EXPERIMENTAL STUDY ON RC BEAMS STRENGTHENED WITH [illegible]RP

A PROJECT REPORT

Submitted by

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BONAFIDE CERTIFICATE

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SYNOPSIS

Fiber-reinforced polymer (FRP) composites have found increasingly wide applications in civil engineering due to their high strength-to-weight ratio and high corrosion resistance. One important application of FRP composites is as a confining material for concrete, particularly in the strengthening of existing reinforced concrete beams by the provision of an FRP wraps. FRP confinement can significantly increase the compressive strength and the ultimate axial compressive strain of concrete. FRP is wrapped around RC beams to determine the difference in their behaviors under concentric loading.

The full wrapping FRP-technique is most used to increase the load carrying capacity and the energy absorption capacity of reinforced concrete beam. RC beam strengthening with FRP strips in-between the existent steel hoops is an economical solution. It is also an adjusted confinement technique when compared with full wrapping.

To study the effect of confinement , an experimental study has been performed using reinforced concrete beams with full wrapping with CFRP and GFRP wrapping schemes. The ultimate strength of the specimens strengthened with CFRP are obtained by measuring from load–deflection graph and by the modulus of elasticity equations. These experimental results are compared with that of the unwrapped sections.

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LIST OF SYMBOLS

Symbol	Expansion
A_g	cross-sectional area of the confined concrete
A_{st}	Area of longitudinal steel
d	diameter of circular column
E_c	modulus of elasticity of concrete
E_{frp}	modulus of elasticity of FRP
E_{sec}	Secant modulus
E_2	slope of linear second portion of stress-strain curve
f'_c	concrete cylinder compressive strength
f'_{cc}	compressive strength of confined concrete
f'_{co}	compressive strength of unconfined concrete
f_{cu}	Ultimate confined concrete strength
f_{frp}	FRP tension strength
f_l	lateral confining pressure
f'_l	effective lateral confining pressure
f_y	steel yield strength
k_e	resistance factor
k_g	gap factor
p_n	nominal axial load carrying capacity
s_{frp}	clear vertical spacing between straps
t_{frp}	thickness of FRP
ε_c	compressive strain of concrete
ε_{cc}	compressive strain of confined concrete at peak stress
ε_{co}	compressive strain of unconfined concrete at peak stress
ε_{cu}	Ultimate confined concrete strain

$\varepsilon_{frp.rup}$	tensile rupture strain of FRP
ε_{t}	strain at transition point in stress-strain curve of FRP-confined concrete
σ_{c}	Axial compressive stress of concrete
ψ_{f}	additional reduction coefficient for FRP wrapped columns
ϕ	strength reduction factor
ρ_{f}	FRP volumetric ratio
ρ_{sc}	Ratio of cross-section area of concrete to longitudinal steel reinforcement
S_{v}	Spacing of Stirrups
V	Shear force
V_{s}	Design Shear force
W	Total load
T_{cmax}	Nominal Shear stresses
M 20	Grade of concrete

CHAPTER 1

INTRODUCTION

1.1 GENERAL

Fiber-reinforced polymer (FRP) composites have been widely used in practice as a confining material for concrete columns to achieve significant enhancements in both strength and ductility.

Reinforced concrete is used in common infrastructures. In the design process, deformed steel bars are used to compliment with the properties of concrete. These steel bars are used as lateral and longitudinal reinforcement to prevent shear and tensile failure. But due to overloading and updates on seismic codes in columns or bridge piers, strengthening becomes dominant in order to improve the compressive strength and ductility of RC columns. One way of strengthening existing beam structure is the application of Carbon Fiber-Reinforced Polymer (CFRP) Sheets to be wrapped around the beam structure. The strengthening method will result to an increase in compressive strength and ductility. This strength and ductility enhancement is done by the confinement effect of the CFRP sheets and the contribution of steel ties present on the existing beam in resisting lateral expansion.

The full wrapping FRP-technique is most used to increase the load carrying capacity and the energy absorption capacity of reinforced concrete beam.RC beam strengthening with FRP strips in-between the existent steel hoops is an economical solution. It is also an adjusted confinement technique when compared with full wrapping.

Various confinement strength models have been presented to predict the compressive strength of confined concrete columns, including those of Mander et al. (1988), Harries et al (2002), Fardis and Khalili (1982) and Lam and Teng (2001). The analytical models were validated with the experimental result.

1.2 LITERATURE REVIEW

1.2.1 T. Jiang and J.G. Teng (2007)

Many stress–strain models have been developed for fibre-reinforced polymer (FRP) confined concrete. These models fall into two categories: (a) design-oriented models in simple closed-form expressions for direct use in design; and (b) analysis-oriented models in which the stress–strain curve is generated via an incremental process. This paper is concerned with analysis-oriented models, and in particular, those models based on the commonly accepted approach in which a model for actively-confined concrete is used as the base model. The paper first provides a critical review and assessment of existing analysis-oriented models for FRP–confined concrete. For this assessment, a database of 48 recent tests conducted by the authors' group is presented; this database includes 23 new tests which have not previously been published.

This assessment clarifies how each of the key elements forming such a model affects its accuracy and identifies a recent model proposed by the authors' group as being the most accurate. The paper then presents a refined version of this model, which provides more accurate predictions of the stress–strain behaviour, particularly for weakly-confined concrete.

In their paper has presented a thorough assessment of the performance of eight existing analysis-oriented stress–strain models for FRP–confined concrete which employ an active confinement model as the base model, leading to the identification of Teng et al.'s model as the most accurate through this assessment. A refined version of Teng et al.'s model has also been proposed. The lateral-to-axial strain relationship, which reflects the unique dilation properties of FRP–confined concrete, is central to models of this kind.

A successful model should accurately predict this relationship. Nevertheless, provided the overall trend of this relationship is reasonably well described, the axial stress–strain curve can be closely predicted, even if local inaccuracies exist in the lateral-to axial strain equation. The definitions of the peak axial stress and the corresponding axial strain in the active-confinement base model are also important to ensure the accuracy of an analysis-oriented model for FRP–confined concrete.

The model of Teng et al. performs the best among the eight models examined in this paper. This model provides accurate predictions of both the lateral-axial strain relationship and the ultimate condition, except that it overestimates the axial stress at ultimate axial strain for weakly-confined and to a lesser extent for moderately confined concrete. As a result, its predictions are likely to be inaccurate for stress–strain curves with a descending branch.

1.2.2 Harries (2002)

The behavior of concrete subject to variable levels of confining pressure under concentric axial loading is presented. An extensive experimental investigation of this behavior, using fibre-reinforced polymer-confined concrete cylinders is used to develop an understanding of the relationships required to accurately predict the behavior of concrete subject to passively induced, varying levels of confinement. In particular, the relationship between transverse and longitudinal strains–the dilation relationship—is investigated, and a model for this behavior, based on the stiffness of the confining materials, is proposed. The established relationships are combined into an iterative model for determining the complete stress-strain relationship of concrete subject to variable confining pressure.

1.2.3 V.C. Rougier and Luccioni (2006)

During their service life reinforced concrete structures can be exposed to mechanical loads and aggressive chemical or thermal agents that produce degradation of their mechanical properties. This results in a loss of security and usually requires a prompt repair or retrofitting in order to preserve the structural serviceability. In this case, the aid of a numerical tool for the assessment of different retrofit and repair systems would be valuable. A numerical model that can be used for the assessment of retrofit and repair systems based on the use of FRP for reinforced concrete columns and beams is presented in their paper. A plastic damaged model that reproduces the behavior even under high confinement pressures is used for concrete.

1.2.4 Marques (2004)

This paper presents a numerical model for evaluating the behavior of axially loaded rectangular and cylindrical short columns of concrete confined by fiber-reinforced polymer (FRP) composites. The proposed formulation considers, for unconfined and confined compressed concrete, a uniaxial constitutive relation that utilizes the area strain as a parameter of measure of the material secant axial stiffness. For unconfined concrete, the model adopts an explicit relationship between axial strain and lateral strain, while for confined concrete, an implicit relation is considered. For this last case, the model employs a simple iterative-incremental approach that describes the entire stress-strain response of the columns. The behavior of the FRP is considered linear elastic until the rupture. To validate the model, a number of columns were analyzed and the numerical results were compared with experimental values published by other authors. This comparison between experimental and numerical results indicates that the model provides satisfactory predictions of the stress-strain response of the columns.

1.3 OBJECTIVES AND SCOPE OF THESIS

This research is aimed at studying the behaviour of small-scale circular concrete columns wrapped with CFRP sheets and subjected to concentric axial compression. A parametric study relating various factors such as concrete strength, confinement ratio and CFRP Volumetric ratio, have been carried out for various existing models. An experimental investigation is also carried out to study the schemes of FRP confinement on the strength of the columns. The research also includes a comparative study on the overall behaviour of unconfined and FRP confined concrete columns.

The main objectives are:

To study the strength enhancement behavior and confinement effectiveness through experimental investigation.

- To develop the stress-strain model from experimental results.
- To study the efficiency of partial wrapping method.
- To develop a program in MATLAB for strengthening of axially loaded RC columns.

