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CHAPTER 1

INTRODUCTION

1.1 Background

During the past earthquakes in Pakistan many existing reinforced concrete (RC) structures were destroyed due to the inadequacy of proper seismic design. It is found that the main failure of columns was due to insufficient shear strength and reduced ductility of structures. Therefore, improvement of seismic performance in such structures with consideration of shear capacity and ductility is vitally required.

From the early stages of scientific study of concrete it was realised that, lateral confinement enhances the compressive strength of concrete. Such confinement is now prescribed by modern seismic design codes of practise as a way of enhancing the ductility of reinforced concrete, (RC).

Reinforced concrete columns are strengthened by numerous methods like concrete jacketing, steel jacketing, and wrapping. Both the Concrete and steel jacketing methods are much labor intensive. But FRP (fiber reinforced polymer) is less labor intensive as compared to others and offers high strength low weight and corrosion resistant jacket with rapid and easy installation with minimal change in the geometry of column. This FRP (fiber reinforced polymer) has become commercially active material for repair and strengthening of aged concrete structure.

FRP has high strength fibers that embedded in polymer resin. With the use of FRP it offers such advantages like high stiffness and strength, high durability, low density, and the ease of its installation. The most common types of FRPs used are made with carbon glass and aramid polymers (Figures 1-1 and 1-2). The versatility of FRPs application make them very popular in construction industry.

The confinement effect on ductility has been recognized since the early days of structural concrete. Ductility of RC sections depends on different parameters like shear reinforcement, anchorage of reinforcement, the amount of longitudinal reinforcement and its properties and effective lateral confinement. The increase in ductility and strength of concrete structures due to lateral confinement is desirable benefit. Lateral type confinement is activated in the reaction to Poisson-type lateral expansion that which generates the lateral pressure. Because of lateral confinement, concrete fails at a larger axial strain and strength than if unconfined. Depending on the amount of confinement, significant increases in ductility can be achieved

The concrete confined by FRP shows different response as compared to concrete which is confined by steel. Initially within the elastic zone of stress-strain curve, the behavior of both unconfined and confined concrete is similar as the jacket is not activated. At the peak value of stress the jacket starts to take load and checks the propagation of further cracking. This type of confinement by FRP is passive confinement

Active confinement can also be achieved by FRP when some expansive material is used in between the member and FRP jacket. That expansive grout causes the FRP to be actively confined

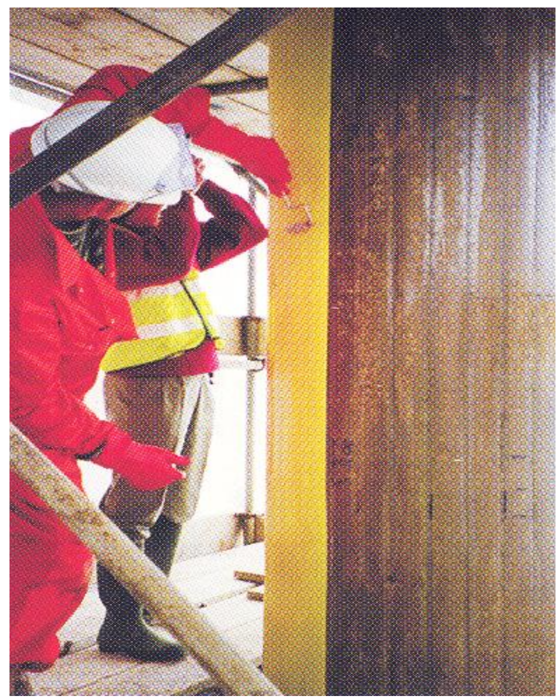

Figure 1-1 Column strengthening with Carbon FRP (left) and Aramid FRP (right)

Figure 1-2 Column Strengthening with Glass FRP

Research has shown that when high strength materials are used as concrete confinement, it is not necessary that their strength can be utilized before the initiation of failure. As a result, a patent was filled which claims that the concrete properties can be enhanced if the lateral confinement is pre-tensioned. Frangou worked on pre-tensioned metal strips and confirmed that pre-tensioning has a beneficial effect on concrete behavior.

1.2 Reasons/Justification for Selection of Topic

The Fiber reinforced polymer (FRP) is vitally used in concrete column rehabilitation retrofitting projects due to their high strength, less weight and good corrosion resistance. A huge research has been done that describes the behavior of FRP confined concrete columns It has been demonstrated in literature that concrete column compressive strength is increased by the additional confinement provided by the FRP wrapping. The objective of present research is to improve ductility in the concrete with FRP wrapping method by using expansive grout.

1.3 Objectives:

The objectives of the present study are

- To investigate behaviour of concrete cylinders wrapped with CFRP
- To study the behaviour of concrete cylinders that were pretension with expanding grout and CFRP jackets.
- To examine the behaviour of concrete cylinders with different expanding grout ratios.

1.4 Area of application:

In developing countries like Pakistan structures are vulnerable to deterioration before their design period and it is necessary to confine the RC structures in these areas using some techniques. FRP (fiber reinforced polymer) can be used to confine the reinforced concrete structures.

1.5 Dissertation Structure

This research is organized in 6 chapters. In chapter 1 there is basic introduction about FRP and its types then objectives and area of application of present study is described. In chapter 2, a literature survey on concrete confinement is presented. How does confinement work, confinement of concrete with FRP is discussed.

Chapter 3 presents the experimental methodology adopted for present research, properties of materials used and test performed on unconfined and confined concrete specimens. Chapter 4 consist of the results obtained from the experimental work regarding the axial strength, ductility and load carrying capacity of the unconfined and confined concrete specimens. In the chapter 5, the general conclusions are drawn from the work described above and are presented and recommendations are presented for future research in this area.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Increase in ductility and axial strength in concrete columns is vitally required when strengthening and repair are concerned. When columns damaged under extreme loading repair is required or may be due to erosion in uncovered environment. When elimination of some of structural members is required or need of modification in structural use strengthening is required. Confinement in lateral direction has been proved to increase strength and ductility for concrete columns in the axial direction and this idea was initially developed in the 1920's by Richart et al. 1927, 1928.

Lateral confinement in concrete columns may provide in the form of spiral reinforcements, steel jacketing, concrete jacketing and jacketing of fiber reinforced polymer (FRP) composite. Steel is an extensively used construction material. Though, corrosion is the major drawback of this material. Weight is another problem. Jacketing by concrete is relatively cheaper but it adds weight and also cross sectional area. On the other hand, FRP composites, which were developed for aerospace and automobiles applications are now known as very capable material due to its applications in civil engineering.

2.2 Concrete Confinement

Confinement of concrete is very efficient technique that used to increase ductility and the load carrying capacity of a column. Confinement is applied to compressive members in form of lateral reinforcement for increase in their ductility as well as load carrying capacity. Lateral confinement also prevents from buckling and slippage of reinforcement in longitudinal direction (Saadatmanesh et al., 1994). Reinforcement in lateral direction can be provided by use of rectangular ties, circular hoops, steel jacketing or by fibre reinforced polymers (FRP).

Concrete can be confined by: a) hoop reinforcement as steel ties or spirals, b) encasing the concrete in the steel tubes c) external fibre composite wraps or d) encasing concrete in fibre composite tubes. All these types of confinement provide passive type confinement and the effect due to confinement is a function of the expansion in radial direction of the concrete core.

The effect of confinement on ductility has been recognized since the early days of structural concrete. Ductility of RC sections depends on different parameters like shear reinforcement, anchorage reinforcement, amount of longitudinal reinforcement and its properties and effective lateral confinement. Due to lateral confinement the increase in strength and ductility is desirable benefit. Lateral confinement is due to the lateral pressure. Due to lateral confinement, concrete fails at a larger axial strain and strength than if unconfined. Depending on the amount of confinement, significant increases in ductility can be achieved. Many investigations and different to predict the behaviour of concrete with variable lateral pressure different models are developed. Concrete is better characterized as restraint sensitive rather than pressure sensitive by Panatazapolou in 1995. This exemplifies why the stiffness of confining members have such a determining effect on the behaviour of confined concrete Mirmiran and Shahaway, 1997. Usually the strength increase is not significant than increase in ductility (fib-Bulletin 14, 2001).

2.3 Fiber Reinforced Polymer (FRP) Confinement

The concrete that confined by the Fiber reinforced polymer (FRP) shows different response as compared to concrete which is confined by steel. Initially within the elastic zone of stress-strain curve, the behavior of both confined and unconfined concrete is similar as the jacket is not activated. At the maximum stress that was of unconfined concrete specimens, the jacket starts taking loading and checks the propagation of further cracking. This type of confinement by FRP is passive confinement.

Active confinement can also be achieved by FRP when some expansive material is used in between the member and FRP jacket. That expansive grout causes the FRP to be actively confined (Murtazavi, 2003). There are many advantages of FRP including high modulus and tensile strength, light weight, durability and corrosion resistance.

There are various materials that can be used for FRP confinement like carbon fiber, fiber glass and Kevlar bonded by using epoxy (Priestley et. al 1996). The FRP confinement can be applied by wrapping FRP straps, FRP sheets, procured shells and belts around the members. Pouring of concrete can also be done in FRP tube for the purpose of FRP confinement (Samaan, et al. 1998). Epoxy is used as binding material if the confinement is to be given to already poured concrete member. The binder uniformly distributes the loading (Fardis and Khalili 1982).

2.4 Analytical Models for FRP Confined Concrete

In literature many stress strain models have been developed in which confinement was provided by FRP. These models can be classified into two groups as described by Lam and Teng, in 2003 one group is of design oriented models and other analysis oriented models. For first group, closed-form equations were proposed empirically by the experimental studies of concrete that was confined by FRP.

For the second group, constitutive models were proposed using an incremental procedure. An active model that was developed to estimate the strain in axial direction and stress in confined concrete in particular stress that was provided due to confinement. Interaction between FRP jacket and concrete is accomplished by using force equilibrium, material properties and strain compatibility.

For circular specimens confined with FRP, the maximum confining pressure due to FRP jacket can be calculated by the following formula:

$$f\,l = \frac{2 f_{frp}\, n_{frp}}{D} \qquad (2.1)$$

where

D = diameter of circular specimen

n_{frp} = layers number of FRP

$f\,l$ = maximum confining pressure induced by FRP jacket

f_{frp} =tensile strength of FRP material

Knowing the linear elastic property of FRP material, we have:

$$f_{frp} = E_{frp} \times \varepsilon_{frp} \qquad (2.2)$$

Where

E_{frp} = elastic modulus of FRP

ε_{frp} = rupture strain of FRP

The maximum strain in radial direction of the confined concrete ε_l equals tensile strain of the FRP in the hoop direction. That is $f_{frp} = \varepsilon_{frp} \times \varepsilon_l$

2.5 Seismic Strengthening of RC Columns

The damage sustained by bridge columns during the recent earthquakes worldwide clearly demonstrates the need for effective and economical techniques for strengthening of these structural elements (Saadatmanesh, 1995). The absence of adequate lateral confinement has been recognized as a main reason for failure of columns. Consequently, new design procedures and construction techniques have been developed and introduced into the code of practice that are for the seismic design of structures. The ACI 318 building code (ACI 318, 2001), New Zealand Concrete Design Standard (NSZ 3101, 1995) and Eurocode 8 (EC8, 2001) are some of the codes that have adopted modern ideas. However, because many structures were built before the new generation of design codes were introduced, their performance and capability to resist earthquakes and other hazard forces is questionable. Therefore, strengthening, the restoration or improvement of RC structures is a major challenge for civil engineers.

