

EXPERIMENTAL EVALUATION OF FRP STRENGTHENED
CONCRETE BRIDGE GIRDERS

By

RAKESH B JAYANNA

Presented to the Faculty of the Graduate School of
The University of Texas at Arlington in Partial Fulfillment of the Requirements
for the Degree of

MASTER OF SCIENCE IN CIVIL ENGINEERING

THE UNIVERSITY OF TEXAS AT ARLINGTON

AUGUST 2015

Copyright © by Rakesh B Jayanna 2015

All Rights Reserved



Acknowledgements

I would like to greatly and sincerely thank Dr. Nur Yazdani for his guidance, understanding, and patience during my graduate studies at University of Texas at Arlington. I am very glad that I got this opportunity to work for Dr. Yazdani in this research. For everything you have done for me, Dr. Yazdani, I thank you. I would also like to thank all the members of DR. Yazdani research group, Narasimha Reddy, Vinod Reddy, Mina Riad, Rakesh K R, Istaq Hasan and most specially Eyosias Beneberu who helped me lot as a mentor until the end the research.

I thank Dr.Chao and his research group for helping me in experimental setup especially Chatchai Jiansinlapadamrong. I would also like to thank my Committee members Dr. Najafi, Dr. Mohammad Razavi for their precious time.

Finally, and most importantly, I would like to thank my mother for her support, encouragement; patience and her love were the bedrock upon which my master's degree is been so successful and I thank her for having faith in me and allowing me to be as ambitious as I wanted.

August 10, 2015

Abstract

EXPERIMENTAL EVALUATION OF FRP STRENGTHENED CONCRETE BRIDGE
GIRDERS

Rakesh B Jayanna, MS

The University of Texas at Arlington, 2015

Supervising Professor: Nur Yazdani

This report presents the details of research study on the use of Carbon Fiber Reinforced Polymers (CFRP) sheets to strengthen the Pre-stressed concrete TxDOT Tx-28 bridge girders in flexure and shear. Four girders were subjected to destructive test in this research. First girder as control specimen without any CFRP applied on it, Second and third girders were flexural strengthened for one and two layers of CFRP and the forth girder is shear strengthened with one layer CFRP. Experimental phases along with the comparison of test results in terms of flexural and shear capacity of bridge girders, strains and deflections are discussed with reference to control and CFRP strengthened specimens. The CFRP strengthening was designed based on the ACI 440 recommendations. The report details the installation process as well as a load-testing program utilized to assess the effectiveness of the strengthening system. The installation process was found to be rapid and simple. The bonding between the FRP installed and the concrete surface is verified by pull off test. Adding to this in order to monitor the strain and displacement, we had strain gages on the surface of FRP at the tension and compression zones of the girders and two transducers near the supports and two more transducers at the center. Good agreement was obtained with the experimental and theoretical findings of strength, strains and deflections. Overall, the strengthened girders behaved as predicted when subjected to the design loads. The detailed design of FRP strengthening is system is reported in this report.

Table of Contents

Acknowledgements	iii
Abstract	iv
List of Illustrations	viii
List of Tables	xii
Chapter 1 INTRODUCTION.....	1
1.1 Background and Research Scope	1
1.2 Research Objectives	2
Chapter 2 LITERATURE REVIEW.....	3
2.1 Introduction	3
2.2 CFRP Laminate strengthening	3
Chapter 3 Material Specifications	6
3.1 Specimen description	6
3.2 Carbon fiber fabric	7
3.3 Epoxy.....	8
3.4 Strain Gages.....	9
1. 3.4.1 Installation of Strain gages	10
3.5 Linear varying differential transformers (LVDT's).....	13
Chapter 4 Specimen Preparation and Test setup.....	14
4.1 Introduction	14
4.2 Girder strengthening	16
4.2.1 Surface Preparation	16
4.2.2 Application of FRP.....	17
4.2.3 Anchorage	20
4.3 Bond behavior of FRP – Concrete surface.....	20

4.4	Strain gage layout.....	22
4.5	LVDT Layout.....	24
4.6	Experimental setup.....	25
Chapter 5 Preliminary analysis		29
5.1	Introduction	29
5.2	Un-strengthened Girder analysis.....	29
5.2.1	Flexure Strength.....	29
5.2.2	Shear Strength	29
5.3	Strengthened Girder Analysis.....	30
5.3.1	Flexural strengthening.....	30
5.3.2	Shear Strengthening	31
Chapter 6 Experimental Results		32
6.1	Introduction	32
6.2	General Observations.....	32
6.2.1	Cracks and Failure Modes	32
6.2.1.1	Flexure	33
6.2.1.2	Shear.....	44
Chapter 7 Test Results		46
7.1	Control Specimen (G1C)	46
7.2	Girder, Flexure 1 layer (GF1)	48
7.3	Girder, Flexure 2 layers GF2	50
7.4	Girder, Shear 1 layer GS1	53
Chapter 8 Discussions		56
8.1	Introduction	56
8.2	Analysis of Strength of Girders.....	56

8.2.1	Comparison of Strength of Control and GF1	56
8.1.2	Comparison of strength of control and GF2	58
8.2	Analysis of Deflections	59
8.3	Importance of Anchorage	60
8.4	Analysis of Strains of the experimental results.....	62
8.5	Comparison of GS1 FRP strengthened with the un-strengthened.....	63
Chapter 9	Conclusions.....	64
9.1	Research Conclusions.....	64
9.2	Recommendations and Future Work.....	64
Appendix A	Flexural Strengthening of Pre-stressed concrete Tx-28 Girder with CFRP sheet	65
Appendix B	Shear Strengthening of Pre-stressed concrete Tx-28 Girder with CFRP sheets.....	71
References	75
Biographical Information	86

List of Illustrations

Figure 3-1 – Girder Cross section.....	6
Figure 3-2- Girder elevation	7
Figure 3-3- Bar specifications	7
Figure 3-4- Carbon fiber fabric.....	8
Figure 3-5- Epoxy components.....	9
Figure 3-6- Strain Gages.....	10
Figure 3-7- Surface preparation	10
Figure 3-8-Surface preparation	11
Figure 3-9- Surface preparation.....	11
Figure 3-10-Gage layout	11
Figure 3-11-Gage application	12
Figure 3-12- Gage application	12
Figure 3-13- Gage application	12
Figure 3-14- Transducer	13
Figure 4-1- Control Girder	14
Figure 4-2- Girder, Flexure, 1 layer.....	15
Figure 4-3- Girder flexure 3 layers	15
Figure 4-4- Girder, shear, 1 layer.....	16
Figure 4-5- Surface preparation.....	16
Figure 4-6- Mixing of epoxy	17
Figure 4-7- Application of epoxy to girders	18
Figure 4-8 – Applying Epoxy on FRP.....	18
Figure 4-9 – Applying thick paste of Epoxy with Silica	19
Figure 4-10 – Installation of saturated FRP on Girders	19

Figure 4-11 – Flexure Anchorage	20
Figure 4-12 – Samples from the Pull off test.....	22
Figure 4-13 – Stain gage layout – GC	22
Figure 4-14 – Strain gage layout – GF1.....	23
Figure 4-15 - Strain gage layout – GF2	23
Figure 4-16 - Strain gage layout – GS1	24
Figure 4-17 – LVDT Layout for GC, GF1 and GF2.....	24
Figure 4-18 – LVDT Layout for GS1	25
Figure 4-19 – Experimental setup.....	25
Figure 4-20 – Experimental setup.....	26
Figure 4-21 – Experimental setup.....	27
Figure 4-22 – Setup Longitudinal section	27
Figure 4-23 – Setup Cross section	28
Figure 6-1- Observed first crack at 94 kips	33
Figure 6-2 – Observed cracks due to loading GC	34
Figure 6-3 - Observed cracks due to loading GC	34
Figure 6-4 - Observed cracks due to loading GC	35
Figure 6-5 -Observed cracks due to loading GC	35
Figure 6-6 -Observed cracks due to loading GC	36
Figure 6-7 - Observed cracks due to loading GC	36
Figure 6-8 - Observed cracks due to loading GC	37
Figure 6-9 - Observed cracks due to loading at first force drop GC	37
Figure 6-10 – Observed cracks due to loading GF1	38
Figure 6-11 -Observed cracks due to loading GF1.....	38
Figure 6-12 – FRP debonding at maximum loading GF1	39

Figure 6-13 – FRP Debonding at Maximum Loading GF1	39
Figure 6-14 - FRP debonding at maximum loading GF2	40
Figure 6-15 – Observed cracks due to loading GF2	41
Figure 6-16 - FRP debonding at maximum loading GF2	42
Figure 6-17 - FRP debonding at maximum loading GF2	43
Figure 6-18 - FRP debonding at maximum loading GF2	43
Figure 6-19 – Loading setup for shear test GS1	44
Figure 6-20 – Observed cracks due to loading GS1	44
Figure 6-21 – Observed cracks due to loading GS1	45
Figure 7-1 – Load deflection plot GC	46
Figure 7-2 – Load versus Strain Curve GC.....	47
Figure 7-3–Magnified Load versus Strain Curve GC.....	47
Figure 7-4 – Load Deflection plot GF1	48
Figure 7-5 – Load versus Strain plot GF1	49
Figure 7-6– Enlarged Load versus Strain plot GF1	49
Figure 7-7–Enlarged Load versus Strain plot GF1	50
Figure 7-8–Load deflection plot GF2	51
Figure 7-9 -Load versus Strain plot GF2.....	52
Figure 7-10 – Enlarged Load versus Strain plot GF2	52
Figure 7-11–Enlarged Load versus Strain plot GF1	53
Figure 7-12 – Load deflection plot GS1	54
Figure 7-13–Enlarged Load deflection plot GS1	54
Figure 8-1 – Load deflection comparison plot - % increase in strength.....	56
Figure 8-2 -Load deflection comparison plot - % increase in strength	57
Figure 8-3- Comparison of strength of control and GF2	58

