	Hercules	
G30-500	234	34,000	3.8	550	USA	Celion	$24
G30-600	234	34,000	4.3	630	USA	Celion	$34
T700	235	34,084	5.3	769	Japan	Toray	
TR50S	235	34,084	4.8	701	Japan		
AS4	241	34,954	4	580	USA	Hercules	$21
T650 '9635	241	34,954	4.6	660	USA	Amoco	$28
AS5	244	35,389	3.5	508	USA	Hercules	
AP38 '96749	262	38,000	5.2	750	Japan	Graphil	
AS6	245	35,534	4.5	653	USA	Hercules	
Intermediate modulus (265-320 Gpa)							
MR40	289	41,916	4.4	638	Japan		
MR50	289	41,916	5.1	740	Japan		
T1000	290	42,000	6.9	1002	USA	Amoco	$326
42-7A	290	42,000	5	725	USA	Celion	$59
T650 '9642	290	42,061	4.8	699	USA	Amoco	$53
T40	290	42,061	5.7	819	USA	Amoco Toray	$55
G40 '96600	296	43,000	4.3	620	USA	Celion	$45
AP43 '96600	296	43,000	4.5	650	Japan	Graphil	
G40 '96700	296	43,000	5	720	USA	Celion	$47
IM6	303	43,946	5.1	740	USA	Hercules	$48
IM7	303	43,946	5.3	769	USA	Hercules	$53
IM8	309	44,817	4.3	624	USA		
XIM8	310	45,000	5.2	750	USA	Hercules	
High modulus (320-440 Gpa)							
XMS4	331	48,000	2.8	400	USA	Hercules	
HMS4	338	49,023	3.1	450	USA	Hercules	
MS40	340	49,313	4.8	696	Japan		
HMS	341	49,458	1.5	220	USA	Graphil Hysol	
AP50 '96400	345	50,000	2.8	400	Japan	Graphil	$55
HMG50	345	50,038	2.1	300	USA	Hitco OCF	
G50 '96300	359	52,069	2.5	360	USA	Celion	$58
AP53 '96650	365	53,000	4.5	650	Japan	Graphil	$100}

3.1.3 Aramid fibers

Aramid fiber is a synthetic organic polymer fiber (an aromatic polyamide) produced by spinning a solid fiber from a liquid chemical blend. Aramid fiber is bright golden yellow and is commonly known as Kevlar®, its DuPont trade name. These fibers have the lowest specific gravity and the highest tensile strength-to-weight ratio among the reinforcing fibers used today. They are 43% lighter than glass and approximately 20% lighter than most carbon fibers. In addition to high strength, the fibers also offer good resistance to abrasion and impact, as well as chemical and thermal degradation. Major drawbacks of these fibers include low compressive strength, degradation when exposed to ultraviolet light and considerable difficulty in machining and cutting [21].

Table 3.3 shows that Kevlar®29 is nearly identical to Kevlar®49, with the exception of tensile modulus. The specific modulus in Table 3.3 is simply the modulus of the material divided by the material density, and is a measure of the stiffness of a material per unit weight. Materials with high specific moduli provide the lowest deflection for the lowest weight. Along with its tendency to yield in compression, Kevlar® exhibits a higher elongation at failure than glass and carbon fibers, resulting in a tougher and less brittle fiber than other commonly used reinforcing fibers. Kevlar® has been extremely successful in a variety of applications including premium tire cords, marine cordage, military body armor, oxygen bottles, high-pressure rocket casings, propeller blades, and in engine cowlings and wheel pants of aircraft, which are subject to damage from flying gravel [21]

3.1.4 Basalt fibers

Basalt fiber is a unique product derived from volcanic material deposits. Basalt is an inert rock, found in abundant quantities, and has excellent strength, durability, and thermal properties. The density of basalt rock is between 175 and 181 lb/ft3 (2800 and 2900 kg/m3). It is also extremely hard –8 to 9 on the Mohs Hardness Scale (diamond = 10) [21]. Consequently, basalt has superior abrasion resistance and is often used as a paving and building material.

While the commercial applications of cast basalt have been well known for a long time, it is less known that basalt can be formed into continuous fibers possessing unique chemical and mechanical properties. The fibers are manufactured from basalt rock in a single-melt process and are better than glass fibers in terms of thermal stability, heat and sound insulation properties, vibration resistance, as well as durability. Basalt fibers offer an excellent economic alternative to other high-temperature-resistant fibers and are typically utilized in heat shields, composite reinforcements, and thermal and acoustic barriers [21]. Table 3.3 compares some typical mechanical properties of basalt fibers with Kevlar®, high-strength carbon, E-, and S-glass. It can easily be seen that the basalt fibers have the highest tensile strength compared to the other fibers.

Table 3.3 Comparative fibers mechanical properties[1] [21]

Property	Basalt High-Strength Carbon		Kevlar© 29	Kevlar© 49	E-glass	S-glass
Fiber density						
(lb./in.3)	0.098	0.063	0.052	0.052	0.092	0.092
(g/cm3)	2.7	1.75	1.44	1.44	2.55	2.49
Break elongation						
(%)	3.1	1.25	4.4	2.9	4.7	5.6
Tensile strength						
(ksi)	702	450	525	525	500	683
(GPa)	4.84	3.1	3.62	3.62	3.45	4.71
Specific tensile strength						
(10^6 in.)	7.2	7.1	10.1	10.1	5.4	7.6
(10^7 cm)	1.8	1.8	2.5	2.5	1.4	1.9
Tensile modulus						
(ksi x 10^3)	12.9	32	12	18	10	12.4
(GPa)	89	221	83	124	69	85
Specific tensile modulus						
(10^8 in.)	1.3	5.1	2.3	3.5	1.1	1.4
(10^8 cm)	3.3	12.6	5.7	9	2.7	3.5

3.1.5 Comparison of fiber properties

Fig. 3.2 presents a simple cost comparison for the most common types of fiber reinforcements. The prices are based upon continuous tows of each fiber type. It shows that E-glass is the most economical type of fiber available today. In addition, the figure illustrates that higher modulus carbon fibers are the most expensive. Fig. 3.3 compares the tensile modulus (stiffness) of typical fibers with that of traditional metals used in engineering applications. The bar chart shows that ultra-high-modulus (UHM) carbon

[1] The specific modulus in Table 3.3 is simply the modulus of the material divided by the material density, and is a measure of the stiffness of a material per unit weight.

fiber has a modulus three times that of steel and standard modulus carbon fiber has a modulus twice that of aluminum.

Consider the tensile strength of common fiber reinforcements when compared to that of titanium, steel, and aluminum (Fig.3.1). The tensile strength of the fibers considered here far exceed that of aluminum by as much as 400%. For the most part, carbon, Kevlar®, and fiberglass also exceed the strength of steel by as much as two times. The specific strength of all of the fibers surpasses that of the metals by as much as ten times. Carbon, Kevlar®, and fiberglass fibers offer superior strength at a lower weight when compared to metals [21].

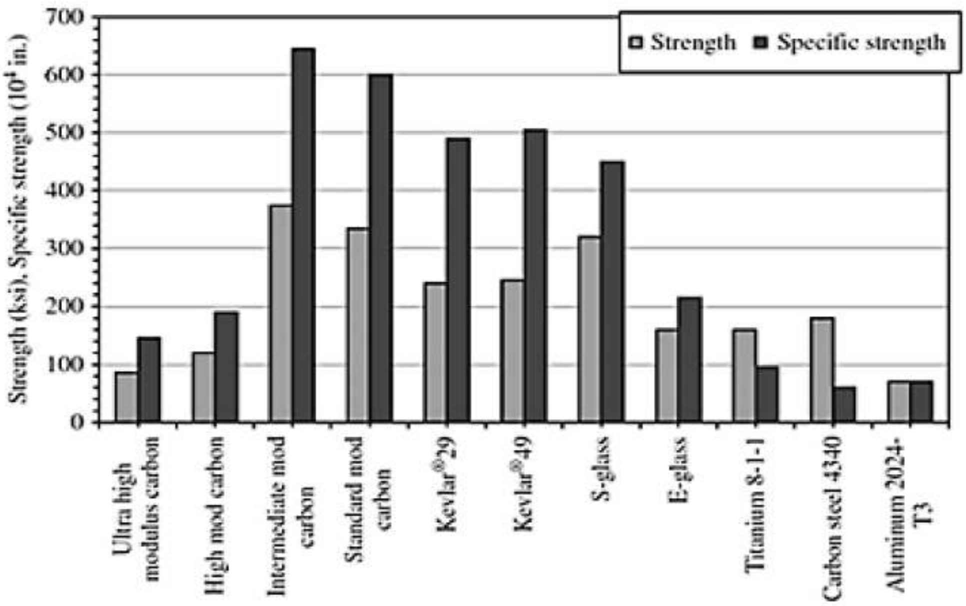

Figure 3.1 Tensile strength of typical fiber sand metals [21].

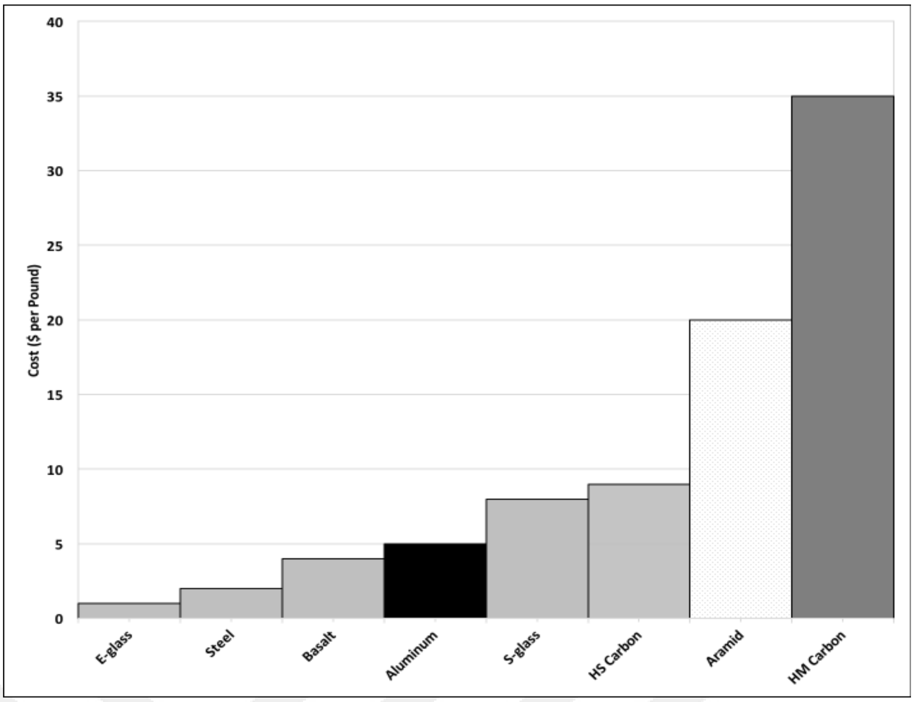

Figure 3.2 Relative ROM (rough order of magnitude) raw material costs (Source: Advanced Composites Inc.,2003, Plant of Insulation Materials, Ltd, 2003).