2.6 Reasons for Post-Strengthening of Structures

Post-strengthening is required in the case of structures which expect to be subjected to higher forces than those for which they were designed. Furthermore, during the modernization and up-grading of structures, some individual supports and main walls might be removed hence, leading to a redistribution of forces and the need for local strengthening. The main reasons for undertaking repair/strengthening works are given below:

- To upgrade the structures that designed allowing to old codes of practice
- To rectify design due to imposed loading errors
- To rectify bad design concepts and poor detailing
- To rectify bad construction with poor materials and workmanship
- To repair damages due to accidental loading such as earthquake, impact and explosive loading

- To upgrade structures due to improvements and change in use
- To prevent concrete and reinforcement deterioration due to salty water, chemical reactions, etc.

2.7 Common Types of Failure of Concrete Columns

Failure of concrete columns is mainly caused by insufficient lateral reinforcement and inadequate lap length of starter bars, resulting in low ductility and strength. Ductility and strength can be guaranteed by avoiding the following types of failures:

- Shear failure (Figure 2-1 left) is the most dangerous failure mode in columns. In this mechanism is related with inclined cracking i.e. (Diagonal tension), rupture or opening of the transverse reinforcement and concrete cover spalling.
- Plastic hinge failure (Figure 2-1 right) which is the second worse mode of failure, where advanced flexural cracking, buckling of the axial reinforcement and compression failure of concrete core. However, this failure mode is more appropriate than brittle column shear failure of the whole column.
- Failure of the reinforcement in the lap splices, which are located at lower column end to make connection between the column and footing. One of the benefits of the strengthening method using lateral pre-tensioning is that it can reduce the risk of taking place of this type of failure.
- anchorage failure

Appropriate detailing and provision of adequate lateral confinement can avoid such failures which are often observed after an earthquake. For repair and strength/ductility enhancement in existing columns, it is obvious that external confinement should be applied. The localized enhancement in ductility/strength of RC members (beams/columns) through a number of novel techniques and the use of advanced composite materials could be a less expensive way of structural retrofitting.

In following a brief explanation of the enhancement of ductility and strength of RC members is made using passive confinement (the lateral pressure varies and starts from zero) by steel and FRP materials. The partially active confinement (the lateral pressure is applied prior to the lateral confinement) using steel and FRP materials is also discussed.

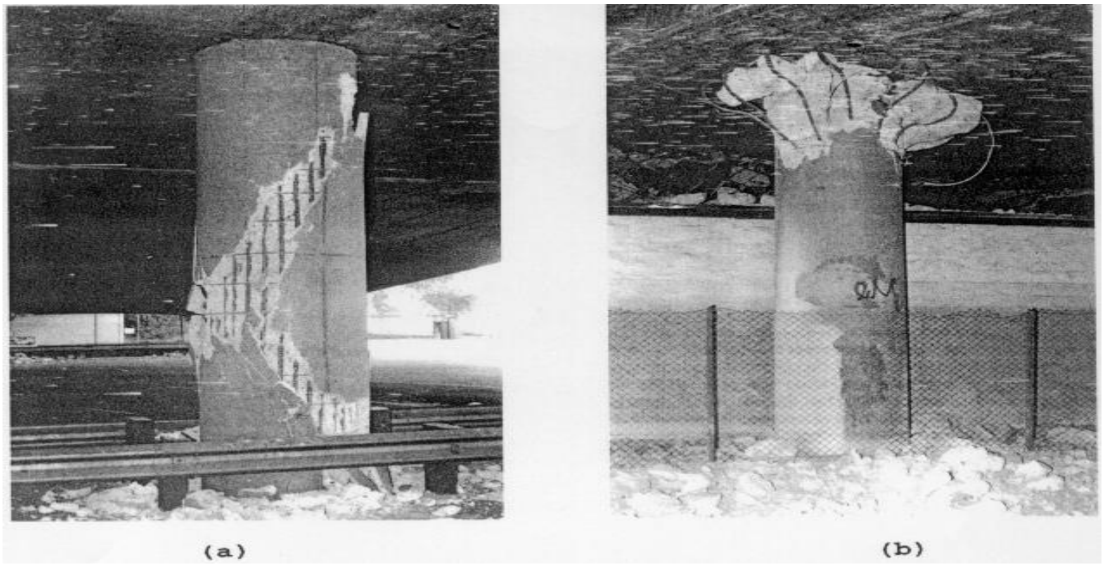

Figure 2-1 Typical Column Failure Modes; Shear Failure, Northridge Earthquake 1994 (left);

Plastic hinge failure Northridge earthquake 1994 (Seible, 1997) (right)

2.8 Strengthening of RC Members by Steel

A great deal of experimental and theoretical work using steel-based materials as confinement reinforcements has been proposed by various investigators like Richart et al. in 1929, Chan in 1955, Furlong in 1967,Knowles et al. in1969, Ahmad & Shah in 1982 Kotsovos et al. in 1986, Chaai et al. in 1991. These investigations show the capability and reliability of steel as a retrofitting material in RC structures. Some of these methods are briefly explained in the following sections.

2.8.1 Spiral Reinforcement

In this method, mild steel is covered around the column that is damaged. The mild steel bars are heated then hammered around the d element that is damaged to form a spiral. Then they can be welded to angle sections that are located at the corners of member. Heating of the bars is necessary to confirm that they are militarized in tension (Frangou & Pilakoutas, 1994).

2.8.2 Gluing of Steel Sheets

Strength and the ductility of damaged columns can enhance by gluing thin steel sheets to the surface using epoxy resin as shown in Figure 2-2. After fitting the steel plate in the right position and fastening using clamps for at least 24 hours, the column is ready to carry the load (Van Gement, 1984).

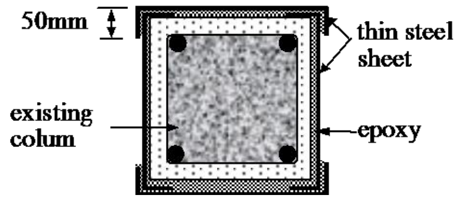

Figure 2-2 Gluing of steel plate

2.8.3 Concrete Jacketing

Concrete jacketing can be applied to part of a column or to an entire column. This technique is effective for increasing ductility, strength and the stiffness of RC members and is recommended for severely damaged columns. In this technique, damaged column is typically temporarily supported during interference. Concrete cover is removed and surface is cleaned and treated to improve bond properties. Additional longitudinal reinforcing bars are then added to the existing reinforcement that is shown in Figure. 2-3 (Frangou et al., 1994) and a concrete jacket is cast onto the prepared surface.

The analytical procedure for the design of repair works of damaged columns is given by Tassios (1982). Research done by Bett et al. (1988) on the response of strengthened and repaired RC columns with RC jacketing proved the effectiveness of this technique.

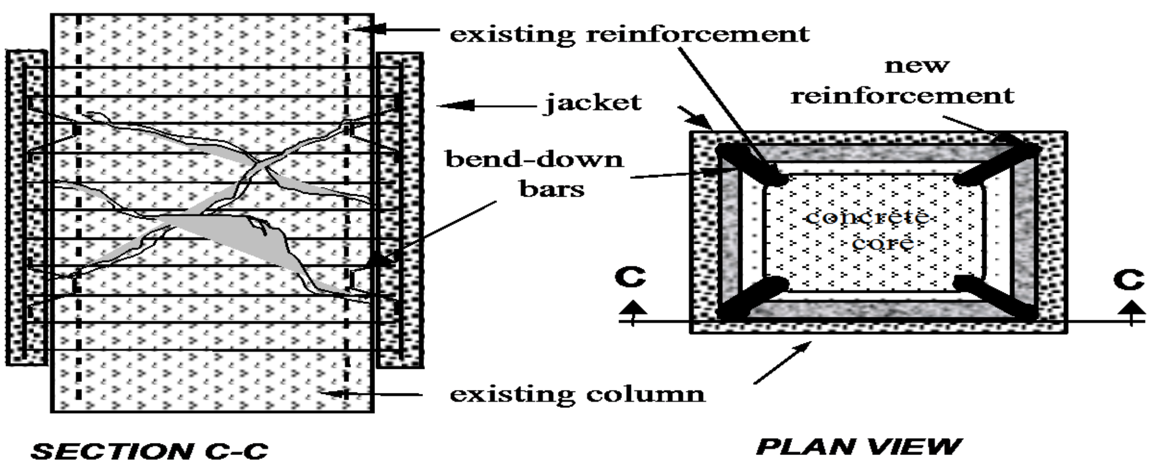

Figure 2-3 Steel bar jacketing

2.8.4 Steel Jacketing

Steel jacketing is the most common technique that used for repairing and strengthening of RC columns. This technique is established on fixing tie plates or thin steel around the entire column, as shown in Figure 2-4. In this technique, steel angles are located on the corners of the column and clamped onto concrete. Steel plates are subsequently welded onto these angles. Heat tensioning can be used to ensure proper tightening of the sheet against the column. Chai et al., (1991) also proposed to use cast-in-place concrete jacket to enclose the potential plastic hinge regions along with a site-welded cylindrical steel jacket.

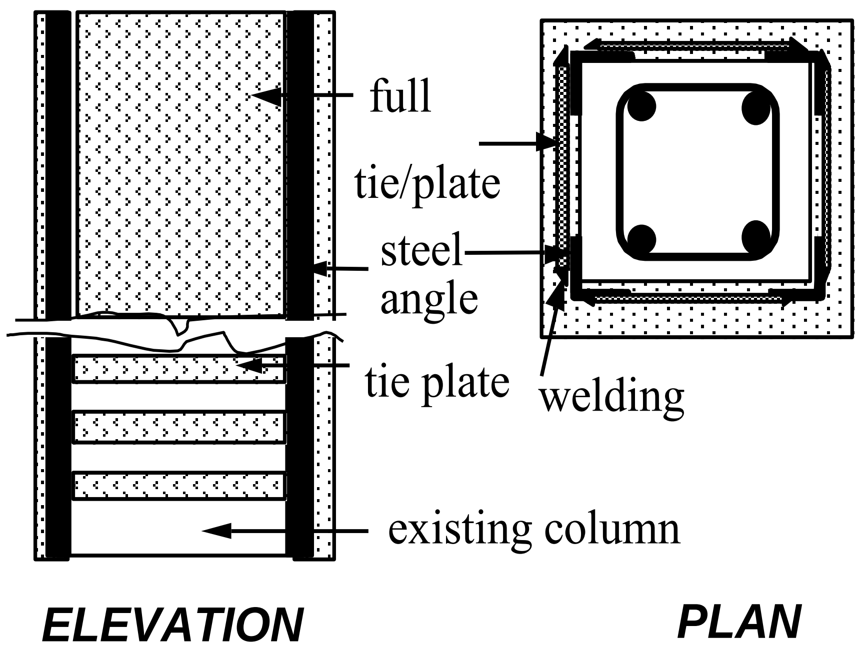

Figure 2-4 Steel Jacketing

Many theoretical and experimental works has been done in this area by using steel based (steel jacketing) confinement techniques by numerous researchers like Richart et al. in 1929,Chan in 1955, Furlong in 1967, Priestly et al. in 1994 and Xiao et al. in 1996).