1.4 RETROFITTING OF EXISTING STRUCTURES BY EXTERNALLY BONDED FRP OVERLAY :

Externally bonded FRP's have been used to retrofit structural members such as columns , beams, slabs and girders in structures such as bridges, parking decks, smoke stacks and buildings and have proved to be an effective way of improving strength and stiffness of existing structural elements. A large number of projects both public and private, have used this technology and escalating deployment is expected, especially in seismically active regions. The application of FRP as external reinforcement to concrete structures has been studied by many groups. This technology is fairly mature enough; extensive research on FRP exists on bond research performance, creep effects, ductility of the repairs, fatigue performance, force transfer, peel stresses, resistance to fire, and ultimate strength.

Today , there are numerous manufacturers of FRP composites systems for repair and retrofitting. Guidelines for the design and application of these materials for flexural retrofit of concrete elements are available from the manufacturers. The American concrete institute(ACI) has incorporated the design and construction of external bonded FRP systems for strengthening concrete structures in its 2002 code. The new Canadian highway bridge design code (2001) also provides some detail on the FRP composite.

These manual can serve as a model for FRP composite specifications and a comprehensive guide to address various design issues. The implementation of these techniques with various available FRP composites such as laminates/shells and sheets demonstrated around the world in the recent years.

Three methods are used for application of external FRP reinforcement-adhesive bonding hand up or wet layup and resin infusion. The important functions of matrix material in FRP composite material include:

1. Bind the fibres together and transfer the load to the fibres by adhesion and/or friction.
2. Provide rigidity and the shape to the structural members.
3. Isolate the fibres so that they can act separately resulting in slow or no crack propagation.
4. Provide protection to the fibres against chemical and mechanical damages.
5. Influence performance characteristics such as ductility, impact strength
6. Provide finish colour and surface finish for connections.

To perform these desirable functions, the fibres in FRP composite must have

i. High modulus of elasticity for use of reinforcement.
ii. High ultimate strength
iii. Low variation of strength among fibres
iv. High stability of their strength during handling
v. High uniformity of diameter and surface dimensions among fibres.

Another area that has received considerable attention in the recent years is that of the seismic retrofitting of concrete bridges using FRP composites. Axial strength and ductility increase of concrete columns piers is needed where ever repair may be required when columns are damaged under excessive external loads or due to erosion in exposed environments. Lateral confinement has been known to add both strength and ductility in the axial direction for concrete columns and this idea was originally developed back in the 1920's.

Lateral confinement for concrete columns can be in various forms. They appear chronologically as a) spherical and circular reinforcements b) concrete jacketing c) steel jacketing d) FRP composite jacketing, wrapping. Steel has been a conventional and widely used construction material. However, corrosion is one of the largest drawbacks of such material. Weight can be another problem because the constructions can surge when the installation is labour intensive. Concrete jacketing, though has a lower cost, but simply adds weight and cross sectional to the original area to the original structure and may be undesirable. On the contrary, FRP composite jacketing systems have emerged as an alternative to traditional construction, strengthening and repair of reinforced concrete columns and bridge piers.

The primary FRP application column FRP wrapping is commonly used in seismic retrofits even under worse site conditions such as repairing corrosion damage in chloride contaminated concrete in high seismic zone. These procedures, which can be used in place of steel jackets, provide additional confinement for the column. This leads to additional column ductility and can also enable rebar splices with insufficient laps to more fully develop. It should be noted that column wrapping could also lead to increased axial capacity. Although this is not the objective in a seismic wrapping application, it can be used as a retrofit technique for column strengthening. Extensive laboratory investigations have been conducted, and several manufacturers have products that are being marketed for this application. Several countries have conducted field projects involving column jacketing using FRP composites.

1.5 ORGANIZATION OF THE THESIS

Chapter 1 gives brief introduction of the project and an extensive literature review of relevant research regarding confinement of concrete beams.

Chapter 2 discusses the properties of different types of FRPs and their strengthening applications. Advantages and disadvantages of FRPs are also included.

Chapter 3 explains the construction, different methods of FRP strengthening and the benefits of confinement of concrete are discussed.

Chapter 4 explains the analytical study

Chapter 5 discusses the experimental program.

Chapter 6 Analysis and discussion of the test results are presented.

Chapter 7 Conclusions are reported along with suggestions for future research.

1.6 SUMMARY

In this chapter a brief introduction is given about the thesis. Earlier research work done on the FRP strengthening is discussed. The purpose and scope of the investigation as well as the organization of the thesis are presented.

CHAPTER 2

FIBER REINFORCED POLYMERS

2.1 GENERAL

A brief description of different types of commonly used fiber reinforced polymers (FRPs) and their properties and applications are presented in this chapter. Factors affecting properties of FRP and applications of FRP including its use in confining concrete are also reviewed.

2.2 FIBER REINFORCED POLYMERS

FRP materials, originally developed for use in the automotive and aerospace sectors, have been considered for use as external reinforcement for concrete structures since the 1970's. However, it is really over the last 10 years or so that FRP materials have begun to see widespread use in civil engineering projects. This is due to drastic reductions in FRP material and manufacturing costs and to numerous research projects that have demonstrated their many advantages over conventional materials. Many types and shapes of FRP materials are now available in the construction industry.

For the purposes of external reinforcement of concrete, there are essentially three types of FRP materials currently available: Glass, Carbon and Aramid polymers. FRP sheets are supplied as flexible fabrics of raw (or pre-impregnated) fibers. The sheet FRP materials are applied by saturating the fibers with an epoxy resin and laying-up the sheets onto the concrete surface. In both of the above applications, the FRP materials used are usually unidirectional (with all fibers oriented along the length of the sheet).

FRP composite materials,which have been used for some time in the aero space and military communities, is at present as a potential solution to some of the highway community's infrastructure. During the past decades a significant amount of exploratory and basic research has been conducted all over the world on the use of FRP

Typically, FRP materials has superior properties has superior properties with respect to strength, weight, durability, creep, fatigue, light in weight and easy to construct, FRP provide excellent strength to weight characteristics can be fabricated for " made to order" strength, stiffness and geometry. The bridge can be strengthened without reduction of vertical clearance, and the FRP can be applied in severe exposure environments that may have resulted in the deterioration of the original structure, corrosion resistant, low axial coefficient of thermal expansion and relatively low cost of maintenance.

FRP composite may be used to extend the life of the bridge infrastructure because of their low dead weight allows for an increase in live load carrying capacity. They do not exhibit yielding , but are elastic up to failure. Figure 1 demonstrates some typical response of uni-axially loaded fibre materials including high modulus(HM) steel and high strength(HS) steel. Fibres have a linear elastic behaviour until failure which is brittle. Table 1 compares the material properties of carbon fibres, concrete and steel. FRP composites exhibit several traditional material structures

MATERIAL	MODULUS OF ELASTICITY (GPa)	COMPRESSIVE STRENGTH (MPa)	TENSILE STRENGTH (MPa)	DENSITY
Concrete	20-40	5-60	1-3	2400
Steel	200-210	240-690	240-690	7800
Carbon fibre	200-800	N/A	2100-6000	1750-1950

Table2.1: Material properties of concrete,steel and carbon fibres

The current commercially available FRP reinforcements are made of continuous fibres of aramid(AFRP), carbon(CFRP) or glass(GFRP) impregnated in a resin matrix each has its own advantages and disadvantages.FRP can be produced by different manufacturing methods in many shapes and forms. The key features and benefits of FRP composites are tabulated in the following table.

Very high strength to thickness ratio	Appreciable increase in strength and load carrying capacity without significant increase in weight
Enhanced stiffness, shear and tensile capacities	Increased load carrying capacity and better resistance to seismic forces and deflection
Light weight and durable	No increase in dead load and long term performance
Chemical resistance	Excellent resistance to acids and alkalis
Corrosion resistant	Protects concrete/steel from corrosion

Impervious	Protection from atmospheric gases
Flexible	Can be applied on any shape or contour of substrate
Economical	Easy to install, time and labour saving
Thin sections	Can be effectively used in space constraint areas

Commonly used FRP's for concrete reinforcement are bars, pre-stressing tendons, pre-cured laminates/shells and fibre sheets. Bars/rods have various types of deformations systems, including externally wound fibres, sand coatings and separately formed deformations, these types are commonly used for internal concrete reinforcement.

FRP procured as laminates/shells and sheets are commonly used for external concrete reinforcement. Based on the results of literature search, the various bridge- related applications of FRP can be divided into five major FRP composite applications categories:

1. repair and retrofitting(laminate applications)
2. FRP composite reinforcement(rebar and tendons)
3. Seismic retrofitting
4. FRP composite bridge decks and super structures
5. Unique applications

Among these the most predominant application for retrofit involves the externally bonded FRP composite that have been used to replace traditional methods such as bonded steel plates , jacketing etc for tensile strength and stiffness for existing structural elements.

2.3 PROPERTIES OF FRP COMPOSITES

Unidirectional FRP materials used in external strengthening applications are typically linear elastic up to failure, and do not exhibit the yielding behaviour that is displayed by conventional reinforcing steel, which demonstrates the significant differences in the tensile behaviour of FRP materials as compared with steel. FRP materials generally have much higher strengths than the yield strength of steel, although they do not yield, and have strains at failure that are often considerably less than steel.

The specific properties of different FRP materials vary a great deal from one manufacturer to another and depend on the fiber and matrix type, the fiber volume content, and the orientation of the fibers within the matrix, among other factors. However, Table 2.1, 2.2 and 2.3 give material properties for a number of typical currently available FRP strengthening systems.