Figure 8-4 – Load deflection comparison plot.....	59
Figure 8-5– Magnified Load deflection comparison plot	60
Figure 8-6 -Load deflection comparison plot for anchorage importance	61
Figure 8-7– Magnified Load deflection comparison plot for anchorage importance.....	61
Figure 8-8 – Crack induced debonding	63

List of Tables

Table 3-1- Girder dimensions and properties	7
Table 3-2- Sika Standards for SikaWrap 117C.....	8
Table 3-3- Sika Standards for Sikadur Hex 300	9
Table 4-1- Girder nomenclature	14
Table 6-1- Observed failure	32
Table 7-1-Deflection at Maximum applied load	46
Table 7-2 - Strain at Maximum Loading:.....	47
Table 7-3 -Deflection at maximum load GF1	48
Table 7-4 -Strain at Maximum Load GF1.....	48
Table 7-5 - Deflection at maximum load GF2	50
Table 7-6 -Strain at Maximum Load GF2.....	51
Table 7-7 -Strain at Maximum Load GF2.....	51
Table 7-8 -Deflection at maximum load	53
Table 7-9 -Strain at maximum load FB	55
Table 7-10-Load versus Strain Plot GS1- FM.....	55
Table 7-11 -Load versus Strain Plot GS1- FT.....	55
Table 7-12 -Load versus Strain Plot GS1- BB	55
Table 7-13 - Load versus Strain Plot GS1- BT	55
Table 8-1- Load deflection comparison plot - % increase in strength.....	56
Table 8-2 - Comparison of strength of control and GF2	58

Chapter 1

INTRODUCTION

1.1 Background and Research Scope

Texas Department of transportation is doing a great job in maintaining over 30,000 bridges every year and many of these girders are damaged due to many reasons like fire, impact, corrosion and many external events and structural deterioration. These damaged girders should be repaired very rapidly as these structures takes its vital position in transportation and any pause or obstructions caused to the flow of the traffic would create a serious loss in many issues mainly economic and social losses. TxDOT is using FRP strengthening since 1999 and has repaired more than 30 bridges for confinement; prevent spilling of concrete texture, to prevent corrosion and to prevent it from fire. But still there are many bridges out there which has to be strengthened and need some quantification in the increase in the strength of the FRP strengthened or FRP repaired concrete bridges. There are many research work conducted to increase the flexural and shear strength of the damaged bridges. The only concern with this strengthening is the debonding of laminates from the concrete surface. There are many attempts to utilize the full tensile strength of FRP which resulted with the reduced efficiency. This paper presents the research work on the quantification on the increase in capacities of FRP strengthened large scale undamaged girder when compared to that of the control specimen. Results of this research can be effectively used to develop the design codes for FRP strengthened systems. As this research is on large scale girders, the results of the strengthened FRP system is very close actual system out there in the field. As it was found that there is lack of design information for FRP repair and strengthening implementation, this research is conducted on large scale pre-stressed girders to closely

simulate the field conditions and utilize the results from this research to refine the design consideration for FRP strengthening of bridge girders.

1.2 Research Objectives

The objective of this research was to design bridge girders and experimentally evaluate its strength after FRP application.

Research plan and methodology:

The following tasks were performed to achieve the objectives

- Select appropriate methodology for FRP retrofitting.
- Prepare representative pre-stressed concrete Girders. The control group will have no FRP application, while the test group will have FRP application as per the design code.
- To determine the theoretical capacities of the samples based on identified literature methods.
- Perform destructive testing of prepared samples, flexure and Shear test.
- Compare performance of the control samples and the FRP strengthened samples, based on theoretical versus experimental capacities, ductility, confinement of concrete, and other identified parameters.

Chapter 2

LITERATURE REVIEW

2.1 Introduction

Fiber Reinforced Polymer (FRP) is used to strengthen the structures since 1999. However, very limited number of researches is conducted to quantify the capacity of FRP strengthening bridge girders. Here are the few valuable research works in the field of CFRP flexural and shear strengthening.

2.2 CFRP Laminate strengthening

I beams are typically strengthened in flexure by externally bonding FRP sheets on the tension face of the member and are oriented along the beam axis.

Several pre-stressed concrete bridge girders are damaged everyday accidentally by over height vehicles or construction equipment impact. Even though complete replacement of the girders is necessary, repair and rehabilitation can be far more economical, especially when the time and cost of installation and repair system are drastically less. The FRP system are used to retain the original capacity of PC bridge girders are being increasingly considered for bridge applications due to its high strength to weight ratios, ease of handling and transport, corrosion and fatigue resistance.

Because of its light weight, high tensile strength and ease to install on irregular surfaces, the use of FRP system for repair and strengthening of reinforced concrete structures has become more important. Many researches are conducted on the Flexural and axial strengthening of concrete structures whereas there are limited researches on the shear strengthening of concrete structures using FRP. Presently there are no widely accepted guidelines for the design of FRP strengthened concrete structures. Using the available design provisions/guidelines is reviewed and those factors that need further investigation are notified.

Even though there are many repair works made on the bridges, there is limited number of studies conducted in the laboratory on full scale bridge girders to explain the overall behavior of the FRP strengthening system.

A study conducted by Adel Elsafty (2012) indicated that there was debonding problem and couldn't successfully achieve the full strength of FRP due to weak bonding of the U-wrap for anchorage and could see decrease in the capacities of the predicted and test results, Rosenboom et al.(2011) resulted in the reduction in the displacement of the FRP system at service loads. Tumialan et al (2001) stated that the FRP strengthened structures performed well under the service loads after the small losses of ruptured pre-stressing strands. Other studies concluded that the proper detailing of FRP termination points is very critical for good bond performance.

The most influential research work was published by Shannafelt and Horn in 1980 which give extensive statistical proof for the damaged pre-stressed girders all over the nation over the years and documented the damages into 3 categories.

Minor Damage: These damages will not affect the capacity of the structures, it need repair works for preventive purposes or aesthetics from small cracks, spalls of concrete, nicks and cracks, water strain and rusts.

Moderate Damage: This state doesn't affect the capacity of the structure, but it needs presentational measure from the future large cracks or loss of concrete.

Severe Damage: The one which requires structural repairs, broken strands and exposed to the environment and results in the loss of the actual capacity of the structures.

There are several field projects relating to FRP strengthened systems but the detailed information on these projects are not available and most of these projects were strengthened for flexural rehabilitation. The following projects are directly related to FRP shear strengthening of concrete bridge girders:

The Willamette river bridge located near Newberg, Oregon, was found to have significant diagonal cracking during an inspection conducted by Oregon Department of Transportation 2001 late summer. CFRP strips of 12 in width were applied vertically in a U-Wrapping scheme. (Williams and Higgins, 2008)

A single span, reinforced concrete T Beam Bridge in New York State was strengthened in shear with externally bonded FRP laminates in November 1999 (Hag-Elsafi et al., 2001b).

The John Hart Bridge in Prince George, British Columbia and Maryland Bridge in Winnipeg, Manitoba, are two bridges in western Canada that have strengthened in shear with externally bonded FRP.

The Langevin Bridge in Calgary, Canada is six spans, four cells, continuous Box Girder Bridge constructed in 1972. The internal webs are found to be deficient at right end of the 2nd span where internal pre-stressing tendons are horizontal and have zero contribution to shear resistance. This is corrected by wrapping the CFRP sheets on both sides of the internal web.

The Grondals Bridge in Sweden is a pre-stressed concrete Box Bridge approximately 1,300 feet in length and a free span of 394 ft. CFRP laminates strips were applied to the inner walls of the steel plates to increase the shear strength.

Chapter 3

Material Specifications

3.1 Specimen description

TxDOT TX-28 girders were used in this research. The design standards of TxDOT were followed to design the girders. PG Super (software) was used as a reference for the design. Each Girder is 33 feet (10.0584 meter) long | Girder. Girder dimensions and section properties are tabulate in Table 1. The actual concrete strength at 7 day was found to be 6988 Psi (48.1805 MPa) as found from the breaking of concrete cylinders.

All girders were precast pre-stressed by Texas concrete located at Waco, Texas.