2.8.4.1 Steel Jacketing Problems

Steel jacketing has been extensively used in practice but still represents one of the most common strengthening techniques, several problems may arise and need to be carefully considered:

- Steel plates can be very heavy and particularly in the retrofit of bridges, need mechanized lifting devices. Handling limitation on site is also a problem
- As steel is an isotropic material, so its resistance in the hoop and directions cannot be optimized or uncoupled (Mirmiran et al., 1997),
- even steel casing is extensively used and recognized for confinement, it agonizes from the negative sides of field welding, corrosion and need for larger jacket thickness to ensure that shell does not buckle while lifted. Due to these aspects there is increased cost, time and weight consumption.
- Due to its high modulus of elasticity in both directions, a significant part of axial load is carried by steel tube. This can lead to premature buckling of the jacket.
- In steel encased concrete members under axial compression, difference among steel and concrete Poisson's ratio, results in fractional separation of the two materials (concrete-steel tube).

2.9 FRP as a New Materials for Lateral Strengthening

Earlier, Confinement in lateral direction was developed by using spiral steel reinforcement or steel reinforced jackets. Recently fiber reinforced plastic (FRP) materials have been used in lateral confinement systems Nanni et al. in 1995. Advanced composite materials have better mechanical and environmental behavior than steel. Mechanical properties of fiber composite depend on the strength, stiffness properties of components and their relative properties, the orientation of the fibers, the curing procedure, method of manufacturing and etc. FRP are composed of fibers inserted in polymeric matrix. They have an isotropic behavior with tremendous tensile strength in direction of fibers. FRP composites do not show yielding but show elastic behavior up to failure. Composite materials that used for strengthening of structures are available in the form of flexible sheets or fabrics and thin uni-directional pultruded strips.(fib-Bulletin, 2001).

Typical stress-strain curves for unidirectional composites such as CFRP (carbon fiber), AFRP (aramid/Kevlar fiber) and GFRP (glass fiber) under short term monotonic loading as shown in Figure 2-5 compared to the stress strain curve. Stress and strain relationships for mild steel and pre-stressing steel are also shown for comparison.

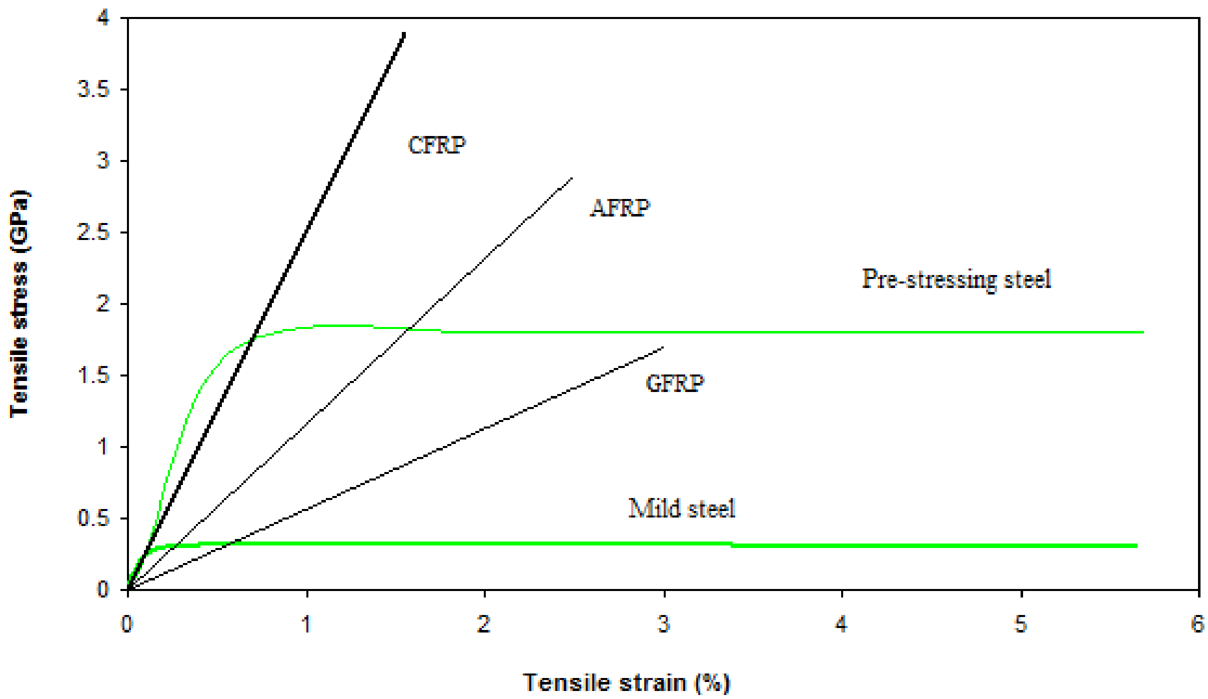

Figure 2-5 Typical stress-strain relationships for different composite materials.

2.9.1 Types of FRP

Majority of the materials are stiffer and stronger in fibrous form than bulk material. Higher amount of fiber aspect ratio permits load transfer effectively to the fibers, thus permitting full advantage of properties. Thus fibers are attractive and effective reinforcement materials. Fibers can manufactured in discontinuous or continuous form, but in this research continuous fibers are taken in account. These fibers have diameter of order of 5 to 20 µm and can be manufactured as bi-directional or unidirectional reinforcement. All fibers that used for strengthening show a linear elastic behavior till failure occurs (fib-Bulletin 14, 2001).

There are three kinds of fibers that used for the strengthening of the concrete members and suitable for use as pre-tensioning materials in civil engineering structures. These are mainly glass, aramid and carbon fibers.

- Glass Fiber Reinforced Polymer (GFRP) are composite materials that are basically composed of glass fiber threads and resin matrix. Glass fiber is the only inorganic fiber and all the other fibers are organic (Hollaway, 1993). Glass fibers are the commonly used FRP. Most commonly used types of glass fibers are E-glass and S-glass (Benmokrane et al., 1995). E glass has the lowest cost and is used if strength, acid resistance, low cost and electric resistant are important. Since the stiffness, strength and ultimate strain of S-glass is higher than E-glass and also it is expensive. The elastic modulus of GFRP is about 25% of steel and the specific weight of GFRP is one-fourth of steel. Compressive strength of GFRP is almost 40%-60% lower than tensile strength, (Benmokrane et al., 1995).
- Aramid Fiber Reinforced Polymers (AFRP) are polymeric components reinforced with organic and man-made fibers, which have a high degree of crystallinity. These fibers have found numerous applications in the field of composites. From a practical perspective, the excellent conformity and drape ability of "Kevlar" which is an aramid fiber produced by E.I. Su Pont de Nemours Company Ltd., permits its use with structural columns and beams which might be difficult or impossible to reinforce economically by other means. "Kevlar" has excellent resilience, giving it the ability to resist repeated impacts. Assemblage of both high strength and elastic modulus offers reinforced structure with an energy absorbing outer skin, which is highly resistant to impact damage. To compare its strength for a similar tensile stiffness, a laminate of "Kevlar" offers a 20% higher strength than one made with carbon (DuPont Eng. Fibers, 2002). There are two grades of stiffness in this type fibers, Kevlar 29 has 60 GPa and Kevlar 49 has elastic modulus of 130 GPa (L.Hollaway, 1993).
  - The Carbon Fiber Reinforced Polymer (CFRP) is another substantial for retrofitting solid concrete columns. Carbon fibers can be classified into four performance groups based on tensile modulus, strength, or pre-cursor type. As far as the Young's modulus is concerned, fibers can be divided into ultra-high modulus, high modulus, standard modulus and intermediate modulus (Saadatmanesh et al., 1994). To achieve high confinement pressure and ductility in concrete columns, it is advisable to use unidirectional tapes of intermediate modulus carbon fiber (Saadatmanesh et al., 1994). Carbon FRP laminates are much more expensive than Glass FRP and more expensive than Aramid FRP, but have much better stiffness characteristics. CFRP is also more

durable than GFRP and AFRP as external confinement (Clarke & Waldron, 1996) and has a larger energy absorbing capacity than E-glass (Saadatmanesh et al., 1994).

Tables 2-1 and 2-2 show a brief description (summary) of the mechanical properties of the three types of fibers for polymeric of composites and a qualitative comparison between them. The combination of these three types is also possible to produce hybrid composites.

Table 2-1 Typical Mechanical Properties of FRPs used in Construction (Herakovich, 1998)

Material	**E** (Gpa)	**σ_t(Mpa)**	**ε_u (%)**	**ρ(gr/cm^3)**	**Poisson's ratio (υ)**
Glass	65-90	1700-4800	2.8-3.5	2.4-2.6	0.22-0.23
Kevlar	125	2760	2.4	1.44	0.34
Carbon	231-310	2199-5171	1.5-1.7	1.7-1.8	0.20

Table 2-2 Qualitative Comparison between the Three Types of FRP (Meier 1995)

Criterion	**Carbon**	**Aramid**	**E-Glass**
Tensile strength	very good	very good	very good
Compressive strength	very good	inadequate	good
Modulus of elasticity	very good	good	adequate
Long term behaviour	very good	good	adequate
Fatigue behaviour	Excellent	good	adequate
Bulk density	Good	excellent	adequate
Alkaline resistance	very good	good	inadequate
Price	Adequate	adequate	very good

2.9.2 Advantages of FRP

Now a days the Use of FRPs is increasing for so many reasons, but main is the strengthening quality of the material which reinforced the sections. These reasons are summarized below:

The ratio of strength-to-weight and stiffness-to-weight is higher in these composites as compared to the conventional materials. However, because they have relatively low Young's modulus, the concrete still takes most of the axial compression. The advantages of FRP composites reinforment / jacketing for horizontal confinement are ; flexibility in construction and design, possibility of pre-tensioning and greater ease of automatic installation (Nanni et al., 1995). FRP materials are most suitable for encasing concrete columns because of the high tensile strength of the fibres and the orthotropy built in by their orientation (Mirimiran et al., 1997). In addition, their resistance to corrosion, low weight (about ¼ of steel), very high tensile strength (for certain types of FRP materials), large deformation capacity and practically unlimited availability in size and geometry (fib-Bulletin 2001), make FRPs very attractive to the construction industry.

2.9.3 Disadvantages of FRP

The likely problems to be encountered with FRP confinement materials are presented below:

Due to their low compressive stiffness, they can buckle easily; hence, they should not be used where the compressive strength is an important parameter. In lateral expansion, due to their lower shear strength (impact resistance) and lower Young's modulus than steel, the dilation of concrete is bigger than that of steel at a same effective stress, hence, it causes premature failure of concrete. However FRP tensile strength is bigger than that of steel, but it drops sharply when it is exposed to elevated temperature in the range of 150-250 degrees C^o (Lees et al., 1995). In addition, because of linear elastic behavior, they fail without any deformation or yielding that leads to reduced ductility.

Moreover, on weight basis the cost of materials is higher than steel are made on a strength basis. Furthermore, some FRP materials like aramid and carbon, have mismatched coefficients of thermal expansions with concrete. Hence due to high temperatures e.g. in fire case may cause early collapse and degradation of the members. So decisions concerning their use for confinement should be based on concern of numerous factors concerning not only mechanical properties aspects but also on long-term durability (fib-Bulletin, 2001).

2.9.4 Types of FRP strengthening systems

Depending on form, strengthening technique of the strengthening and constituent materials, three types of strengthening systems can be identified:

1. Pre-fabricated systems

2. Wet lay-up systems

3. Special systems such as pre-tensioning or automated wrapping

Pre-fabricated systems such as pre-manufactured cured strips, jackets, curved shell and other shapes are installed using adhesives.

When using wet lay-up system, the fabric can applied directly on to the resin which has been uniformly applied on the surface of concrete, or fabric manually can saturated with resin or by using the saturator machine and after that applied to sealed substrate.