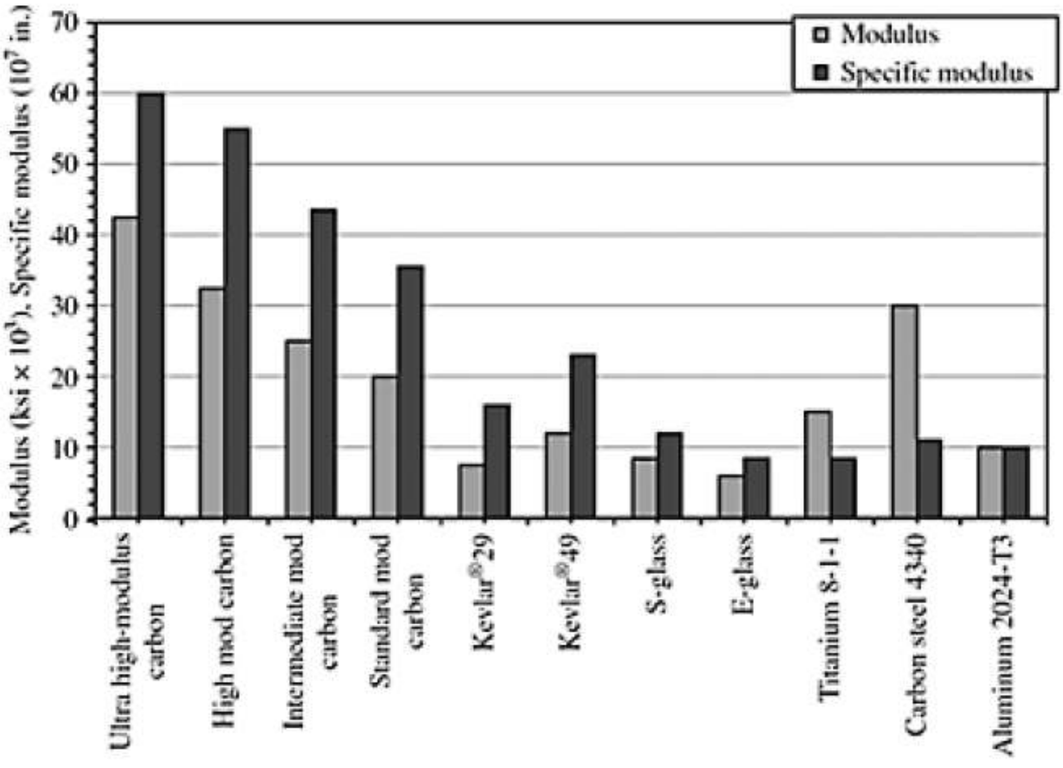

Figure 3.3 Tensile modulus (stiffness) of typical fibers and metals [21].

3.2 FRP composite Usage

Although FRP composites usages in civil engineering structures has happened since 1980s, but since then it became a conventional material and a large number of projects have been implemented to guarantee the effective usage of FRP composites in rehabilitation and even newly built structures member such as bridge deck, buildings columns and etc. The usage of FRP composites in rehabilitation of reinforcing and Prestressed concrete has been proven complete usefulness. In retrofitting, reinforcing and Prestressed structure's members such as columns, beams, slabs and walls, the FRP fibers application has demonstrated the great usefulness and effectiveness. Another type of structures which have been subjected to the application of FRP for strengthening purpose are storage tanks and chimneys. In general, the FRP fibers can be applied to the existing structures to enhance and improve any or several of following properties:

- axial, flexural, or shear load capacities;
- ductility for improved seismic performance;
- improved durability against adverse environmental effects;
- increased fatigue life;
- stiffness for reduced deflections under service and design loads [21].

The common way of FRP composite application is to work it out manually using the hand-impregnation technique. This technique which is known as hand lay-up method, involves placing successive layers of resin-impregnated reinforcement in aimed position by hand. To make sure that there isn't any entrapped air under the resin layer, squeegees and grooved rollers are used, which also helps to densify the FRP structure.

To avoid potential delamination failures from occurring, a denser FRP must be manufactured by removing nearly all air voids within the composite. Two methods that are capable of accomplishing this task are vacuum-assisted impregnation (vacuum bagging) and pressure bag molding (pressure bagging). Vacuum bags apply additional pressure to the composite and aid in the removal of entrapped air, as shown in Fig. 3.4. Pressure bags also invoke the use of pressure but are considerably more complex and expensive to operate. They apply additional pressure to the assembly through an electrometric pressure bag or bladder contained within a clamshell cover, which fits over a mold. However, only mild pressures can be applied with this system [21].

During the last 20 years, FRP composites has covered a large number of field application. Although, it was the Japan who took the first place to use it, but the application of FRP fibers in rehabilitation and retrofitting followed by Europe, North America and recently middle east countries such as Turkey. The popular usage of FRP in North America has been in rehabilitation of bridges to enhance and improve the seismic resistance, repair and retrofitting the parking structures, strengthening of unreinforced walls, and rehabilitation of various structures such as tunnels, chimneys and industrial structures such as liquid retaining tanks [2]. Typical example of such as applications are shown in Fig.3.4 and Fig. 3.5.

Figure 3.4 Hand lay-up process used to strengthen reinforced concrete slab [21].

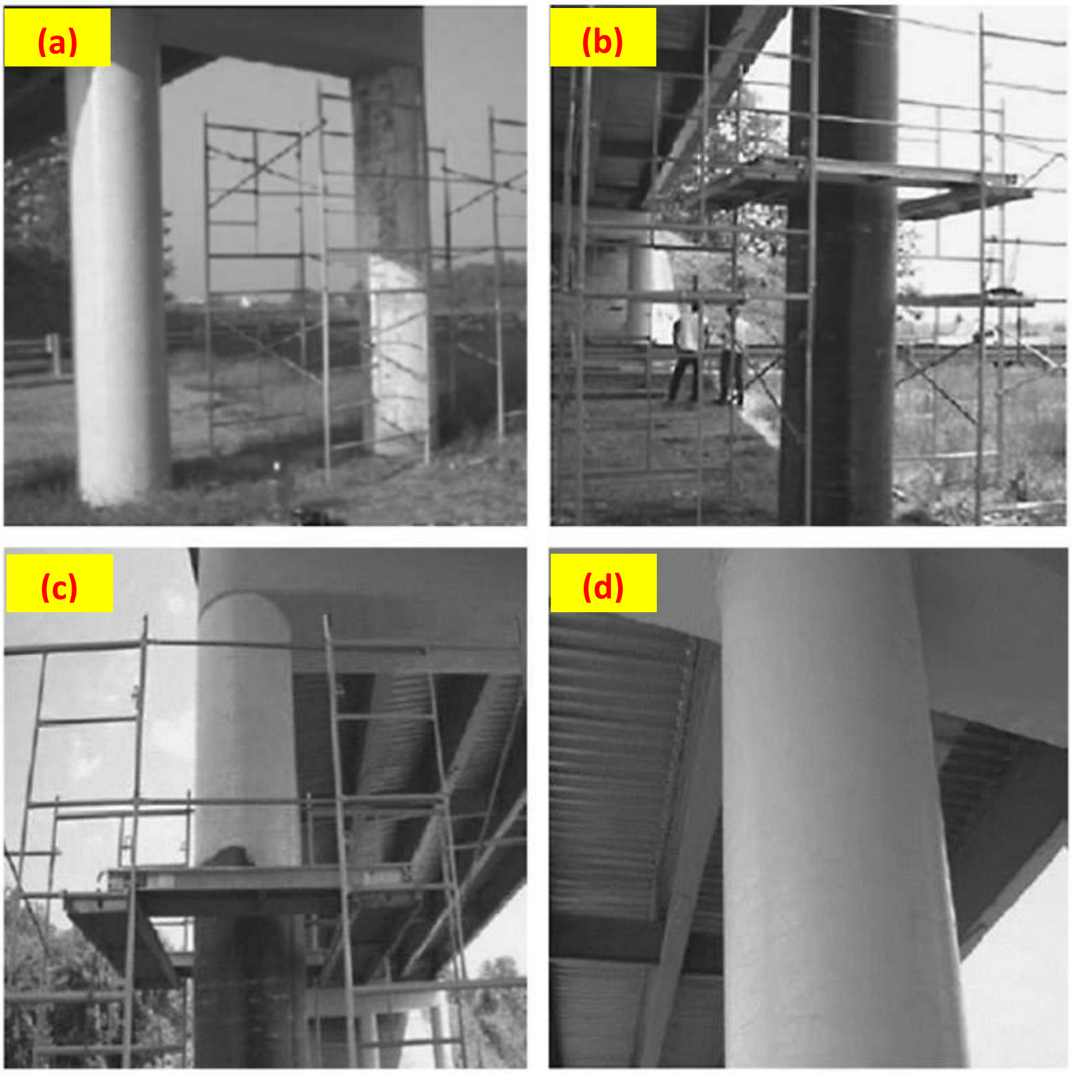

Figure 3.5 (a) Column after cleaning; (b) Column wrapping with carbon tape, followed by coating of inorganic resin;(c) During final coating application; (d) Column after coating [21].

3.2.1 FRP bridge application

One the most outstanding application of FRP is in bridge's deck construction and since late 80s many decks have been constructed in the world by using the FRP composites. In the United States, federal technology transferred initiatives taken to utilize composite manufacturing capacities by the military and aerospace industries have led to the proliferation of FRP use in the bridge industry. Some companies capitalized on the potential of the transportation market and helped advance the use of FRP on bridge structures. Based on NCHRP Report 564 (2006), more than 100 bridges with FRP bridge decks have been built since the mid-1990s, and they are currently in good condition in general. The number is still increasing with the maturing of the technology [22].

Primary benefits of FRP decks include durability, light weight, high strength, rapid installation, lower or competitive life cycle cost, and high-quality manufacturing processes under controlled environments. Compared with cast-in-place concrete decks, FRP bridge decks typically weigh 80% less, can be erected twice as fast, and have service lives that can be two to three times greater. Although, based on initial in-place material cost, FRP bridge decks typically cost two to three times more than a conventional deck, life cycle costs, light weight, and rapid installation tend to be features that justify the use of FRP bridge decks.

FRP bridge decks commercially available at the present time can be classified according to two types of construction: sandwich and adhesively bonded pultruded shapes. For sandwich constructions, cellular geometries are the most efficient use of core materials for weight-sensitive applications. Due to the ease with which facesheets and core materials can be changed in manufacturing, sandwich construction presents great flexibility in designing for varied depths and deflection requirements. Facesheets of sandwich bridge decks are primarily composed of E-glass mat or roving infused with polyester or vinyl ester resins.

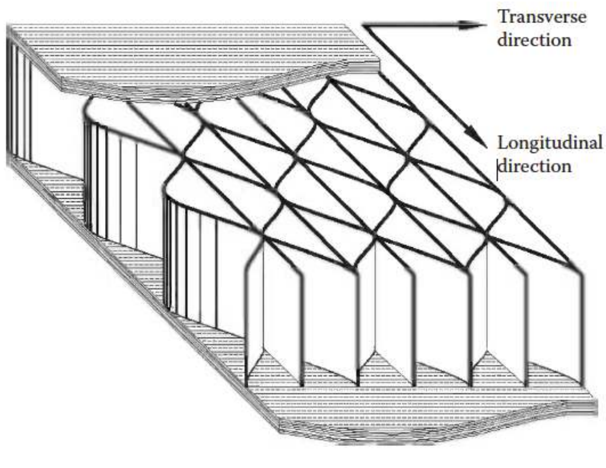

Figure 3.6 HFRP panels with sinusoidal core configuration (KSCI), [22].

Current core materials are rigid foams of thin-walled cellular FRP materials. Fig.3.6 displays a honeycomb fiber-reinforced polymer (HFRP) panel, with sinusoidal core configuration in the plane extending vertically between face laminates, which was introduced for highway bridge decks by Plunkett (1997). More recently, a sandwich panel with I-beam-type core configuration (Fig.3.7) was developed by ZellComp, Inc. This system was installed on the Morrison Bridge in Portland, Oregon, and is the largest FRP bridge deck in the United States to date.