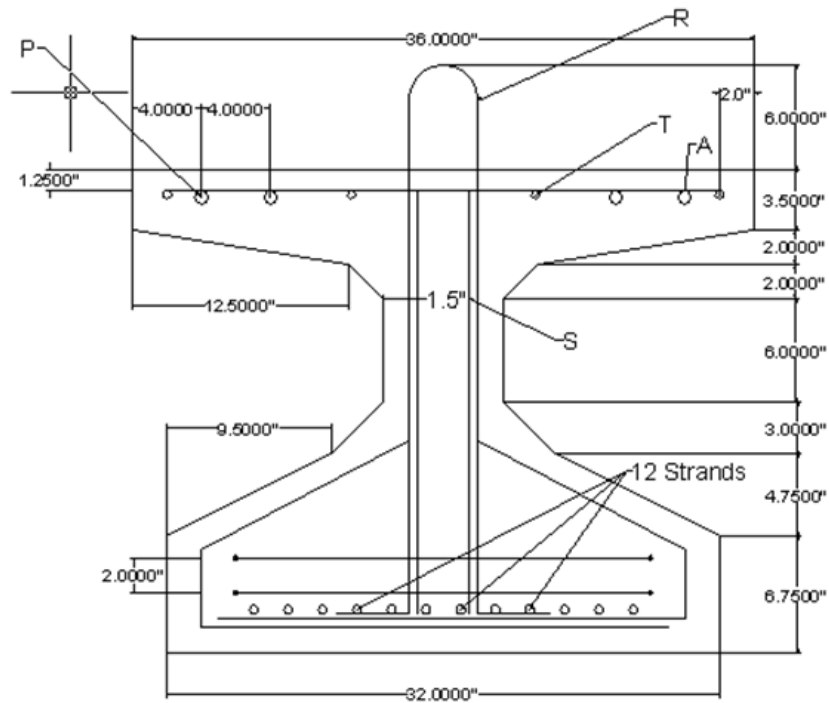


Figure 3-1 – Girder Cross section

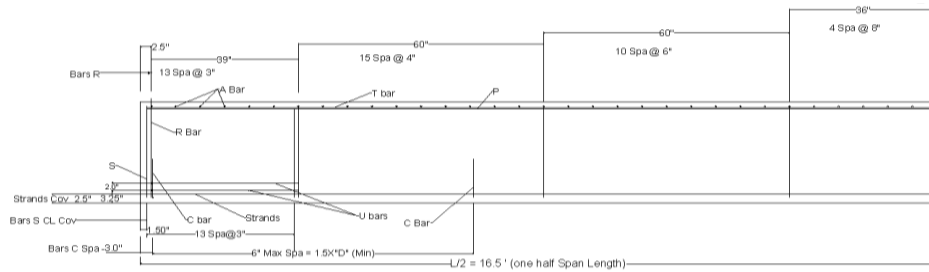


Figure 3-2- Girder elevation

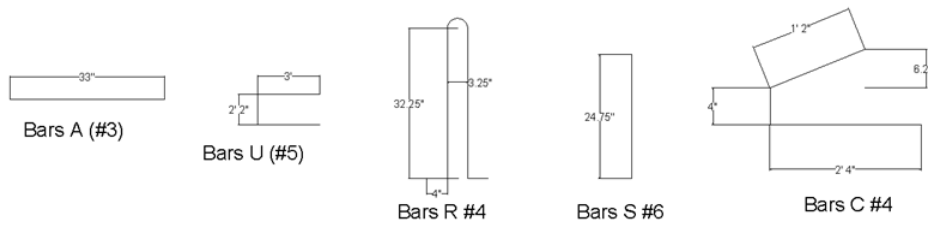


Figure 3-3- Bar specifications

Girder Dimension and properties

Table 3-1- Girder dimensions and properties

Girder	D in (mm)	Area in ² (mm ²)	Ix in ⁴ (mm ⁴)	Weight plf (KNm)
Tx -28	28	585	52,772	610

3.2 Carbon fiber fabric

A Carbon fiber is a long, thin strand of material about 0.0002- 0.0004 inch in Diameter and composed of mainly carbon atoms. The carbon atoms are bonded together in microscopic crystals that are more or less aligned parallel to the long axis of the fiber. Several thousand of Carbon fibers are twisted together to form a yarn, which may be used itself or woven into a fabric.

Carbon Fiber Fabric from Sika Corporation is used in this research.

SikaWrap Hex 117C is a unidirectional carbon fiber fabric. This material is laminated using Sikadur 300 epoxy to form Carbon fiber reinforced polymer, the composite used to strengthen the structural elements.

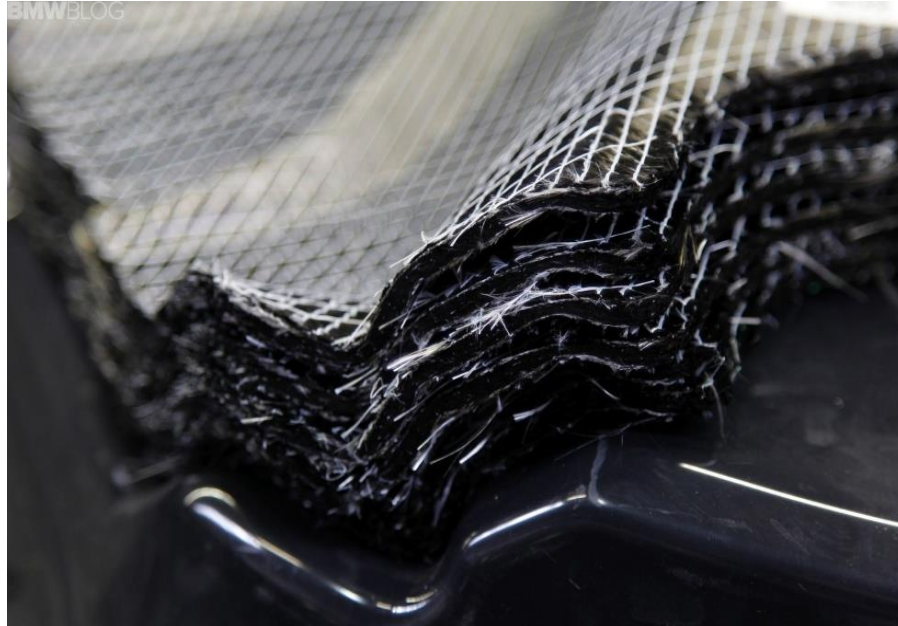


Figure 3-4- Carbon fiber fabric

Table 3-2- Sika Standards for SikaWrap 117C

Cured laminate properties	Design Values
Tensile strength	$1.05 * 10^5$ Psi (724) Mpa
Modulus of elasticity	$8.2 * 10^6$ Psi (56,500) Mpa
Elongation of Break	1.0%
Thickness	0.02 in (0.51) mm
Width	24 n (609) mm

3.3 Epoxy

In order to make different composite materials epoxy plays a vital role. It acts adhesive to hold the Fibers together and molded into different shapes.

Sikadur Hex 300- High strength, High modulus, Impregnating Resin is the epoxy used in this research. Sikadur® Hex 300 is a two-component 100% solids, moisture-tolerant, high strength, high modulus epoxies. Sikadur® Hex 300 is approved for use by ICBO/ICC (ER 5558). Sikadur is used as a seal coat and impregnating resin for horizontal and vertical applications.



Figure 3-5- Epoxy components

Table 3-3- Sika Standards for Sikadur Hex 300

Properties	Design Values
Tensile strength	10,500psi (72.5) Mpa
Tensile modulus	4, 60,000psi (3174) Mpa
Elongation of Break	4.8%
Flexural strength	17,900 Psi (123.5) Mpa

3.4 Strain Gages

Strain gage is a device used to measure stain in an object. Invented by Edward E Simmons and Arthur C Rugein 1983

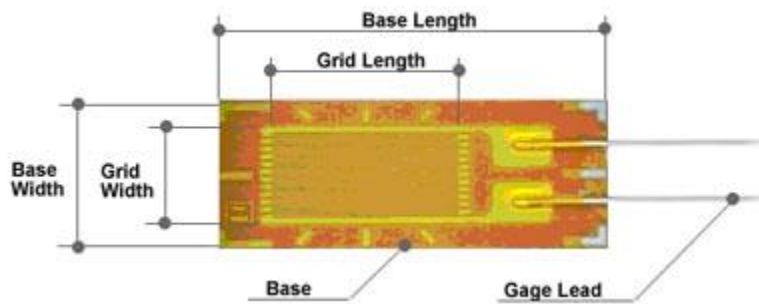


Figure 3-6- Strain Gages

1. 3.4.1 Installation of Strain gages

The composite strain gages from the Texas measurements were used in this research. Texas measurements have a particular standard for the installation of strain gage. Since these are composite strain gages, epoxy is applied on the concrete surface before the installation of strain gages. As the epoxy dries, the procedure below if followed to install strain gages.

- Surface conditioning- Use a solvent (distilled water) to clean the surface of installation. When it dries, use the sand grit to remove rough texture, dust, paint, loose material and wipe it using sponge gauze. Use distilled water again to clean the surface and allow it to dry. Note that the use of sponge gauze should be in one direction only. Refer Figure – 5, 6, 7.

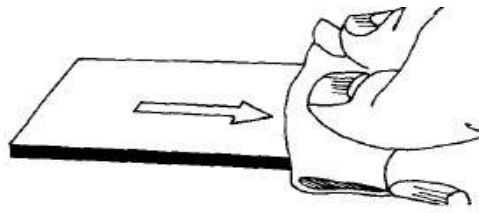


Figure 3-7- Surface preparation

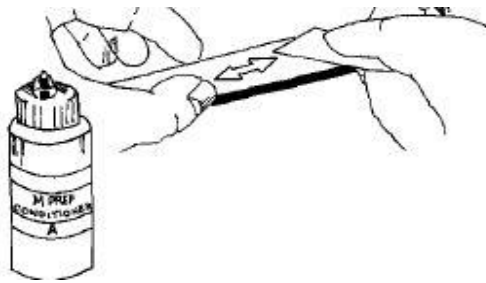


Figure 3-8-Surface preparation



Figure 3-9- Surface preparation

- Outline reference for gage- Using the tape and pen mark the correct position at which the strain gage has to be placed and get the strain gage on the tape. Clean the surface again using sponge gauze. Refer Figure 7.

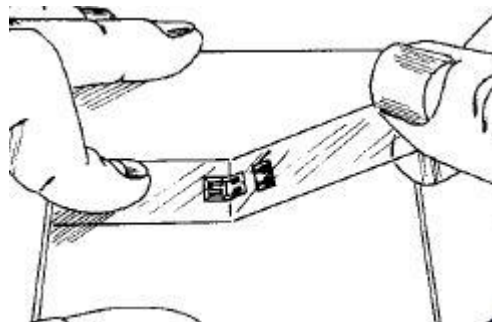


Figure 3-10-Gage layout

- Application of strain gage- This step has to be followed with extra care. The tape with the strain gage is perfectly attached to its correct position. The tape is slightly

removed with some angle from the opposite end of the strain gage. Once you can see the backing material of the strain gage apply the adhesive on it and place the tape back to its position to stick the gage on the surface, soothing the figure on it for uniform distribution of the adhesive. Keep the gage pressed with the figure for one minute for perfect bond on the surface. Refer Figure - 9, 10, 11.