2.10 Review on External Lateral Confinement with FRP

In the last few years, different advanced composite (FRP) confinement methods for columns have been considered and developed to speed up retrofitting, reduce maintenance and improve durability. These developments have ranged from hand lay-up of FRP tapes/ strips to pre-fabricate layered in the form of shells or jackets. The general policy of retrofitting or strengthening of concrete structures with FRP materials is similar to that used for steel but applied in different ways and techniques.

2.10.1 Conventional Techniques

Matsuda et al. in 1990 for bridge pier retrofit tested a system by using uni-directional carbon fiber sheets that wrapped transversely and longitudinally around the potential plastic hinge region or in section of main bar cut off. Figure 2-6 (left) shows an example of lap splice strengthening in RC bridge piers with carbon sheets and bridge beams strengthening by means of carbon plates. Saadatmanesh et al. in 1994 proposed technique by wrapping carbon fiber straps for reinforced concrete column strengthening (Figure 2-6 right). This technique was found to be highly effective for confinement of concrete core and avoiding the longitudinal bars under cyclic loading from buckling. Saadatmanesh et al. (1994) reported that Carbon FRP straps have a larger energy absorbing capacity than E-glass, which has a larger elongation at failure.

Figure 2-6 Carbon Lap Splice Strengthening (left) and Carbon Strap Confinement (right)

Another wrapping system by using E-glass fibers which is more economical as compared to carbon fibers, has been studied by several investigators like Mirmiran et al. in 1997 and Xiao et al. in 1997. Mirmiran et al. in 1997 worked on GFRP tube confinement and showed that FRP reduces the propensity of concrete to expand by reversing its volumetric strains direction, and also improves the ductility and strength of columns. Xiao et al. (1997) tested pre-fabricated glass composite sheets to retrofit the as-built column which suffered brittle failure due to low ductility. Test results confirmed improvement in seismic performance by increasing in ductility.

Kobayashi et al. in 1995; Clarke and Waldron in 1996, Nanni et al. in 1995,Wang et al.in 1996,Ersoy et al. in1993 and Magi et al. in 1997 are among many investigators who consider the FRP confinement as a good retrofit material. Figures 2-7 and 2-8 show the wrapping of concrete columns with carbon, glass and Kevlar sheets respectively.

Figure 2-7 Circular and rectangular columns wrapped with CFRP sheets

Figure 2-8 Kevlar wrapping (left) and glass wrapping (right)

2.10.2 Special Techniques

Three techniques that are related to application of composite materials to RC could be mentioned as following:

- The first one involves wrapping system (columns or chimneys) which can be applied with or without pre-stretching, using automated machinery (robots) as shown in Figure 2-9. This technique was developed for the first time in Japan in early 90s and then later on in USA. Seible et al.in 1995 have confirmed a carbon fiber system that uses an automatic machine for wrapping incessant winding of fibers under minor angle around the columns to form a continuous FRP jacket. The advantages of described technique are good quality control and rapid installation but this method has disadvantage that it requires very expensive equipment as well as professional staff.
- The second technique involves the FRP laminates application that are combined with pre-tensioning. This technique applicable in beam strengthening, has been studied by Triantafillou (1991, 1992) and its field application is still at development stages [Meier et al., 1996].

Figure 2-9 Automatic FRP wrapping by means of robot

- The third technique involves lateral pre-tensioning of steel or FRP jackets mainly applied to RC columns. In case of FRP jacketing, the lateral pre-tensioning forces are applied to the laminates after application on to a column. The experimental work that was carried out in my research focuses on the validation of this technique. It is expected that, using lateral pre-tensioning will result in higher strength and ductility than for unstressed confinement.

CHAPTER 3

MATERIAL PROPERTIES AND EXPERIMENTAL PROGRAM

3.1 Introduction

This chapter focuses on material properties and experimental work that was conducted out on the specimens. Experimental program was consisting of a total of fifteen specimens having 101.6 mm × 203.2 mm concrete cylinders. Out of those, three specimens were control specimens. Three specimens were directly wrapped by CFRP and in other twelve cylinders, expanding grout was injected between pre-tensioned CFRP tube and concrete. Specimens were then subjected to the axial compression loading. Strain gauges were used to record strains induced in present study during testing.

3.2 Materials

The materials that were used in the study which are described as follows:

3.2.1 Cement

Type 1 Ordinary Portland cement was used in the concrete specimens of present study. One of the most popular brand of ordinary Portland cement (OPC) in Pakistan is “BESTWAY CEMENT” which has been used in this work. The chemical composition and some physical properties of Ordinary Portland cement are shown in Table 3-1.

Table 3-1 Physical Properties of OPC

Compound	**Value (%)**
Sio_2	22.0
Al_2O_3	5.50
Fe_2O_3	3.50
CaO	64.25
MgO	2.50
SO_3	2.90
Na_2O	0.20
K_2O	1.00

3.2.2 Aggregate

The aggregate used in the present study was Margalla crush of 9.50 mm. the properties of the Margalla crush were as described in the Table 3-2.

Table 3-2 Properties of Margalla Crush

Aggregate	Test performed	ASTM Standard	Result
Margalla Crush	Bulk Density	C-29 / C-29 M	1550 kg/m^3
	Specific Gravity	C-127-04	2.62
	Water Absorption	C-127-04	1.10%
	Fineness Modulus	C-136-05	6.89

3.2.3 Sand

The fine aggregate that was used in present study was Lawrencepur sand. Which has angular particles. The properties of Lawrencepur sand are described in the Table 3-3

Table 3-3 Properties of Lawrencepur Sand

Aggregate	Test performed	ASTM Standard	Result
Lawrencepur Sand	Bulk Density	C-29 / C-29 M	1700 kg/m^3
	Specific Gravity	C-128-04a	2.7
	Water Absorption	C-128-04a	1.20%
	Fineness Modulus	C-136-05	2.49

3.2.4 CFRP Laminate

CFRP used in the study was WRAP CFW 600. It is mainly used for repairing in cracks and strengthening of the structures.it can also be used in retrofitting of structures. Its advantage is that the fabric is made up of weft fibers due to which fibers keep the system or fabric stable. It can be used for variety of purposes for strengthening and retrofit. This fiber can be used in a wide variety of shapes or it has a better geometric configuration the thickness of laminate was 1.4 mm. tensile strength of 4900 MPA , tensile E-modulus was 231000 MPA and strain at elongation was 1.5%. The values given in the Table 3-4 and 3-5 are the dry fiber properties but the properties of the fiber wrap with epoxy are given in the Table 3-6

Figure 3-1 WRAP CFW-600

CFRP Wrap CFW 600 is uni-directional knitted carbon fiber fabric used for wet application process. Some properties of CFRP wrap CFW-600 are as follows

- It is manufactured with the weft fibers to keep stable fabric during heat set process
- Its Multifunctional use is for every type of strengthening system.
- It is Flexible for surface geometry.

- It has very low density for nominal additional weight.
- It is Economical as compared to other techniques.

Table 3-4 Dry Fiber Properties of WRAP CFW-600

Fiber type	High strength fibers
Fiber orientation	0 degree uni-directional
Areal Weight	(610 ± 20) g/m2
Fabric Thickness	0.337 mm
Density of fiber	1.79 g/cm3

Compatibility of system must not be changed. It can be done by strictly sticking to the proposed epoxy that is given in the table named Chemdur 300. This fiber wrap can be applied both in wet as well as dry application. In the data sheet the thickness and weight per unit area of the epoxy to be applied is mentioned.it is written that the fiber should not be fold and the fiber should nit be splitted in to pieces with sharp instrument. The wrap is to be coated with epoxy named Chemdur 300 for ensuring proper bonding with the WRAP CFW-600. The following table 3-5 shows the properties of laminate.

Table 3-5 Dry Fiber properties of WRAP CFW-600

Dry Fiber Properties	Values
Tensile strength of fiber	4900 MOA
Tensile E modulus	230, 000 MPA
Elongation at break	1.5 %

The overlapping must be minimum 10 cm or according to the requirements of the system where it is to be installed. The properties given in the table are dependent on resin used with system. The epoxy was applied with gloves in hand and irregular profile was adjusted with cutting so that the resin can be applied on the smooth surface. Other additional properties are in Table 3-6.

Table 3-6 Properties of Laminate

thickness	1.4 mm per layer
Ultimate load	1000 GPA
Tensile E modulus	48.0 GPA

3.2.5 Epoxy and Primer

To make pre-formed tubes from fiber carbon sheets, the use of Epoxy Primer and Epoxy Adhesive was necessary. Epoxy Primer is based on two component epoxy resin primer that was used for masonry and concrete surface and helps to stabilize and seal prepared surfaces before laying fiber sheets for strengthening. Epoxy adhesive is the same material as epoxy primer, but used to structurally adhere composite sheets as well as to transfer all loads to the fiber composite. The epoxy used in the present research was Chemdur 300. Table 3-7 and 3-8 shows the technical data and physical data of Chemdur 300 respectively.

Table 3-7 Technical Data Chemdur 300

Color	Comp. A in white color
	Comp. B in grey color
Mix ratio	Component A: component B = 4:1 by weight

Table 3-8 Chemdur 300 physical properties

Density	At 20°C 1.31 Kg/Liter when comp. A+ B mixed
Pot life	At 15°C 90 min
	At 35°C 30 min
Open time	30 min
Viscosity	Pasty
Application Temperature	15°C to 35°C.
Tensile Strength and Curing	30 MPA and 7 days curing

3.2.6 Expanding Grout

The locally available expanding grout named ULTRA EXPANDING GROUT was used in the experimental work.1%, 2% and 3% grout to dry ratio of cement was used in the test. ULTRA EXPANDING GROUT is a mixture of a medium that expands and plasticizing agent. Expanding agent generates gas during the hydration process prior to initial setting, it counteracts the natural shrinkage and settlement of grout. Plasticizing agent in the grout enables high workability mixes with low water/cement ratio, as well as the stability and the cohesion of the grout are increased.

3.3 Specimen Preparations

3.3.1 Concrete mix design

The motor operated drum mixer was used for mixing of the concrete. The maximum capacity of the mixer was 2.5 cft.

3.3.2 Mix Proportions

Low strength concrete was aimed a typically in Pakistan low strength concrete is in practice. For this purpose a concrete cylinders of 1:2:4 were casted with water cement ratio of 0.75. Quantities of ingredients that used in the concrete mix design are shown in Table 3-9

Table 3-9 Proportions of ingredients used for concrete mix

Ingredients	Quantity
cement	30.72 kg
sand	61.44 kg
aggregate	122.87 kg
w/c	0.75

3.3.3 Test specimens

A total number of fifteen cylinders were casted. Table 3-10 describes the experimental program conducted for this study and Figure 3-2 shows the geometric properties of specimen for the present study.