Adhesively bonded pultruded shapes can be economically produced in continuous lengths by numerous manufacturers using well-established processing methods. Design flexibility on this type of deck is obtained by changing the constituents of the defined shapes (such as fibers and fiber orientations), but changes in geometry are very difficult to implement. Several decks constructed with pultruded shapes are shown in Fig. 3.8. The pultruded shapes are typically aligned transverse to the traffic direction over supporting stringers. Each deck design has advantages in terms of stiffness, strength, and field implementation. In laboratory testing, the observed failures in such decks are generally by local punching shear and crushing or large-scale delamination of the shapes constituting the cross section. [22]

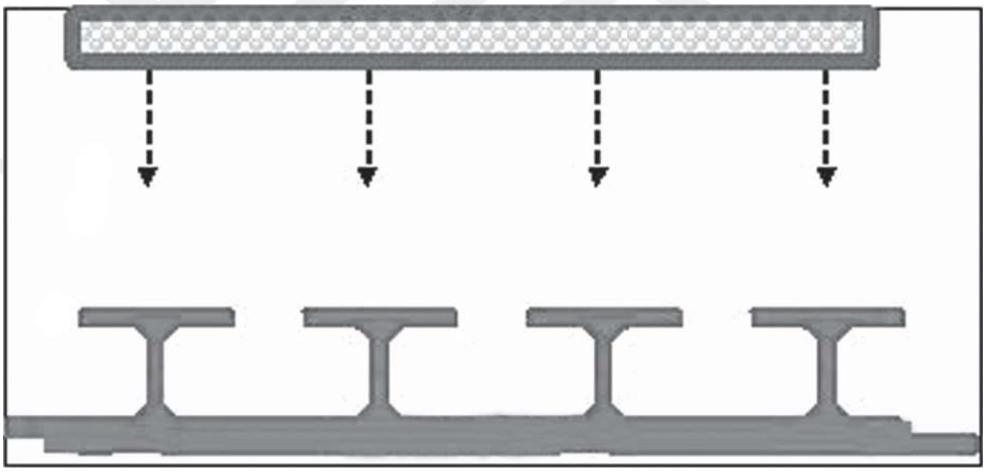

Figure 3.7 ZellCompe decking system [22].

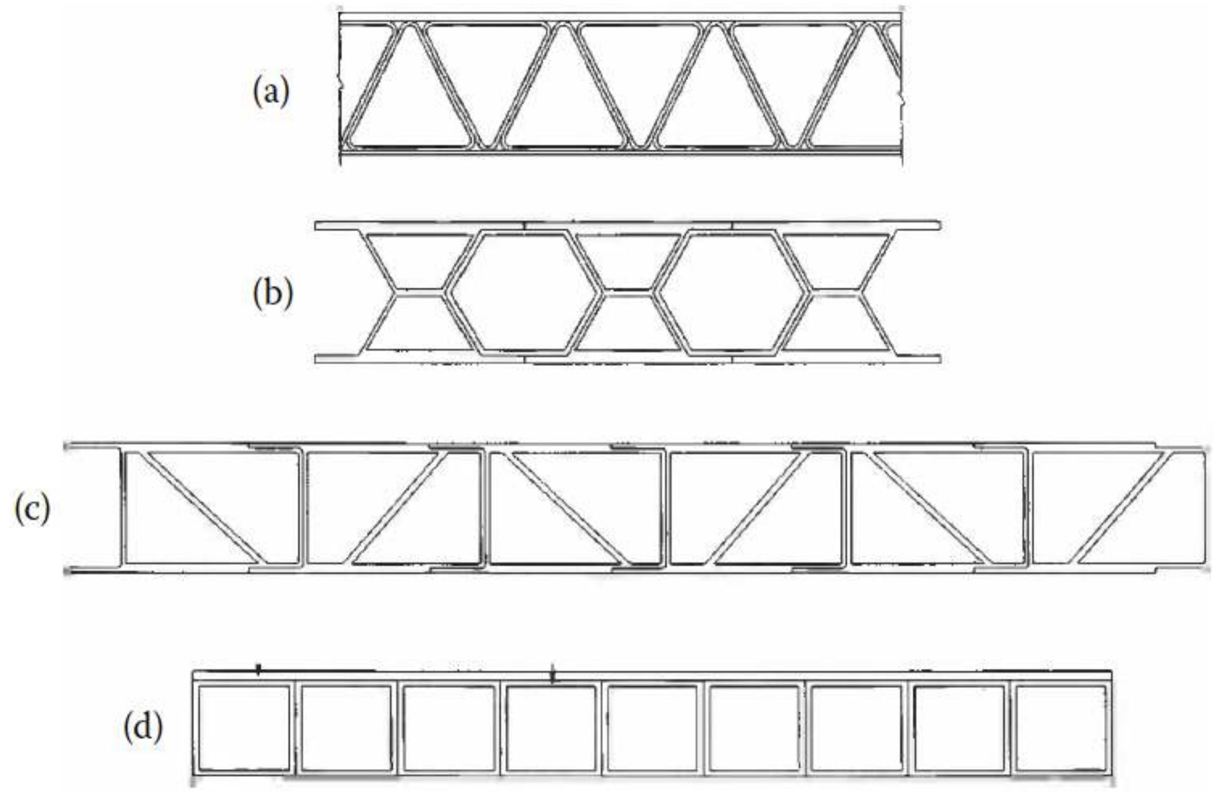

Figure 3.8 FRP decks produced from adhesively bonded pultruded shapes: (a) EZSpan (Atlantic Research), (b) Superdeck (Creative Pultrusions), (c) DuraSpan (Martin Marietta Materials), and (d) square tube and plate deck (Strongwell), [22].

3.3 GFRP Tubes Usage

GFRP tubes has been in use since past five decades and its technology has been busted by high demand in industrial, gas and oil and water engineering fields. The progress of GFRP tube usage and its boons in construction industry, made these composite tubes to become a popular and conventional material during last two decades. Pipe application of GFRP material has shown to be the dominant, in FRP composite application specially in industry, O&G (i.e. Oil and Gas), and water engineering. The general advantages of GFRP pipes used in industry, O&G and water fields are listed as:

- **Lightweight Structure**
  Fiberglass material is light and strong, means it has high strength-to-weight ratio.
- **Longevity**

Fiberglass life cycle is beyond of alternative materials. This durability characteristic makes it economical and environmentally friendly.

- **Resilience**

  Fiberglass is corrosion resistant against corrosive environments such as H2S, soils and salt water.

- **Efficiency**

  By providing better structure (e.g. hydraulic) performance compared to steel and concrete, effectively reducing the life cycle cost. That is fiberglass is considered as cost effective material.

- **Versatility**

  Fiberglass is applicable in various assemblage modes and complex configuration. Due to its flexibility compared to steel, it its capacity to withstand high temperature, pressure, load and harsh chemical resistant, fiberglass usage covers various mode and configurations [23].

3.3.1 GFRP Industrial Application

GFRP pipes usage in oil rich economics and industrial countries has experienced growth during the last years. The GFRP pipe utmost are applied in industrial plant piping, cooling water networks, mining and petrochemical plants. In industrial plant piping systems, the GFRP pipes application involves sugar refineries all pipe network, resin plant's pipe system and aluminum production plants [23]. In gold and phosphate minds exploration process, water supply lines are provided by GFRP pipes. Petrochemical plants also use the GFRP pipes for all pipe systems such as circulating water, process piping, chemical lines, fire water and cooling systems.

As an example of GFRP pipe application in industry field, Qatar Petroleum has carried out the world largest GFRP pipe network for mega project of water network in Ras Laffan Industrial City [23]. For typical GFRP industrial application see the Fig. 3.9.

3.3.2 GFRP O&G Application

As corrosion poses major challenges for conventional pipe material in high-pressure upstream applications, the excellent non-corrosive characteristic of fiberglass has made it the clear material of choice. In particular, fiberglass piping systems have repeatedly demonstrated their superiority for usage on ships and vessels, offshore platforms, and in the dredging industry.

The GFRP usage in O&G industry covers a vast range, from line pipes of production to transmission pipe lines of O&G, involving refinery piping as well as downhole tubing and well casings. The high strength and corrosive resistance made the GFRP to be a favorite material offshore platform and even underwater piping systems (Fig. 3.9).

Figure 3.9 (a) GFRP pipes underground application (O&G and Wastewater application); (b) GFRP industrial application; (c) GFRP underwater application (Bridge, O&G platforms..); (d) GFRP marine application (vessels, submarine…) [23].

3.3.3 GFRP Water Application

Water and wastewater industry has been emerged as a growing industry and its demand for high pressure, flexible and corrosive resistance products has been increased day by day since 20th century. The GFRP which meets gently the required quality of water and wastewater industry, has become the common partner of piping systems of private and public in these fields.

Fiberglass pipes provided up to 6m diameter and high strength has eased the construction of wastewater network in cities and industrial mills (Fig. 3.9). The GFRP piping in power generation plants and district cooling and heating water system has become a common tool for companies and government worldwide. The range of GFRP pipes application in water and wastewater is long, but here are some examples of it [23]:

- Water Transmission and Distribution

  Fiberglass pipes are light and strong as mentioned before, so it provides high strength-to-weight ratio which is essential in transportation and installation cost as well as durability.
- Infrastructure and Municipal

  The GFRP pipes are applicable in surface drainage, sewer and storm water discharge networks as well as irrigation lines.
- Desalination and Power

  All pipe systems that are within power or desalination plants such as salt water systems (intake and discharge/outfall), cooling water systems, chlorination lines, flu gas desulphurization(FGD), firefighting networks and process and utility piping.
- Water Treatment

  GFRP pipes are used for all pipe systems related to pumping stations and treatment plants.

CHAPTER 4

METHODOLOGY

4.1 Test Specimens

A total number of ten specimens (Table 4.1) were provided for this experiment. The GFRP square tubes fabricated by E-type fibers were chosen and eight specimens were filled with SCC (Fig. 4.1). Another two specimens of short length (i.e. 300mm) but different in thickness (i.e. 4.5 and 6.0mm) were tested empty to compare the GFRP tube independent compressive strength. The specimens were designated as “Length of tube-size of tube-f_c of SCC”, (e.g. 60-10-32). Tubes are commercially available in Turkey and no crack or damages were present at the time casting due to transportation or fabrication processes.

Table 4.1 Test specimen dimensions and designations

No	Length (mm)	Size (mm)	f_c (MPa)	Sample Designation
#1	600	100	32	60-10-32
#2	600	100	50	60-10-50
#3	600	75	32	60-7.5-32
#4	600	75	50	60-7.5-50
#5	300	100	50	30-10-50
#6	300	100	32	30-10-32
#7	300	75	50	30-7.5-50
#8	300	75	32	30-7.5-32
#9	300	100	0	30-10-E
#10	300	75	0	30-10-E


Figure 4.1 Test Specimens

4.2 GFRP tube

Glass fiber-reinforced polymer of E-type Produced in Turkey was used. The specification and dimensions of tubes are given (Table 4.1). Tubes were cut by machine to 30 and 60 cm length (Fig. 4.2 (a)) and due to cutting operation the nominal lengths were slightly effected; hence the actual lengths of tubes were measured again to be considered in axial strain calculations (Table 4.2). Tube inner and outer surfaces were clean and smooth which couldn't impose any extraordinary slip or roughness. The cutting machine was cooled-functional one, which was using the cooled liquid in process in order to prevent any significant increase in temperature which could affect the tubes (Fig. 4.2(b)).