Table 2.2 Typical Matrix Properties

Materials	**Density** ℓ	**Modulus of elasticity in tension** E_t	**Strength in tension** f_t	**Strength in Comparison** f_c	**Poisson's ratio** γ	**Co-efficient of thermal expansion** α
	Kg/m^3	**MPa**	**MPa**	**MPa**		**10^{-6}/C**

Polyester	1200-1400	2500-4000	45-90	100-250	0.37-0.40	100-120
Epoxy	1400	2800	58	-	-	50
Nylon	1140	2800	70	-	-	100
Polyethylene	960	1200	32	-	-	120

Table 2.3 Typical Fiber Properties

Materials	**Density** ℓ	**Modulus of elasticity** **E**	**Strength in tension** f_t	**Strain in tension** ε_t
	Kg/m^3	**MPa**	**MPa**	**%**
E-glass	2500	70000	1500-2500	1.8-3.0
s-glass	2500	86000	4800	-
High modulus carbon	1950	380000	2000	0.5
High strength carbon	1720	240000	2800	1

Carbon	1400	190000	1700	-
Boron	2570	400000	3400	-
Graphite	1400	250000	1700	-
Kevlar49	1450	120000	2700-3500	2.0-2.7
Kevlar	1450	60000-130000	2900	-

Table 2.4 Typical Mechanical Properties of GFRP, CFRP & AFRP Composites

Advanced Composite Materials	**Fiber content**	**Density ρ**	**Modulus of elasticity in tension E_t**	**Strength in tension f_t**
	% by weight	**kg/m^3**	**GPa**	**MPa**
Glass fiber/Polyester GFRP laminate	50-80	1600-2000	20-55	400-1250
Carbon/Epoxy CFRP	65-75	1600-	120-250	1200 –

Laminate		1900		2250
Aramid/Epoxy	50-80	1050 – 1250	40-125	100-1800

2.4 COMMON FRP-STRENGTHENING APPLICATIONS

There are currently three main applications for the use of FRPs as external reinforcement of reinforced concrete structures:

2.4.1 Flexural Strengthening

In this application, FRP materials are bonded to the tension and/or side faces of a concrete beam to provide additional tensile reinforcement and to increase the strength of the member in bending (Fig. 2.1). The fibers are oriented along the longitudinal axis of the beam.

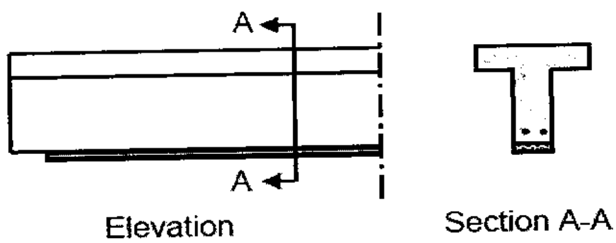


Fig. 2.1 Typical Flexural Strengthening of a Reinforced Concrete T-beam Using Externally Bonded FRP Reinforcement

2.4.2 Shear Strengthening

In this application, FRP materials are bonded to the side faces of a concrete beam (often in the form of U-wraps) to provide shear reinforcement which supplements that provided by the internal steel stirrups (Fig. 2.2). The fibers are oriented perpendicular to the longitudinal axis of the beam.

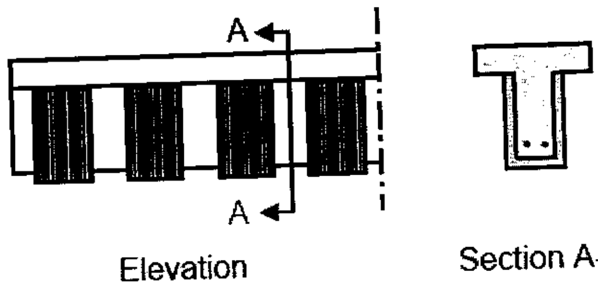


Fig. 2.2 Typical Shear Strengthening of a Reinforced Concrete T-Beam Using Externally Bonded FRP Reinforcement

2.4.2 Confining Reinforcement

In this application, columns are wrapped in the circumferential direction with FRP sheets (Fig. 2.3). Under compressive axial load, the column expands (dilates) laterally and the FRP sheets develop a tensile "confining" stress that places the concrete in a state of triaxial stress. This significantly increases the strength and ductility of the concrete and the column. The fibres are most commonly oriented perpendicular to the longitudinal axis of the member.

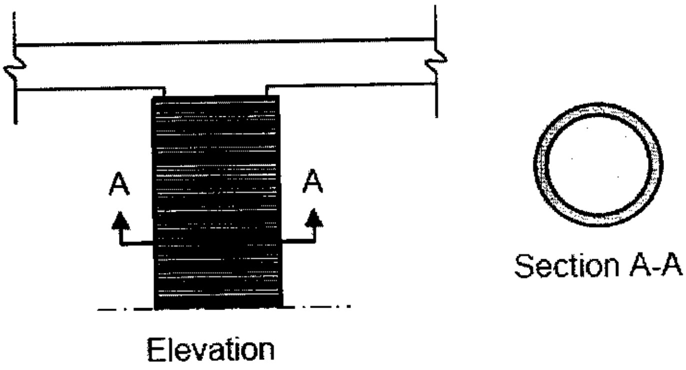


Fig 2.3 Typical Axial Strengthening of a Circular Reinforced Concrete Column Using An Externally Bonded FRP Wrap

2.5 CFRP CONFINEMENT IN RC STRUCTURE:

Different behavior between steel and CFRP was observed due to the stress-strain relationship of each material shown in Fig 2.4. Carbon Fiber-Reinforced Polymer is elastic up to failure while steel has an elastic-plastic region. These different material properties contribute to a complex interrelationship between the two confining materials.

In Fig 2.5, the geometric dimensions used as parameters in circular columns are shown. The positions of lateral steel and longitudinal steel bars are within the core diameter, *d*, while the wrapping of CFRP in concrete is made by applying epoxy in the outer column diameter, *D*.

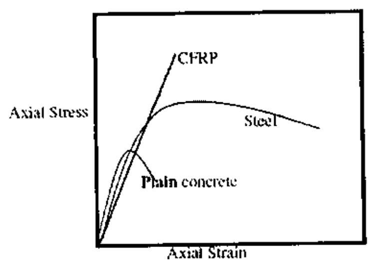


Fig:2.4 stress-strain curve

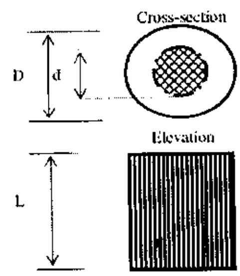


fig:2.5 diagram of confining materials

2.6 ADVANTAGES AND DISADVANTAGES OF FRPs

2.6.1 Advantages

FRP materials for use in concrete strengthening applications have a number of key advantages over conventional repair materials such as steel. In many cases, these advantages make FRP materials the only possible solution to a strengthening problems include:

- FRP materials do not corrode electrochemically, and have demonstrated excellent durability in a number of harsh environmental conditions,
- FRP materials have extremely high strength-to weight ratios. FRP materials typically weigh less than one fifth the weight of steel, with tensile strengths that can be as much as 8 to 10 times as high,
- FRP materials are extremely versatile and are quickly and easily installed. This reduces the downtime required for repair and offsets indirect repair costs,
- FRP materials are electromagnetically inert. This means that they can be used in specialized structures such as buildings to house magnetic resonance imaging (MRI) or sensitive communications equipment, etc.

2.6.2 Disadvantages

- Higher initial cost
- FRP material properties like strength and stiffness naturally degrade over time
- Lack of design standards and conventions
- Lack of long term performance data

2.7 SUMMARY

In this chapter properties of various FRPs and their strengthening applications, advantages and disadvantages are discussed with an emphasis on CFRP confinement of RC structure.

CHAPTER 3

METHODS OF STRENGTHENING RC STRUCTURES

3.1 GENERAL

A number of different techniques have been developed for strengthening existing RC columns using FRP composites. The aspects described in this section are common to both strengthening under static loads and seismic retrofitting. The methods for strengthening can be placed into the following three categories in terms of the method adopted for constructing the FRP composite:

(a) Wrapping,
(b) Filament winding, and
(c) Prefabricated shell jacketing.