Table 3-10 Geometric properties and dimensions of specimens

Specimen	**Description**	**D (mm)**	**L (mm)**	**r (mm)**	**NO. of specimens**
C	control specimens	101.2	203.2	50.6	3
W	directly wrapped with CFRP	101.2	203.2	50.6	3
GC1	pre-tensioned tubes of CFRP with 1% expanding grout	101.2	203.2	50.6	3
GC2	pre-tensioned tubes of CFRP with 2% expanding grout	101.2	203.2	50.6	3
GC3	pre-tensioned tubes of CFRP with 3% expanding grout	101.2	203.2	50.6	3
Total					15

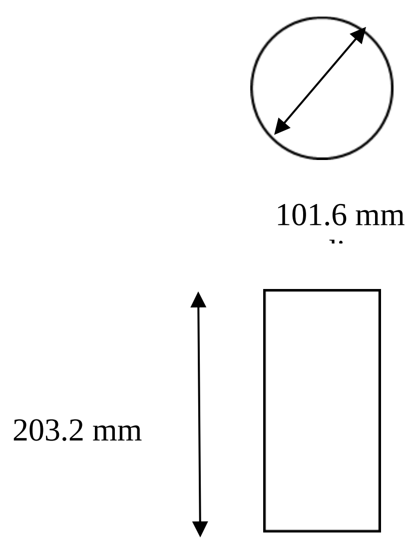

Figure 3-2 Dimensions of specimens tested

Three concrete cylinders were control specimens. Three cylinders were directly wrapped with CFRP WRAP CFW-60 and epoxy Chemdur 300 was used. The CFRP laminate was cut according to desired dimension. All weak, honeycombed surfaces were removed and voids and deformities were filled with epoxy repair mortar (Chemdur 30). The surface of application was primed with Chemdur 300-impregnationepoxy via roller and the CFRP laminates were directly applied on the specimen surfaces. Special attention was carried out to eliminate voids between concrete surfaces & CRFP laminate. An overlap zone of 100mm was ensured of CFRP laminate which was 1/3 of the circumference of concrete cylinder. Figure 3-3 and Figure 3-4 shows filling gaps on concrete cylinders surface and primer epoxy on concrete cylinders surface respectively.

Figure 3-3 Filling the gaps

Figure 3-4 Primer epoxy on concrete

Nine specimens were casted for making pre-tensioned specimens. For this purpose preformed tubes of CFRP were casted. An ABS tube of inside diameter of 100 mm was used for this purpose. The ABS tube was smeared with silicon grease, a sheet of acetate sheet was wrapped around the tube former. The sheet material was cut to size and laid down on the desk.

One side of the jacket was kept in place using a heavy steel plate while the free end was rolled around the pre-cut ABS tube of appropriate diameter. The length of the ABS tube was about two times the length of the jacket width (200 mm).

A rubber blade was used on the surface area of the jacket to remove any air bubbles from the composite. A strip of acetate sheet was placed on the wet material at the location where the strain-gauges had to be mounted. This ensured that when the resin had hardened, a smooth surface was obtained. After about 48-72 hours, the tubes were ready for making pre-tensioned specimens. For this purpose the concrete specimens that were already casted were placed inside the pre-formed tubes. And the expanding grout was injected between concrete core and the pre-formed tube. And the specimens were left for proper setting. Figure 3-5 shows the concrete samples of cast-in CFRP tubes

Figure 3-5 Cast-in pre-formed CFRP tube

3.3.4 Instrumentation

3.3.4.1 Strain gauges

Each cylinder was instrumented by the two strain gauges that were attached 90^0 apart at middle height of each specimen on jacket and concrete surface to measure lateral and axial strains as in Figure 3-6. The wires of load cell and strain gauges were attached to the data acquisition system. Model of surface strain gauge (SG) used in the experimental work was MFL ST Series. MFL ST Series is supposed to have excellent adhesive properties, excellent wettability, thin gauge backing and it is flexible. The nominal gauge resistance is 120 Ω. Table 3-11 shows the dimensions of strain gauges. And Figure 3-7 shows the procedure to install strain gauges

Table 3-11 Dimension of Strain Gauges

Resistance	**Sizes**	**Gauge Length**	**Gauge Width**	**Overall Length**	**Overall Width**	**Matrix Length**	**Matrix Width**
120 ohms	mm	6	3.49	10.58	3.49	12.08	5
	inches	0.236	0.137	0.417	0.137	0.476	0.197

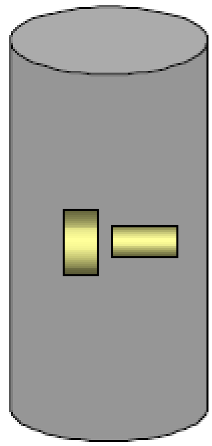

Figure 3-6 Instalment of Strain Gauges

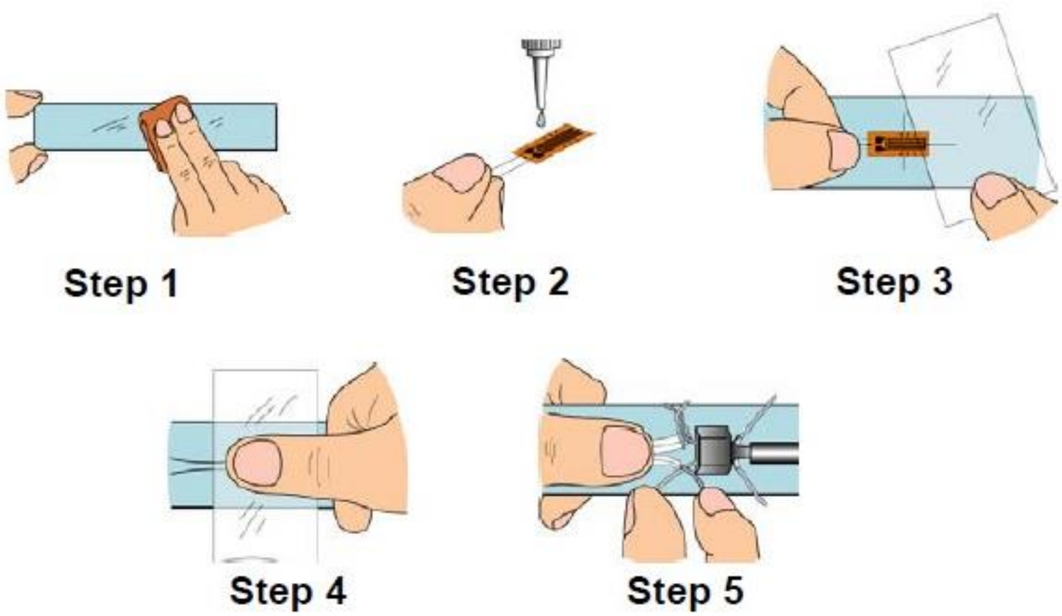

Figure 3-7 Procedure to install strain gauges

3.3.4.2 Universal testing machine

The testing was done using computer controlled hydraulic-Servo SHIMAZU UNIVERSIAL testing machine, which was employed hydraulic loading servo value for uniform loading. The capacity of the machine was 1000 kN. To automatically read the applied load from data acquisition system load cell was used. Figure 3-8 shows the universal testing machine and 3-9 shows the load cell.

Figure 3-8 Universal testing machine

Figure 3-9 Load cell

3.3.4.3 Data acquisition system

The Solartron Orion data acquisition system able to collect data from many different types of sensors has been used during experimental program. . The Orion was used to collect data from all these channels at any given point or on a time-scale, and was programmed for zero offset and displaying readings in engineering units. Figure 3-10 shows the data acquisition system

Figure 3-10 Data acquisition system

3.3.5 Test Procedure

All cylinders were capped by using plaster of Paris paste to confirm level surface and distribute uniform load. Test was accompanied by first placing the specimen in machine then centered under load cell. The loading rate was kept 2 mm/min.

Testing was carried out in displacement control. In general, a single control mode was used for each specimen. Each test was conducted up to failure of the specimen and the failure type and failure load was recorded. Figure 3-11 test setup.

Figure 3-11 Test setup

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

In order to estimate the effect of CFRP wrapped specimens and the specimen pretension CFRP with expanding grout on strength and ductility of concrete. Compressive strength as well as stress-strain measurements were carried out. On the basis of test results, comparison of axial compressive strengths, ultimate load carrying capacities, axial strains and lateral strains were carried out. Moreover, visual observations were also made to failure response of the specimens.

4.2 Mechanical Properties

Axial compression tests were conducted on the confined and unconfined specimens and effect of confinement due to CFRP wrap and pretension CFRP tubes with expanding grout was determined in terms of strain, strength and stiffness.

4.2.1 Ultimate Strength

Ultimate strength of the cylinder specimen were noted when the specimens failed under compressive force. Values of load and displacement were also recorded continuously

4.2.1.1 Control Specimens

Ultimate strength of control specimens without wrapping is shown in Table 4-1. The average of three tests conducted on the specimens is given below. The test specimens were 4 inch in diameter and 8 inch in height. Table 4-1 Test data for axial strength of control specimens

Type of Confinement	**Axial load Carrying Capacity**	**Axial Crushing Strength**	**Average Axial load Carrying Capacity**	**Average Axial Crushing Strength**
	KN	**MPA**	**KN**	**MPA**
Unconfined	88.9	11.3	85.33	10.9
	78.29	10		
	88.8	11.3		

4.2.1.2 CFRP Wrapped Specimens

The specimens that were wrapped with CFRP and tested in axial compression. An overlap of 100mm was provided and wet laying method of wrapping was employed. The epoxy was spread uniformly without any delay that might start setting of the epoxy. The ultimate strengths of the specimens are shown in Table 4-2

Table 4-2 Test data for axial strength of CFRP wrapped specimens

Type of Confinement	**Axial load Carrying Capacity**	**Axial Crushing Strength**	**Average Axial Load Carrying Capacity**	**Average Axial Crushing Strength**
	KN	**MPA**	**KN**	**MPA**
confined by wrapping with CFRP	209.19	26.6	198.9856667	25.3
	187.2	23.8		
	200.567	25.5		

4.2.1.3 Confined with Preformed CFRP Tubes

Nine specimens were casted for making pre-tensioned specimens. For this purpose preformed tubes of CFRP were casted. An ABS tube of inside diameter of 100 mm was used for this purpose. The ABS tube was smeared with silicon grease, a sheet of acetate sheet was wrapped around the tube former. The sheet material was cut to size and laid down on the desk.

One side of the jacket was kept in place using a heavy steel plate while the free end was rolled around the pre-cut ABS tube of appropriate diameter. The length of the ABS tube was about two times the length of the jacket width (200 mm).

A rubber blade was used on the surface area of the jacket to remove any air bubbles from the composite. A strip of acetate sheet was placed on the wet material at the location where the strain-gauges had to be mounted. This ensured that when the resin had hardened, a smooth surface was obtained. After about 48-72 hours, the tubes were ready for making pre-tensioned specimens. For this purpose the concrete specimens that were already casted were placed inside the pre-formed tubes. And the expanding grout of 1%, 2% and 3% was injected between concrete core and the pre-formed tube. And the specimens were left for proper setting.

