STRENGTHENING OF R.C BEAMS USING FIBER REINFORCED POLYMERS

Bachelor of Engineering in Civil Engineering

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ABSTRACT

R.C structures have a certain age after which they are not safe to use. They deteriorate over time and become unsuitable for the purpose they were built for. R.C structures could be in the form of beams, columns, footings, slabs, girders, pylons etc but the scope of this project is limited to beams only.

R.C beams could either be replaced or they can be repaired using different retrofitting techniques. Retrofitting techniques are of various kinds that are used in industry with both advantages as well as drawbacks. Retrofitting techniques are more suitable, especially for a country like Pakistan, where weak economy and high inflation rate are prevalent. Retrofitting techniques are only used when the structure has not been completely damaged. Instead of replacing damaged structures, effective techniques of repairing can result in time saving and minimal cost. Fiber Reinforced polymers (FRP) is relatively new class of composite materials which has proven itself efficient and economical for the development and repair of new and deteriorated structures in construction industry. Because of its high strength to weight ratio, FRP's and have been widely used in developed countries for retrofitting and other maintenance operations. Though in Pakistan, this technology needs to be highlighted. Most of the engineers and consultancy firms are reluctant to use this technology probably because they have enough confidence in classical methods. The objective of this project is to present a cheaper solution of retrofitting/repair damaged beams. One possible option is to repair the damaged sections using Fiber Reinforced Polymers.

Fibers in a polymer matrix make up FRP's. Fibers can be glass, carbon, aramid etc. This project demonstrates the application of carbon Fiber Reinforced Polymers on R.C beams. Two different

types of CFRPs were used. The response was found from experimental program and design calculations. Study results from experimental program were compared with design calculations. Recommendations were made on the basis of comparison of results.

This is to certify that the

report entitled

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LIST OF ABBREVIATIONS

f’c = compressive strength

R.C = reinforced concrete structure

FRP = Fiber Reinforced Polymers

CFRP = Carbon Fiber Reinforced Polymers

A_s = Area of steel

E = Young’s Modulus

F_y = Yielding stress

a = depth of neutral axis

V_c = Shear stress

BEAM1 = Control beam

BEAM2 = Beam treated with FRP plate

BEAM3 = Beam treated with FRP wrap

BEAM4 = Pre-cracked beam treated with FRP wrap

ILD = Influence line diagram.

Chapter 1

INTRODUCTION

Concrete is the most widely used construction material. The reason behind this fact is simple; all the materials in its composition are easily and naturally available except for cement which is a man-made material used as a cementing agent. Ordinary concrete generally has 4000psi compressive strength which makes it an excellent material for resisting compression but on the other hand its tensile strength is very low as compared to its compressive strength. That is why concrete is always used in combination with steel. Reinforced concrete thus becomes a perfect material for resisting both compressive and tensile stresses. Reinforced concrete structures comprises of bridge girders, slabs, columns, piers etc. These structures once built have a certain capacity and age after which they should be replaced. Technique of retrofitting enables us to repair and upgrade R.C structures, thus increasing their life span(Miller, Chajes, Mertz, & Hastings, 2001). Besides its use in Civil engineering industry FRPs find its applications in aerospace engineering, automotive engineering, sports and in electronics. FRPs have high strength to weight ratio that accounts for their enormous usage in the world (Khalifa & Nanni, 2000). In Pakistan FRPs have been used to retrofit bridge girders and piles. But this technology needs to be highlighted so that it can be used extensively. Demolishing a structure and constructing a new bridge is costlier and a time consuming operation as compared to the retrofitting by FRP which is cost effective and does not even stops the structure from performing its function. Standard FRP wraps and plates are available in markets that are used to increase both the flexure and shear capacity of the girders. Epoxy resins are used as a bonding material between substrate and FRPs. Similarly the ultimate load capacity of columns can also be significantly enhanced by wrapping the FRPs around the columns. In this project effectiveness of

CFRPs was demonstrated with the help of experimental program, software program and design calculations.

1.1 Objectives

FRP’s are now much highlighted in the field of engineering. It finds its application in all disciplines of engineering in one way or other. This project is primarily aimed to study the properties of FRPs and its various types and how they affect the strength parameters of R.C beams. After successfully achieving the goals of this project, we would be able to understand the behavior of retrofitted R.C beams upon loading. The objectives are as under:

- Cast T-beams of reduced dimensions for test purpose.
- Repair reinforced concrete T beams using two types of fiber reinforced polymers (FRP).
- To present an evaluation of deteriorated reinforced T beam retrofitted with different types of FRP.
- To check the structural response of T beams with or without FRP by design calculations.
- To make conclusions and recommendations regarding retrofitting with different types of FRP.

1.2 Reasons/Justifications

Pakistan being a developing country finds it difficult to construct new bridges once they get deteriorated /damaged, whereas F.R.P’s do not cost more than half of total budget spent on constructing a new bridge. So there is a definite need to highlight this technology in Pakistan. The following are some of the reasons of choosing this project:

- Understand the behavior of F.R.P composite polymers in detail, their area of application, their limitations and modes of failures.

- To give industry a cheaper solution of repairing damaged R.C beams. Scope will be limited to T-beams only. Renovation or even up-gradation of bridge girders with F.R.P composites have successfully been in use all over the world.
- Recasting a deteriorated reinforced concrete bridge component (girder or pier) costs great and it also interrupts traffic and trade, crippling the economy and mobility.
- Bridges in Pakistan are usually suspected to loads more than what they are designed for. They are used even after their service life, in this regard an appropriate retrofitting material to increase load carrying capacity and service life as well must be devised, and retrofitting by FRP is one possible option.
- Plies of Carbon Fiber Reinforced Polymers (CFRP) are not much cheap, yet it lowers the overall cost because it is still a cheaper technique than to reconstruct a new structure.

Chapter 2

Literature Review

2.1 R.C Beams

Beam is a structural element that primarily transmits gravitational loads to girders and columns. Vertical forces that act on a beam could be external loads as well as self-weight. The acting loads on the beams are resisted by bending action of the beam. Beam always resist external load by resisting to bend. This capacity of beam is termed as bending moment. Typical beam is composed of concrete and steel used as rebar. Rebar can be used to resist the tension forces on tension face of concrete and also to increase compression capacity of the beams.

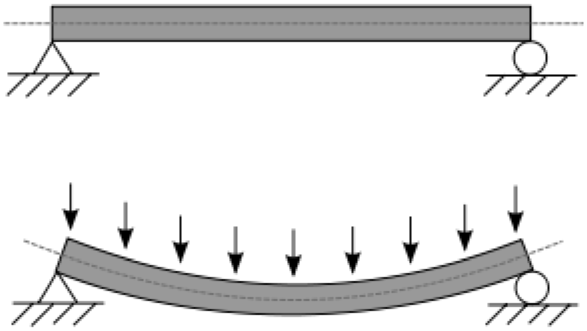


Figure 2.1: Beam under loading

Beams are generally meant to bear vertical loads but they can also be used to withstand horizontal loads. Horizontal loads can both induce compression as well as tension in the beam section depending upon the structural configuration.

2.1.1 Typical types of R.C beams

- **Simply supported**

One of the most common type of support arrangement is simply supported. The beam is restricted in horizontal and vertical direction on one support, while on the other vertical displacement is restricted. For sake of simplicity, sometimes complex structural arrangement is analyzed as simply supported. Simply supported beams are easy to design and construct.

- **Fixed beam**

A beam that has zero degree of freedom is known as fixed beam. Moment, horizontal and vertical displacement are restricted. A beam with both ends fixed is statically indeterminate to the 3rd degree, and any structural analysis method applicable on statically indeterminate beams can be used to calculate the fixed end moments.

- **Continuous beam**

Beams that continuous over more than two supports are known as continuous beams. These multi-span beams are indeterminate beams and the degree of indeterminacy depends upon number of supports. The supports can lie on a same horizontal level but can vary as well. Continuous beams provide an alternate load path in case one span fails.

- **Cantilever beam**

A cantilever is a beam anchored at only one end. The beam carries the load to the support where it is forced against by a moment and shear stress. Cantilevers are widely found in construction, notably in cantilever bridges and balconies. In cantilever bridges the cantilevers are usually built as pairs, with each cantilever used to support one end of a central section.

2.1.2 Common failure in R.C beams

Beams fail due to inadequate design strength, loss in durability. When poorly designed concrete is subjected to freeze thaw and corrosion, it may lead to severe damage. If rebar gets oxidized, oxidation products as a result of rusting swells up and produces cracks in the concrete. Thus damaging the structural concrete as well. Most common types of failures are discussed below:

- **Mechanical failure**

Cracking in concrete structures is a problem which cannot be avoided. However, effort should be put in to control the size and to limit the location of cracks by appropriate reinforcement, control joints, curing methodology and concrete mix design. If a section gets cracked moisture can penetrate inside the section which in turn can cause corrosion of rebar. Thus reducing the life span of concrete beams. Inadequate amount of rebar or too much spacing between can result in cracking. Besides aforementioned causes, concrete beams may also fail because of over loading. Loading a beam beyond a safe limit can cause yielding of concrete or crushing of concrete.

- **Chloride ions**

Chlorides, including sodium chloride, can promote the corrosion of embedded steel rebar if present in sufficiently high concentration. Chloride anions induce both localized corrosion (pitting corrosion) and generalized corrosion of steel reinforcements. For this reason, one should only use fresh raw water or potable water for mixing concrete, ensure that the coarse and fine aggregates do not contain chlorides, and not use admixtures that contain chlorides.

2.2 Retrofitting Techniques

Beam is one of the most important part of structure that transmits the loads to piers and abutments. Nowadays, bridge girders are found of various types depending upon the type of bridge they are supporting. Beams deteriorate over their life because of inadequate design strength, reduced durability, seismic activities, exceeding its life time or simply because of some unforeseen activity for example terrorist attack. A number of different techniques are employed to address this issue. Either the entire structure is replaced by constructing a new bridge or it is repaired by steel jacketing, epoxy injection, span shortening, increasing beams sectional area etc (Jumaat et al., 2006). Steel jacketing is widely used in Pakistan because its properties are well defined and engineers have developed a confidence in using it. Externally bonding FRPs is also a technique of beam retrofitting in which different composite materials are externally bounded on beams in layered form. We will compare different retrofit materials to get a clear picture.