Figure 3-11-Gage application

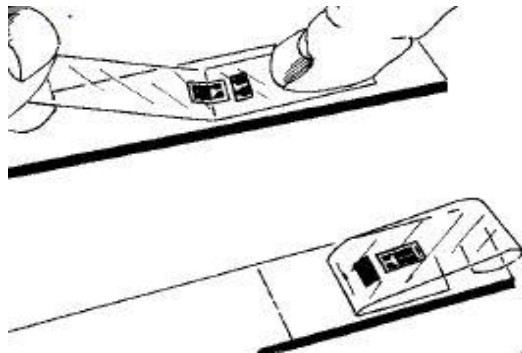


Figure 3-12- Gage application

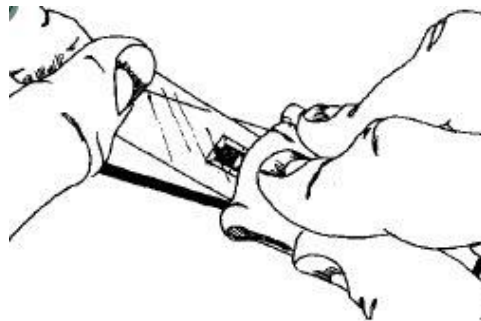


Figure 3-13- Gage application

Layout of Strain gages

3.5 Linear varying differential transformers (LVDT's)

LVDT is device used to measure deflection. The principle of LVDTs is that the physical energy is converted into electrical signals.

These LVDT's are clamped to wooden plank to reach the bottom of the girder and placed pointing the bottom surface of the girder reading zero with its calibration values.



Figure 3-14- Transducer

Chapter 4

Specimen Preparation and Test setup

4.1 Introduction

Specimen designation: This research is conducted on four girder specimens. One control and three test specimens, the control specimen is the one without FRP applied on it, on the other hand the test specimens had CFRP applied on it. The designation or nomenclature of these specimens is as shown in the Table 4 below.

Table 4-1- Girder nomenclature

Name	Abbreviation	Reference figure
Girder 1 control	GC	Figure 4.1-1 – GC
Girder 2, Flexure, 1layer FRP	GF1	Figure 4.1.2 - GF1
Girder 3, Flexure, 2 layer FRP	GF2	Figure 4.1.3 - GF2
Girder 4, Shear, 1 layer FRP	GS1	Figure 4.1.4 - GS1

Girder 1 control (GC)

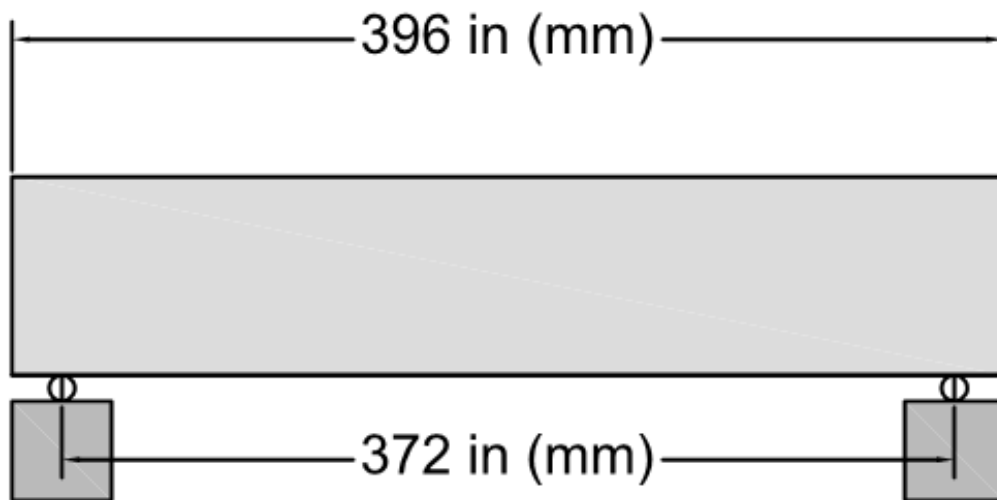


Figure 4-1- Control Girder

Girder 2, Flexure, 1 layer FRP (GF1):

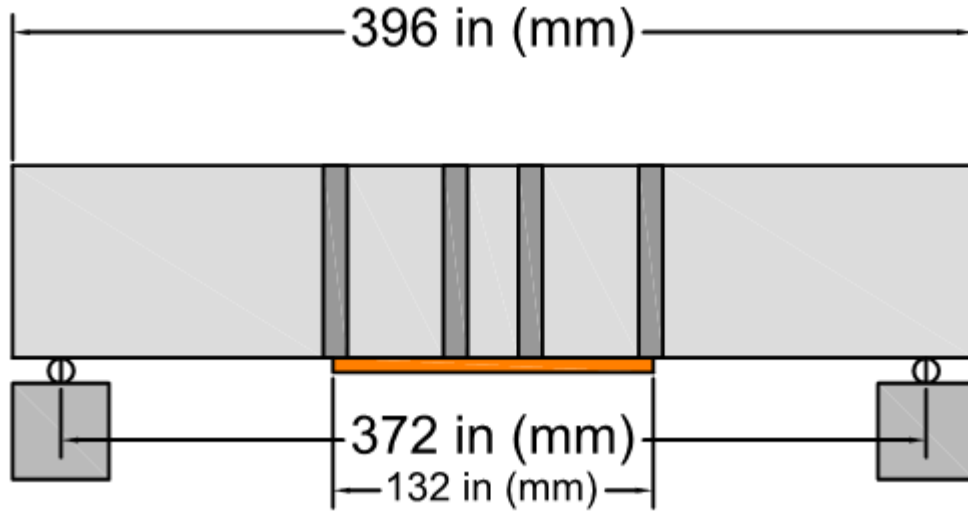


Figure 4-2- Girder, Flexure, 1 layer

Girder 3, Flexure, 2 layers FRP (GF2)

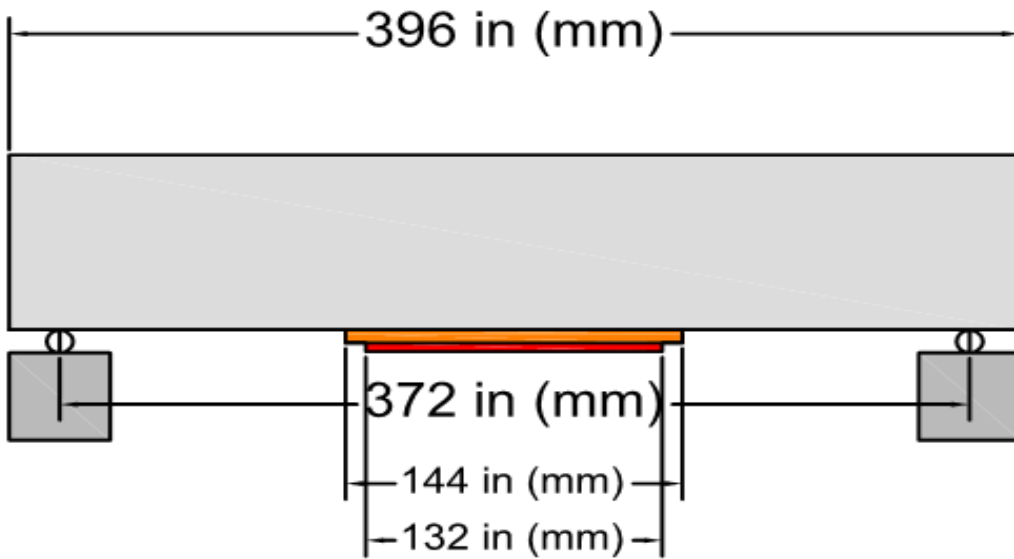


Figure 4-3- Girder flexure 3 layers

Girder 4, Shear, 1 layer FRP (GS1)

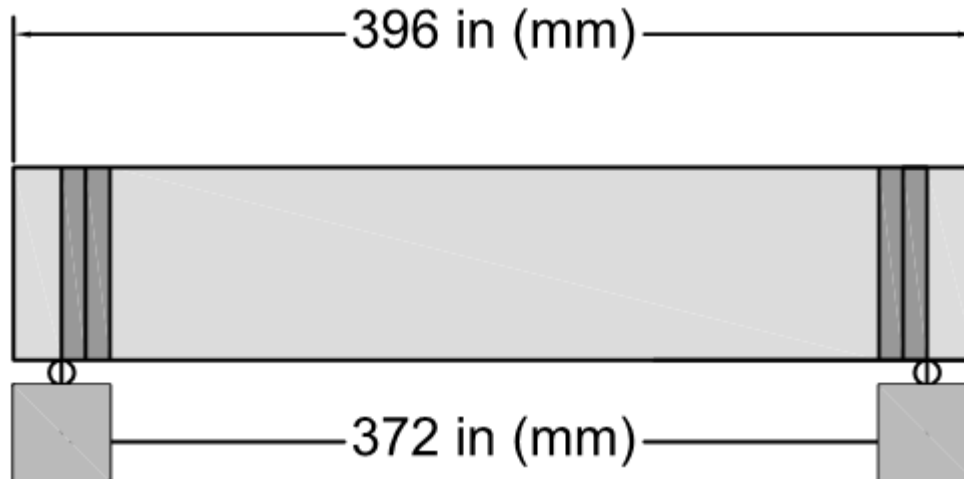


Figure 4-4- Girder, shear, 1 layer

4.2 Girder strengthening

4.2.1 *Surface Preparation*

All girders except the control specimen were subjected to surface preparation. The convex covering or rough surface on the girders is smoothed using concrete grinder. Once the grinding is done the girders were cleaned using compressed air and brushes to remove the concrete dust.