4.2.1.3.1 Confined with Preformed CFRP Tubes with 2% Expanding Grout

The preformed CFRP tubes were created. And 1% expanding grout was injected between the concrete and CFRP preformed tubes. The ultimate strengths of specimens are shown in Table 4-3

Table 4-3 Test data for axial strength of confined specimens with preformed CFRP Tubes with 1% expanding grout

Type of Confinement	**Axial load Carrying Capacity**	**Axial Crushing Strength**	**Average Axial Load Carrying Capacity**	**Average Axial Crushing Strength**
	KN	**MPA**	**KN**	**MPA**
Confined with preformed CFRP Tubes with 1% expanding grout	247.15	31.469	262.4133333	33.412
	261.95	33.353		
	278.14	35.414		

4.2.1.3.2 Confined with Preformed CFRP Tubes with 2% Expanding Grout

The preformed CFRP tubes were created. And 2% expanding grout was injected between the concrete and CFRP preformed tubes. The ultimate strengths of specimens are shown in Table 4-4

Table 4-4 Test data for axial strength of confined specimens with preformed CFRP Tubes with 2% expanding grout

Type of Confinement	**Axial load Carrying Capacity**	**Axial Crushing Strength**	**Average Axial Load Carrying Capacity**	**Average Axial Crushing Strength**
	KN	**MPA**	**KN**	**MPA**
Confined with preformed CFRP Tubes with 2% expanding grout	284.64	36.242	308.055	39.22333333
	304.27	38.742		
	335.255	42.686		

4.2.1.3.3 Confined with Preformed CFRP Tubes with 3% Expanding Grout

The preformed CFRP tubes were casted. And 3% expanding grout was injected between the concrete and CFRP preformed tubes. The ultimate strengths of specimens are shown in table 4-5

Table 4-5 Test data for axial strength of confined specimens with preformed CFRP Tubes with 3% expanding grout

Type of Confinement	**Axial load Carrying Capacity**	**Axial Crushing Strength**	**Average Axial Load Carrying Capacity**	**Average Axial Crushing Strength**
	KN	**MPA**	**KN**	**MPA**
Confined with preformed CFRP Tubes with 3% expanding grout	400.53	50.99776412	391.7466667	49.87942137
	399.12	50.818		
	375.59	47.8225		

4.2.2 Effectiveness of Confinement on Concrete

This section shows the increment in compressive strength of confined concrete as compared to unconfined concrete strength. The research shows that the confinement becomes less effective as the unconfined strength increases. The cylinders confined with the preformed CFRP tubes with 3% expanding grout showed the maximum confinement.

Table 4-6 Comparison of confined specimen with unconfined specimens.

Specimen Designation	**Average axial compressive strength (MPA)**		**Increase (%) as compared to unconfined**
	Unconfined	**Confined**	
W	10.8	25.3	133
GC1	10.8	33.4	207
GC2	10.8	39.2	260
GC3	10.8	49.8	359

The results indicate an increase in confining strength of about 133, 207,260,359 percent for specimens directly wrapped with CFRP, confined with preformed CFRP tube with 1% expanding grout, confined with preformed CFRP tube with 2% expanding grout, confined with preformed CFRP tube with 3% expanding grout respectively. Figure 4-1 shows the comparison of compressive strength of unconfined specimens with confined specimens and shows that the strength increment was more significant for concrete confined by preformed tubes with 3% expanding grout.

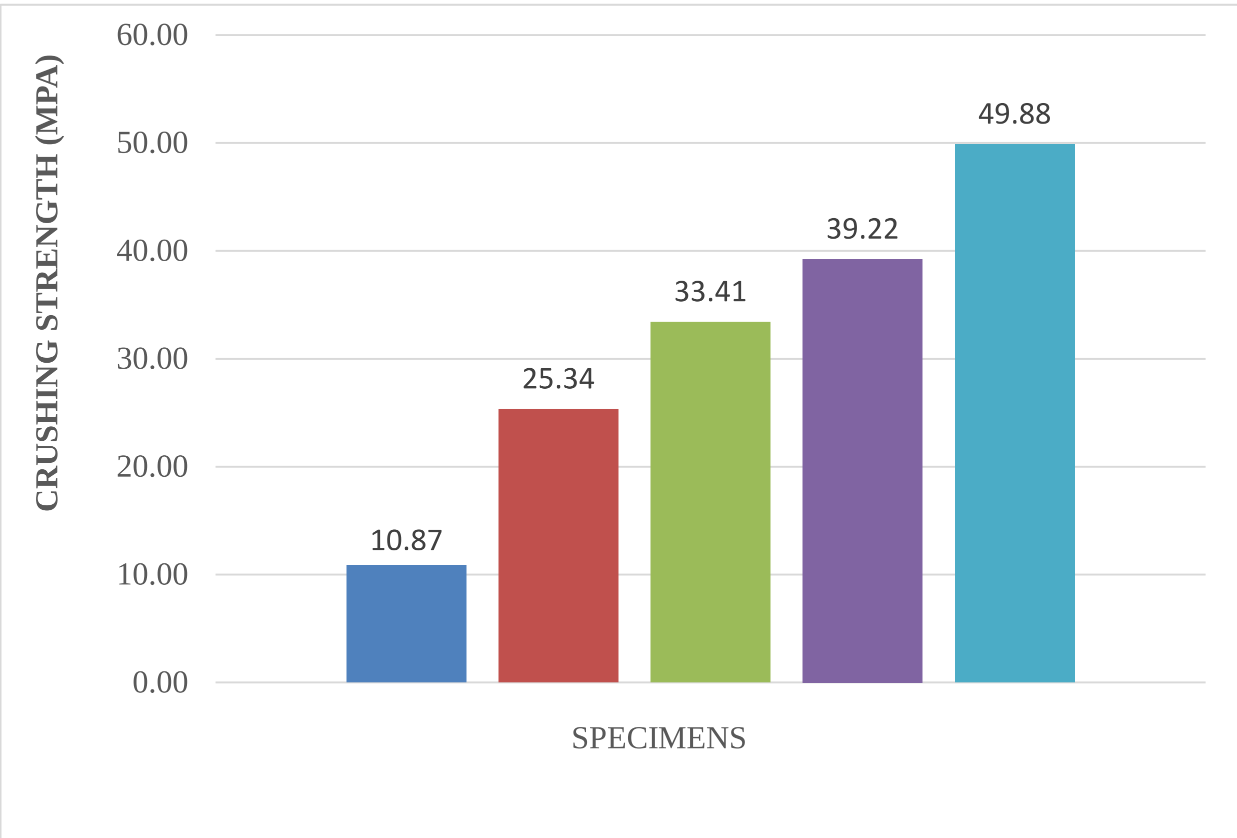

Figure 4-1 Comparison of compressive strength of confined and specimens

4.2.3 Stress-Strain response

The specimen were subjected to axial compressive test during which the applied stresses were recorded along with the corresponding strains in order to plot their stress-strain response

4.2.3.1 Control specimen

Strain gauges were installed to measure strains induced in specimens. Table 4-7 shows the stress and strains of the control specimen.

Table 4-7 Stress and strains of control specimen

Type of Confinement	Crushing Strength(Mpa)	Average Crushing Strength (Mpa)	Longitudinal Strain at Peak Stress	Average Longitudinal Strain	Lateral Strain at Peak Stress	Average Lateral Strain
UNCONFINED	11.323	10.85067	-0.0019	-0.0022	0.0029	0.00
	9.922		-0.0025		0.0030	
	11.307		-0.0021		0.0026	

4.2.4 Confided Specimen with CFRP Wrap

Strain gauges were installed to measure the strain values that induced in the specimens. Table 4-8 shows the stresses and strains of the CFRP confined specimens.

Table 4-8 Stress and strains of confined specimens with CFRP WRAP

Type Of Confinement	Crushing Strength(Mpa)	Average Crushing Strength (Mpa)	Longitudinal Strain At Peak Stress	Average Longitudinal Strain	Lateral Strain At Peak Stress	Average Lateral Strain
Directly Wrapped With CFRP	26.636	25.33633	-0.00106	-0.0094	0.0070	0.0060
	23.836		-0.0089		0.0054	
	25.537		-0.0086		0.0057	

4.2.4.1 Confined with preformed CFRP Tubes with 1% expanding grout

Strain gauges were used to measure the strains induced in specimens. Table 4-9 shows the stress and strains of the control specimen.

Table 4-9 Stress and strains of specimens Confined with preformed CFRP Tubes with 1% expanding grout

Type Of Confinement	Crushing Strength (MPA)	Average Crushing Strength (MPA)	Longitudinal Strain At Peak Stress	Average Longitudinal Strain	Lateral Strain At Peak Stress	Average Lateral Strain
Confined With Preformed CFRP Tubes With 1% Expanding Grout	31.469	33.412	-0.01695	-0.01834	0.008993	0.009819
	33.353		-0.01833		0.00974	
	35.414		-0.01975		0.010723	

4.2.4.2 Confined with preformed CFRP Tubes with 2% expanding grout

Strain gauges were used to measure the strains induced in specimens. Table 4-10 shows the stress and strains of the control specimen.

Table 4-10 Stress and strains of specimens Confined with preformed CFRP Tubes with 2% expanding grout.

Type Of Confinement	Crushing Strength (Mpa)	Average Crushing Strength (Mpa)	Longitudinal Strain At Peak Stress	Average Longitudinal Strain	Lateral Strain At Peak Stress	Average Lateral Strain
Confined With Preformed CFRP Tubes With 2% Expanding Grout	36.242	39.22333333	-0.02088	-0.022213	0.012272	0.016964
	38.742		-0.02355		0.017883	
	42.686		-0.02221		0.020736	

4.2.4.3 Confined with preformed CFRP Tubes with 3% expanding grout

Strain gauges were used to measure the strains induced in specimens. Table 4-11 shows the stress and strains of the control specimen.

Table 4-11 Stress and strains of specimens Confined with preformed CFRP Tubes with 3% expanding grout

Type Of Confinement	Crushing Strength (Mpa)	Average Crushing Strength (Mpa)	Longitudinal Strain At Peak Stress	Average Longitudinal Strain	Lateral Strain At Peak Stress	Average Lateral Strain
Confined With Preformed CFRP Tubes With 3% Expanding Grout	50.992	49.879	-0.04092	-0.02978	0.04576	0.042475
	50.818		-0.02532		0.0438354	
	47.8225		-0.0231		0.03783	