Table 4.2 Actual and Nominal GFRP tubes' dimensions

No	Nominal Length (mm)	Nominal Size (mm)	Actual Length (mm)	Thickness (mm)
#1	600	100x100	600	6
#2	600	100x100	594	6
#3	600	75x75	600	4.5
#4	600	75x75	594	4.5
#5	300	100x100	300	6
#6	300	100x100	300	6
#7	300	75x75	300	4.5
#8	300	75x75	292	4.5
#9	300	100x100	300	6
#10	300	75x75	292	4.5

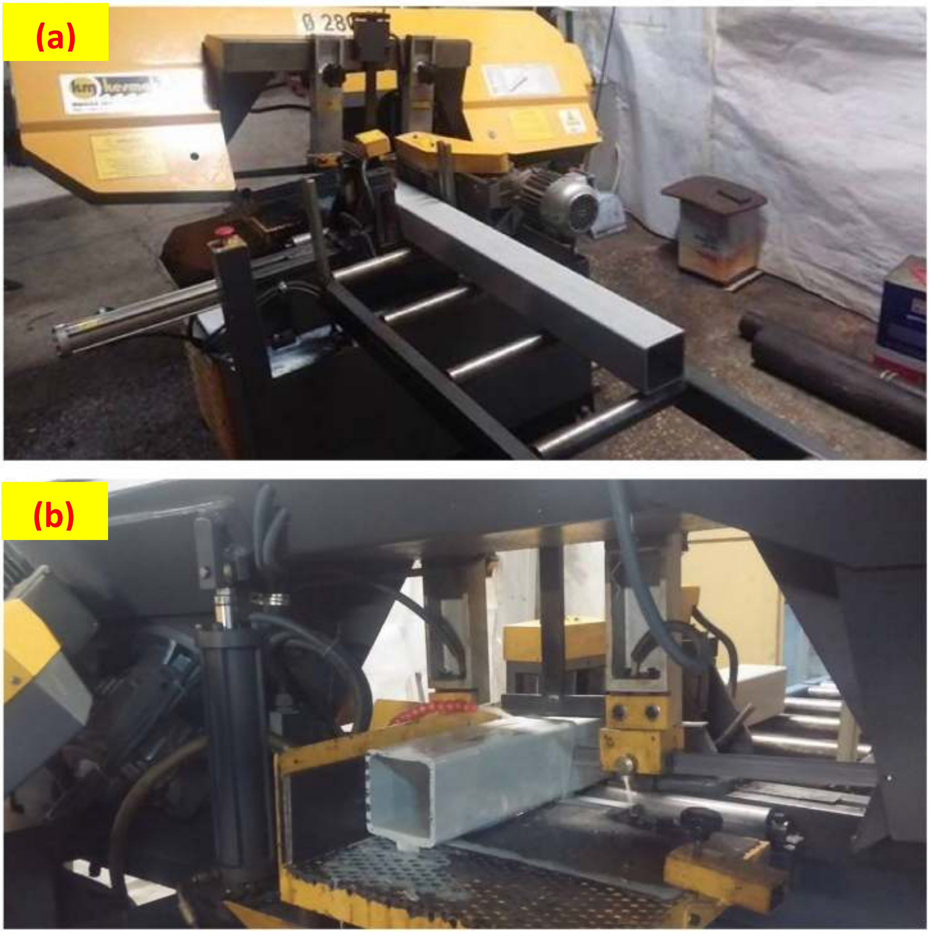

Figure 4.2 Cutting process GFRP tubes by machine (a) & (b)

4.3 Glass panels attachment

To prevent any leakage of concrete paste during the casting and curing process, all specimens were attached at the bottom a glass plate of 4mm thick (Fig. 4.3). The glasses were stake to bottom of specimens by silicon glue to block any air penetration from bottom as well and keep the specimen stable during the casting process.

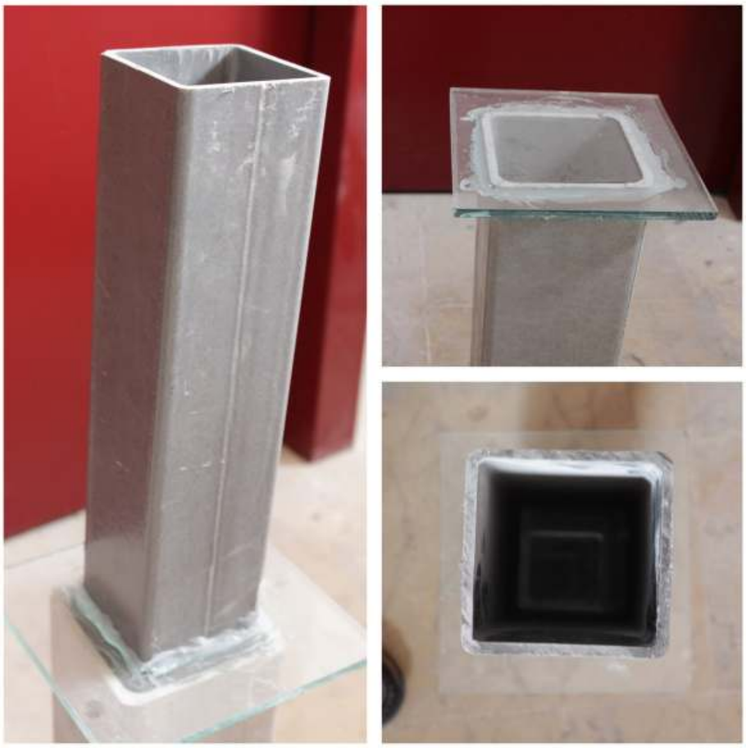

Figure 4.3 Glass panel attachment of GFRP tubes

4.4 SCC Mix-design

As one of experiment major variables f_c of concrete core was selected normal and high strength concrete of 32MPa and 50MPa respectively (Table 4.3). Aggregate of maximum 2mm diameter size (Fig. 4.4) were selected due to the self-compacting criteria of concrete based on ACI guidelines [2]. The samples of aggregates plus fly ash and silicon fume is shown in Fig. 4.4, it is to be noticed as well that cement which used in this experiment program was normal cement (i.e. Type N).

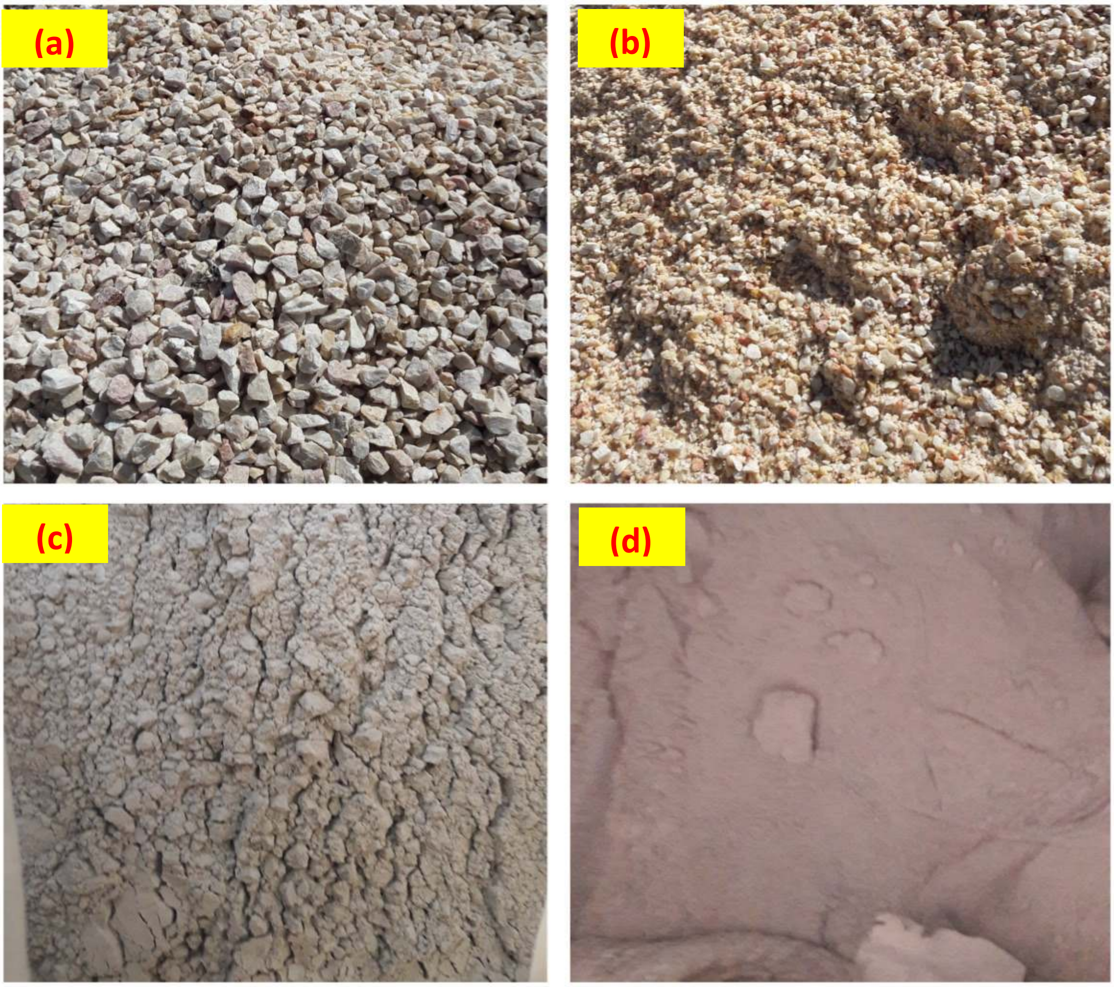

Figure 4.4 Concrete mix composition, (a): Gravel, (b): Sand, (c): Silicon Foam, (d) Fly Ash

Table 4.3 Concrete mix design

Material	Mix Design (Kg/m3)	
	32MPa	50MPa
Gravel	730	700
Sand	900	950
Cement	300	400
Silicon Foam	0	50
Fly Ash Admixture	250	150
Water	200	150
Superplasticizer	4	5

4.5 Casting and curing

The casting process of specimens took place inside the laboratory with room temperature (i.e. 18 to 22 °C). A mechanical mixer with 400-liter capacity of used. For each mix the Slump-Flow test according to the ACI specification [2] was applied to control the SCC behavior of concrete mix before casting. No vibrator and hand shacking or hummer tools were used to place the concrete, due to self-compacting behavior of concrete. The addition of superplasticizer increased the viscosity of concrete and increase the wet bond between aggregates, hence concrete possessed the Slump-Flow requirement.

For both 32 MPa and 50 MPa mix, numbers of cylinder and cubic simples were casted to be used a reference for the concrete strength after period of curing. After casting, specimens were place in a room with mechanically stabilized temperature of 20°C for 24 hrs. then all specimens with concrete cubic and cylinders were placed in a plastic-pool (Fig. 4.5) filled with tap water with room temperature for 28 days.

Figure 4.5 Specimens curing process

4.6 Epoxy layer application

Epoxy type "TeknoBond 200 TIX" produced in Turkey was applied as a layer to provide smooth surface on both side of columns (Fig. 4.6). The roughness of surface was caused by casting and in some case cutting of tubes. The thickness of epoxy layer was thin (i.e. 0.5 to 2 mm), therefore was ignored in load capacity of columns measurements. The epoxy layer application to both ends of columns was to provide a leveled surface in order to distribute the axial compressive load uniformly.