Figure 4-5- Surface preparation

4.2.2 Application of FRP

According to the Sika standards the epoxy composite comes up with two liquids, Impregnating resin and epoxy. Standard ratio of these two liquids is mixed properly following their instruction on the containers.

For better thickness of epoxy silica was added which also helps in filling the pores on the concrete surface.

Once the epoxy is ready, paint rollers are used to apply the epoxy on the surface of the concrete where the FRP has to be installed. FRP is cut into required dimensions and laid on a wide rubber sheet to apply epoxy on it.



Figure 4-6- Mixing of epoxy



Figure 4-7- Application of epoxy to girders



Figure 4-8 – Applying Epoxy on FRP



Figure 4-9 – Applying thick paste of Epoxy with Silica

Once the FRP is wet with epoxy, it is installed on the Girder surface and special care was taken to avoid the voids between the concrete and epoxy surface.

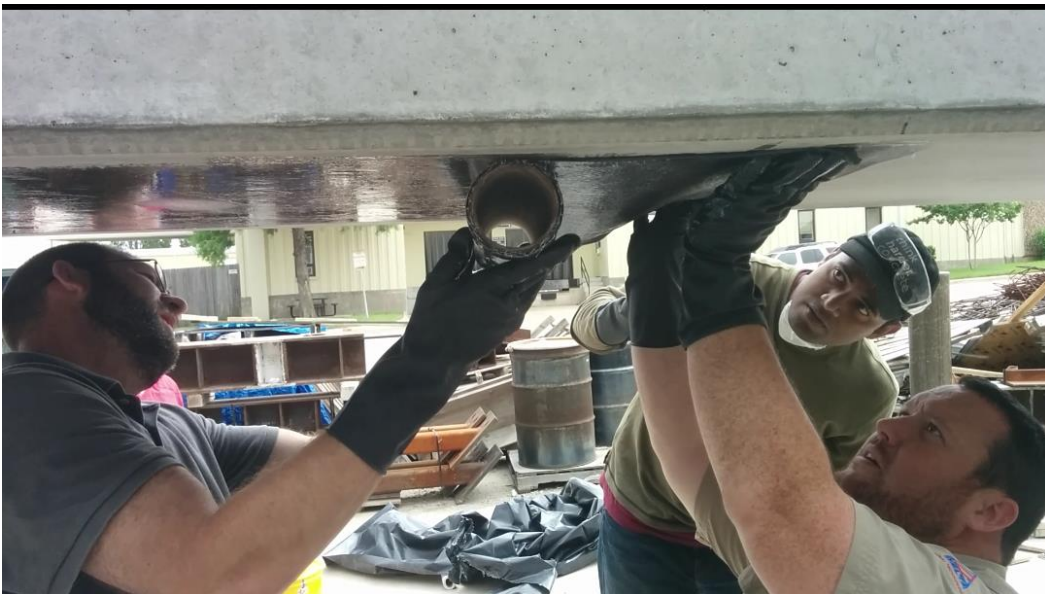


Figure 4-10 – Installation of saturated FRP on Girders

4.2.3 Anchorage

To provide anchorage or extra bonding, the U-wraps were applied on both end of the flexural layers of the FRP and two more strips near the center of the girder. These U-Wraps also provide additional shear capacities along with the anchorage.

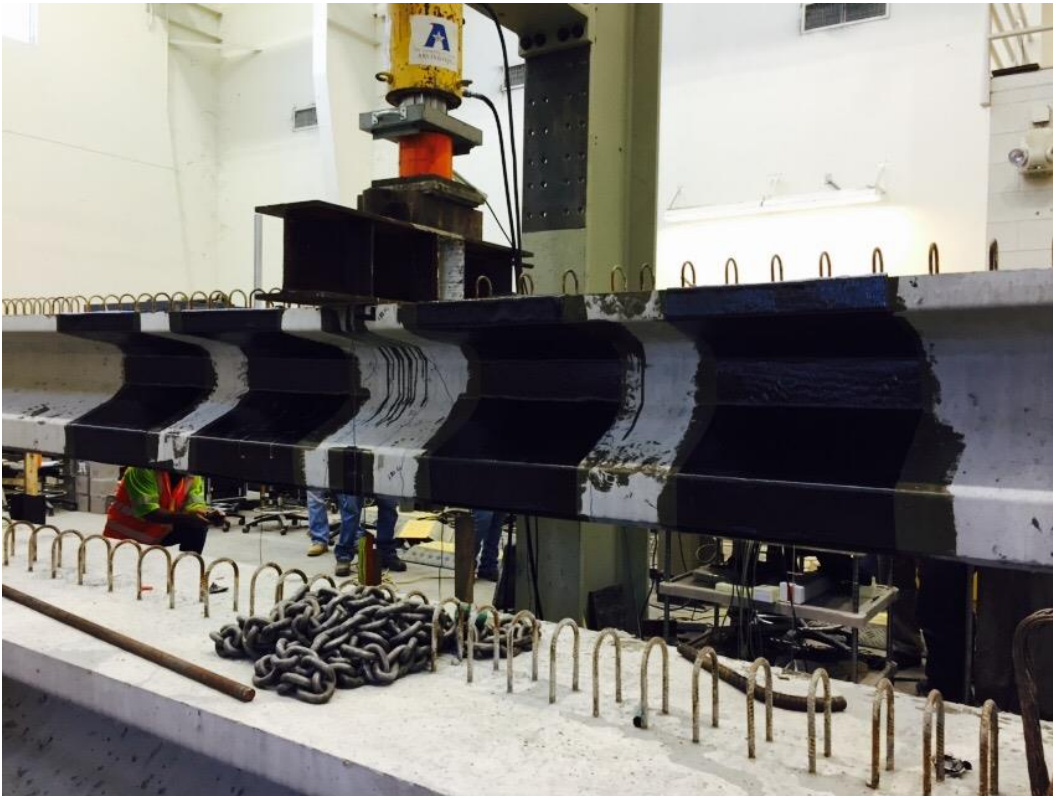


Figure 4-11 – Flexure Anchorage

4.3 Bond behavior of FRP – Concrete surface

The strengthening of concrete structures by using FRP system depends mainly on the interface bond between the FRP sheets and concrete surface. Very important role of the bond between the FRP and concrete is that it transfers the stresses from the

concrete surface as it reaches its maximum to the FRP system which further resists, resulting in the increase of the strength of the existing concrete specimen.

There are many test methods that evaluates the average interfacial bond strength between the FRP sheets and the concrete surface. There are many elements and it's affecting factors which influences the bond behavior between FRP and concrete surface

- Concrete - Strength, thickness, modulus of elasticity, water content and drying shrinkage.
- Loading condition - Bending, shearing, punching and cyclic.
- Environmental actions - Sunlight, ambient temperature, moisture, radiation etc.
- FRP application – Fiber sheets, resins and primer.

Pull off Test: ASTM D4541

Pull off test the near to surface method, in which a circular dolly is glued on the point of interest where we need to verify the bond strength. After its curing time, the dolly is pulled off from the surface. We can see the concrete surface ripping off from the pull, idf the bond strength is very good. But if the bond strength is week then the FRP or thr epoxy could be seen.

Below are the samples of the Pull off test conducted on the girder specimens to verify the bonding with epoxy and concrete surface. The bond strength of all the three samples exceeded 5000 psi indicating very high concrete and epoxy bonding



Figure 4-12 – Samples from the Pull off test

4.4 Strain gage layout

Control specimen (GC)

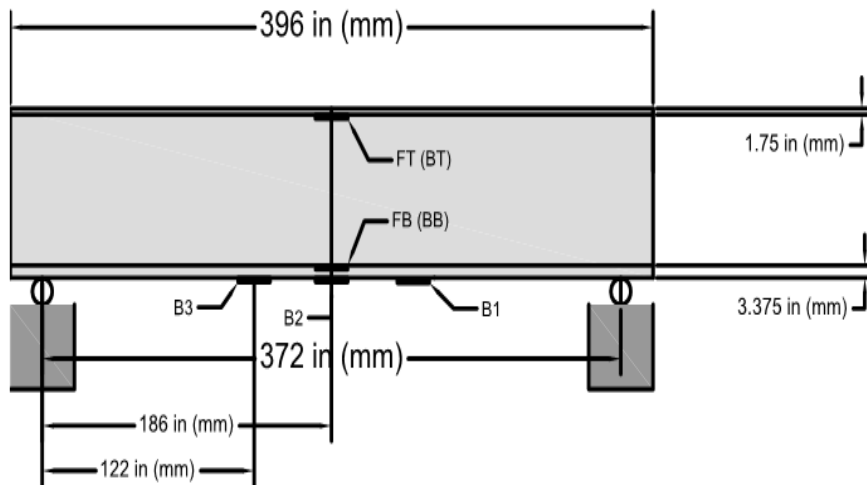


Figure 4-13 – Strain gage layout – GC

Girder 2, Flexure, 1layer FRP (GF1)

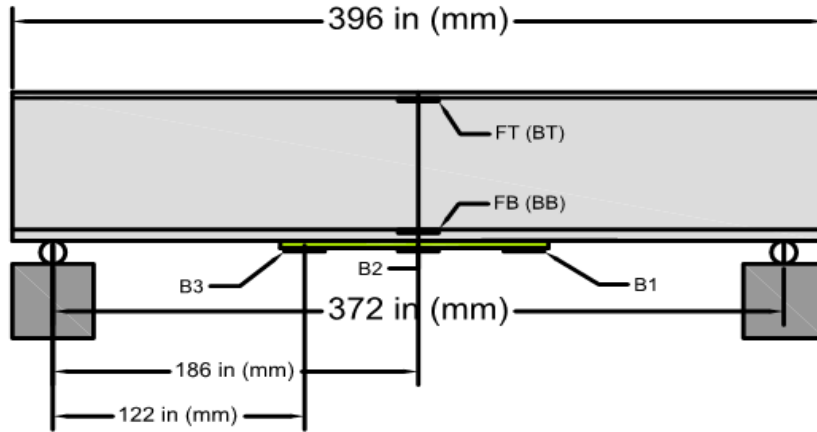


Figure 4-14 – Strain gage layout – GF1

Girder 3, Flexure, 2 layers FRP (GF2)