2.2.1 Concrete Jacketing

Involves increasing size of the existing reinforced concrete section by adding more reinforcement and concrete. It could be accomplished by either of the following methods:

- Conventional Concrete
- Sprayed Concrete (Shotcrete)
- Pre-Packed Aggregate Grouting

Conventional Concrete

Pouring concrete around the member to be strengthened with additional steel reinforcement properly anchored to the existing section. Ordinary concrete jacketing requires formwork and is time consuming due to long curing time. Furthermore, it is difficult to achieve a dense mix in constrained conditions. Adhesion is also an issue, especially for overhead applications (Miller et al., 2001).

Sprayed Concrete (Shotcrete)

Pneumatically projecting concrete on to the reinforced (usually with wire mesh) and prepared surface of the member being strengthened with a spray gun. A variety of additives and admixtures are also introduced to expedite strength gain, reduce rebound, reduce water requirement, curb shrinkage and improve adhesion. The grading of aggregates is critical in sprayed concrete due to the absence of external vibration and the reduction in the quantity of coarse aggregates as a result of rebound. Shortcrete does not require formwork and is useful to retrofit large areas in a relatively short-period of time. But, the operation is very messy with enormous loss of sprayed materials, resulting not only wastage of materials but an unsightly-rough surface finish too. (Mukherjee & Joshi, 2005).

Pre-cracked aggregate grouting

Pumping of cementitious grout into washed/ graded coarse aggregates placed with properly anchored reinforcement around the member to be strengthened in a tightly sealed formwork (refer to Fig: 2.2). It is one of the better ways of jacketing a concrete member as it results in a dense mix with good surface finish (Meier & Kaiser, 1991).

Figure 2.2: Aggregate grouting

2.2.2 Steel Plate Bonding

This technique involves enhancing strength (shear, flexure, compression) or improving stiffness of deficient reinforced concrete members by bonding steel plates of calculated thickness with adhesives and anchors to the existing sections. Steel plate not only acts as externally bonded reinforcement to the concrete section but it also improves the moment of inertia (stiffness) of the composite (concrete-steel) section. Steel plate is bonded using nut-bolts epoxy to the sand blasted concrete surface. Steel has been well studied and practices have been laid out in code of practice. Holes are drilled and filled with epoxy and then nuts are inserted (refer to Fig: 2.3). Steel plates are coated with epoxy primer and after curing another epoxy resin is applied. Then steel plates are drilled in the same manner and aligned with nuts. Bolts are tightened and hence the bonding strength is achieved and we can say that steel is aiding in strength. Despite its advantages, it too has got limitations (Miller et al., 2001).

Figure 2.3: Steel plate bonding

Disadvantages of steel plating

Because we know that steel is susceptible to corrosion, we have to use some water repelling agents. Once steel gets in contact with water, corrosion begins and it leads to its strength reduction. Besides durability issues, steel plates are heavy and sometimes it becomes difficult to install them. Joint formation process in steel plates also creates trouble (Khalifa & Nanni, 2000).

2.2.3 Fiber Reinforced Polymers

When steel and its alloys are used as building material, they are very expensive and their repair and maintenance cost is very High. For years, Civil Engineers have been in search of such alternative to steel and its alloys which can combat the high cost of repair and maintenance of structures damaged by corrosion and Heavy Use (Barnes & Mays, 1999).

Fiber Reinforced polymers (FRP) is relatively new Class of composite materials which has proven itself efficient and economical for the development and repair of new and deteriorating Structures in Civil Engineering. High Strength to Weight Ration of FRP’s makes them ideal for widespread use. Carbon and glass FRP’s are used to Seismic repair, retrofit, rehabilitation and strengthening of columns and bridge piers leads to Magnificent Economy in Construction , Saving time and materials (Cai et al., 2008).

FRP’s can give us 3 times the strength of concrete in just 24 hours. Columns in building and piers in bridges require repair very often .Design and construction with conventional materials leads to expensive and time consuming solutions. However, in most applications, repair, retrofit and rehabilitation of columns and bridge piers with FRP can result in major time and cost savings (Cai et al., 2008).

FRP is high resistant toward corrosion impacts. So, it would not rust as easy as steel when prone to open atmosphere. We have many composites of FRP which vary in strength, some of them are stronger even than steel. Its composites are anisotropic so, they have more strength lengthwise.

- Provide Strength equal to Steel Even with ¼ weights.
- No welding of joint needed, easy fabrication.
- Composites could be molded into many color as in many strengths.

2.2.3.1 FRP Composites

To achieve specific properties one or more materials are combined. They are called composites. Composites have anisotropic properties. A designer should have very sound knowledge of materials. All mechanical and physical properties of FRP are controlled by composition.FRP composites are made by combining to materials one is FIBERS and second is Matrix. These two components are bonded in interface. Each Phase has its own property towards the composite. We choose composition of these materials as per our requirement (Miller et al., 2001).

Fibers give Stiffness and strength and Matrix is responsible of rigidity and also protects for environmental hazards.

2.2.3.2 Fibers

Fibers are long filament with very less diameter about 10 tm. The length/diameter ration ranges from thousands to onward. Fibers provide strength and stiffness to composite. Fibers are mainly used to carry load in tension and they no doubt have very much strength in tension. Fibers are responsible of thermal stability and many other Structural properties (Meier & Kaiser, 1991).

- Large values of E (Elastic modulus)
- High values for Yield & ultimate strength.

- Stabled strength while handling
- Uniform in diameter and other dimensions.

Types of fibers

In Civil engineering mainly 3 types of Fibers are used; glass, carbon and aramid.

Glass and carbon Composites are relatively easy to form as compared to third one, so use of these two is relatively extensive.

Material	Density (g/cm^3)	Tensile Modulus (E) (GPa)	Tensile Strength (GPa)	Specific Modulus (E/c)	Specific Strength	Relative Cost
E-glass	2.54	70	3.45	27	1.35	Low
S-glass	2.5	86	4.5	34.5	1.8	Moderate
Boran	2.6	400	3.5	155	1.3	High
Kevlar 29	1.45	80	2.8	55.5	1.9	Moderate
Kevlar 49	1.45	130	2.8	89.5	1.9	Moderate

Table 2.1: Comparison of different fibers used in matrix

2.2.3.3 Matrix

Matrix is polymer material which is composed of molecules. These molecules are monomer in nature which are made up of little simpler unit. Without matrix fiber could not perform effectively. The matrix should not have elastic modulus greater than fibers and it should have greater elongation so that fibers could carry maximum loads (Jumaat et al., 2006). Function associated with matrix materials is as follows.

- Binds the fibers and provide strength by adhesion same as concrete.
- Provide Rigidity

- Reduces Crack propagation by isolating fibers.
- Shield fibers for Hazard of Chemicals.
- Final color and finish depends on it.
- Improves ability of carrying impact loads.

Resin Material	Density (g/cm 3)	Tensile Modulus GPa (106 psi)	Tensile Strength MPa (103 psi)
Epoxy	1.2-1.4	2.5-5.0 (0.36-0.72)	50-110 (7.2-16)
Phenolic	1.2-1.4	2.7-4.1 (0.4-0.6)	35-60 (5-9)
Polyester	1.1-1.4	1.6-4.1 (0.23-0.6)	35-95 (5.0-13.8)
Nylon	1.1	1.3-3.5 (0.2-0.5)	55-90 (8-13)

Table 2.2: Comparison of different types of matrix

2.2.3.4 Interface

Interface can be considered a bond which is present between fibers and matrix molecules. Many types of bonds are found as interface such as, Hydrogen Bond etc. While making composites we assume that bond between the fibers and matrix is perfect there is no discontinuity present. As we know properties of composites completely depends upon composition of fibers and matrix, so comparison of many composites are given on the next page.

Material	Specific Weight	Tensile strength (MPa)	Tensile modulus (GPa)	Flexural strength (MPa)	Flexural modulus (GPa)
E-glass	1.9	760-1030	41	1448	41
S2 glass	1.8	1690	52	-	-
Aramid 58	1.45	150-1380	70-107	-	-
Carbon(PAN)	1.	1930-2689	130-172	1593	110

Table: 2.3 Comparison of the properties of different composites

Properties also depend upon reinforcement forms such as continuous, aligned fibers and woven fabric. In unidirectional fibers composites are straight and parallel which are considered orthotropic materials because they have two planes of symmetry at 90 degree. The orientation of fibers depends upon relative sizes of fibers resulting in multi-dimensional fiber orientation.

2.3 Benefits of Retrofitting using FRP composites

Fiber reinforced polymers have been widely used in different parts of the world. FRP’s have proved their efficiency in resisting earthquake loads and sustaining seismic activities but still research is being carried out in order to know more about its limitations and application (Triantafillou & Antonopoulos, 2000). Nowadays, FRP’s are used in retrofitting different structural members such as columns, masonry walls, bridge decks (pedestrian bridge decks), piers, girders etc. Retrofitted structural members show an extraordinary performance level as compared to their damaged state. Out of its wide range benefits some are mentioned below:

1. They have a high tensile strength to weight ratio that makes it suitable for light structures. In this way they do not contribute much to dead load of the structure itself (Takahashi, Todoroki, Shimamura, & Iwasaki, 2007).