Figure 4.6 Epoxy layer application

4.7 Test configurations

A normal hydraulic-powered compressive machine was used to test the specimens (Fig. 4.7(a)). Two pairs of longitudinal and lateral LVDTs (Linear Variable Differential Transformer) gauges were provided to measure the axial strain (deformation) and lateral buckling (lateral deformation). Two metallic clambers where installed to keep the LVDTs constantly, but not to interfere in specimen’s deflection movements, there for the clambers had now interface touch ever after deflection of

GFRP tube edges (Fig. 4.7(b)). Additional stick papers were numbered on specimens to provide better visualization for photographing purpose.

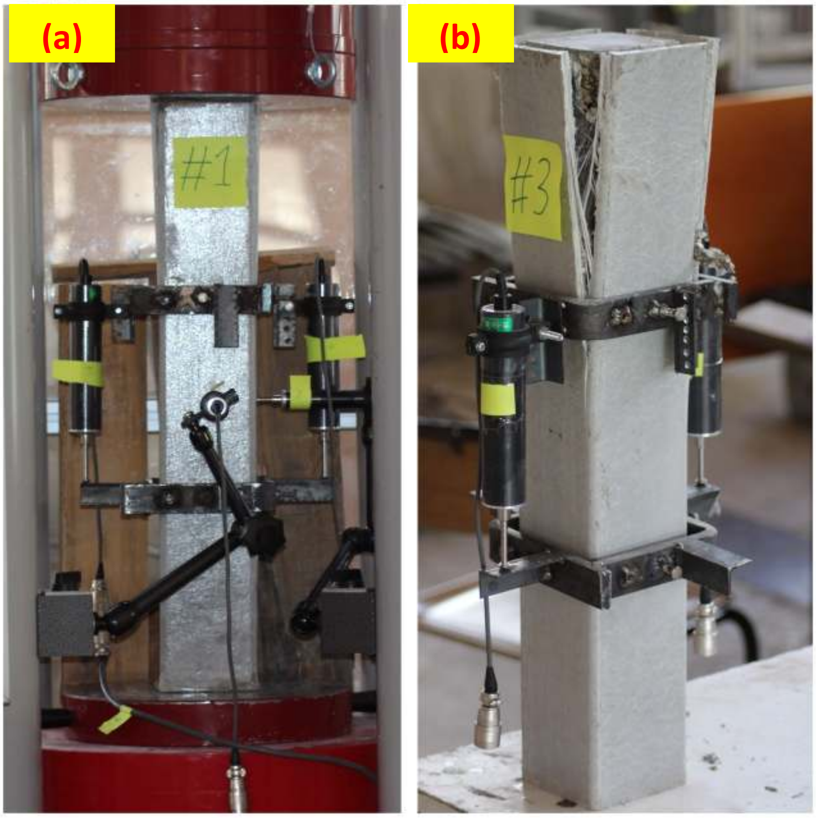

Figure 4.7 (a)&(b)-LVDTs installation and test configuration.

4.8 Procedure’s summery

- GFRP tubes were cut by machine into 30 and 60 cm length.
- A square glass plate of 4mm thick was attached by silicon glue to prevent any penetration of cement paste or water out of column’s core.
- Concrete mix was prepared and Slump-flow test was applied before casting the specimens.
- Specimens all were placed after 24 hrs. in plastic bunker of water fully submerged inside the water for 28 days. Water temperature was adjusted to normal room temperature.
- Epoxy layer of 0.5-2.0 mm thick was applied at both ends of specimens to provide smooth surface for uniform load distribution.
- Compressive machine was equipment by two pairs of LVDT, one for axial strain and the second one for lateral deformation measurements.

Note: The LVDT for lateral deflection measurement was realized to be useless as it gave us fake data due to the tube and concrete separation under axial loading. This separation resulted from weak bond between the inner surface of GFRP tube with concrete core, that why the measurements of lateral deformation or buckling wasn’t analyzed in this paper and neglected.

CHAPTER 5

DISCUSSION ON RESULT

5.1 Result

Test result plotted in Fig. 5.1 to Fig. 5.3 are in force versus strain. The reason force was used instead of stress is because of composite structure of GFRP cross-section. The thickness of tubes was thin which deflected before real deflection of column so the stress calculated at these stages were including the miscalculation of real cross-section. In contrast to this pitfall, load carrying capacity of column was more reliable due to fact that weather tube contributes to surface or not, the columns load bearing capacity is measured correctly.

The curves that represents the result are uniaxial force v_s axial strain, rather than stress v_s strain. The reason for this adaption is heterogeneous surface of specimen's cross-section. As it is obvious the cross-section is composed of GFRP tube with thickness of 4.0 and 6.0 mm respectively for 10 and 7.5 cm square tubes, and concrete core cross-section. Although the contribution of GFRP tube to load carrying capacity of specimen under uniaxial compression load is meager, but in ultimate strength and plastic ranges it significantly effects the failure and load carrying capacity. So to be more accurate stress v_s strain plot mode has been neglected, and force v_s axial strain curves has been provided to interpret the mechanical performance of GFRP composite columns under uniaxial compressive loading.

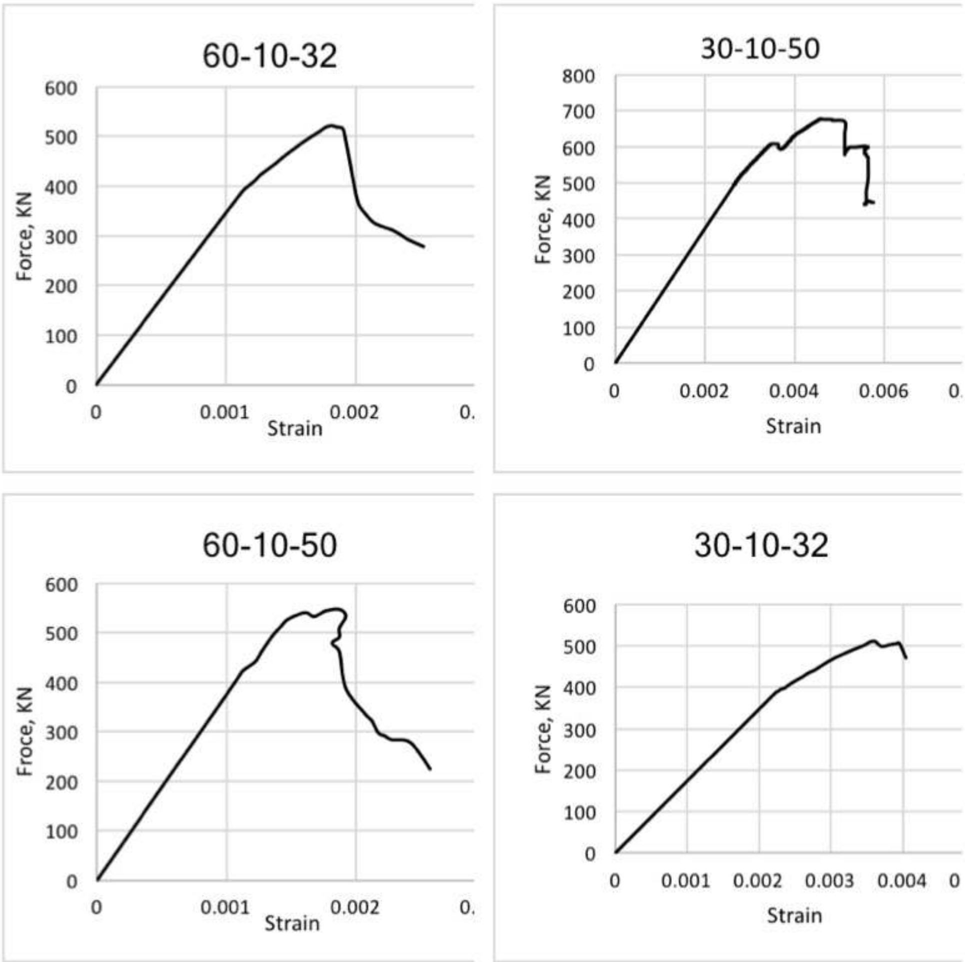

Figure 5.1 Test result graphs, Force Vs Axial Strain

Although The lateral deformation and buckling status was also part of test measurements, therefore two LVDTs were installed, as shown in Fig. 4.7(a), But as it mentioned before, the data found to be fake and inaccurate. This test pitfall was due to the weak inner surface bond between the GFRP tube and concrete core, as it resulted in separation of tube from concrete and it deflected dramatically under the axial load independently, while the lateral deflection in concrete core was at its initial stages. Due to this fact the buckling data was neglected in this paper and only axial load carrying capacity and axial strain were studied as its curves have been given in the following section.