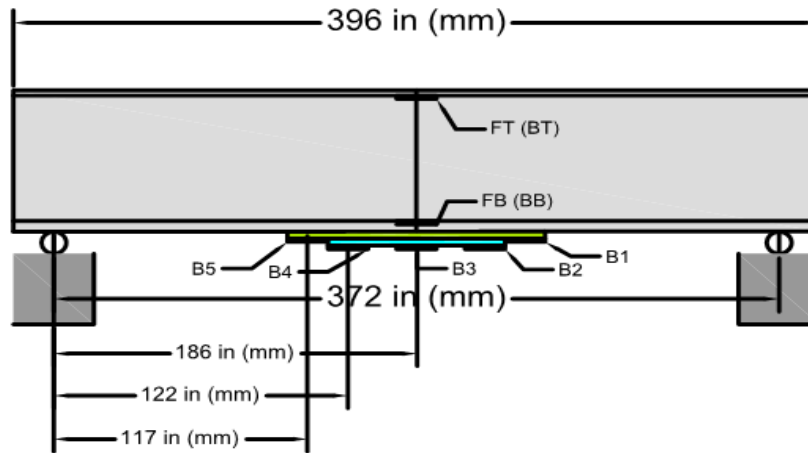


Figure 4-15 - Strain gage layout – GF2

Girder 4, Shear, 1 layer FRP (GS1)

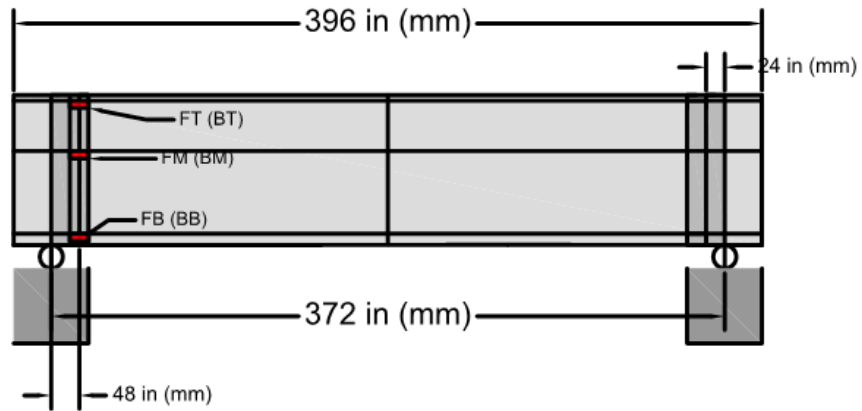


Figure 4-16 - Strain gage layout – GS1

4.5 LVDT Layout

The design layout for LVDT's is same for GC, G1, and G2.

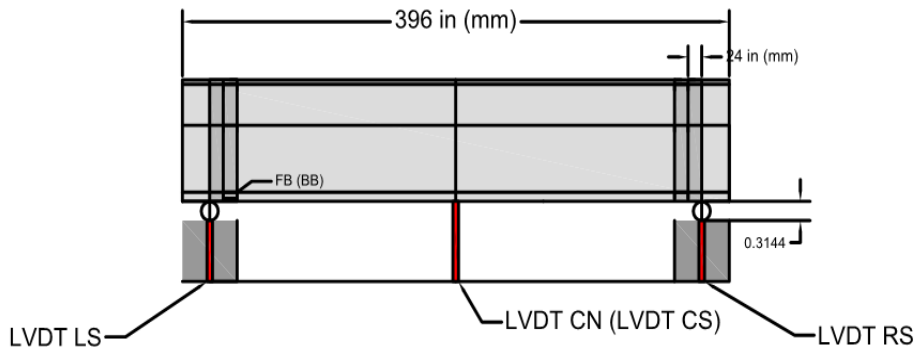


Figure 4-17 – LVDT Layout for GC, GF1 and GF2

LVDT layout for GS1

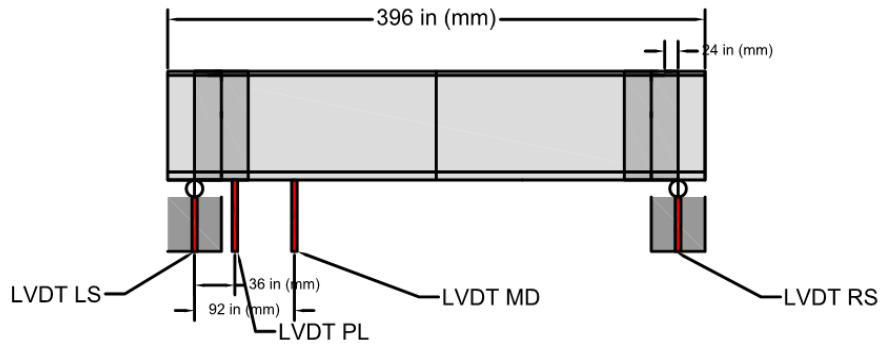


Figure 4-18 – LVDT Layout for GS1

4.6 Experimental setup



Figure 4-19 – Experimental setup

The three point loading condition is applied on the girder for flexure and shear test. The two pedestals of 3ft height above which the rollers and steel plate assembly were used on both supports to facilitate the support conditions. Girder is placed on this assembly. Steel beam and plates were used to apply the uniform load all along the width of the girder. A standard load cell was placed on the steel beams. Finally hydraulic pump was used to apply load on the load cell followed by the girders. In addition to this there were arrangements made for strain measurements with strain gages and deflection measurements with LVDT's. The test setup is as shown in the figures in this section.