4.2.4.4 Stress strain response of specimens

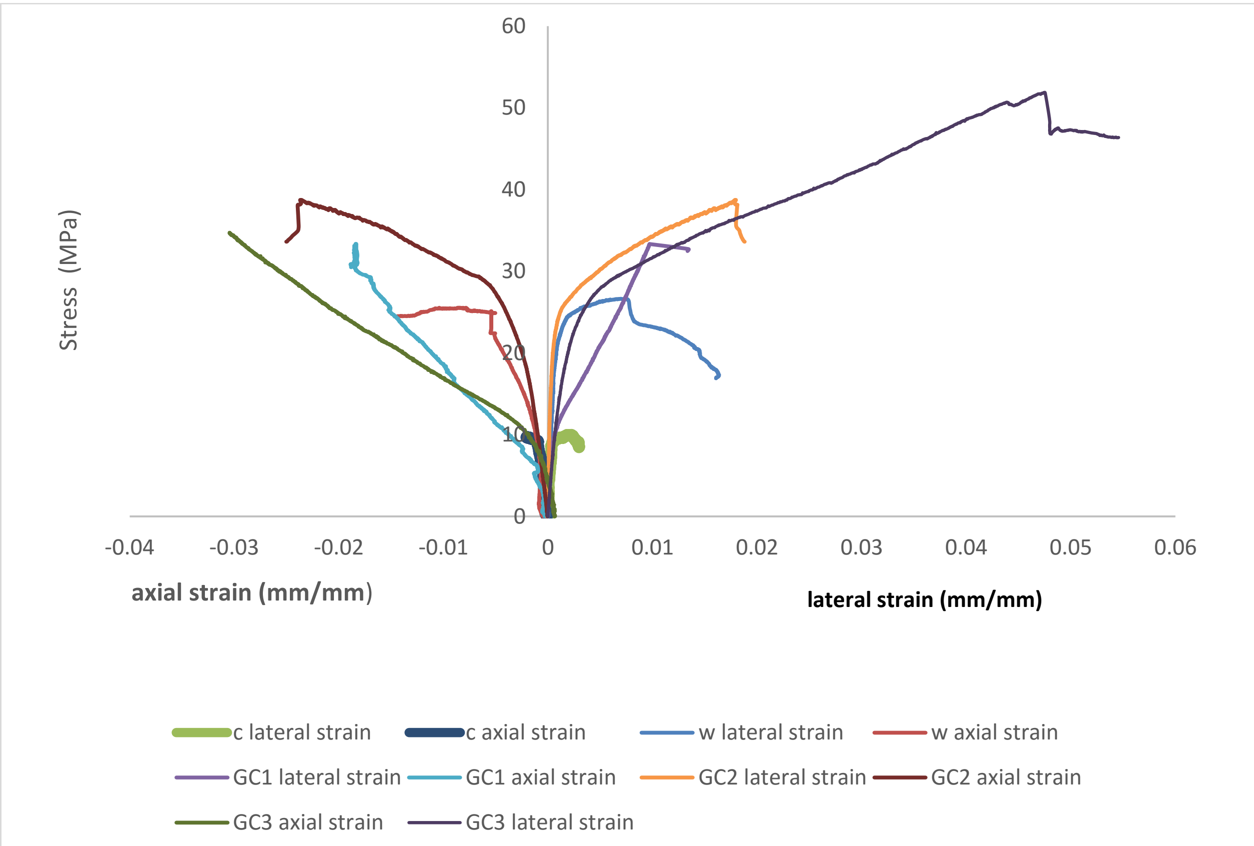

Figure 4-2 stress strain response of specimens

4.2.5 Elastic Modulus

The Elastic modulus in longitudinal direction increases from 1.0 to 1.18 for specimens directly wrapped with CFRP. This is due to that the stiffness in longitudinal direction mainly depends on mechanical properties of the concrete and role of CFRP is not much significant. While in the case of specimens confined with pre formed tubes of CFRP and expanding grout as the expanding grout increases the stiffness in longitudinal direction increases from 1.0 to 1.48, 1.87 and 2.799 for specimens confined with pre formed tubes of CFRP and 1% expanding grout, specimens confined with pre formed tubes of CFRP and 2% expanding grout and specimens confined with pre formed tubes of CFRP and 3% expanding grout respectively. Table 4-12 shows the stiffness of unconfined and confined specimens.

specimens designation	**E1**		**E2**		**comparison of E1 to unconfined E1**		**comparison of E2 to confined E1**	
	longitudinal direction	**lateral direction**	**longitudinal direction**	**lateral direction**	**longitudinal direction**	**lateral direction**	**longitudinal direction**	**lateral direction**
C	17.93	23	5.04	11.9	1	1	-	-
W	20.63	25.19	6.63	13.6	1.15	1.10	0.32	0.54
GC1	25.89	33.48	9.49	18.33	1.44	1.46	0.37	0.55
GC2	32.57	46.31	14.18	23.81	1.82	2.01	0.44	0.51
GC3	48.69	56.78	25.76	33.97	2.72	2.47	0.53	0.60

In lateral direction Elastic modulus increases from 1 to 1.09, 1.45, 2.01 and 2.46 for specimens confined with pre formed tubes of CFRP and 1% expanding grout, specimens confined with pre formed tubes of CFRP and 2% expanding grout and specimens confined with pre formed tubes of CFRP and 3% expanding grout respectively. The Elastic modulus decreases from m1 to m2 in all cases. This is due to the fact that before bifurcation point the load is carried by the concrete alone which is much stiffer as compared to combination of concrete and CFRP confinement where load is partly carried by concrete and partly by CFRP confinement.

4.2.6 Axial stress

Values of stress corresponding to axial strain limits of 0.0008, 0.002 and 0.003 are tabulated below in table 4-13.the stress of confined and non-confined specimens in Table 4-13 shows values of stress which are similar at an axial strain of 0.0008. Initially the slope is linear up to 0.0008 value of strain. At the strains of 0.002 and 0.003 confined specimens show an increased value of stress when compared to un-confined specimens. Thus the 0.0008 strain limit was chosen as the limiting curvature to calculate the deformability factor. Confined concrete specimen show a bilinear load strain curve. Slope of the stress-strain curve is linear to a strain value of about 0.002. After the bifurcation point the concrete and the wrap start acting together and the specimens take up a different slope, which is lower than the initial slope.

Table 4-12 Axial stress values at 0.0008, 0.002 and 0.003 for unconfined and confined concrete specimens.

Confinement Provided	**Specimens Designation**	**Strength At 0.0008 Strain**	**Strength At 0.002 Strain**	**Strength At 0.003 Strain**
		Mpa	**Mpa**	**Mpa**
Unconfined	C	8.01	11.02	-
Confined By Directly Wrapped With CFRP	W	16.92	20.43	22.07
Confined By Preformed CFRP Tube With 1% Expanding Grout	Gc1	18.36	23.79	26.83
Confined By Preformed CFRP Tube With 2% Expanding Grout	Gc2	19.27	21.79	29.69
Confined By Preformed CFRP Tube With 3% Expanding Grout	Gc3	29.557	31.379	32.4

4.2.7 Strain

The strain to failure of specimens was recorded using the strain gauge. Gauges were attached in both horizontal and vertical direction and hence both the values of longitudinal and lateral strain were recorded. The maximum values of strain are recorded and are shown in Table 4-14.

Table 4-13 Longitudinal and lateral strain values of confined and unconfined specimens.

`Type Of Confinement	Specimen Designation	Average Longitudinal Strain At Failure	Average Lateral Strain At Failure	% Increase In Longitudinal Strain	% Increase In Lateral Strain
Unconfined	C	-0.00314	0.00189	0	0
Confined By Directly Wrapped With CFRP	W	-0.00937	0.006046	198.4076433	219.8941799
Confined By Preformed CFRP Tube With 1% Expanding Grout	GC1	-0.018343	0.009819	484.1719745	419.5238095
Confined By Preformed CFRP Tube With 2% Expanding Grout	GC2	-0.0222	0.01696	607.0063694	797.3544974
Confined By Preformed CFRP Tube With 3% Expanding Grout	GC3	-0.0298	0.04248	849.044586	2147.619048

In un-confined specimens the lateral strain value was lower than the axial strain values. The increase in lateral strain of confined specimen was noted to be much higher than the longitudinal strain increase as shown in the Table 4-14. The increase in strain is due to enhancement provided by the CFRP and expanding grout to the concrete.

4.2.8 Ductility

Ductility of a material is its capacity to absorb energy. Ductile materials allow better stress distribution and warning to impending failure. In case of confined specimens ductility of the specimens is given in terms of deformability which is defined as the ratio of energy absorption (or area under load-deflection curve) at ultimate to energy absorption at limiting curvature. In these tests deformability was calculated by finding the total energy under the curve up to failure and calculating the ratio between total energy and energy at a limiting strain of 0.008, 0.002 and0.003. In this section, energy absorption of unconfined and confined specimens is discussed.

4.2.8.1 Energy Absorption

Table 4-15 and 4-16 shows the ratio of area under the curve at limiting strains of 0.0008, 0.002 and 0.003 as described in UBS 2018 code that will be deformability factors of confined and unconfined concrete specimens at limiting strains as shown in tables 4-17 and 4-18.

Table 4-14 Comparison of energy absorption of unconfined and confined concrete specimens in longitudinal direction.

Type Of Confinement	**Total Area**	**Area Under 0.0008 Strain**	**Area Under 0.002 Strain**	**Area Under 0.003 Strain**	**Ratio Of Areas**		
	Kpa	**Kpa**	**Kpa**	**Kpa**	**0.0008 Strain**	**0.002 Strain**	**0.003 Strain**
Unconfined	130.1	6.27	32.56	52.91	20.74	4	2.46
Confined By Directly Wrapped With CFRP	242.92	6.29	33.7	71.13	38.63	7.24	3.42
Confined By Preformed CFRP Tube With 1% Expanding Grout	382.68	8.05	39.3	83.41	47.55	9.74	4.59
Confined By Preformed CFRP Tube With 2% Expanding Grout	431.46	8.22	49.34	113.19	52.49	8.74	3.81
Confined By Preformed CFRP Tube With 3% Expanding Grout	466.08	8.28	49.54	113.51	56.26	9.41	4.11

The stress-strain response curves were used to calculate the area under the curve that represents the energy absorbed by the confined specimens to unconfined specimens. The area under the curve at a limiting strain of 0.0008, 0.002 and 0.003 is used to calculate the deformability factor. The ratios of energy absorption within limiting strains in lateral direction are given in Table 4-16.

Table 4-15 Comparison of energy absorption of unconfined and confined concrete specimens in lateral direction.

Type Of Confinement	Total Area	Area Under 0.0008 Strain	Area Under 0.002 Strain	Area Under 0.003 Strain	Ratio Of Areas		
	Kpa	Kpa	Kpa	Kpa	0.0008 Strain	0.002 Strain	0.003 Strain
Unconfined	216.47	10.47	43.07	82.4	20.68	5.03	2.63
Confined By Directly Wrapped With CFRP	301.23	11.2	47.67	93.06	26.89	6.32	3.24
Confined By Preformed CFRP Tube With 1% Expanding Grout	585.01	16.09	67.1	130.51	36.35	8.72	4.48
Confined By Preformed CFRP Tube With 2% Expanding Grout	540.41	11.91	50.98	100.98	47.05	11.02	5.57
Confined By Preformed CFRP Tube With 3% Expanding Grout	583.5	11.87	50.92	101.14	49.17	11.46	5.77

Table 4-16 Deformability factors for unconfined and confined concrete specimens in longitudinal direction.

Type Of Confinement	Deformability Factor		
	Limiting Strain=0.0008	Limiting Strain=0.002	Limiting Strain=0.003
Unconfined	20.74	4	2.46
Confined By Directly Wrapped With CFRP	38.63	7.24	3.42
Confined By Preformed CFRP Tube With 1% Expanding Grout	47.55	9.74	4.59
Confined By Preformed CFRP Tube With 2% Expanding Grout	52.49	8.74	3.81
Confined By Preformed CFRP Tube With 3% Expanding Grout	56.26	9.41	4.11

Table 4-17 Deformability factors for unconfined and confined concrete specimens in lateral direction.

Type Of Confinement	Deformability Factor		
	Limiting Strain=0.0008	**Limiting Strain=0.002**	**Limiting Strain=0.003**
Unconfined	20.68	5.03	2.63
Confined By Directly Wrapped With CFRP	26.89	6.32	3.24
Confined By Preformed CFRP Tube With 1% Expanding Grout	36.35	8.72	4.48
Confined By Preformed CFRP Tube With 2% Expanding Grout	47.05	11.02	5.57
Confined By Preformed CFRP Tube With 3% Expanding Grout	49.17	11.46	5.77

The deformability factors ratios of energy absorption (or area under stress strain curve) at ultimate to limiting curvature value (Ganga Rao and Vijay in 1998) and are measure of finding deformations induced in a specimen under unit load. In longitudinal direction, the deformability factors of concrete have been enhanced by confining pressure provided by CFRP and expanding grout which means that the confined concrete is able to absorb more energy as compared to unconfined concrete by taking more loads.

In lateral direction, the deformability factors of the unconfined concrete have been enhanced by using CFRP and expanding grout which enable the confined concrete to absorb more energy as compared to unconfined concrete by being more ductile in lateral direction.

4.3 Visual observations

In addition to mechanical strength tests, visual observations were also made to observe the failure modes and patterns. All the jacket specimens were cracked at the middle. The specimens that were confined by wrapping with CFRP showed explosive behavior at failure, prior the cracking noises were heard which showed that stress is being transferred to CFRP from concrete.