2. They can be molded and casted in various shapes depending upon their utility. They can have shapes like cylindrical shells, spheres and horizontal layers. For circular piers we use jacketed F.R.P layer around them to increase their shear strength (Sawant, Sawant, & Kumthekar, 2013).
3. In structural members, where FRP's are applied, a reduction of approximately 40% in fatigue stresses and crack width is observed (Neubauer & Rostasy, 1997).
4. They show resistance against corrosion and weathering in contrast to traditional rebar, where corrosion once becomes severe, accounts for reduction in flexure and shear strength (Shahawy & Beitelman, 1999).
5. They generally are applied in layers for girders, beams, slabs and columns without much complication. The depth of the layer is usually not much i.e. minimum depth (Singhal, 2009).
6. With the application of retrofitting, the shape and profile of the structure is not harmed. Because of this property, it finds its application in important historical buildings where shape of the structure could not be changed (Rabinovitch & Frostig, 2003).
7. FRP composite layers are costlier than traditional rebar but their service life and low maintenance cost make it economical altogether (Triantafillou & Antonopoulos, 2000).
8. They are also used in offshore construction because of low permittivity.
9. Their light weight makes them economical to transport from casting to site.

2.4 Areas of applications

2.4.1 Up-gradation of existing structures

Structures all over the world due to heavy loading and long service life have deteriorated and they need repair and up gradation. In such cases it is very difficult to break down the whole bridge and build a new one with more strength, which also is very costly (Meier & Kaiser, 1991). In some cases due to applied load concrete cover cracks from the bottom of beam that exposes the reinforcements to the factors that can affect it, compromising the tensile strength of steel, for such cases a thin coat of FRP is applied at the bottom of the beam as FRPs are non-corrosive materials (Triantafillou & Antonopoulos, 2000).

In this method to provide flexural strength to the beam we place a Carbon Fiber Reinforced Polymer (CFRP) plate that is attached to the lower flange, the part that usually takes the tension.

To provide shear strength the CFRP are wrapped around the beam. They are attached to the beam by an epoxy (Cai et al., 2008).

2.4.2 Seismic retrofitting

There are two cases of FRP retrofitting:

- The first case being when an earthquake has damaged a structure that needs to be retrofitted.
- In the second case we improve the performance of the existing structure considering that the structure could face seismic activity being in the seismic zone

In case of the earthquakes columns in the structures are considered the weakest component. The lateral movement due to earthquakes introduces shear stresses in columns causing spalling in the concrete structure.

We either place FRP panels laterally in the column or wrap the columns with FRP material. This increases the strength of the columns. Sometimes high strength concrete is also used for seismic protection but brittle nature of such concrete makes it unfavorable, so we rather use FRP’s which are more ductile in nature.

Also if this arrangement of FRP’s in the structure are not providing enough strength then in these areas column jacketing using FRP plates is done. In this method we provide FRP plates all around the column confining it inside. FRP’s have shown quite promising results in seismic retrofitting specially in columns (Spadea, Bencardino, & Swamy, 1998).

2.4.3 Blast retrofitting

Due to the present Law and Order situation different experiments are being carried out all over the world in securing the structures from blasts and explosives. From 2000- present government buildings, embassies dams and nuclear facilities have been the main targets of the terrorists. The simplest method used to protect these buildings is moving these buildings away from the main walls but it is not effective. Then focus turns on materials like FRP’s which have the potential of absorbing a lot of energy by deforming to some extent. Experiments have shown that the use of FRP’s in building components decreases their deflections. The FRP’s like Kevlar have great capability of absorbing huge impacts, the reason why it is used in production of bulletproof jackets. Carbon fibers are also important as their higher flexibility decreases the expansion of concrete greatly (Shahawy & Beitelman, 1999).

2.4.4 Off-shore construction

Two magnificent properties of FRP’s make them durable to be used as reinforced bars.

1. One being its much higher tensile strength.
2. Second being its non-corrosive behavior.

Because of the above two factors and no effect of water on the FRP they are very much used in off-shore construction and submerged construction. Steel reinforcement bars however deteriorate very early due salinity and corrosion in marine structures. Due to high strength structures have long life span and don’t need repairs, thus still by having higher construction cost they have a low total cost of project due to minimum repairs.

However the FRP as a whole does not have an effect of water but the fibers and matrix may get damaged by water (Jumaat et al., 2006).

2.5 LIMITATIONS OF FRP

2.5.1 Brittle behavior

One of the main issues with use of FRP’s is its brittle behavior in reinforced structures. The problem with brittle failure is that it once started increases violently causing serious threat to the lives of people below the structure. In concrete larger cracks show that the failure may be occurring, however FRP’s do not show any signs of cracks which makes it unpredictable when the structure will fail (Miller et al., 2001).

2.5.2 Bond failure

This is one the most common mode of failure in reinforced concrete beams strengthen with FRP laminates. As failure commonly occurs at the bonds between FRP plates and concrete, proper attention should be given to the bonding. The quality of bonding depends on its preparation and the way it is placed. The surface of concrete should properly cleaned before FRP application, removing loose particles and cracks and spalling in concrete should be properly filled with mortar or concrete. To provide an appropriate bonding, an interface layer of matrix has to be applied between FRP plates and concrete beam (Khalifa & Nanni, 2002).

One of the most common boning failures is due to the cracking of the concrete due to its lack of ability to withstand tension and transmit it to FRP plate. The rupture due to this particular reason is brittle so care should be taken (Miller et al., 2001).

It must be noted that this type of failure only appears for beam retrofitting and not when columns are retrofitted.

2.5.3 Other failure modes

One of the problems that have to be taken care of is the increase in the shear capacity of the beam. The beam will always fail in shear around its typical shear capacity even if FRP plate is added. Therefore when upgrading a bridge for larger loads, one must verify that the new shear encountered by the beam is still within its limits (Mukherjee & Rai, 2009).

Chapter 3

METHODOLOGY

The project followed the following steps:

1. Cast T-beams of reduced dimensions.
2. Application of FRP to test beams.
3. Beams were tested under flexure loading to study the effect of FRP.
4. Determination of improved flexural capacity.
5. Experimental calculations.

3.1 Casting of R.C. T Beams

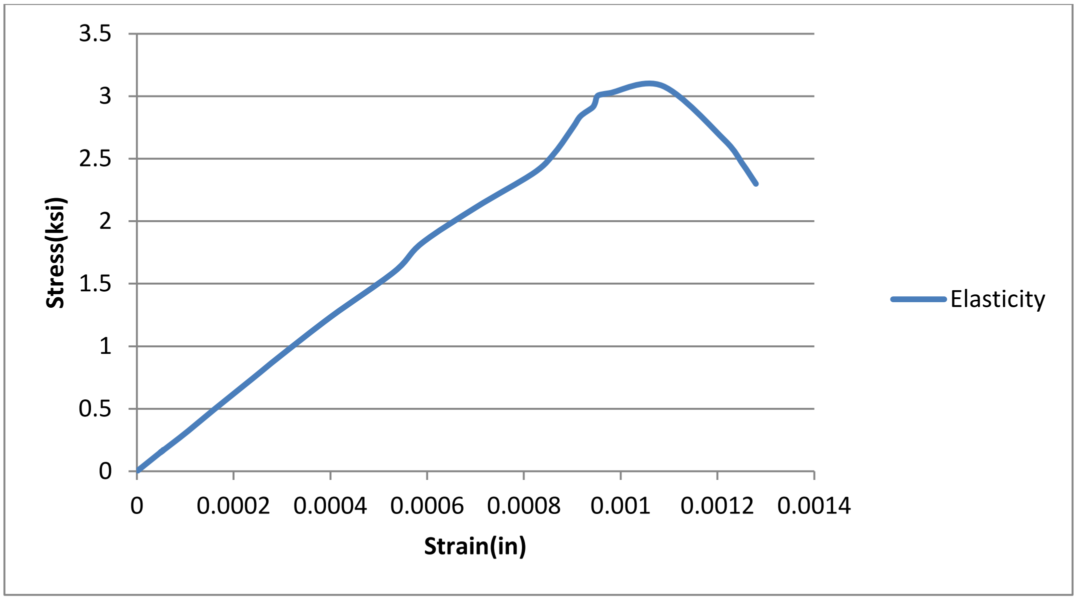
Four T beams were casted. Average temperature during which the beams were casted was 76.3° F. 1:2:4 mix design was used on site and desired water cement ratio was (0.5). 3000 psi strength was expected from this mix design. The beams were allowed to attain strength for 21 days. Beams were appropriately cured. After twenty one days the beams were transported to UET Taxilla for carrying out the testing process. One beam was taken as a reference beam while two beams were applied with two different CFRP materials and the last one was applied with load and before its failure when cracks started to appear loading was removed and the beam was retrofitted with one of the CFRP material used on the other two beams.

Figure 3.1: Formwork and cage of reinforcement

Concrete cylinders were cast on the site for compression strength test and also for determining its young’s modulus.

Compressive strength of concrete was determined to be 3.08 ksi.

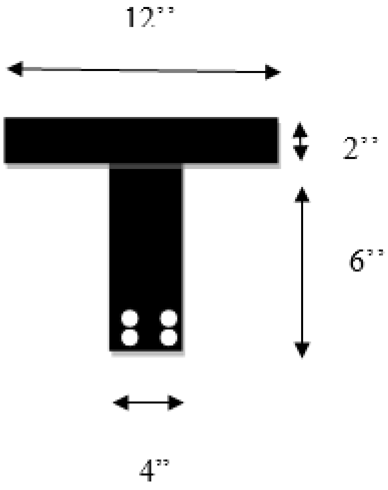
The value of E for concrete comes out to be Modulus of Elasticity = 2835 ksi.