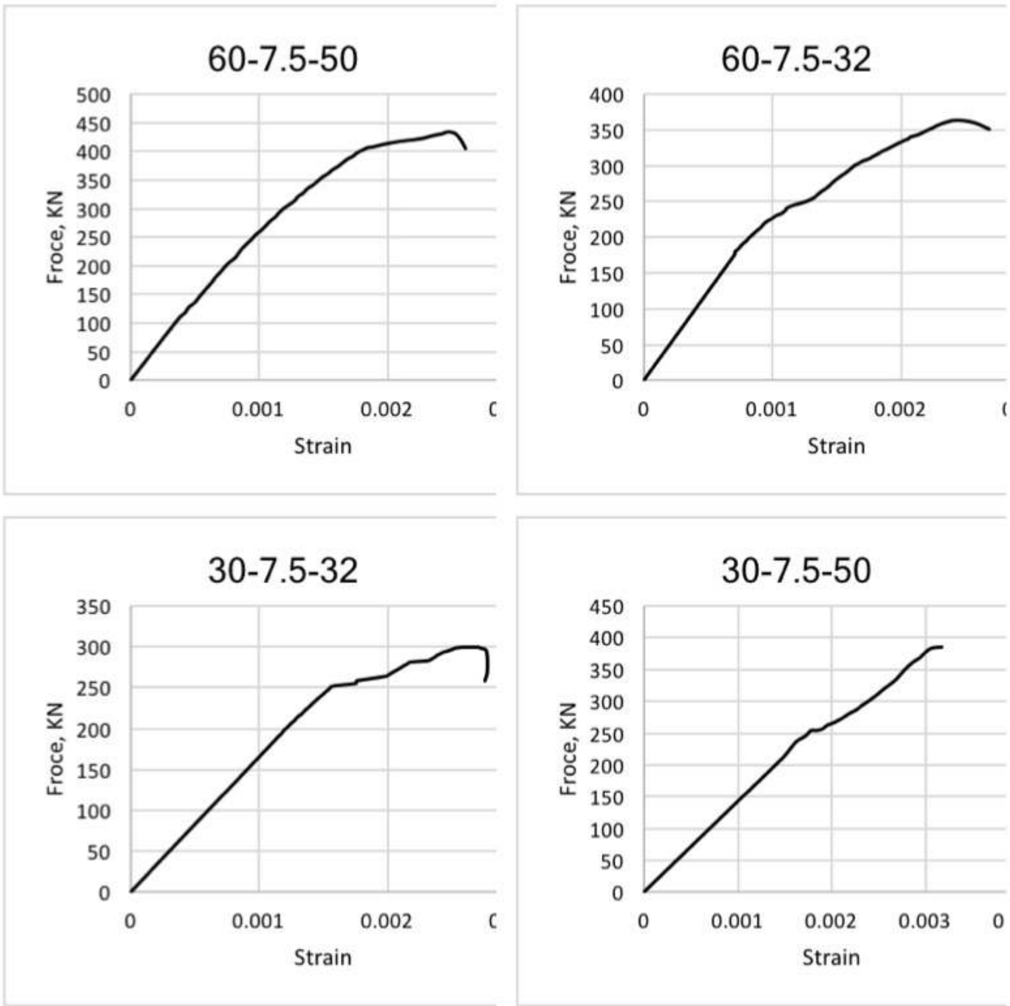

Figure 5.2 Test result curves, Force Vs Axial Strain

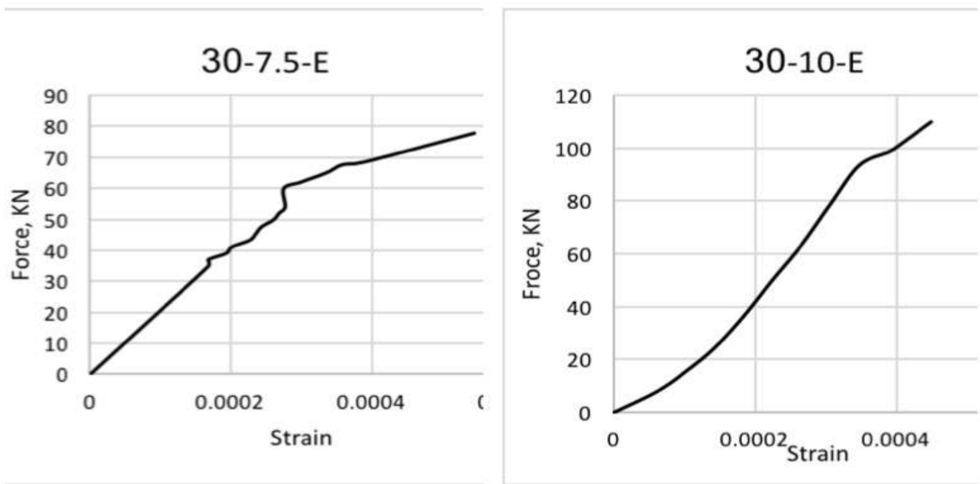

Figure 5.3 Test result curves, Force Vs Axial Strain

5.2 Parameters Comparison and Analysis

5.2.1 Compressive Strength

As the axial compressive strength of GFRP concrete-filled square tubes was the main goal of current experiment, the following graphs compare the effect of filling concrete (i.e. SCC) compressive strength of GFRP column's load carrying capacity. The contrast of load carrying capacity of specimens showed that enhancement in load carrying capacity was higher in 32MPa with regard of 50MPa SCC filled tubes, while the cross-section and length of columns were kept identical (Fig. 5.4). Specimen filled with 32MPa SCC, enhanced the load carrying capacity of column by 20 %, while with the same dimension specimen filled with 50MPa, resulted in 11 % increase in load carrying capacity of columns. The SCC compressive strength almost had no effect on the strain (i.e. energy absorption capacity) of column (Fig. 5.4).

The compressive strength of tubes was also affected by the thickness of tubes, which were 4.50mm and 6.0mm respectively for the 7.5x7.5 and 10x10 cross-section. But this enhancement of compressive strength was found to be not significant, comparing to the contribution of tubes thickness on ductility of column. The specimens with higher thickness of tubes showed better ductile behavior than the lower ones.

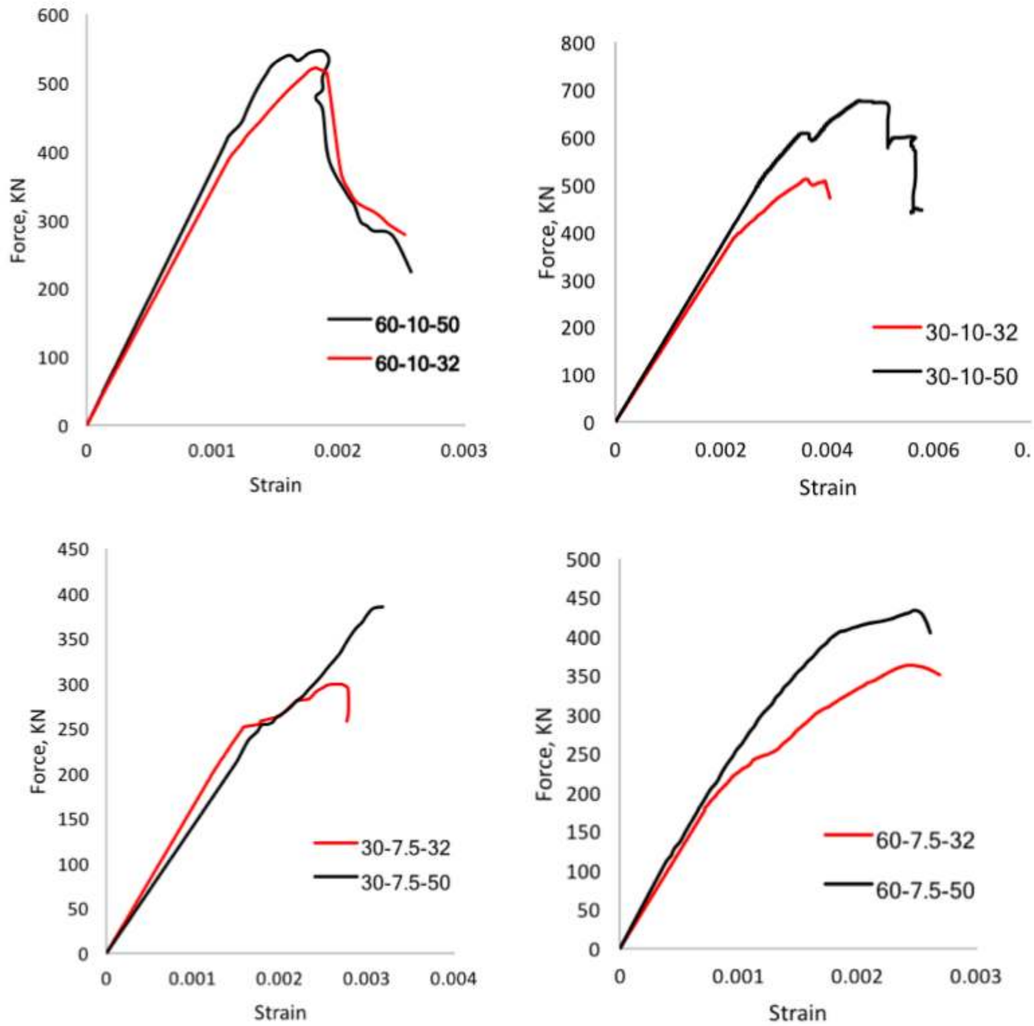

Figure 5.4 Compressive Strength Comparison

5.2.2 Length Parameter

Two length of 300 and 600 mm specimens were compared to investigate the length effect on axial compressive load carrying capacity of GFRP columns. The test result showed that the length increases the load carrying capacity in low quantity but it occurs specially in elastic range of columns behavior as it is shown in Fig. 5.5. The length effect was more obvious and important for energy absorption of columns in strain terms, it significantly reduced the axial strain which means less ductile failure behavior.

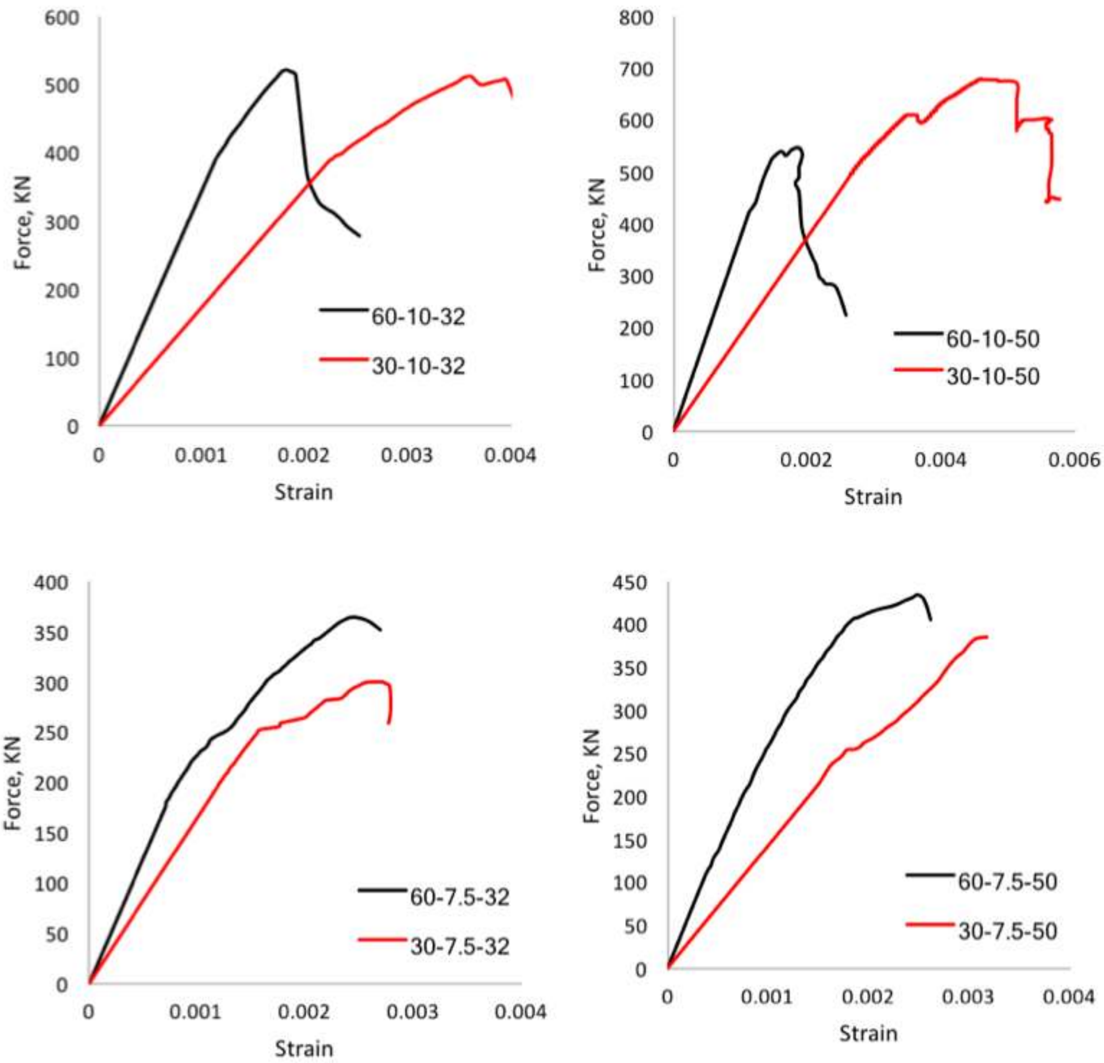

Figure 5.5 Length Comparison

5.2.3 Cross-Section Parameter

Specimens cross-section was the third parameter of conducted experiment. For all specimens with square cross-section two size was selected (i.e. 75x75mm and 100x100 mm). It was found form test result that the cross-section of specimens hadn't significant effect in axial strain of GFRP concrete-filled tubes under monotonic axial compressive loading (Fig. 5.6). In other hand the load carrying capacity of columns was enhanced as it was expected due to the column's cross-section enlargement. It addition, to above two points, it was encountered was well that the cross-section of specimens had significant effect on failure mechanism resulting for bigger cross-section more ductile behavior than the smaller ones (Fig. 5.6).