The specimens that were confined by pre-formed tube of CFRP and expanding grout cracked in more explosive manner which showed that large amount of energy was evolved. Inspection of broken samples showed that the outer side of CFRP was ruptured and inner side was still in contact with expanding grout and was stretched as shown in Figure 4-3, 4-4 which showed that a good bond between the CFRP and expanding grout and pre-tensioning was achieved. There was a huge increase in stress and strain values as compared to samples that were directly wrapped to the concrete which showed that pre-tensioning delayed the start of intensive cracking.

Figure 4-3 Failed confined specimens by wrapping with CFRP

Figure 4-4 Failed confined specimen by preformed tubes of CFRP and expanding grout

CHAPTER 5

CONCLUSIONS AND RECOMENDATIONS

5.1 INTRODUCTION

This chapter provides the conclusion drawn from the present study which compares the effectiveness of CFRP and expanding grout for low strength concrete. The effect of confinement has been studied with respect to the ratio of expanding grout used. While studying the behaviour of concrete cylinders under compression, various aspects have been compared which include the axial compressive strength, the ultimate load carrying capacity, stiffness, the longitudinal and lateral strains and ductility. While studying ductility the energy absorption and the deformability factors are calculated. Recommendations for future extension of work have also been made.

5.2 Conclusions

The conclusions derived from this research are as follows.

- Axial compressive strength of concrete specimens is increased by confining them with CFRP and expanding grout. The axial compressive strength is increased to 133,207,260 and 359% respectively for W, GC1, GC2, and GC3 specimens as compared to unconfined specimens. This huge increment is due to fact that CFRP confinement is more effective for low strength concrete.
- Both the longitudinal and lateral strains increase for confined specimens as compared to unconfined specimens The increase in strain is due to enhancement provided by the CFRP and expanding grout to the concrete but this confinement enhances the lateral strain far more than longitudinal strain.
- In longitudinal direction stiffness increases from 1.0 to 1.48, 1.87 and 2.799 for specimens confined with pre formed tubes of CFRP and 1% expanding grout, specimens

confined with pre formed tubes of CFRP and 2% expanding grout and specimens confined with pre formed tubes of CFRP and 3% expanding grout respectively.

- In lateral direction stiffness increases from 1 to 1.09, 1.45, 2.01 and 2.46 for specimens confined with pre formed tubes of CFRP and 1% expanding grout, specimens confined with pre formed tubes of CFRP and 2% expanding grout and specimens confined with pre formed tubes of CFRP and 3% expanding grout respectively.
- In lateral direction, the deformability factors of the unconfined concrete have been enhanced by using CFRP and expanding grout which enable the confined concrete to absorb more energy as compared to unconfined concrete by being more ductile in lateral direction.
- Mode of failure in the case of CFRP wrapped on concrete was explosive and jacket was rupture. Which means that concrete core was fractured before the failure of CFRP warp. In case of preformed tubes that were tensioned by expanding grout the mode of failure was not explosive and CFRP was intact with the concrete.

5.3 Recommendations

A research work is never complete, as there will always come new questions to the researcher's mind as the work progresses. Lateral pre-tensioning of confined concrete with expansive grout is a new subject. Base on this fact, many interesting subjects still remain to be investigated, new topics of research have been opened for further investigations and several propositions require validation as below

- Using of expansive agent directly in the concrete of cast-in specimens. By this method it is possible to apply further lateral pre-tensioning over the jacket plus compensate the effect of shrinkage.
- Work done on this research mainly focused on cylindrical specimens while this method might be useful for the other cross sections like rectangular, square or oval shapes.

REFERENCES

ACI 440.2R-02. Guide for the design and construction of externally bonded FRP systems for strengthening concrete structures. American Concrete Institute, Farmington Hills, Michigan, 2003.

Demers M, Hebert D, Labossiere P, Neale KW. The strengthening of structural concrete with aramid woven fiber/epoxy resin composite. In: Proceedings of advanced composite materials in bridges and structures II, Montreal, August 1995. p. 435–42.

Fam A, Flisak B, Rizkalla S. Experimental and analytical modeling of concrete-filled fiber-reinforced polymer tubes subjected to combined bending and axial loads. ACI Struct J 2003;100(4):499–509.

Haroun MA, Feng MQ, Elsanadedy HM, Mosallam AS. Composite jackets for the seismic retrofit and repair of bridge columns. In: Proceedings of the seventh US national conference on earthquake engineering, Boston, USA, 2002.

Haroun MA, Feng MQ, Youssef MN, Mosallam AS. Seismic retrofit of reinforced concrete columns using FRP composite laminates. In: Proceedings of second conference on seismic repair and rehabilitation of structures (SRRS2), Fullerton, CA, USA, March 21–22, 2000.

De Lorenzis L. A comparative study of models on confinement of concrete cylinders with FRP composites. Division of Building Technology, Chalmers University of Technology, Work No. 46, Publication: 01:04.

Hosotani M, Kawashima K, Hoshikuma Jun-ichi. A stress–strain model for concrete cylinders confined by carbon fiber sheets. J Concr Eng JSCE 1998;39(592):37–52 [in Japanese].

Rousakis T. Experimental investigation of concrete cylinders confined by carbon FRP sheets, under monotonic and cyclic axial compressive load. Research report, Chalmers University of Technology, Gteborg, Sweden.

Picher F, Rochette P. Confinement of concrete cylinders with CFRP. In: Proceedings of first international conference on composite infrastructures, Tucson, Arizona, 1996. p. 829–41.

Priestley MJN, Fyfe E, Seible F. Column retrofit using fiberglass/epoxy jackets. In: Proceedings of the first annual seismic research workshop, California Department of Transportation, Division of Structures, December 3–4, 1991. p. 217–24.

Saafi M, Toutanji HA, Li Z. Behavior of concrete columns confined with fiber reinforced polymer tubes. ACI Mater J 1999;96(4):500–9.

Seible F, Hegemier GA, Priestley MJN, Innamorato D, Ho F. Carbon fiber jacket retrofit test of rectangular flexural column with lap spliced reinforcement. Advanced Composites Technology Transfer Consortium Report No. ACTT-95/02, UCSD, March 1995. 53 p.

Xiao Y. Compression tests of concrete cylinders confined by carbon fiber composite jacket. USC Structural Engineering Research Report No. USC-SERP 98/06, September 1998.

Xiao Y, Wu H. Compressive behavior of concrete cylinders confined by carbon fiber composite jackets. Am Soc Civil Eng, ASCE J Mater Civil Eng 2000;12(2):139–46.

Xiao Y, Wu H. Compressive behavior of concrete confined by various types of FRP composite jackets. J Reinf Plast Compos 2003;22(13):1187–202.

Kono S, Inazumi M, Kaku T. Evaluation of confining effects of CFRP sheets on reinforced concrete members. In: Proceedings of the second international conference on composites in infrastructure ICCI'98, Tucson, Arizona, 5–7 January 1998. p. 343–55.

Mirmiran A, Shahawy M. Model of concrete confined by fiber composites. J Struct Div ASCE 1988;123(5)

Pilakoutas, K. and Mortazavi, Ali. A. "Ductility through external lateral confinement of RC members with FRP". Non-metallic (FRP) reinforcement for concrete structure, Proceeding of the Third international Symposium, E & FN Epson, No. ST1, Japan, October 1997. Vol. 1, No.107, pp. 225-232.

Pilakoutas, K. and Mortazavi, Ali. A. "Laterally Pre-stressed Concrete with Composites". Proceedings of the Fifth International Conference on Fibre-reinforced Plastics for Reinforced Concrete Structures, Thomas Telford Ltd, Cambridge, UK, July 2001. Vol. 2, pp. 855-864.

Frangou, M. "Strengthening of concrete by lateral confinement". Civil and structural engineering. Sheffield, Sheffield University. 1996.

Fardis, M.N. and Khalili, H.H. "FRP- encased concrete as a structural material". Magazine of concrete research, December 1982. Vol. 34, No. 121, pp. 191 - 202.

Saadatmanesh, H. "Fibre composites for new and existing structures". ACI Structural Journal, 1994 Vol. 91, No. 3, pp. 346 - 354.

Saadatmanesh, H., M. R. Ehsani, et al. “Strength and ductility of concrete columns externally reinforced with fibre composite straps”. ACI Structural Journal, 1994 Vol. 91, No. 4, pp. 434-447.

Saadatmanesh, H. “Wrapping with composite materials”. Non - metallic (FRP) Reinforcement for concrete structures by E & FN Spon, 1995 Vol. 1, No. 1, pp. 593-600.

Saadatmanesh, M., R. Ehsani, Jin, L. “Seismic Strengthening of circular bridge pier models with fibre composites”. ACI Structural Journal,1996 Vol. 93, No. 6, pp. 639-647.

Nanni, A. and Bradford, N. M. “FRP jacketed concrete under uniaxial compression”. Construction and Building Materials,1995 Vol. 9, No. 2, pp. 115-124.

Nanni, A. and Norris, M.S. “FRP jacketed concrete under flexure and combined flexure-compression”. Construction and Building Materials,1995 Vol. 9, No. 5, pp. 273-281.

Miyauchi, K. “Estimation of strengthening effects with carbon fibre sheet for concrete column”. Non - metallic (FRP) Reinforcement for concrete structures by E & FN Spon,1997 Vol. 1, No. 1, pp. 217- 224.

Hoppel, C.P.R. Bogetti, T.A. Gillespie, J.W. Howie, I. and Karbhari, V.M.“Analysis of a concrete cylinder with a composite hoop wrap”. Infrastructure repair methods, 2002 pp. 190-197.

Howie, I. and Karbhari, V.M. “Effect of materials architecture on strengthening efficiency of composite wraps for deteriorating columns in the North-East”. Infrastructure repair methods, 2002 pp. 198-207.

Karbhari, V.M. “Seismic retrofitting and strengthening of columns with composite materials”. University of California, Sandiago, LaJolla, pp. 899 - 908.

Karbhari, V.M. and Gao, Y. “Composite jacketed concrete under uniaxial compression- Verification of simple design equations”. Journal of materials in civil engineering (ASCE), 1997 Vol. 9, No. 4, pp. 185 - 193.

Mirmiran , A. Shahawy, M. Samaan, M. Echary, H.E. and Pico, O. “Effect of coloumn parameters on FRP-confined concrete”. Journal of composites for construction, 1998 Vol. 2, No. 4, pp. 175 – 185.

Samaan, M. Mirmiran, A. and Shahawy, M. “Model of concrete confined by fibre composites”. Journal of structural engineering (ASCE), 1998 Vol. 124, No. 9, pp. 1025–1031.

Samaan, M. S. “An analytical and experimental investigation of concrete-filled fibre reinforced plastics (FRP) tubes”.1997 Ph.D. Thesis, University of Central Florida, Orlando, Florida.

Toutanji, H. and Balaguru P. “Durability characteristics of concrete columns wrapped with FRP two sheets”. Journal of materials in civil engineering (ASCE)1998, Vol. 10, No. 1, pp.52-57.

Toutanji, H. “Stress-strain characteristics of concrete columns externally confined with advanced fibre composite sheets”. Journal of materials in civil engineering (ASCE) 1999, Vol. 96, No. 3, pp.397 - 404.

Saafi, M., Toutanji, H.A. and Li, Z. “Behaviour of concrete columns confined with fibre reinforced polymer tubes”. 1991ACI materials Journal,1999 Vol. 96, No. 4, pp. 500-509.

Spoelstra, M.R. and Monti, G. “FRP-confined concrete model”. Journal of composites for construction, 1999, Vol. 3, No. 3, pp. 143 – 150.