Stress vs Stain for concrete cylinder

3.1.1 Design calculations

Area of steal for 1 #3 bar=0.11 in^2



As min= (3(fc')$^{0.5}$ bXd)/fy

As min=0.32in^2

As max=200 X b X d/fy

As max=0.44in^2

As= 4X0.11= 0.44 in^2 (4 no.3 Bars)

Taking concrete cover 1''

d=8-1.5-0.5=6 in

f_y= 40 ksi

fc´=3 ksi

Length of beam= 1.224 m=4 ft

A = (A_s.f_y)/ (0.85fc´.b)

A = (40X0.44)/ (0.85X3X12)

a= 0.5751 in   Ans<2 (neutral Axis lies within flange i.e. the beam will act as rectangular beam)

Mu=$A_s f_y$ (d-0.5a)

Mu=40X0.44 (6-0.28758)

Mu=100.538 kip-in

Mu=8.378 kip-ft

Mu=11.358 KN-m

Mu=$wl^2/8$

P=Mu*8/l

P=11.358X8/1.224

P=74.237 KN   (Max. Point load)

Shear:

P = 74.237 KN

P = 74.237 X 0.22480894   (1 KN = 0.22480894 Kip)

P = 16.689 Kip

Total shear = V = 8.344 Kip

$V_c = 2(fc')^{0.5}$ X d X bw

$V_c = 2\ (3000)^{0.5}$ X 6 X12

V_c = 8544.472 lbs

$_{\varphi}V_c$ = 7690 lbs

$V = V_s + {}_{\varphi}V_c$

$V_s = V - {}_{\varphi}V_c$

$V_s = 8344-7690$

$V_s = 654$ lbs (Beam needs Shear Reinforcement)

Supposing that Load capacity of beams applied with CFRP will increase as compared to reference beams. Fearing that they will fail in shear due increase of shear due to higher load capacity we had provided reinforcement to make them safe in shear. Required shear reinforcement has been calculated by following method.

Supposing Maximum Load capacity of beams retrofitted with CFRP=15 Kips

$V = 15$ Kips

$V_s = V-\varphi V_c$

$V_s = 15000-7690$

$V_s = 7310$ lbs

$A_v = (V_s*s)/(d*f_s)$

$A_v = (7310*3)/(6.5*36000)$ Spacing between the stirrups have been taken 3 in i.e. <d/2

$A_v = 0.093710 in^2$

#2 Bars were used as stirrups

$A_v = 2 \text{ X } 0.049 in^2$

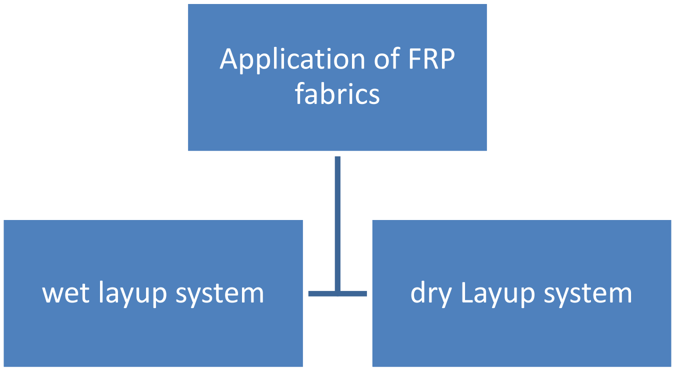
$A_v = 0.098 \text{ in}^2$

3.2 Apply FRP to test beams

In construction industry fiber reinforced polymers find its application in two ways. One being as internally bonded reinforcement e.g in the form of bar, rods or tendons replacing steel bars and other being externally bonded reinforcement like the use of FRP in rehabilitation of existing concrete structures. The scope of our project only encompasses fiber reinforced polymer's use as externally bonded reinforcement.

3.2.1 Methods of application

There are two methods for the application of FRP to concrete using epoxy adhesives, depending upon the ease of application, material used, substrate (concrete surface) etc.



In wet Layup method, fibers are saturated before layup operation whereas in dry layup method fibers are saturated with epoxy resin after the layup operation.

3.2.2. Steps for the application of CFRP wrap on beams

Four beams were casted for testing purpose; one was left untreated as reference beam, one was applied with CFRP strip, the third one was applied with CFRP wrap and the fourth section was first cracked and then treated with FRP wrap.

1.Surface preparation

- Grinding of surface using concrete grinder
- Removal of dust and unwanted material from concrete surface
- Making surface even and rounding the sharp edges

Application of chemdur-30 to concrete

- Fill up all strutural voids, honeycombing etc.
- Bond CFRP wrap to concrete surface

3.Batching quantites to prepare CHEMDUR-300

- Impregnating epoxy adhesive for carbon fiber wraping
- Provides mechanical strength to CFRP wrap
- Batching by weight Comp A: Comp B = 4:1

4. ng components for chemdur-300

- Add comp(B) to comp(A)
- Stir to keep air entrainment minimum
- Pot life start soon after mixing that is 30 mins

Application of chemdur-300 to substrate

- Chemdur-300 matrix is applied to concrete surface and CFRP wrap aswell.
- CFRP wrap is contacted to concrete with hand roller.

6. Curing conditions

- Temperature during application and curing must be between 10° C - 35° C
- Maximum moisture must be 4 %
- There must be no mechanical disturbance otherwise the bonding will not be good

3.3 Beam Testing Procedure

Final experimental setup is shown as in figure 3.14. Following steps are taken to carry out the Beam testing.

1. Steel girders and steel plates were used as supports with a width of 2 inches to both ends of the beam. To level the underneath surface sand were used, so that experimental results could not be effected by slope of any kind.
2. The loading points and deflection measuring points were identified on the beam by using marker and measuring tape.
3. Load was to be applied at mid-span and deflections were measured at an interval L/4.
4. Wooden beams were placed on the beam under testing to achieve the desired height.
5. Proving ring was placed above the wooden beams. Proving ring had a maximum capacity of 30 tons.
6. Hydraulic jack rested above proving ring had a maximum capacity of 10 tons. Downward reaction to hydraulic jack was provided by steel frame.
7. Dial gauges and P3 strain gauges were reset to zero.
8. Control beam was tested first, load was applied from zero in increments of 10 units of dial gauge readings. Deflections and strains were calculated after every 10 units of dial gauge readings. Dial gauge readings were converted to KN loads using conversion tables of the proving ring.
9. One beam was pre-cracked prior to the application of FRP. As soon as the cracks appeared on the beam, FRP was applied and allowed to cure for gaining the bonding strength. After two days the retrofitted beam was tested again to check the improved capacity of cracked section.

Rest of the two beams were un-cracked. One was wrapped with FRP and the second one was strengthened with FRP plate at bottom. They were tested to the failure.

3.3.1. APPARATUS

Proving Ring:

Proving Rings were originally developed to serve as a portable force standard that could be accurately calibrated and then transported and used to measure forces applied by a testing machine.

A Proving Ring is an elastic ring in which the deflection of the ring when loaded along a diameter is measured by means of a micrometer screw and a vibrating reed mounted diametrically in the ring.

In our case, for beam testing we used a proving ring of Maximum Capacity 300 KN (30 Tons) as shown in figure 3.2. The readings of dial gauge are converted to KN (Kilo Newton) by using load conversion tables.

P3 Strain Gauge:

The Model P3 Strain Indicator and Recorder as shown in figure 3.3 is a portable, battery-operated instrument capable of simultaneously accepting four inputs from quarter-, half-, and full-bridge strain-gage circuits, including strain-gage-based transducers. Some of the strain gauge specifications are

- Gage Factor Control Range:0.500 to 9.900
- Strain Range:±31,000 µεat at GF = 2.000. (±15.5 mV/V)
- Measurement Accuracy ±0.1% of reading ±3 counts

Hydraulic Jack:

Hydraulic jack of 10 Ton maximum capacity was used to load the beam under testing.

Deflection Gauge:

Deflection gauges are used to measure the deflection of beam under testing. There were three deflection gauges are used in total during testing.

3.3.2 Assisting Apparatus

To complete the test arrangement there were used some simple instruments and apparatuses. The name of those simple instruments are given below.

- 2 Timber beams

  Each timber planks having mass respectively 15 and 20 kg.
- Steel girders
- Ropes
- Bricks

Figure 3.2: Proving ring

Figure 3.3: P3 strain gauge

3.3.3 ARRANGMENTS

Supports:

Roller supports were given at both ends of beam by using steel girders. Thematic and practical illustration of supports are given in figure 3.4 and 3.5.

Loading Arrangement:

A uniformly distrubuted load was applied on beams under testing by using hydraulic jack. A steel frame was used as a cushion to provide reaction by hydraulic jack to exert a point load on under test beam. Thematic and practical arrangement is shown in figure 3.4 and 3.5.

Location of Deflection Gauges:

Three deflection gauges are used to measure deflection at three different points. The location of points is as follows 0.25 L, 0.5 L and 0.75 L. The very same arrangement is shown in figure 3.5.

Location of Strain Gauges:

Strain gauges are attached to beam at both ends. The strain gauges were installed on lower surface of web at mid-span. The very arrangement is shown in figure 3.5.

Timber Beams:

Timber Beams were used in between hydraulic jack and beams under test to fill the gap in between. So that the load transfer mechanism could be completed efficiently.

Proving Ring:

Proving Ring was used in between hydraulic jack and steel frame which was providing support for exerting load.