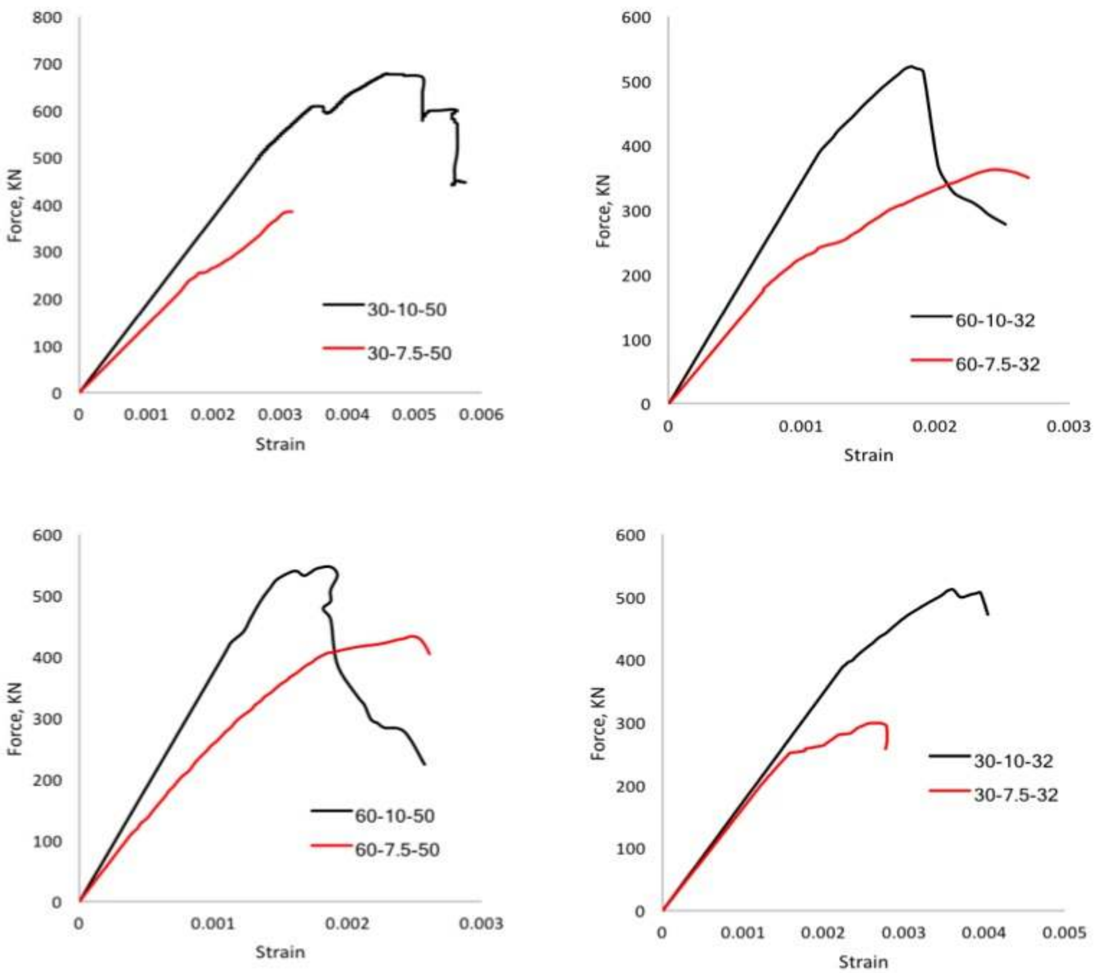

Figure 5.6 Cross-Section comparison

5.3 Failure mechanism

Although the load carrying capacity of GFRP square tubes concrete-filled under uniaxial compressive loading was the major goal of this paper, nevertheless failure of such as specimens in column application was a major concern as well. The behavior of GFRP composite columns in failure stage and its fracture mechanic study was as valued as the mechanical performance of column in terms of load carrying capacity. The finding of this paper in failure mechanism are:

a. The FRP flexibility criteria allows it to deform without any crack at the initial stages but which is different from concrete rigid behavior at the same situation. This difference of flexibility causes the FRP tubes to deflect prior to concrete and as the result, concrete carries the applied load and that why the concrete failure occurs before the FRP rupture. In fact, the lateral strain in concrete cause hoop tensile stress in FRP tube which is confining the concrete core and preventing the lateral deformation, therefore the rupture of FRP tube is after the concrete core's one, because of its differences in modulus of elasticity (Fig. 5.7(a)-(c)).

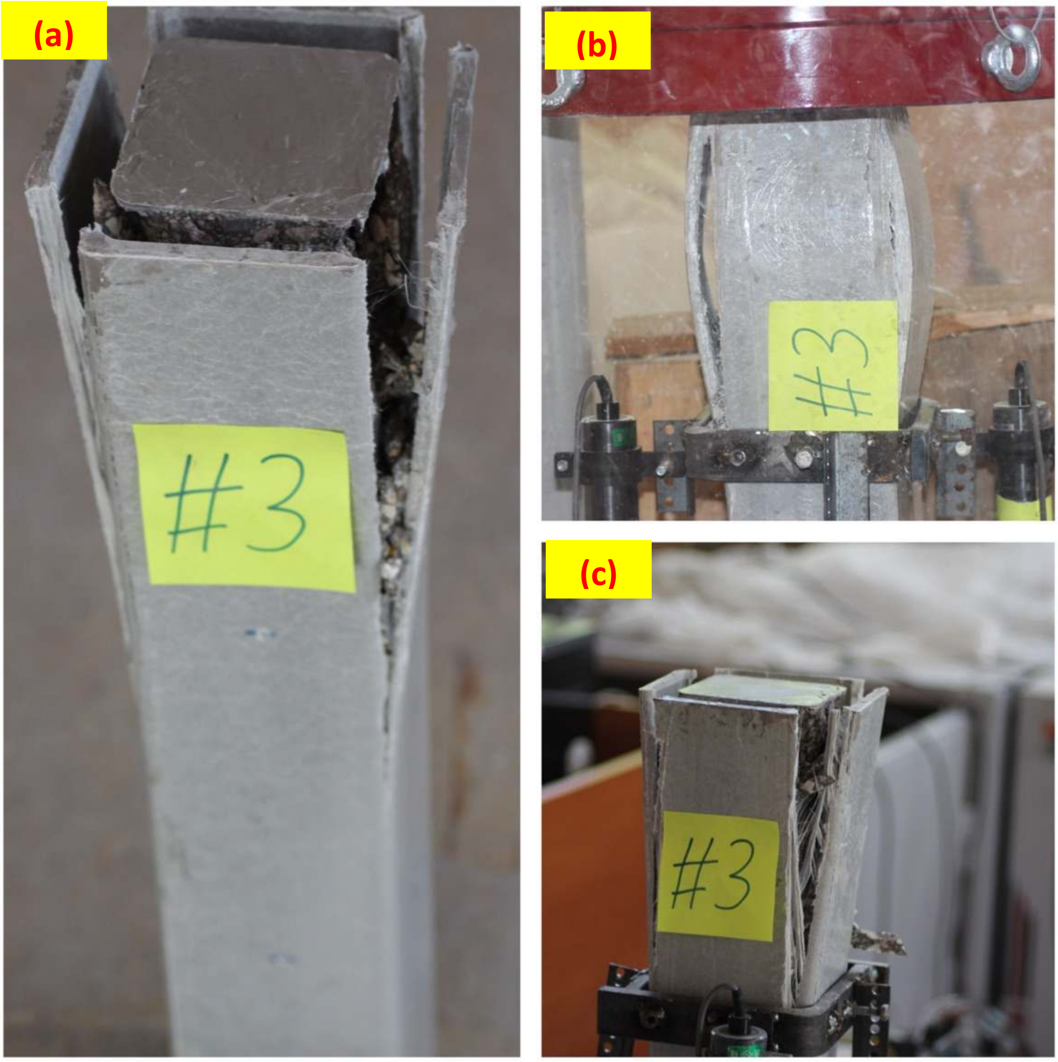

Figure 5.7 (a&c) failure of tube and concrete, b-Tube separation prior to concrete

b. Due to the low confinement bending stiffness of FRP square tubes, the stress distribution in cross section is none uniform, and higher hoop tensile stress is developed in FRP tube, hence the FRP tube tears up at the corner. The FRP tube rupture is intensified by the fact that the filaments of fiberglass are used in vertical direction rather than looped around the column. This filament arrangement weakens the tensile strength of FRP tube subjected to the tension force developed by concrete compressive force reaction. In other term the concrete core exerts an outward force on its perimeter as a compressive reaction to the FRP tube's wall which is the hoop tensile force on FRP tube, hence due to higher tensile stress in corner than sides ($\frac{\sigma_f}{\sigma_r} < 1$)[24] the tube failure occurs at corners (Fig. 5.8(a)-(d)).

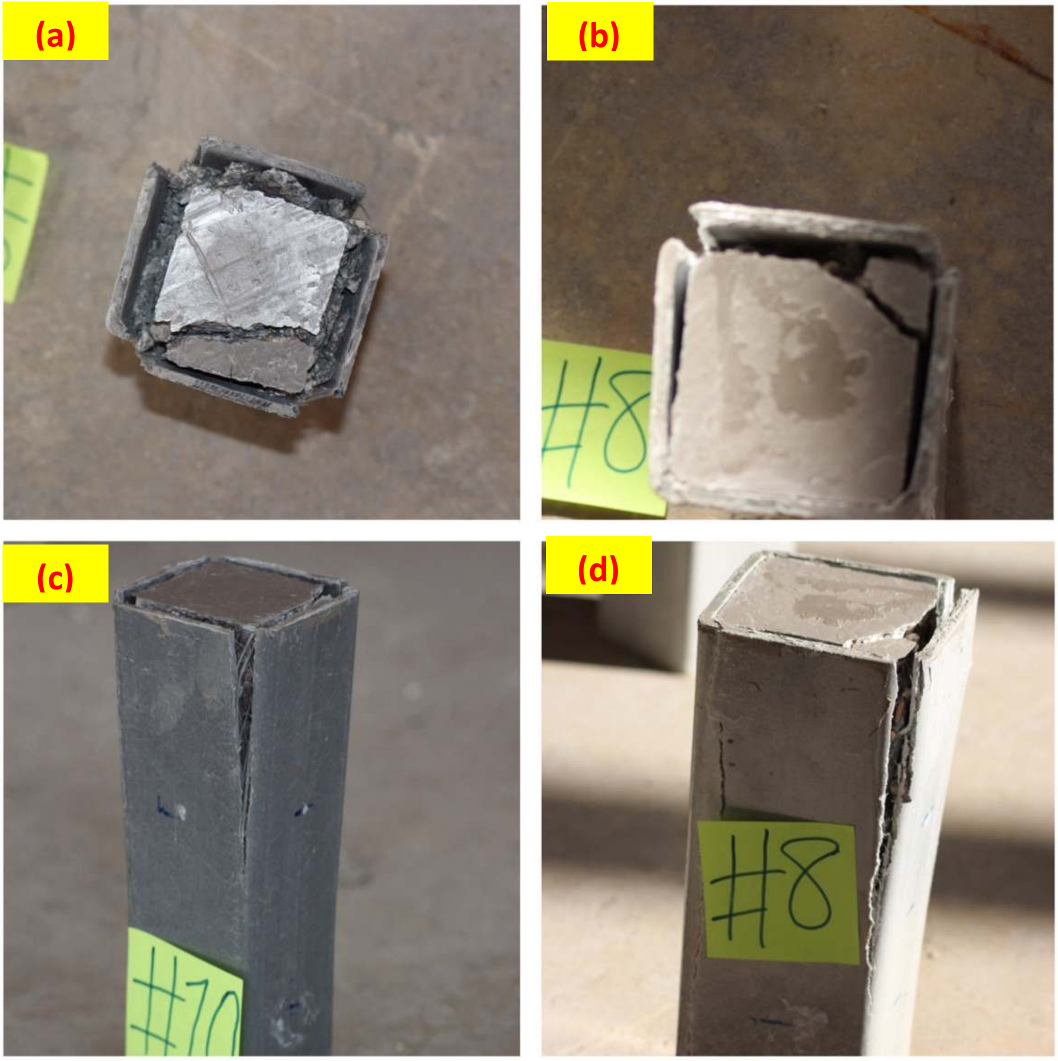

Figure 5.8 (a)-(d)- corner failure governing the complete collapse

c. Since natural bond between FRP tube interface and Concrete core almost nonexistent, the bond strength between FRP tube and concrete core is the second reason why failure accelerates at perimeter much more than the central zone of concrete (Fig. 5.9(a)). The concrete core tension stress zone develops at perimeter in parabolic pattern between corners, and this stress results to tensile stress between concrete and tube which pulls apart the tube from concrete core, as the result the separation between columns core and FRP tube take places before concrete cores reaches its rupture failure.