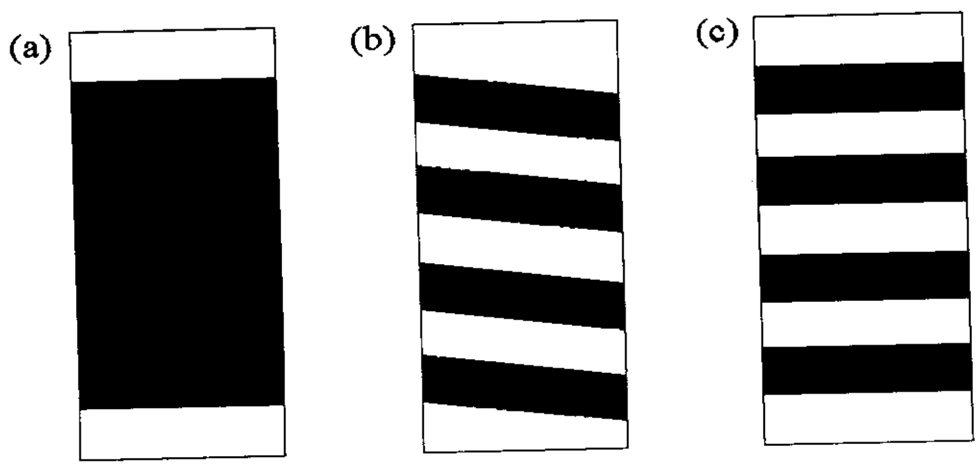


Fig 3.1 Typical FRP Wrapping Methods for RC Columns: (a) Full Wrapping using FRP Sheets; (b) Partial Wrapping using FRP Straps in a Continuous Spiral; and (c) Partial Wrapping using FRP Straps in Discrete Rings

3.2 WRAPPING

In-situ wrapping has been the most common technique for beam strengthening using FRP composites. In this method, unidirectional fiber sheets or woven fabric sheets are impregnated with polymer resins and wrapped around beams in a wet-lay-up process, with the main fibers oriented in the hoop direction. A column can be fully wrapped with FRP sheets in single or multiple layers, but it can also beam be partially wrapped using FRP straps in a continuous spiral or discrete rings.

The compressive strength enhancement of concrete due to external wrapping of FRP was first demonstrated by Fardis and Khalili. This concept was first applied to the strengthening of real RC beam in Japan in the mid 1980s [American Concrete Institute (ACI) 1996]. There have been many reports of the application of this technique in the retrofitting of bridge and building columns since then (e.g., ACI 1996; Neale and Labossiere 1997; Tan 1997).

3.3 FILAMENT WINDING

The principle of filament winding is similar to wrapping, except that the filament winding technique uses continuous fiber strands instead of sheets/straps so that the winding can be processed automatically by means of a computer-controlled winding machine. An FRP jacket with controlled thickness, fiber orientation, and volume fraction can be produced by this process. The idea of confining concrete by winding continuous resin-impregnated fiber strands was first mentioned by Fardis and Khalili (1981). The first winding machine for column retrofitting was developed in Japan in the mid 1980s (ACI 1996).

3.4 PREFABRICATED SHELL JACKETING

Existing RC beams can also be strengthened using prefabricated FRP shells. The shells are fabricated under controlled conditions using fiber sheets or strands, with impregnation by resins before field installation. They can be fabricated in half-circles or half-rectangles (Nanni and Norris 1995), in circles with a slit, or in continuous rolls (Xiao and Ma 1997), so that they can be opened and placed around the beams.

To achieve effective FRP confinement, full contact between the beam and the FRP shell is essential. This contact can be ensured by either bonding the shell to the beam using adhesives (Xiao and Ma 1997), or injecting shrinkage-compensated cement grout or mortar into the space between the shell and the beam (Nanni and Norris 1995). An interesting application of prefabricated shells is for formwork in modifying beam shapes as part of a strengthening measure. This has recently been discussed by Teng et al (2002), who suggested that square or rectangular columns can be strengthened by reshaping them into circular or elliptical columns in which a prefabricated FRP shell is used to provide both the permanent formwork and the required confinement after the curing of concrete.

3.5 COMPARISON OF STRENGTHENING METHODS

Each of the methods discussed above has its advantages and disadvantages, as listed in Table 3.1. Overall, external wrapping appears to be the most popular method because its advantages (flexibility and ease in site handling) appear to be far more important than its disadvantages.

Filament winding bears much similarity to wrapping because both involve a wet-lay-up process, so in the rest of this chapter the term "wrapping" is used to cover both methods, except when specific distinction has to be made between the two.

3.6 CONSTRUCTIONAL ASPECTS

Before FRPs are applied using any of these techniques, the beam should be properly prepared to provide a hard, dry, and clean surface. Any damaged or deteriorated parts should be removed and the surface patched with good concrete, cement mortar, or epoxy putty as appropriate. The repaired surface should be trowelled

Table 3.1 Comparison of Different Methods of Beam Strengthening

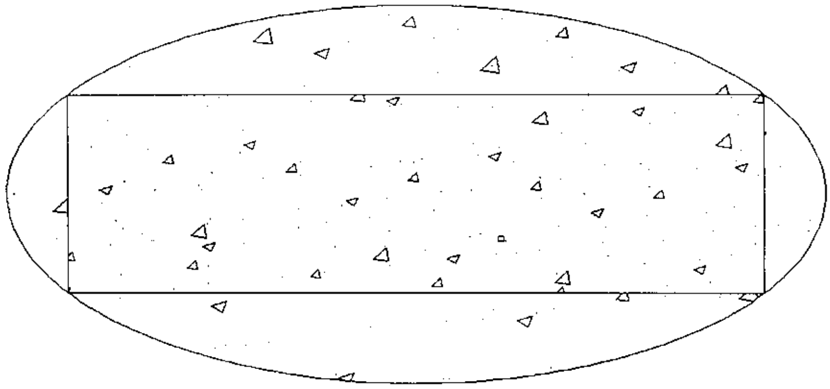
Method	Advantages	Disadvantages
Wrapping	Flexibility in coping with different beam shapes Ease in site handling, without the need for special equipment	Least quality control Most labor intensive
Filament winding	Improved quality control Reduced on-site labor	Reduced flexibility in coping with different beam shapes Special equipment required
Prefabricated shells	Best quality control Least on-site labor Useful for beam shape modification	Limited flexibility in coping with different beam shapes High prefabrication cost

3.7 SHAPE MODIFICATION

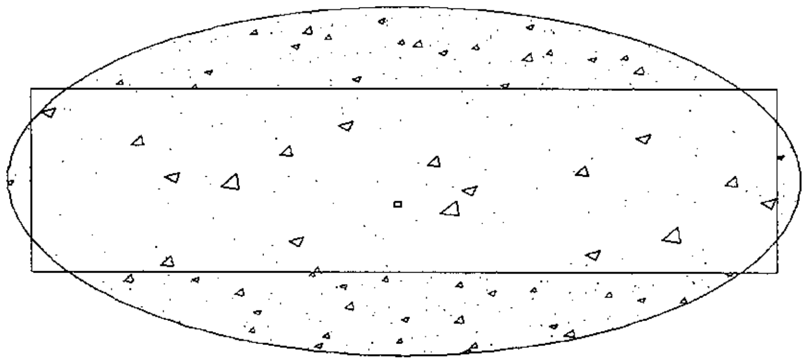
In case of columns,FRP jacketing provides very effective confinement to circular columns, but is much less effective for rectangular columns. For these columns, more effective confinement can be achieved by modifying the column section into a circular or elliptical section before FRP Jacketing.

Whereas in case of beams, the Shape Modification idea appears to have been first explored by Prisestley and Seible (1995). In their approach precast concrete bolsters are added to obtain elliptical section before wrapping FRP sheets. Shape Modification before wrapping has also been achieved using fast cured cement. Rectangular beams are generally modified into Elliptical shape to avoid excessive sectional enlargement. The general idea of Shape Modification followed by FRP confinement can be extended to many other sectional shapes.

Prefabricated circular or elliptical FRP Shapes can also be used for Strengthening Beams. For strengthening Beams, an FRP shell of elliptical section is placed around the beam (fig 3.2 (a)). The space between the FRP shell and the original beam can then be filled with concrete. The FRP shell serves both as the form work for the concrete in-fill and as confinement for strength enhancement for the modified beam of elliptical section. To reduce further the size of the strengthened beam, the corners of the original beam may be rounded, leading to a scheme as shown in fig 3.2 (b)



(a)



(b)

Fig 3.2 Strengthening of Beams by Shape Modification

and FRP Confinement, without (a) and with (b) Corner Rounding

3.8 SUMMARY

This chapter illustrates the various methods of strengthening of RC Structures in detail.

CHAPTER 4
ANALYTICAL STUDY

4.1 INTRODUCTION

When a FRP confined beam is subject to flexure, the concrete expands laterally and this expansion is confined by the FRP. For RC Beams the concrete is subjected to uniform confinement, and maximum confining pressure provided by FRP composite is related to the amount and strength of FRP.

4.2 FRP CONFINEMENT OF CONCRETE

In FRP confined concrete, the concrete core expands laterally when it is subjected to an axial compression load. This expansion of the concrete core is confined by the FRP jackets or shells, and thus transforms the concrete core to a 3-D compressive stress condition. The 3-D compressive stress condition serves to significantly increase the compressive strength and the ductility of brittle concrete. Compared with other cylindrical columns, FRP confined concrete columns behave uniquely when subjected to an axial compression load. The FRP begins to confine the concrete shortly after the unconfined concrete strength is reached. It then reverses the direction of the volumetric response, and the concrete responds through large and stable volume contraction. As a result, the stress-strain curve is characterized by a distinct bilinear response with a transition zone at a stress level near the strength of unconfined concrete. Fig 4.2. shows the axial stress-strain behavior of the FRP-confined concrete.