Figure 4-20 – Experimental setup

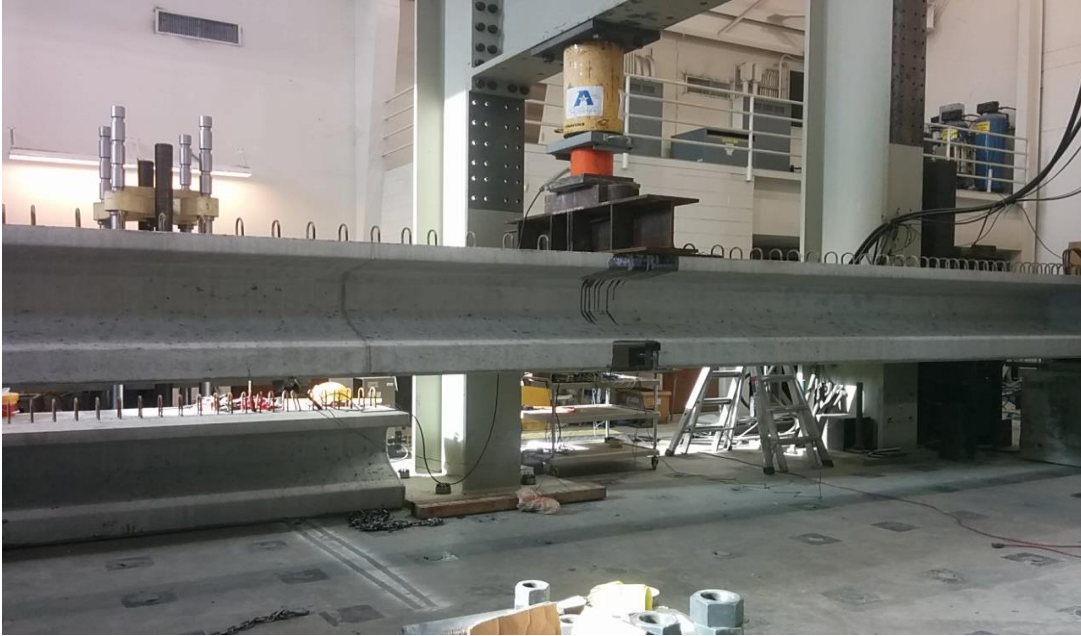


Figure 4-21 – Experimental setup

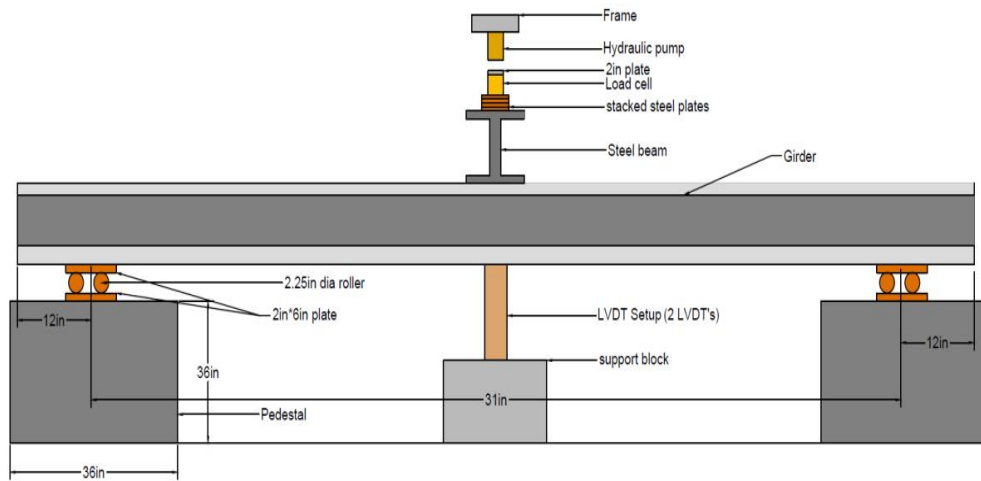


Figure 4-22 – Setup Longitudinal section

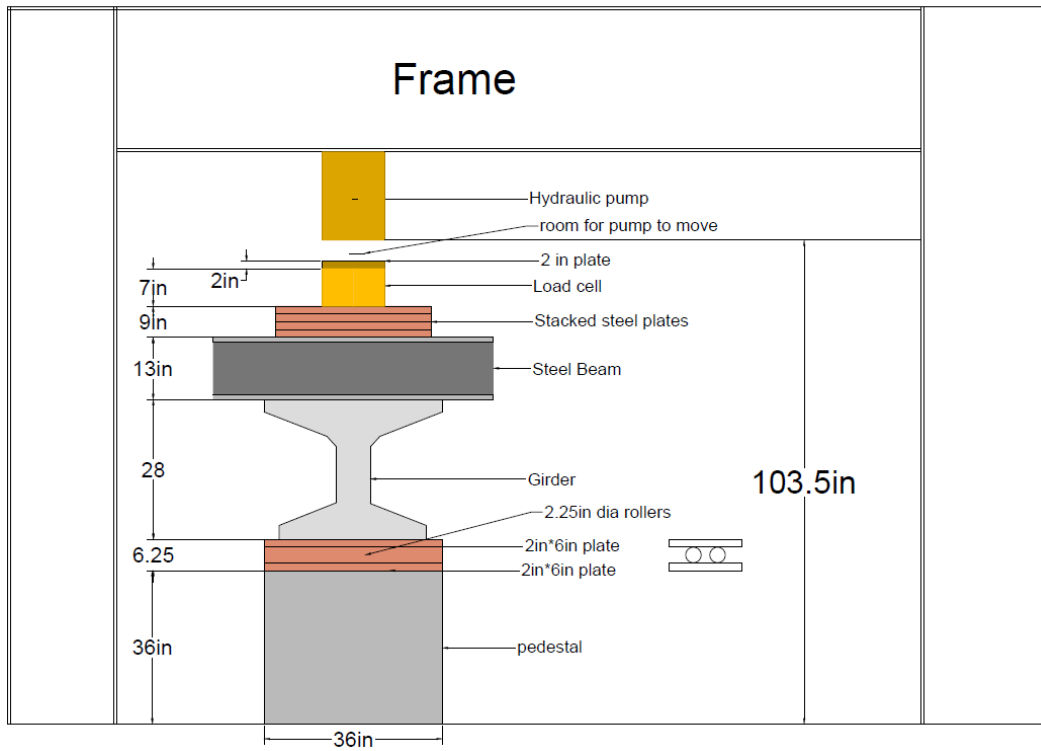


Figure 4-23 – Setup Cross section

Chapter 5

Preliminary analysis

5.1 Introduction

Analysis was performed on Pre-stressed concrete girder specimens TxDOT Tx-28 to find the un-strengthened properties of all specimens for Flexure and Shear. Later after the Un-strengthened girder analysis, the analysis for flexures strengthened and shear strengthened girder analysis is done.

5.2 Un-strengthened Girder analysis

Using ACI 318 to determine the cracking moment, Flexural capacity and shear capacity. This analysis is done for the girders before the application of FRP. Compressive strength of concrete is found to be 6988 Psi. The ultimate strength of the strands is 270 Ksi (1862 Mpa) and steel has yield strength of 60 Ksi (414 Mpa).

5.2.1 *Flexure Strength*

All girders have same flexural reinforcement. Each Girder was reinforced with 12 Pre-stressing straight strands, ½ inch in Diameter Low relaxation strands is used in this research and concrete stress block is found after iterations. The Moment capacity is 901 Kft and corresponding to that moment the load at failure is 116.25 Kips.

5.2.2 *Shear Strength*

All girders have same shear reinforcement. Stirrups of #4 bars are used here at different spacing all along the girder length. Refer Figure 2 that the spacing of stirrups is very less at the ends and more near the mid span. The shear strength of the girders is calculated based on the following equation $V_n = V_c + V_s$. According to ACI 318 all the four girders have same amount of shear contribution from the concrete. Since all girders had same flexure and shear reinforcement, the only way we can make the girder fail in shear is to

load near the end span of the girder. So the shear contribution from the internal reinforcements depends on the section we are loading.

5.3 Strengthened Girder Analysis

After the un-strengthened girder analysis, in order to quantify the increment of the strength of the girders flexural and shear strengthening is carried out. The CFRP, Sika-wrap 117C and Sikadur 300 from Sika Corporation is used in this research to strengthen the girders. Two girders were strengthened in flexure and one girder is strengthened in shear.

5.3.1 *Flexural strengthening*

As stated above two girders were strengthened in flexure. The properties of Sika-wrap 117C and Sikadur 300 are stated in Table 2 and 3 respectively were used in the strengthening. ACI 440 has design standards and specifications for FRP laminate strengthening. In this research the importance of flexural anchorage is also stated.

One girder is strengthened with two layers of CFRP and designated as GF2. GF2 has one CFRP layer of 12ft and the second layer of 11ft center span at the bottom of the girder. Following the ACI 440 design specifications (Appendix A) the moment capacity of the strengthened girder is 1149.16 Kft. Rupture strain, debonding strain and effective strain according to the design procedure are all shown in Appendix A. Refer Appendix A for CFRP strengthening for two layers of CFRP.

The other girder is strengthened with one layer of CFRP. This is designated as GF1. GF1 has one layer of CFRP, 11 ft at the center span of the girder. This flexural strengthening has anchorage of U-wraps at the two ends of the CFRP layer and two strips near the center of the girder. This is to provide anchorage for the CFRP layer and to prevent the possibility of debonding and thereby utilizing the full tensile strength of the FRP. The

moment capacity for GF1 following the ACI 440 is 1064.9 Kft. Refer Appendix for ACI 440 calculations for Flexural strengthening of GF1.

5.3.2 Shear Strengthening

One girder is strengthened in shear with one layer of CFRP and is designated as GS1.

GS1 has four strips of U-Wrap, two on each side of the girder which are installed side by side. Refer Figure 4.1.4. These U-Wraps are not inclined and is installed vertical to the length of the girder. Following ACI 440 Shear design standards the FRP layer contributes 32.8 Kips to the un-strengthened girder. Refer Appendix B for ACI 440 design calculation of GS1.

Chapter 6

Experimental Results

6.1 Introduction

With the flexure and shear test being conducted, the test reading, measurements, Data from DAQ are all compiled to test the effectiveness of each testing. Firstly the actual loading, expected failure modes and the actual failure modes during the test is tabulated below.

Table 6-1- Observed failure

Specimen	Applied Load	Expected Failure	Observed Failure
GC	128 Kips (569KN)	FRP Rupture	FRP Debonding
GF1	143 Kips (636 KN)	FRP Rupture	FRP Debonding
GF2	142 Kips(631 KN)	FRP Rupture	FRP Debonding
GS1	380 Kips (1690 KN)	FRP Rupture	Couldn't reach the Capacity

All other reading and measurements of strains, deflections were collected in the data acquisition system. The graphs of strain at different sections of the girder and the load deflection curves were plotted to check the serviceability and effectiveness of the FRP system.

6.2 General Observations

6.2.1 Cracks and Failure Modes

The cracks that were observed during the experiments were captured and few of them from each test are shown below. The actual experimental failure modes when compared to the expected failure modes is documented here. Generally we can see the failure

made is FRP debonding which states that the full tensile strength of the FRP is not utilized.

6.2.1.1 Flexure

Control Girder (GC)