Hence the second columns failure factor is weakness in bonding strength between FRP tube and concrete core (Fig. 5.9(b)).

Figure 5.9 (a)-weak interface bond, (b): Tube and concrete separation

d. The cracks and final complete collapse in FRP tubes is in vertical path, whether it is empty or filled with concrete core. This failure mechanism is first because of constitutive filament used in FRP tube production in vertical and parallel mode which results in weak transvers strength of tube, and tension force developed from volumetric deformation of concrete core. The lack of horizontal filament in tube composition, weakens the bond between adjacent strap of filament as a result the lateral load bearing capacity of FRP is lower than the vertical, therefore the cracks in FRP tubes and following rupture is in vertical pattern (Fig. 5.10(a), (b)).

Figure 5.10 (a)-Vertical crack in filled specimen, (b)-Vertical crack in empty specimen

e. Filled FRP tube failure is due to longitudinal deformation rather than buckling, while in empty FRP tube is the opposite case. An empty FRP tube failure is due to weak buckling capacity of FRP material and is failure case is similar to steel under compression. In the other hand filled FRP tube with concrete core, behaves as a short concrete column which has the high strength against buckling (Fig. 5.11(a), (b)).

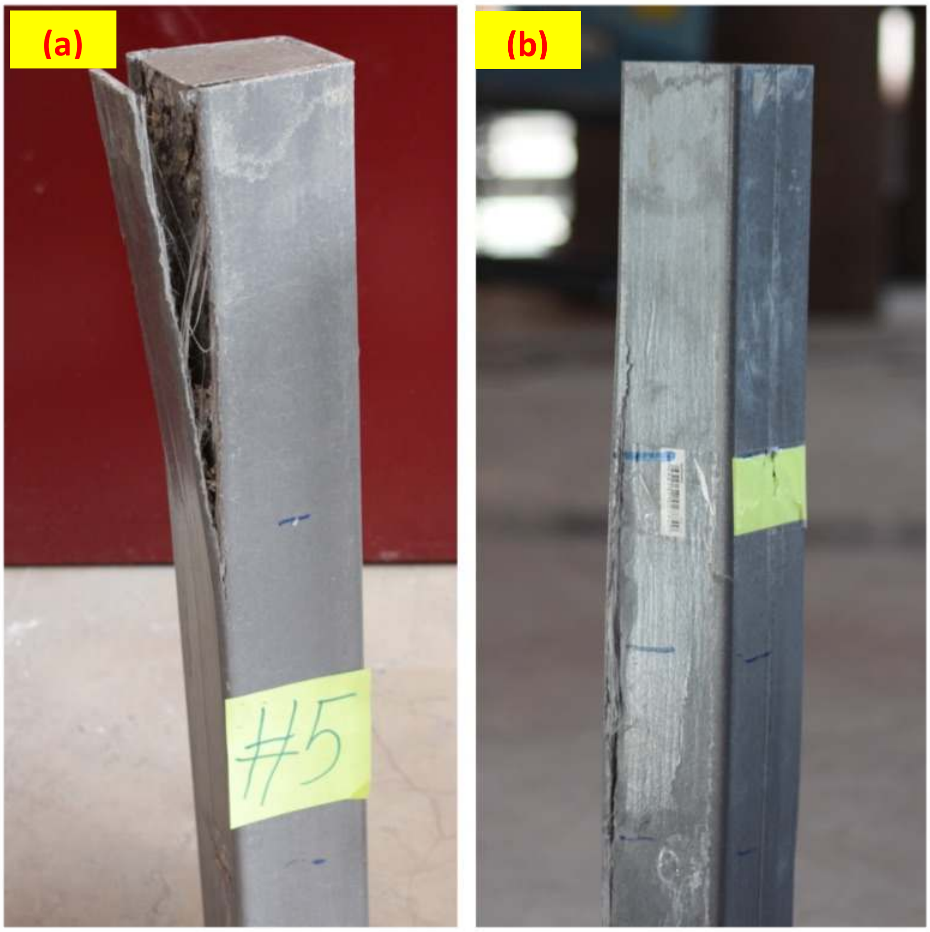

Figure 5.11 (a)- Outward rupture in filled specimen, (b)-Inward failure in empty specimen

f. The GFRP tube functions as permanent formwork, and due to corrosion resistance it protects the structure member against harsh environmental effects. At the failure stages also the tube prevents the concrete core to spread and blowout which in collision type failure it can be dangerous for surrounding inhabits or material. In general, the GFRP tube acts as a box to keep collected the separated parts of concrete even after complete failure.

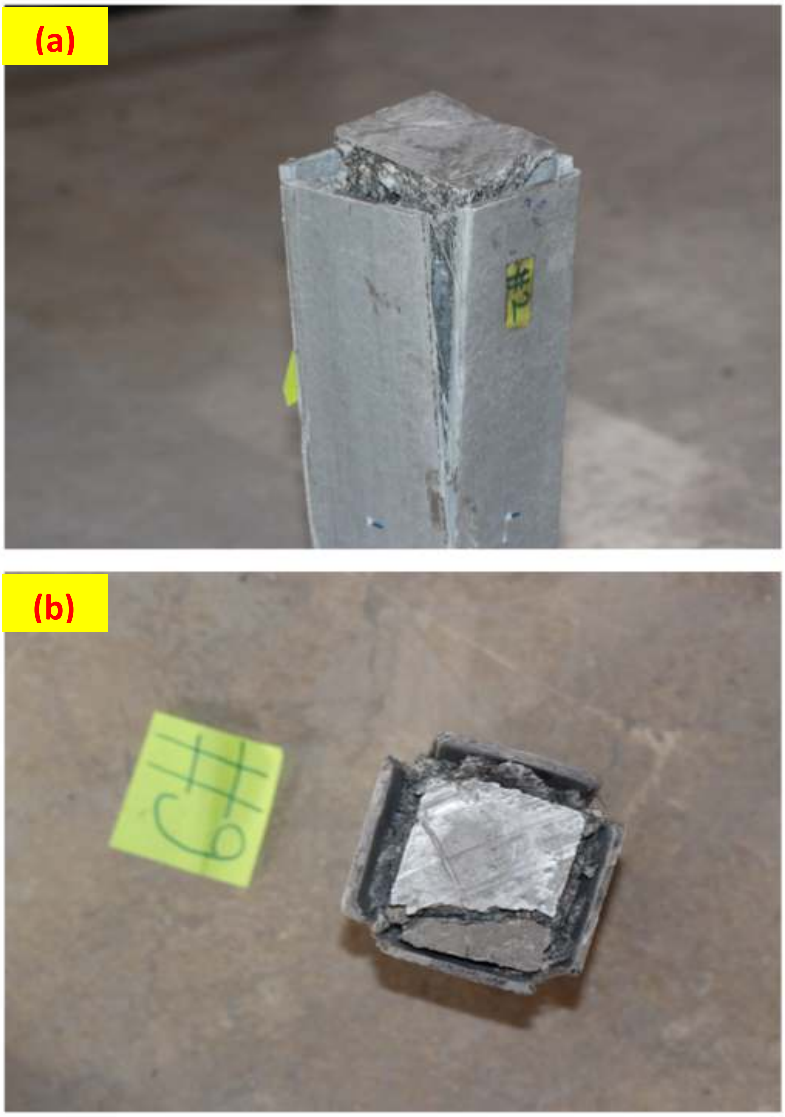

Figure 5.12 (a) & (b)- Concrete core complete failure without blowout

In general, the failure mechanism of GFRP columns were encountered to be brittle and similar to the RC columns which experience the intense crack at ends. Although The GFRP confinement of concrete does enhances the compressive strength and improves the mechanical performance of the column, but it doesn't absorb much energy as it does in steel jackets mode. The cracks found to be deep and pebbles of crushed concrete found to be poured in tube.

CHAPTER 6

CONCLUSION AND FUTURE WORK

6.1 Conclusion

This experiment on GFRP-square-tubes SCC-filled and literatures review on similar work has shown that GFRP composites would be the future efficient material in construction field and specially in structural part of it. The column application of this study has prevailed that concrete confinement by GFRP, significantly enhances the mechanical performance of columns. In addition, the function of GFRP square tubes as permanent formwork can facilitate the construction process and better environmental protection for the concrete columns. The GFRP square tube SCC-filled test results has showed an increase up to 20 % in axial compressive strength, compared to the none confinement concrete specimens of the identical strength. Confinement provided by GFRP tube has not only functioned as a contributor to the enhancement in load carrying capacity, but also given a good protection to the environment even after the collapse of column, this was due to the GFRP fiber resistant in plastic stage to enclose the concrete pebbles from pouring out of column after the failure. The fracture and failure mechanism has been encountered to be brittle rather than ductile, this phenomenon was observed to be caused by brittle behavior of concrete core without the steel reinforcement and as well as the brittle behavior of GFRP fiber in failure stage which tore out at the corners suddenly. The ultimate axial stain was considered to be not effected significantly by GFRP tube confinement to the concrete. The ultimate axial strain was almost the same as in normal concrete elements, this similarity was due to the very high GFRP elasticity compared to the concrete (i.e. Young's modulus of 70+ Vs 17-25, respectively for GFRP and concrete). The concrete core compressive strength comparison resulted that the lower the compressive strength, the higher will be the amount of enhancement in compressive strength of column, this means that the GFRP confinement contribution to the higher concrete strength is less than the lower one, in terms of ultimate compressive strength enhancement.

6.2 Future Work

The study of GFRP square tube filled with SCC under uniaxial compressive loading has simulated further researches work to be done on this composites to ensure better columns performance in future construction. Although many points can be mentioned to be considered in the future studies on the same type, but there are two major recommendations for future work:

a. The usage of SCC in GFRP tubes is an excellent step which was done in this paper work, but as it was mentioned the brittle behavior of concrete core overwhelmed the meager ductility of FRPs, and columns behaved under loading in complete brittle manner. It is suggested that in future work steel fiber to be used rather than conventional steel reinforcement, in order to cope this shortage. The steel fiber filaments can provide enough ductility which effectively increase the energy absorption of GFRP composite columns, as a result the axial ultimate strain will be increased.
b. The corrosion poses tremendous threat to the concrete and steel rebar used in RC elements. One of the great advantages of GFRP composites is the resistance against corrosion. The usage of GFRP tubes as a complete jacket for concrete elements provides full protection against the acid or alkali attacks in offshore and onshore construction sites. This GFRP composites ability can immensely enhance the durability of structural element which significantly would reduce the life cycle cost of structures and improve its strength in harsh and hazardous environments. Due to this important characteristic of GFRP composites, the acid and sulfate medium is strongly recommended to be included in future studies in order to study the durability of GFRP composite elements.

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