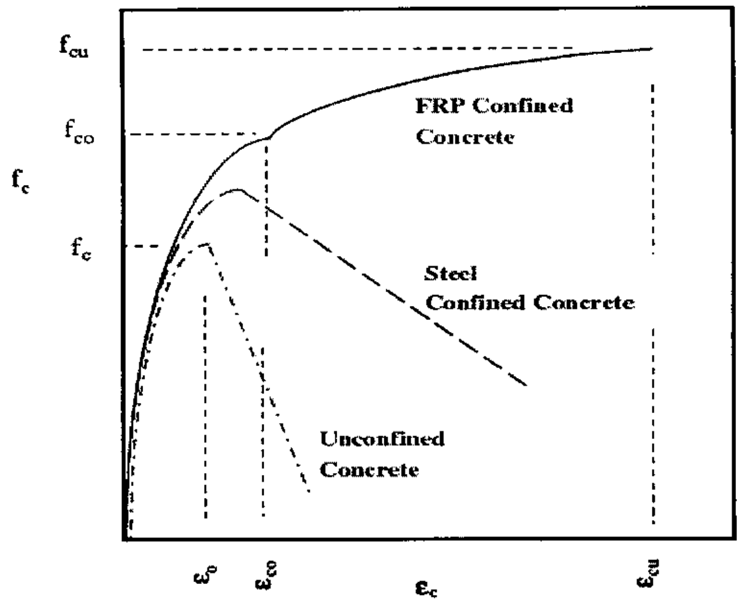


Fig. 4.1 Typical stress–strain relationship for FRP confined concrete

4.3 DETERMINATION OF MODULUS OF ELASTICITY

The value of E found by actual loading of concrete ie., the static modulus of elasticity does not truly represent the elastic behavior of concrete. It will get affected more seriously at higher stresses when the effect of creep is more pronounced.

Attempts have been made to find out the modulus of elasticity from the data obtained by the data obtained by non-destructive testing of concrete. The modulus of elasticity can be determined by subjecting the concrete member to longitudinal vibration at their natural frequency. This method involves the determination of either resonant frequency through a specimen of concrete or pulse velocity traveling through the concrete. By making use of above parameters modulus of elasticity can be calculated from the following relationship.

$$E=Kn^2L^2\rho$$

Where,

E= dynamic modulus of elasticity

K=constant

n=resonant frequency

L=length of the specimen

ρ = density of concrete

if L is measured in mm and ρ in Kg/m^3, then

$$E = 4x10^{-12} \times n^2L^2\rho \ MN/m^2$$

The Dynamic Modulus of Elasticity can also be found out from the following equation

$$E = \rho v^2(1+\mu)(1-2\mu)/(1-\mu)$$

Where,

V=pulse velocity

ρ =density

μ =poissons ratio

The value of E found using this method by the velocity of sound or frequency of sound is referred as dynamic modulus of elasticity, in contrast to the value of E found using the actual loading of the specimen and from the stress-strain relationship, which is known as static modulus of elasticity.

4.4. SUMMARY

In this chapter various stress-strain of FRP strengthened beams and determination of modulus of elasticity by using various equations is done.

CHAPTER 5
EXPERIMENTAL INVESTIGATION

5.1 INTRODUCTION

Confinement of reinforced concrete beams by means of FRP wrapping has been shown to be a very effective technique for structural enhancement. Indeed, numerous studies have demonstrated that wrapping FRP sheets around a beam can increase its strength considerably as well as provide improved ductility. This study focuses on method of strengthening of FRP-confined concrete beam. The partial wrapping method of strengthening are examined by testing both reinforced concrete beams and FRP wrapped beams, each set having the same dimension. Finally, the results are compared. In this study, a total of 3 numbers of concrete beams were tested . The data recorded included the load, deflection and modulus of elasticity.

5.2 MATERIALS

5.2.1 Concrete

The mix proportion adopted using IS method of Mix design is 1:1.638:3.372 and the water cement ratio is 0.52. The Ordinary Portland cement, naturally available river sand, coarse aggregate of maximum size of 20 mm and potable water were used for concrete making. Admixtures were not used in any of the concrete mixes.

5.2.2 Steel

The HYSD steel bars of diameter 10mm with yield strength of 351 MPa were used as longitudinal reinforcement and stirrups of 8mm were used.

5.2.3 CFRP

The CFRP sheets used have the trade name of S&P C-Sheet 240 (400 g/m^2 of fibers). According to the supplier, C-Sheet 240 have a thickness and width of 0.234mm and 300mm, respectively, and have a tensile strength higher than 3700 MPa, and an elasticity modulus and an ultimate strain in the fiber direction of about 240 GPa and 1.5%, respectively. To check the values of these properties, samples of CFRP were tested according to ASTM D 3039 recommendations .Wet lay-up FRP type specimens were first impregnated with resin and cured under a laboratory environment for at least 7 days.

Table 5.1 Tensile Properties of CFRP Sheets and the Longitudinal Steel Bars

Specimen type	Modulus of elasticity (MPa)	Tensile strength (MPa)
8 mm dia of longitudinal steel bar	200000	352
CFRP-sheet (400 g/m^2)	240000	3800

5.3 TEST SPECIMENS

The experimental program was carried out using 3 numbers of FRP-confined concrete beams specimens .The specimen notations presented in Table 5.2 are as follows. The first two letters refers RC for Reinforced concrete. The next two letters specifies the method of FRP wrap: FW for Full wrapping and NW to indicate no wrapping that is, a reference specimen. The details of the specimens are summarized in table 5.2

Table 5.2 Details of the Test Specimens

Specimens Name	Cross section	Method of wrapping	Concrete
RCNW	Rectangular	No	RC
RCCW	Rectangular	Full	RC
RCGW	Rectangular	Full	RC

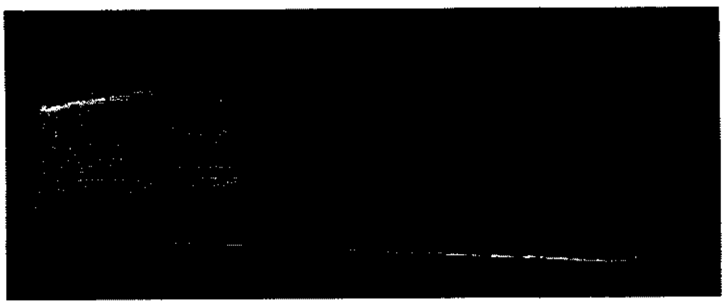
5.4 FABRICATION OF SPECIMENS

A single batch of normal concrete was used to cast 3 samples. After a 24-hours cure, the molds were removed and all specimens were checked for irregularities such as holes or other surface imperfections. All holes and cracks were filled with mortar cement and imperfections were buffed away, leaving an appropriate bonding surface for the FRP wrap. The samples were then watered for a 28-days cure, after which the concrete was left to cure in dry-air conditions. The concrete surface was then cleaned and an epoxy primer was applied with a foam roller to seal any remaining cracks and voids. The fiber sheets, precisely cut to fit each specimen, were then applied using a wet-lay-up process. The sheets were placed so that the primary fibers made a 90° angle with respect to the longitudinal axis of the specimen. Pressure was applied on the FRP surface with a foam roller in order to remove all voids. Once confined, the specimens were allowed to cure for at least another 5 days before testing.

5.5 WRAPPING CONFIGURATION AND BEAM DIMENSIONS WITH REINFORCEMENT DETAILS

The wrapping configuration and beam dimensions are shown in fig 5.1a,5.1b and 5.1c respectively.