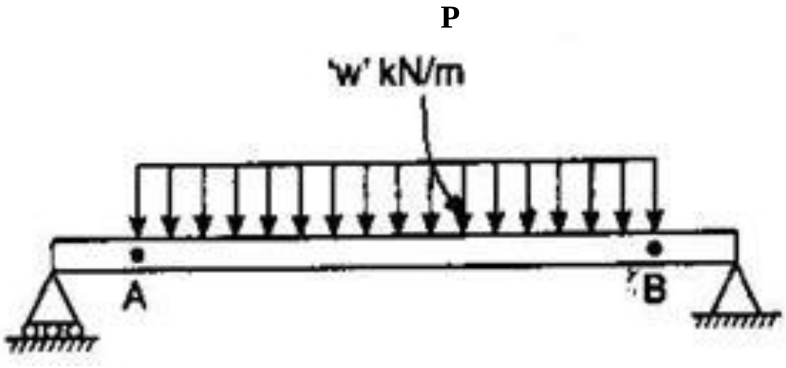


Figure 3.4

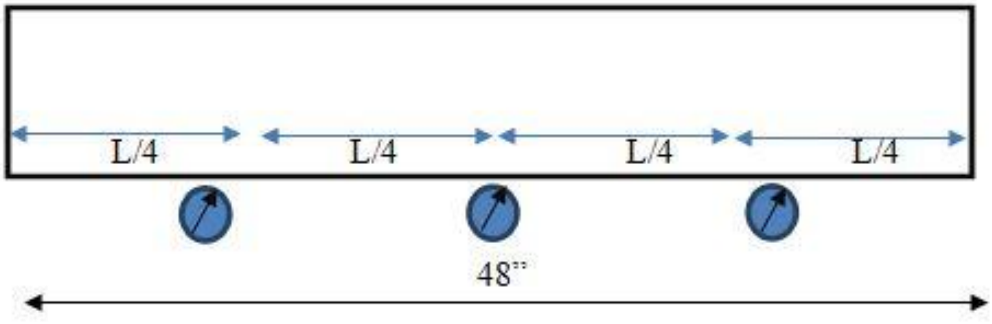
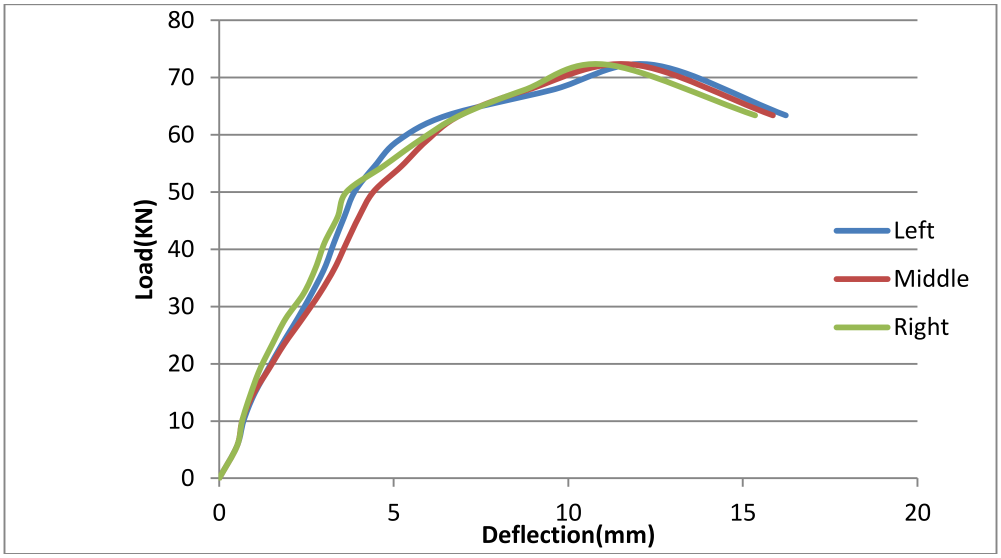


Figure 3.5: Experimental arrangement

3.4 Determine the improved flexure capacity

Reference Beam (BEAM1)

Ultimate Load = 67.84 KN



Load and deflections for BEAM1

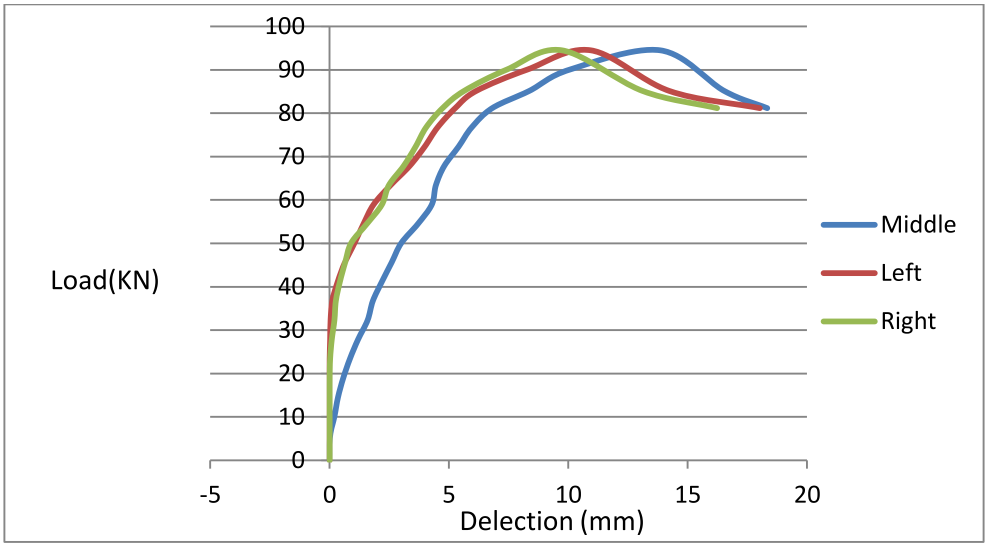
Figure 3.6: Failure pattern of BEAM1

Discussion

Flexure cracks at mid-span are visible in this beam. Shear cracks near supports are also seen. The beam ultimately failed near supports due to shear failure. Beam's flexure capacity was not fully utilized.

Beam retrofitted with CFRP strip (BEAM2)

Ultimate Load = 94.49 KN



Load vs Deflection for BEAM2

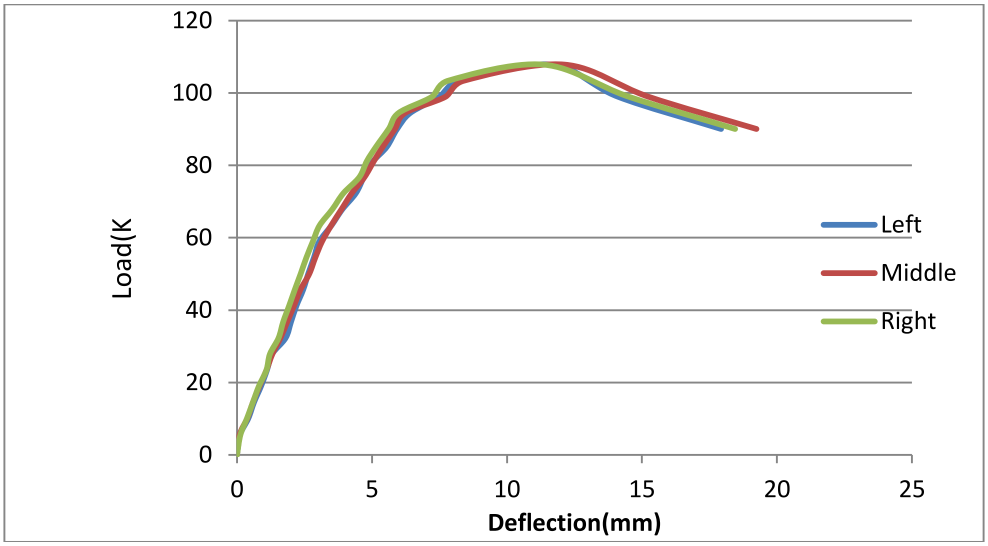
Figure 3.7: Failure pattern of BEAM2

Discussion

Beam under test was treated with CRFP strip at bottom of the web to increase flexure capacity. Flexure cracks at mid-span are absent. Shear cracks near supports could be seen that resulted in shear failure.

Beam retrofitted with CFRP wrap (BEAM3)