Carbon Fibre



Glass fibre

Completed section

Fig 5.1a, 5.1b and 5.1c Wrapping Configuration

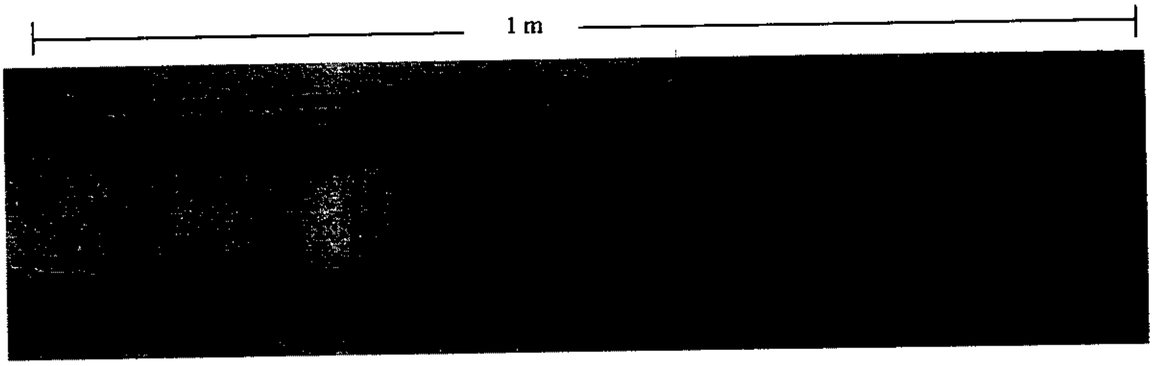


Fig 5.2 Beam Dimensions With Reinforcement Details

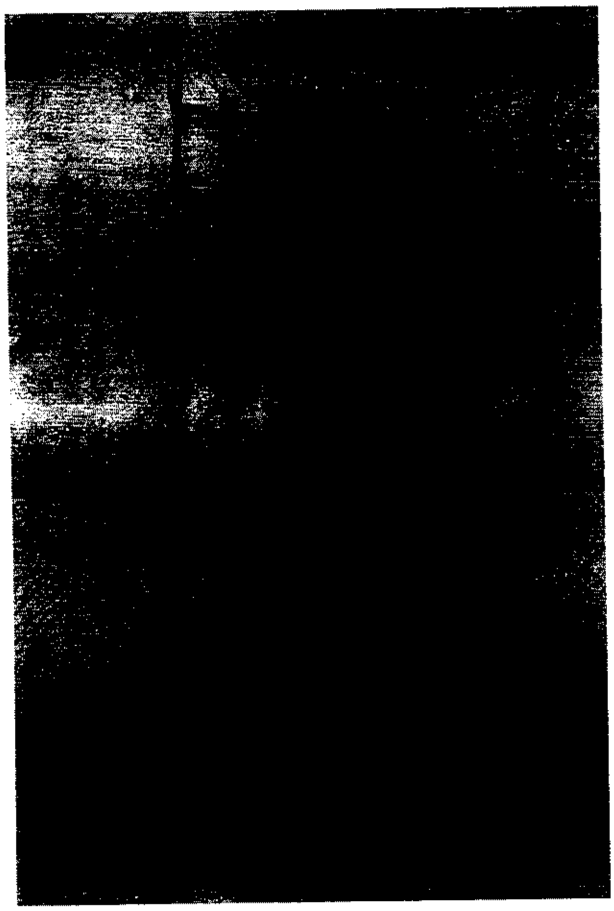


Fig 5.3 Reinforcement Skeleton for beam

5.6 INSTRUMENTATION AND TESTING PROCEDURE

We conducted a cube testing for the same design mix of 1:1.638:3.372. Cube of size 150x150x150mm was casted and tested at 28 days.Then the testing was done in the UNIVERSAL TESTING MACHINE. By which we acquired an average strength of 27.2N/mm2.

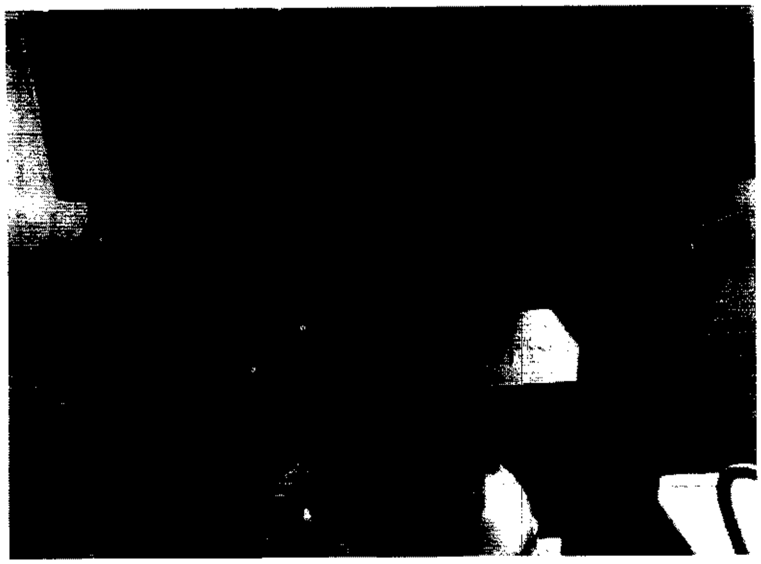


Fig 5.4 Cube Testing

5.7 SUMMARY

The material properties of the concrete, steel and CFRP used in the experimental program are reported in this chapter. Reinforcement details, construction details of the specimens, instrumentation details are also presented.

CHAPTER 6

RESULTS AND DISCUSSIONS

6.1 GENERAL

The results of experimental investigation of the reinforced concrete beam confined with carbon fiber reinforced polymer (CFRP) composites, subject to concentric loads.

The results of the beams tested in the experimental program are reported and discussed in this chapter. Load-Deflection responses of confined concrete specimens are plotted and used to study the strength enhancement characteristics. The results of parametric study carried for studying the effects of concrete strength and CFRP volumetric ratio are reported. The modulus of elasticity of the various polymers are studied and reported.

6.2 EXPERIMENTAL TEST RESULTS

The load carrying capacities of wrapped beams were obtained and compared to the corresponding unwrapped control beams and the corresponding flexural strength is determined. The load –deflection graphs is plotted and the modulus of elasticity is determined. The Load –Deflection enhancements for the various specimens are detailed using bar charts.

6.3LOAD – DEFLECTION CHART FROM EXPERIMENTAL RESULTS

Fig 6.1 ,6.2 and 6.3 shows the relationship between LOAD and DEFLECTION. The concrete stress is the ratio between the applied load and the specimen cross section. 1st graph shows the variations for the normal beam, as load increases deflection increases. Whereas the 2nd and 3rd graphs shows a corresponding decrease in deflection as the load increases .

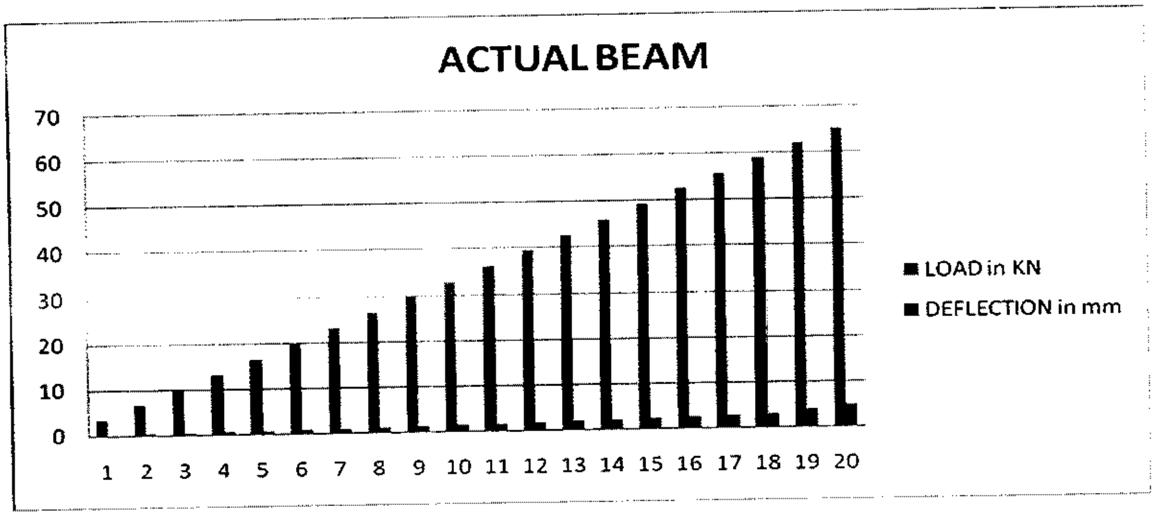


Fig:6.1, Bar Chart for Actual Beam

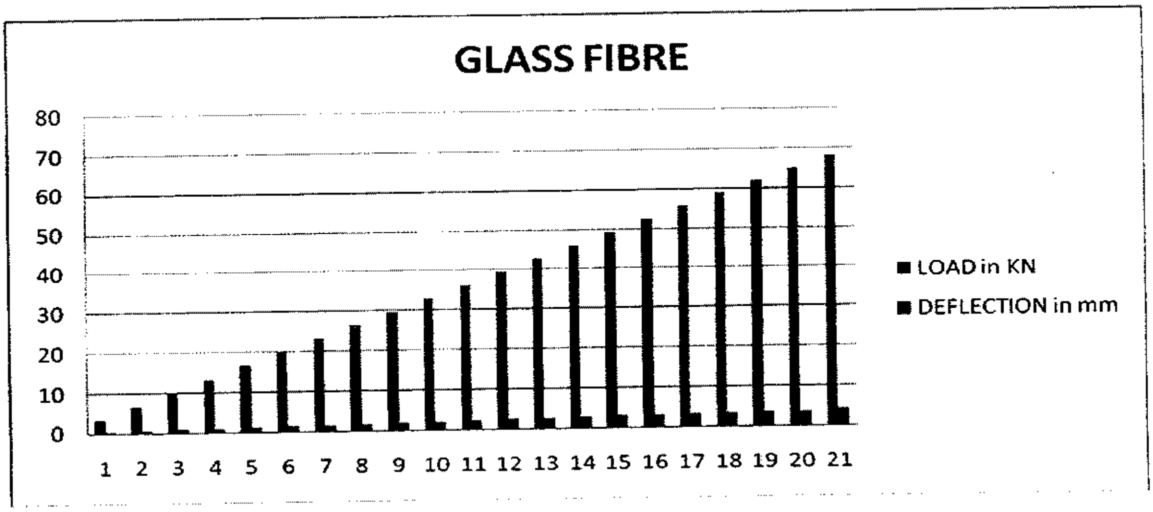


Fig: 6.2, Bar Chart for Glass Fibre Wrapped Beam

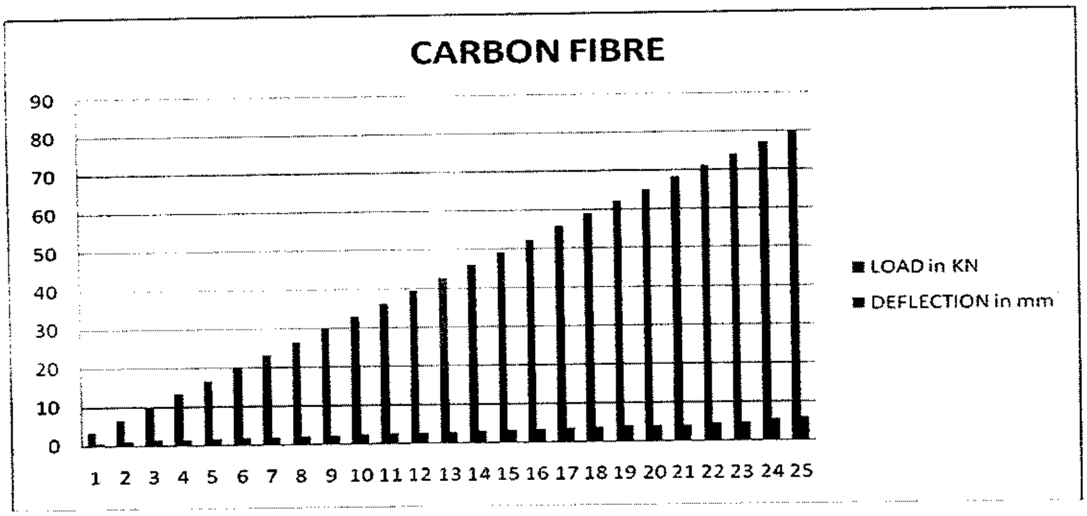


Fig:6.3, Bar Chart for Carbon Fibre Wrapped Beam

6.4 ULTIMATE LOAD AND STRENGTH ENHANCEMENT VALUES OF THE TEST SPECIMENS

The maximum loads taken by the test specimens are compared with maximum load designed. The ultimate load enhancement is shown in the bar graph.

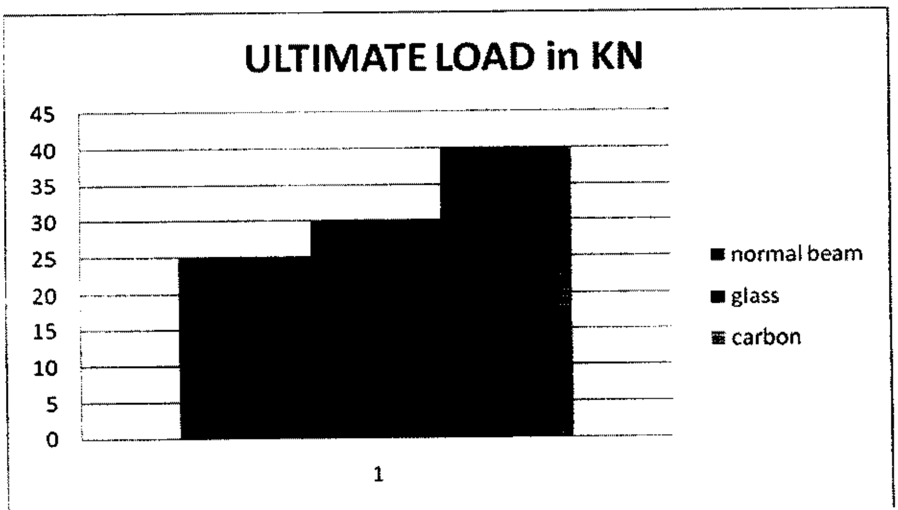


Fig:6.4, Ultimate load comparisons

6.5 PERFORMANCE OF STRENGTH MODELS

The fully wrapped beam element was chosen and the c/c distance between the supports were marked. Two dial gauges are placed at a distance of l/2 and l/4.The beam has been subjected to flexure under point load in a loading frame. The load was gradually increased for which the corresponding rise in deflection was noted in dial gauge. The initial crack was identified and marked.

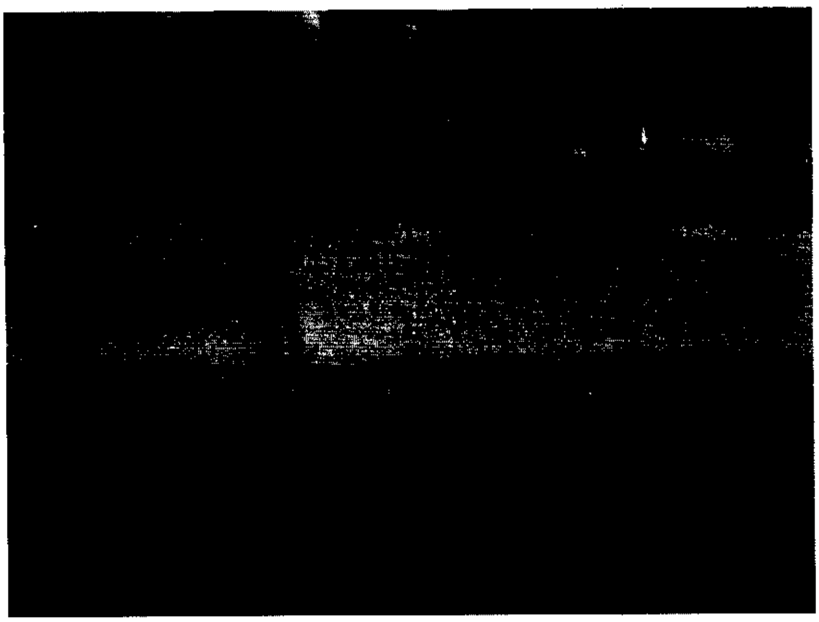


Fig: 6.5, Beam in loading frame with dial gauges

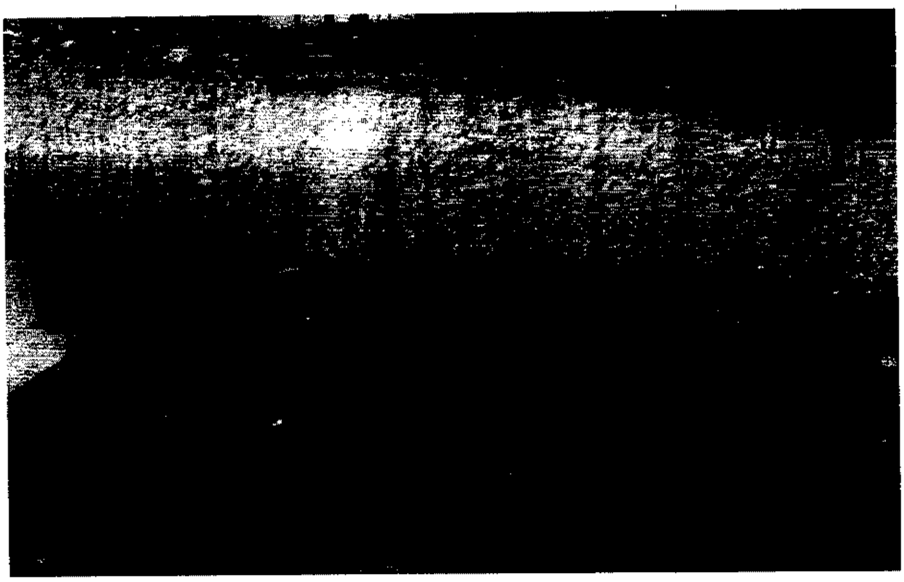


Fig: 6.6, Formation of cracks

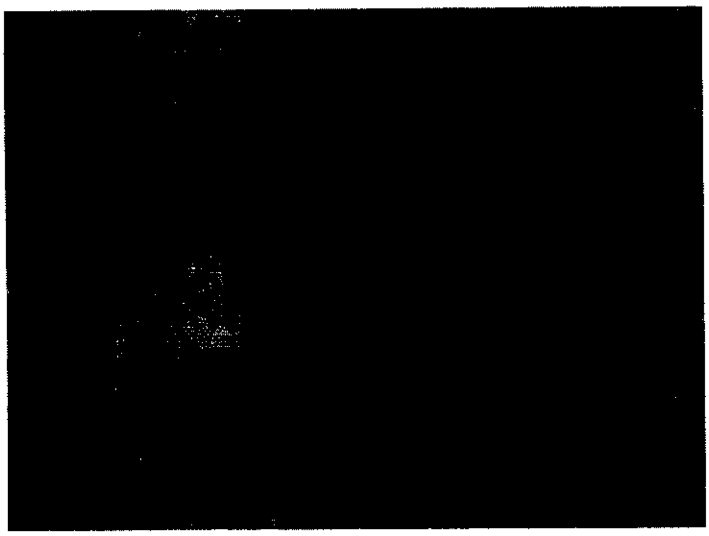


Fig: 6.7, Development of crack in carbon wrapping

The flexural strength of the specimen is expressed as the modulus of rupture fb, which if 'a' equals the distance between the line of fracture and the nearer support, measured on the centre line of the tensile side of the specimen , in cms, is calculated to the nearest 0.5kg/m2 as follows.

$$fb = (pl)/bd^2$$

when 'a' >20cm for 15cm specimen or>13.3cm for a 10cm specimen or

$$fb = 3pa/(bd^2)$$

when 'a'<20cm but >17cm for 15cm specimen, or <13.3cm but >11cm for a 10cm specimen where b= measured width in cm of the of the specimen

d= measured depth in the cm of the specimen at the point of failure

l= length in cm of the span on which the specimen was supported and

p= maximum load in kg applied to the specimen

If 'a' is less 17cm for a 15cm specimen or less than 11cm for a 10cm specimen, the results of the test be discarded.