Ultimate Load = 107.84 KN



Loads and deflections for BEAM3

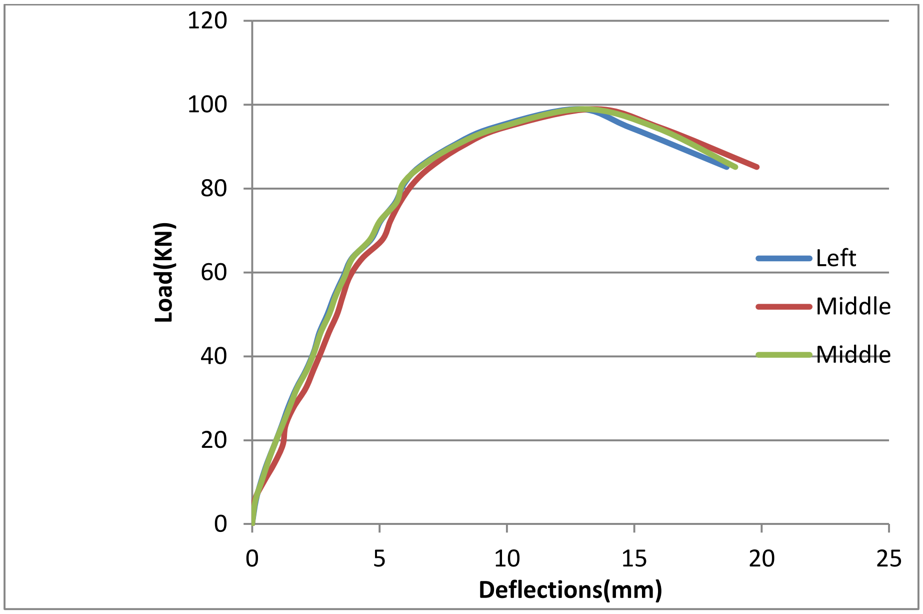
Figure 3.8: Failure pattern of BEAM3

Discussion

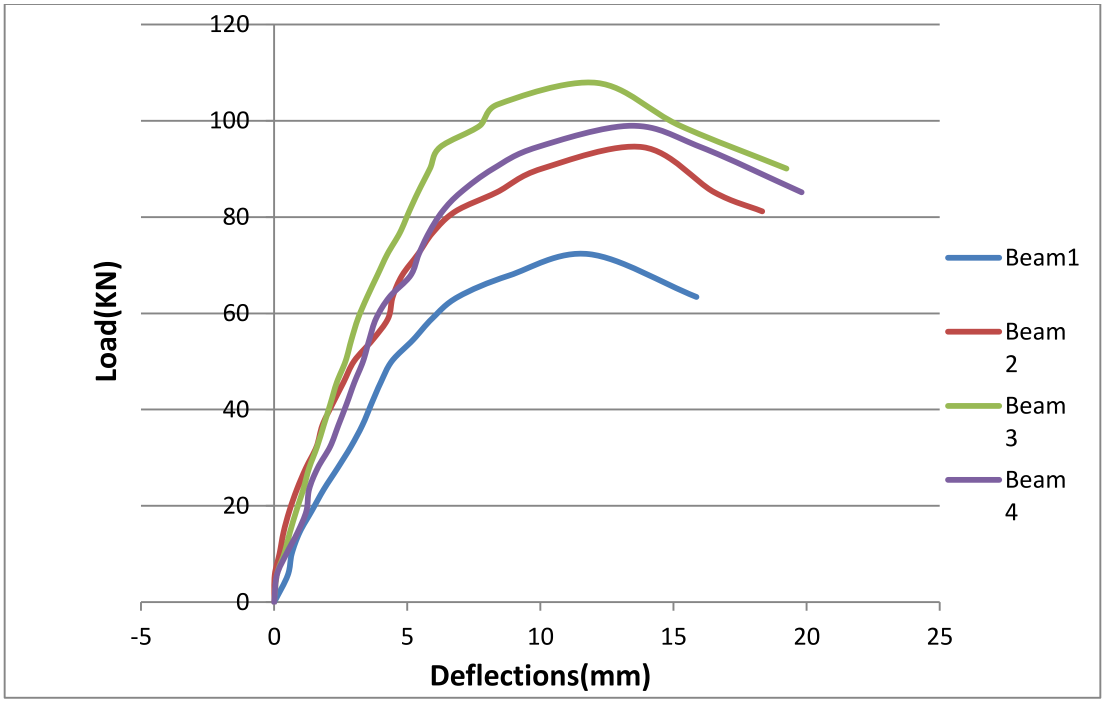
As the beam was wrapped with CRFP jacket, which is an opaque substance, it was not possible to observe the crack pattern. The beam's cross-section remained intact except at one support, where de-bonding of CFRP wrap caused the section to split up. The beam failed at the same support where CFRP wrap de-bonded.

Cracked beam retrofitted with CFRP wrap (BEAM4)

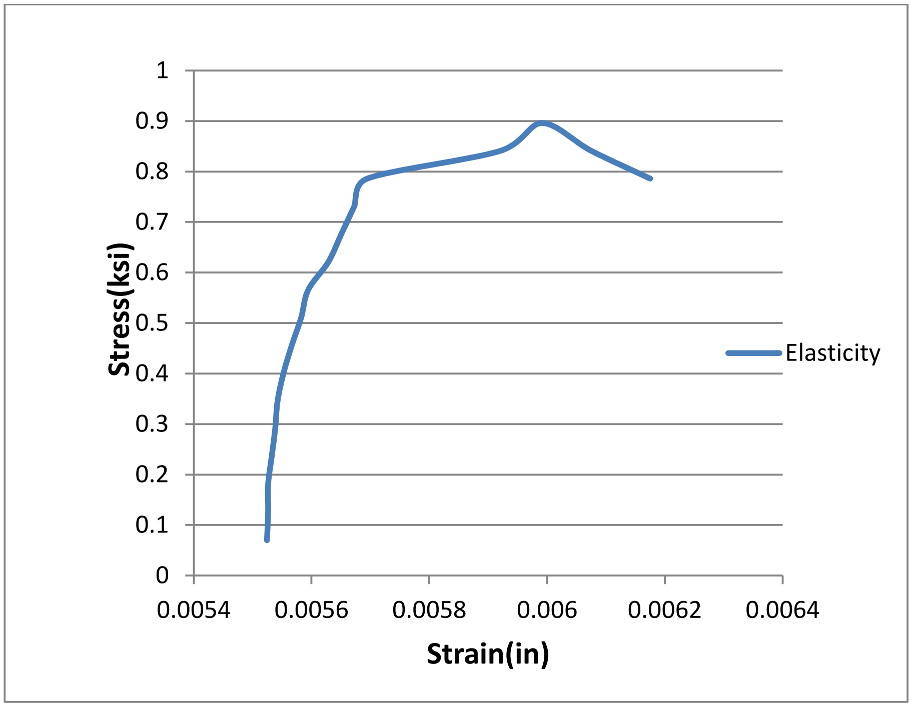
Ultimate Load = 98.94 KN



Loads and deflections for BEAM4

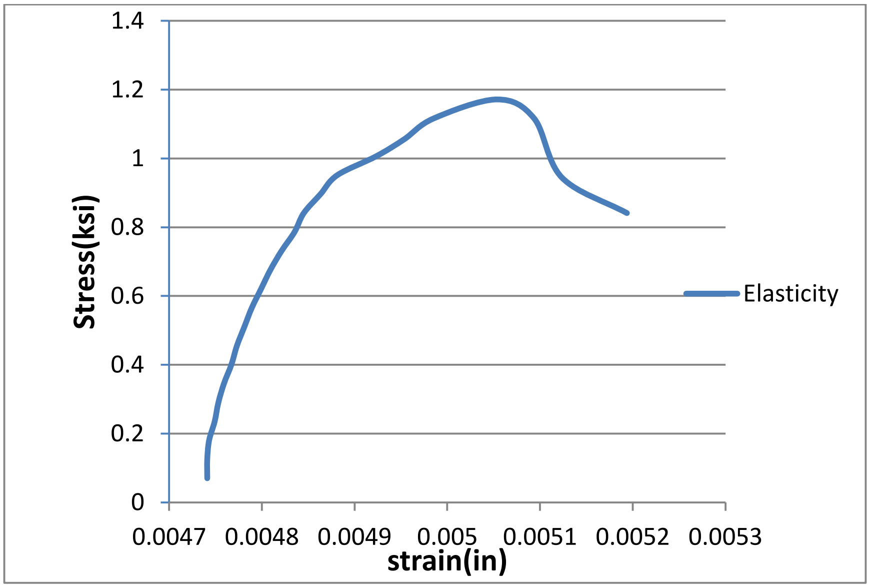


Load and Deflections comparison of four test beams



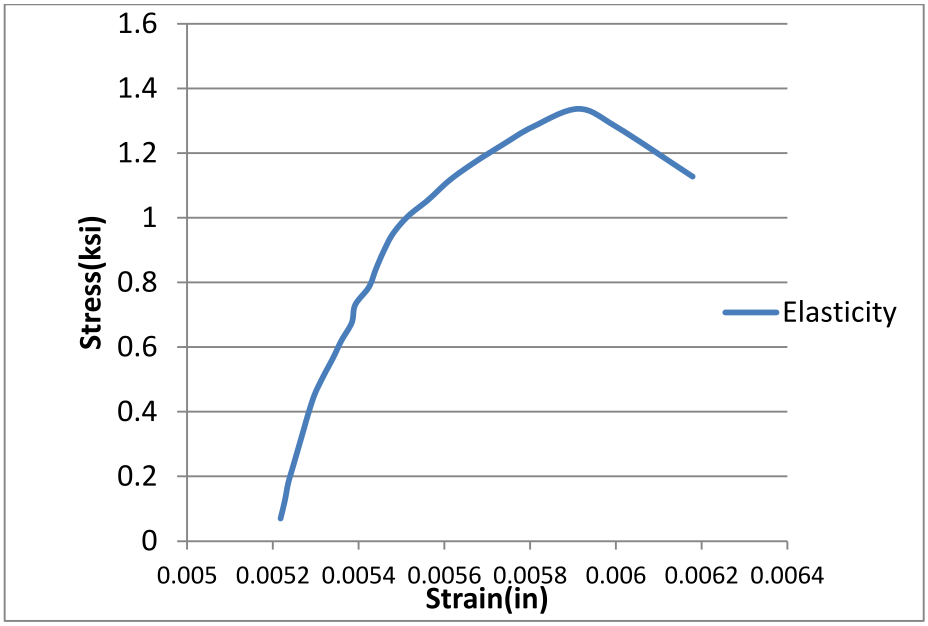
Stress and Strain for Reference Beam

Modulus of Elasticity of BEAM1= 3794 ksi



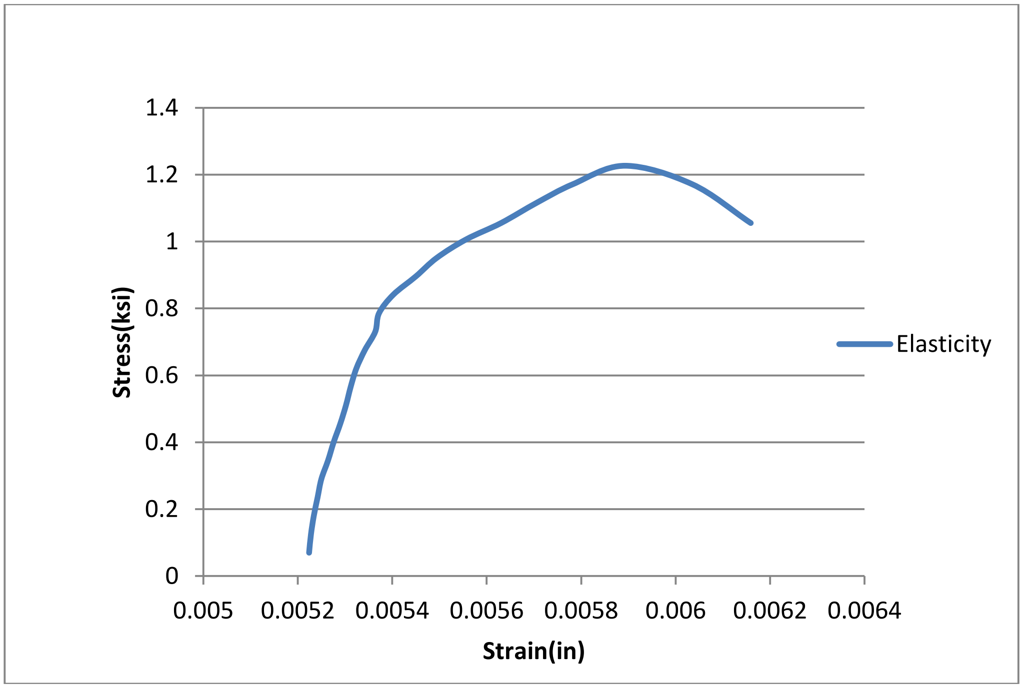
Stress and Strain for Beam with FRP strip

Modulus of Elasticity of BEAM2 = 5888 ksi



Stress and Strain for Beam with CFRP wrap

Modulus of Elasticity of BEAM3 = 5743 ksi



Stress and Strain for BEAM4

Modulus of Elasticity of BEAM4 = 3799 ksi

	Modulus of Elasticity (ksi)	Failure Mode	Ultimate Load(KN)	Ultimate Moment (KN-m)
BEAM1	E= 3794 ksi	Flexural	67.84	20.760
BEAM2	E = 5888 ksi	Flexural	94.49	28.914
BEAM3	E = 5743 ksi	Shear	107.84	33.000
BEAM4	E = 3799 ksi	Shear	98.94	30.275

Table: 3.1 Comparison of Properties of Beams

3.5 Steps to check design adequacy of CFRP

Following steps are followed to check whether the design of FRP is adequate for the increase in live loads or not.