The values are substituted in the above formula and the flexural strength is determined.

Table:6.1 Comparison of Flexural Strength

Specimen details	**Flexural strength in N/mm²**
Normal beam	3.625
Glass wrapping	5.250
Carbon wrapping	7.820

6.6 COMPARISON OF MODULUS OF ELASTICITY OF VARIOUS SPECIMENS

One of the important factors affecting modulus of elasticity of concrete is strength of concrete. This can be represented in many ways such as the relationship between ratios of mix or water-cement ratio. It also depends upon the state of wetness of concrete, when other conditions being the same. The quality and quantity of aggregate will have a significant effect on the modulus of elasticity.

In this study we plot a graph of load Vs deflection which is shown in fig:6.8 from which we obtain elasticity, for which a straight line is drawn from the origin. From the straight line, any point of load and deflection in N and mm respectively are noted for which E is calculated. We know that deflection for a point load on a simply supported beam is given by,

$$\delta = Wl^3/48EI$$

Where,

W & δ are obtained from the load deflection graph

l = c/c distance between the supports

E= modulus of elasticity to be calculated

I = moment of inertia which is given by $bh^3/12$

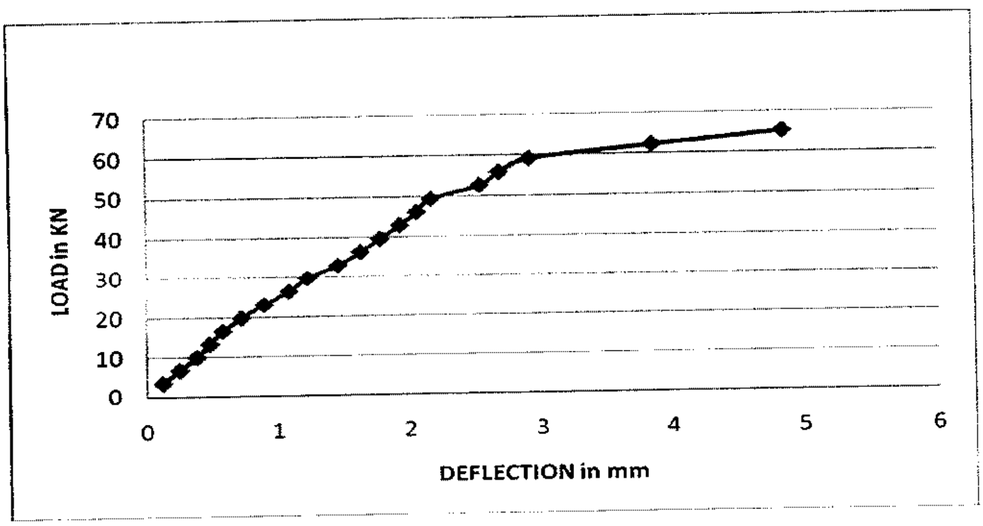


Fig:6.8, Load-Deflection graph for Actual Beam

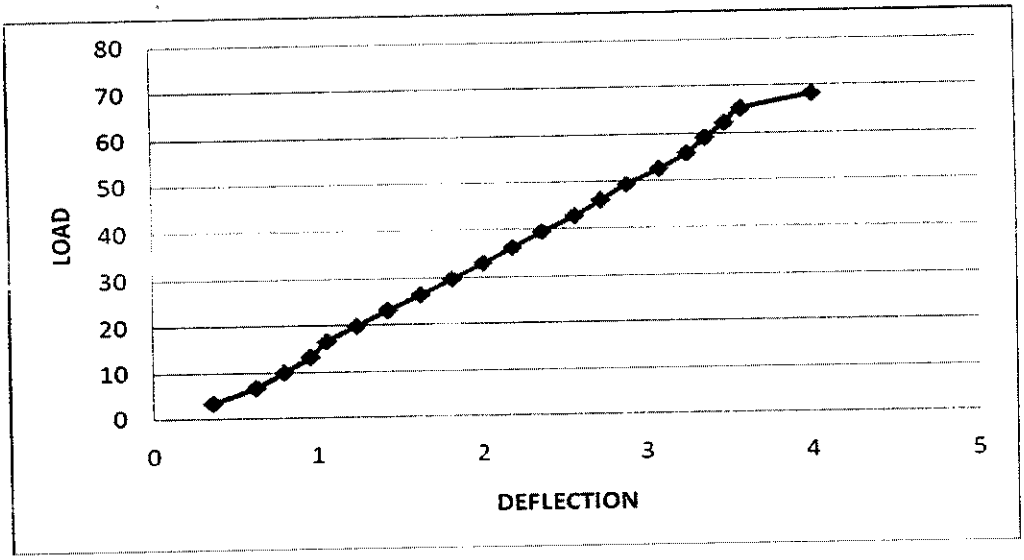


Fig:6.9, Load-Deflection graph for Glass wrapped beam

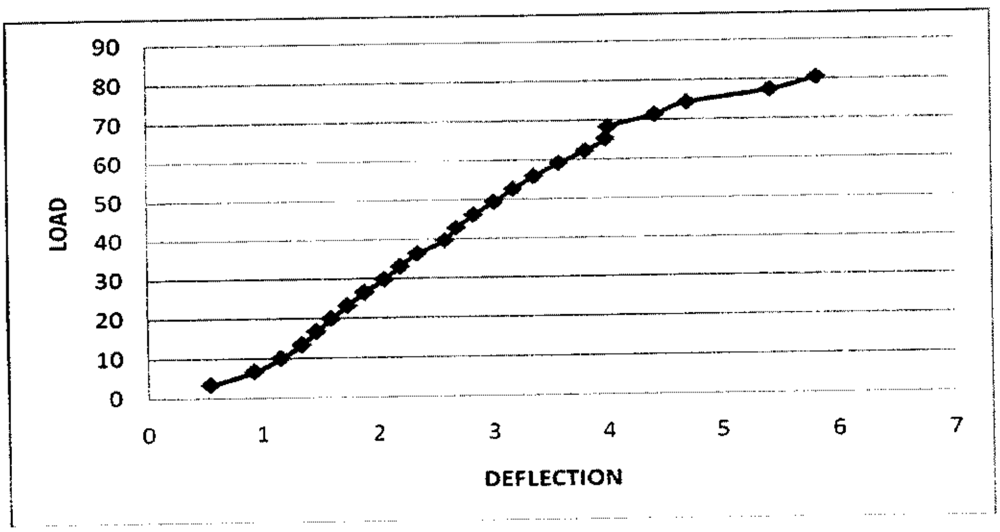


Fig:6.10, Load-Deflection graph for Carbon wrapped beam

From these graphs, the modulus of elasticity is determined and given below.

Actual beam = 23GPa

Glass fibre wrapping = 36GPa

Carbon fibre wrapping = 200GPa

6.7 SUMMARY

The results of Experiments carried out for different specimens such as load-deflection, maximum load taken by the specimens, performance of strength models, comparison of modulus of elasticity and strength enhancement are presented.

CHAPTER 7
CONCLUSIONS

7.1 GENERAL

The study dealt with an experimental research involving the application of carbon fibre reinforced polymer (CFRP) wet lay-up sheets to strengthen reinforced concrete (RC) beams subjected to direct concentric loading. The experimental program was conducted to observe the influence of fully wrapped and unwrapped confinement arrangements in RC beams. The main objective of this study was to evaluate the behavior of wrapped beams confined with CFRP sheets and GFRP subjected to concentric loading. In the Experimental investigation 3 beam specimens were constructed and tested.

7.2 CONCLUSIONS

The study performed on concrete beams confined by CFRP and GFRP indicates that this method of confining concrete is effective in significantly improving the performance of concrete structures.

The following conclusions are drawn form the test results by comparing with controlled beam (unwrapped) specimens

- There is a significant increase in compressive strength of concrete beams owing to confinement provided by CFRP and GFRP sheets.
- For RC beam specimens, the strength enhancements ranged between 68.4% with fully wrapped CFRP Sheets.
- The load - deflection response of confined concrete improves considerably for full wrapping schemes in CFRP.
- The load carrying capacity of GFRP specimens was a little bit lower than the one of the fully wrapped CFRP specimens. Partial confinement

arrangements were, however, easier and faster to apply than full confinement arrangements.

- ❖ RC Beams confined with fully wrapped CFRP sheets had the maximum load carrying capacity among all the specimens in the test series.
- ❖ Modulus of elasticity showed a very considerable increase for CFRP than GFRP.

7.3 SCOPE FOR FUTURE STUDY

- ❖ Behavior of beams, wrapped on three sides and their responses can be studied.
- ❖ Further studies can be carried out using experimental investigation, to study the influence of concrete strength and number of layers of FRP.
- ❖ Prefabricated FRP shells can also be adopted and their behaviour can be studied.
- ❖ Size and slenderness Effect of FRP wrapped columns can be studied.
- ❖ Durability aspects such as FRP beams subjected to corrosive environment, freezing & thawing, exposed to fire etc. can be studied.
- ❖ Further experiments of varying thickness and spacing of the CFRP strips are recommended to come up with a model for predicting the strength enhancement. A complex interaction between the lateral steel reinforcements and the CFRP strip exists and this needs further investigation.

7.4 SUMMARY

In this chapter, conclusions were drawn from the research conducted. A few recommendations for future study are also made.

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