FRP material design properties

FRP material design properties include design stress and strains in FRP material reduced by environmental reduction factor C_E. Environmental reduction factor is incorporated because of environmental effects on FRP system like corrosion, weathering, moisture, freezing effect, humidity effects and hot weather effect etc. C_E is taken to be 0.95.

3.5.1 Preliminary calculations

In preliminary calculations β_1 of concrete is worked out according to ACI code.

Then area of main steel bars, and FRP strips is calculated to find out the steel ratio (ρ), FRP ratio and modulus ratio (n) is calculated.

Determine existing strain on the soffit of beam

Value of ‘k’ is determined by:

$K = (\rho n^2 + 2\rho n)$ ^0.5 – ρn

This k multiplied with‘d’ gives the value of compression fiber depth.

$J = 1-(k/3)$

Jd gives the value of distance between compression resultant and tension resultant force.

Moment of inertia of cracked section is determined by:

$I_{cr} = b\ k^2 j\ d^3 / 2$

The value of moment of inertia comes in in^4

Existing strain on soffit is determined by:

$\varepsilon_{bi} = M_{DL}(d_f - k_d)/I_{cr}E_c$

3.5.2 Determination of effective level of strain in FRP system

$\varepsilon_{fe} = 0.003(d_f\text{-}c/c)\text{-}\varepsilon_{bi}$

The effective level of strain calculated from this formula must be less than the design strain of FRP strips. But in comparison to concrete crushing, FRP must be in failure mode.

Because FRP will control the failure of section the concrete strain at failure (ε_c) must be less than 0.003.

The concrete strain ε_c can be determined by using formula.

$\varepsilon_c = (\varepsilon_{fe} + \varepsilon_{bi})(c/d_f\text{-}c) \quad < 0.003$

This will ensure that first FRP will fail not the concrete.

Calculate the strain in existing reinforcing steel:

Existing steel will undergo some deflections and strain level under loads, which can be calculated by.

$€_s=(\varepsilon_{fe}+\varepsilon_{bi})(d-c/d_f-c)$

Calculation of stress level in EBR FRP strips and Steel rebars.

Stress level in reinforcing steel is:

$f_s=E_s€_s$

But the value of stress must be less than the grade of steel f_y= 40 ksi.

While the stress level in FRP is calculated by:

$f_{fe}=E_f€_{fe}$

FRP strip is only useful when the stress in FRP is more than the stress in steel (f_s). That will ensure that, at first FRP will take more stresses after the load application.

Calculation of internal force resultant and checking equilibrium:

Strain in concrete corresponding to compressive strength (fc') can be determined by:

$€_{c'}=1.7fc'/Ec$

Parabolic stress strain relation in reinforced concrete section can be examined by using formula:

$\alpha_1= 3\varepsilon c'\varepsilon c-\varepsilon c^2/ (3\beta 1\varepsilon c'^2)$

and$\beta_1=4\varepsilon c'-\varepsilon c/6\varepsilon c'-2\varepsilon c$

Value of ‘c’ was estimated first but now the original value can be determined by using α_1 and β_1.

$c=A_sf_s+A_ff_{fe}/ (\alpha_1fc'\beta_1b)$

Calculation of flexure strength components:

Both the FRP, reinforcing steel and concrete section will contribute to the total flexure strength of beam section.

I. Steel contribution to bending.

$M_{ns}=Asfs(d-\beta_1 c/2)$

This will give the value of additional moment because of reinforcing steel.

II. FRP contribution to bending

Since the FRP strips increase the moment capacity of beam which is quantified by formula:

$M_{nf}=A_f f_{fe}\,(d_f-\beta_1 c/2)$

The design flexure strength of section will be the summation of both the above moment contributions with strength reduction factors.

Using ACI code moment reduction factor φ can be checked out using c/d_t ratio.

$c/d_t= 1.87/6.1875= 0.3022 < 0.375$

So, $\varphi= 0.9$

And strength reduction factor for FRP (Ψ_f) is 0.85 according to the user manual

$\varphi M_n= \varphi(M_{ns}+\Psi f M_{nf})$

This formula gives the nominal moment of the section after application of FRP this moment must be greater than the anticipated moment due to increased live loads. So design will be safe.

Chapter 4

CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusions

On the basis of experimentation and research, conclusions were made to sum up the outcomes of our project. Failure patterns of all four test beams were carefully analyzed and following conclusions were drawn:

1. FRP wraps are expensive as compared to steel arrangement, yet its properties like corrosion resistance and light weight make it suitable for repair of R.C beams.
2. After application of FRP Load Deflection ratio of beams increased significantly. Beams retrofitted with FRP under the same load showed less deflection as compared to control beam.
3. Un-cracked beams resulted in lesser deflection as compared to pre-cracked beams. Pre-cracked beam also yielded at lower loads as compared to un-cracked beam.
4. Stress to strain ratio also increased after application of CFRP as compared to control beam. Beams retrofitted with CFRP under the same load showed lower Flexural strains.
5. CFRP strip reduced flexure cracks at mid span as obvious from diagrams. Cracks in the beam treated with CFRP strip were primarily because of shear failure.
6. De-bonding of FRP wrap near the support resulted in shear failure, thus preventing the beam from utilizing its full flexure capacity.
7. FRP wrap confines the cross-section, thus preventing bursting of concrete. As soon as the FRP wrap fails, concrete fails either in shear or in flexure.

8. FRP wraps and plates failed near the supports. Attempts should be made to shift the failure zone from supports to maximum moment zone so that full capacity of FRPs could be utilized.

4.2 Recommendations

A lot of hurdles came in the way of project that resulted in wastage of time. For example acquisition of structural drawings of Patoki bridge located on National Highway N-5 for research purpose. The authorities were not willing to share the required information. On the basis of experimentation and results, recommendations were made for the future use of FRP. Following recommendations were made:

1. Firstly, industry-academia linkage should be made stronger.
2. Since there are a number different fibers that are used in FRPs, different fibers exhibit different properties and research should be carried out to investigate their behavior.
3. Adhesives that are used as a bonding agent should be studied more deeply because they are responsible for imparting the strength. If bonding agent fails, de-bonding of FRP wrap would result into sudden failure.
4. FRP should be introduced in those areas that are susceptible to earthquake activity.
5. Short columns and long columns should be jacketed with FRP wraps. Piles of bridges constructed over rivers that are susceptible to floods should be jacketed with FRP to check erosion of piles.
6. Different types of concrete mixes for example fiber reinforced concrete, light weight concrete etc should be used and the effect of FRP on those mixes should be studied.
7. Research should also be carried out on anchorage techniques of CFRP laminates that could reduce the chances of failure caused by de-bonding of CFRP wrap.

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Appendix

Stress-strain relationship of concrete cylinder

Stress(ksi)	Strain(in)
0	0
0.1723048	$5.55 \text{ X}10^{-5}$
0.1522896	$4.92 \text{ X}10^{-5}$
0.2291596	$7.52 \text{ X}10^{-5}$
0.3234341	0.000106
0.492403	0.000159
0.742593	0.000239
0.9209894	0.000296
1.238622	0.000402
1.5983155	0.000533
1.8245743	0.000589
2.1117489	0.000701
2.3902213	0.000822
2.5497628	0.000864
2.7499148	0.000901
2.8398382	0.000917
2.9080059	0.000941
2.9428149	0.000947
3.0051811	0.000953
3.024036	0.000976
3.0820511	0.001087
2.6414266	0.001217
2.458389	0.001252
2.2988475	0.00128

Load and deflections for reference beam

Load(KN)	Left Gauge Deflection(mm)	Middle Gauge Deflection(mm)	Right Gauge Deflection(mm)
0	0	0	0
5.6382	0.51	0.51	0.51
10.0812	0.7	0.66	0.66
14.5242	0.99	0.955	0.89
18.9672	1.39	1.41	1.16
23.4102	1.8	1.86	1.52
27.8532	2.24	2.38	1.9
32.2962	2.65	2.88	2.42
36.7392	3.02	3.31	2.76
41.1822	3.29	3.65	3.02
45.6252	3.58	4	3.39
50.0682	3.88	4.42	3.65
54.5112	4.45	5.22	4.7
58.9542	5.12	5.94	5.72
63.3972	6.53	6.9	6.9
67.8402	9.53	8.82	8.74
72.2832	12.35	11.83	11.07
63.3972	16.23	15.86	15.35

Load and deflections for BEAM2

Load(KN)	Left Gauge Deflection(mm)	Middle Gauge Deflection(mm)	Right Gauge Deflection(mm)
0	0	0	0
5.6382	0	0.02	0
10.0812	0	0.2	0
14.5242	0	0.35	0
18.9672	0	0.57	0
23.4102	0	0.85	0.02
27.8532	0.02	1.19	0.09
32.2962	0.04	1.59	0.2
36.7392	0.11	1.81	0.26
41.1822	0.34	2.19	0.43
45.6252	0.64	2.6	0.65
50.0682	1.04	3	0.9
54.5112	1.42	3.7	1.56
58.9542	1.84	4.28	2.19
63.3972	2.55	4.45	2.48
67.8402	3.35	4.8	3.1
72.2832	3.98	5.4	3.6
76.7262	4.52	5.95	4.04
81.1692	5.26	6.81	4.73
85.1322	6.14	8.36	5.63
90.0552	8.28	10.06	7.42
94.4982	10.94	13.85	9.73
85.1322	14.23	16.53	13.11

Loads and deflections for beam with CFRP wrap

Load(KN)	Left Gauge Deflection(mm)	Middle Gauge Deflection(mm)	Right Gauge Deflection(mm)
0	0	0	0
5.6382	0.12	0.1	0.13
10.0812	0.42	0.38	0.37
14.5242	0.63	0.59	0.59
18.9672	0.89	0.83	0.81
23.4102	1.11	1.09	1.09
27.8532	1.3	1.31	1.22
32.2962	1.8	1.61	1.54
36.7392	2	1.86	1.71
41.1822	2.2	2.11	1.93
45.6252	2.45	2.35	2.14
50.0682	2.64	2.68	2.36
54.5112	2.85	2.9	2.57
58.9542	3.05	3.15	2.81
63.3972	3.5	3.49	3.06
67.8402	3.9	3.87	3.53
72.2832	4.4	4.25	3.94
76.7262	4.7	4.72	4.53
81.1692	5.05	5.07	4.81
85.1322	5.55	5.4	5.15
90.0552	5.93	5.85	5.62
94.4982	6.42	6.23	5.99
98.9412	7.5	7.72	7.22
103.3842	8.23	8.4	7.82
107.8412	11.65	12.13	11.35
98.9412	14.12	15.25	14.52

Loads and deflections for cracked section applied with CFRP wrap

Load(KN)	Left Gauge Deflection(mm)	Middle Gauge Deflection(mm)	Right Gauge Deflection(mm)
0	0	0	0
5.6382	0.15	0.1	0.13
10.0812	0.35	0.46	0.37
14.5242	0.59	0.88	0.61
18.9672	0.88	1.21	0.88
23.4102	1.16	1.31	1.18
27.8532	1.42	1.63	1.47
32.2962	1.73	2.1	1.76
36.7392	2.12	2.41	2.15
41.1822	2.43	2.72	2.45
45.6252	2.64	3.01	2.69
50.0682	2.96	3.34	3.03
54.5112	3.24	3.57	3.29
58.9542	3.58	3.83	3.63
63.3972	3.92	4.33	3.94
67.8402	4.67	5.12	4.63
72.2832	5.05	5.43	5.02
76.7262	5.63	5.81	5.67
81.1692	5.97	6.32	5.92
85.1322	6.56	7.01	6.61
90.0552	7.83	8.23	7.91
94.4982	9.45	9.87	9.67
98.9412	12.75	13.43	13.01
94.4982	14.86	16.03	15.87
85.1322	18.63	20.32	19.57

Stress and Strain for Reference beam

Load(KN)	Load(Kips)	Moment(Kip-in)	Stress(ksi)	Strain(in)
0	0	0	0	0
5.6382	1.26751778	15.21021339	0.06989988	0.00552427
10.0812	2.26634392	27.19612699	0.1249822	0.00552628
14.5242	3.26517005	39.1820406	0.18006452	0.00552628
18.9672	4.26399618	51.1679542	0.23514685	0.00553229
23.4102	5.26282232	63.15386781	0.29022917	0.0055383
27.8532	6.26164845	75.13978141	0.3453115	0.0055423
32.2962	7.26047458	87.12569502	0.40039382	0.00555232
36.7392	8.25930072	99.11160862	0.45547614	0.00556634
41.1822	9.25812685	111.0975222	0.51055847	0.00558236
45.6252	10.256953	123.0834358	0.56564079	0.00559438
50.0682	11.2557791	135.0693494	0.62072311	0.00562843
54.5112	12.2546053	147.055263	0.67580544	0.00565046
58.9542	13.2534314	159.0411766	0.73088776	0.0056725
63.3972	14.2522575	171.0270903	0.78597008	0.00569453
67.8402	15.2510837	183.0130039	0.84105241	0.00592087
72.2832	16.2499098	194.9989175	0.89613473	0.00599097
67.8402	15.2510837	183.0130039	0.84105241	0.0060751

Stress and Strain for Beam with FRP strip

Load(KN)	Load(Kips)	Moment(Kip-in)	Stress(ksi)	Strain(in)
0	0	0	0	0
5.6382	1.26751778	15.21021339	0.069899878	0.0047411
10.0812	2.26634392	27.19612699	0.124982201	0.0047411
14.5242	3.26517005	39.1820406	0.180064525	0.0047431
18.9672	4.26399618	51.1679542	0.235146848	0.00474911
23.4102	5.26282232	63.15386781	0.290229172	0.00475312
27.8532	6.26164845	75.13978141	0.345311495	0.00475913
32.2962	7.26047458	87.12569502	0.400393819	0.00476714
36.7392	8.25930072	99.11160862	0.455476142	0.00477315
41.1822	9.25812685	111.0975222	0.510558466	0.00478116
45.6252	10.256953	123.0834358	0.56564079	0.00478917
50.0682	11.2557791	135.0693494	0.620723113	0.00479919
54.5112	12.2546053	147.055263	0.675805437	0.0048092
58.9542	13.2534314	159.0411766	0.73088776	0.00482122
63.3972	14.2522575	171.0270903	0.785970084	0.00483524
67.8402	15.2510837	183.0130039	0.841052407	0.00484526
72.2832	16.2499098	194.9989175	0.896134731	0.00486328
76.7262	17.2487359	206.9848311	0.951217054	0.00488131
81.1692	18.2475621	218.9707447	1.006299378	0.00492337
85.1322	19.1384799	229.6617588	1.055430876	0.00495342
90.0552	20.2452143	242.9425719	1.116464025	0.00498547
94.4982	21.2440405	254.9284855	1.171546349	0.00505357
90.0552	20.2452143	242.9425719	1.116464025	0.00509363

Stress and Strain for Beam with CFRP wrap

Load(KN)	Load(Kips)	Moment(Kip-in)	Stress(ksi)	Strain(in)
0	0	0	0	0
5.6382	1.267517782	15.21021339	0.06989988	0.00521782
10.0812	2.266343916	27.19612699	0.1249822	0.00522783
14.5242	3.26517005	39.1820406	0.18006452	0.00523584
18.9672	4.263996184	51.1679542	0.23514685	0.00524786
23.4102	5.262822317	63.15386781	0.29022917	0.00525988
27.8532	6.261648451	75.13978141	0.3453115	0.0052719
32.2962	7.260474585	87.12569502	0.40039382	0.00528391
36.7392	8.259300719	99.11160862	0.45547614	0.00529794
41.1822	9.258126852	111.0975222	0.51055847	0.00531797
45.6252	10.25695299	123.0834358	0.56564079	0.00534
50.0682	11.25577912	135.0693494	0.62072311	0.00536003
54.5112	12.25460525	147.055263	0.67580544	0.00538406
58.9542	13.25343139	159.0411766	0.73088776	0.00539208
63.3972	14.25225752	171.0270903	0.78597008	0.00542412
67.8402	15.25108365	183.0130039	0.84105241	0.00544015
72.2832	16.24990979	194.9989175	0.89613473	0.00545818
76.7262	17.24873592	206.9848311	0.95121705	0.00548021
81.1692	18.24756206	218.9707447	1.00629938	0.00551626
85.1322	19.1384799	229.6617588	1.05543088	0.00556233
90.0552	20.24521432	242.9425719	1.11646402	0.00561241
94.4982	21.24404046	254.9284855	1.17154635	0.00567049
98.9412	22.24286659	266.9143991	1.22662867	0.00573659
103.3842	23.24169272	278.9003127	1.281711	0.0058067
107.8412	24.24366618	290.9239942	1.33696688	0.00591286
103.3842	23.24169272	278.9003127	1.281711	0.00600099

Stress and Strain for Cracked Beam Retrofitted with CFRP wrap

Load(KN)	Load(kips)	Moment(Kip-in)	Stress(ksi)	Strain(in)
0	0	0	0	0
5.6382	1.2675178	15.21021339	0.0698999	0.005224
10.0812	2.2663439	27.19612699	0.1249822	0.005228
14.5242	3.26517	39.1820406	0.1800645	0.005234
18.9672	4.2639962	51.1679542	0.2351468	0.005242
23.4102	5.2628223	63.15386781	0.2902292	0.00525
27.8532	6.2616485	75.13978141	0.3453115	0.005264
32.2962	7.2604746	87.12569502	0.4003938	0.005276
36.7392	8.2593007	99.11160862	0.4554761	0.00529
41.1822	9.2581269	111.0975222	0.5105585	0.005302
45.6252	10.256953	123.0834358	0.5656408	0.005312
50.0682	11.255779	135.0693494	0.6207231	0.005324
54.5112	12.254605	147.055263	0.6758054	0.005342
58.9542	13.253431	159.0411766	0.7308878	0.005364
63.3972	14.252258	171.0270903	0.7859701	0.005372
67.8402	15.251084	183.0130039	0.8410524	0.005402
72.2832	16.24991	194.9989175	0.8961347	0.00545
76.7262	17.248736	206.9848311	0.9512171	0.005494
81.1692	18.247562	218.9707447	1.0062994	0.005556
85.1322	19.13848	229.6617588	1.0554309	0.00563
90.0552	20.245214	242.9425719	1.116464	0.005707
94.4982	21.24404	254.9284855	1.1715463	0.005783
98.9412	22.242867	266.9143991	1.2266287	0.005893
94.4982	21.24404	254.9284855	1.1715463	0.006035
85.1322	19.13848	229.6617588	1.0554309	0.006159