Figure 6-1- Observed first crack at 94 kips



Figure 6-2 – Observed cracks due to loading GC



Figure 6-3 - Observed cracks due to loading GC



Figure 6-4 - Observed cracks due to loading GC



Figure 6-5 - Observed cracks due to loading GC



Figure 6-6 -Observed cracks due to loading GC



Figure 6-7 - Observed cracks due to loading GC



Figure 6-8 - Observed cracks due to loading GC



Figure 6-9 - Observed cracks due to loading at first force drop GC

Girder, Flexure 1 Layer

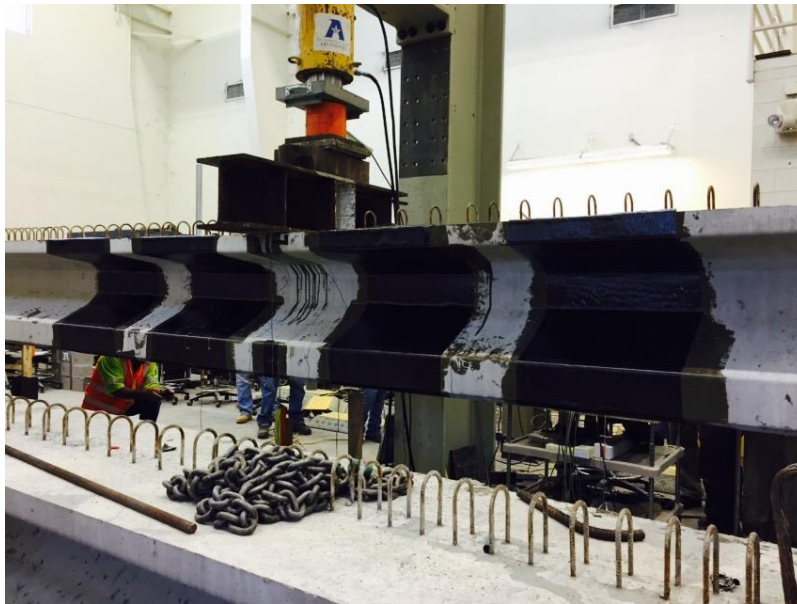


Figure 6-10 – Observed cracks due to loading GF1



Figure 6-11 -Observed cracks due to loading GF1



Figure 6-12 – FRP debonding at maximum loading GF1



Figure 6-13 – FRP Debonding at Maximum Loading GF1

Girder, Flexure 2 Layers



Figure 6-14 - FRP debonding at maximum loading GF2

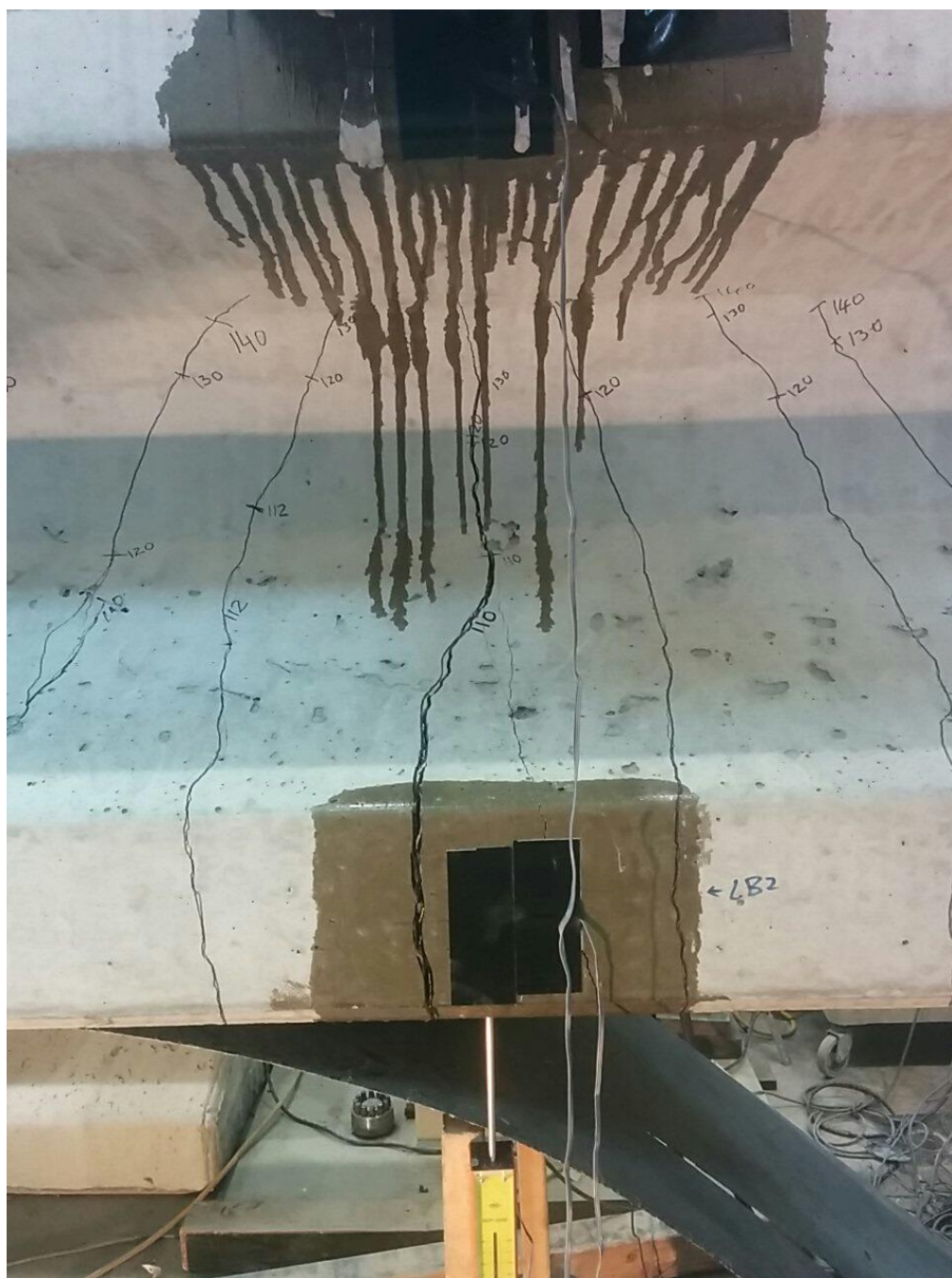


Figure 6-15 – Observed cracks due to loading GF2



Figure 6-16 - FRP debonding at maximum loading GF2

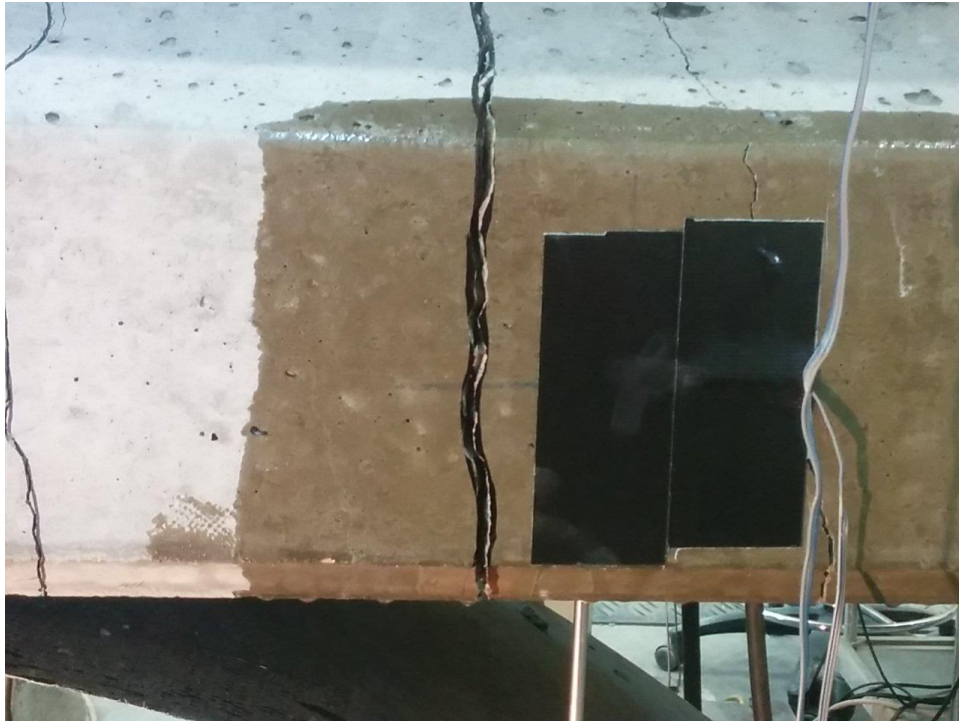


Figure 6-17 - FRP debonding at maximum loading GF2



Figure 6-18 - FRP debonding at maximum loading GF2

6.2.1.2 Shear

Girder, Shear 1 Layer



Figure 6-19 – Loading setup for shear test GS1



Figure 6-20 – Observed cracks due to loading GS1



Figure 6-21 – Observed cracks due to loading GS1

Chapter 7

Test Results

7.1 Control Specimen (G1C)

The control girder started showing the first crack at 94 kips, and the number of cracks and the crack width increased along with the load. When the load reached 125 kips the rate of loading that the girder could resist was very less when we compared to the actual loading rate as it reached the strain hardening state and the first drop of load was found at 130 kips.

Deflection at Maximum load applied

Table 7-1-Deflection at Maximum applied load

Loading, lb (N)	RS, in (mm)	CS in, (mm)	CN in. (mm)	LS, in (mm)
135005, (600532)	-0.0122, (0.30)	2.255, (57.27)	2.198, (55.82)	0.0319, (0.81)

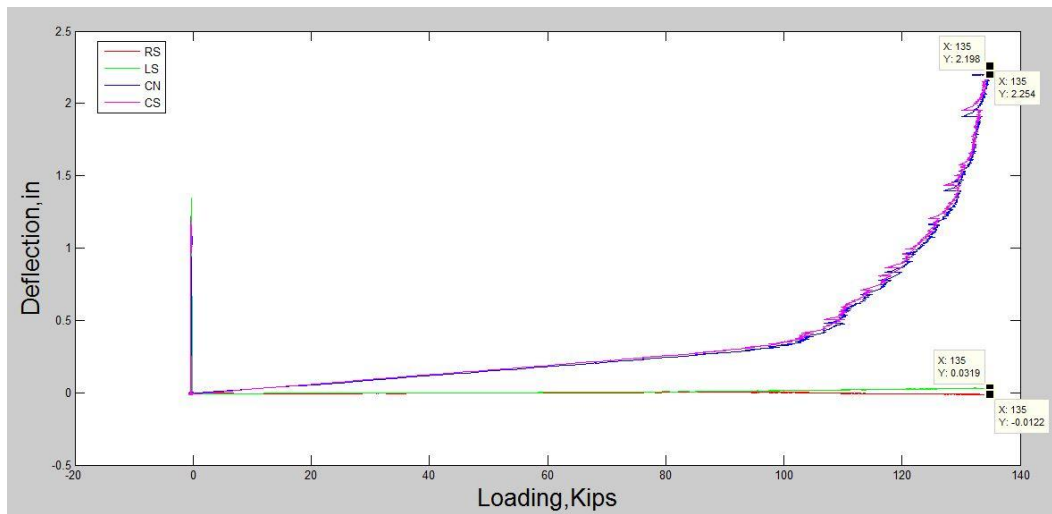


Figure 7-1 – Load deflection plot GC

Strain at Maximum Loading

Table 7-2 - Strain at Maximum Loading:

Loading, lb (N)	B1($\mu\epsilon$)	B2($\mu\epsilon$)	B3($\mu\epsilon$)	FB($\mu\epsilon$)	FT($\mu\epsilon$)	BB($\mu\epsilon$)	BT($\mu\epsilon$)
135005, (600532)	227.3	-580.2	227.3	52.6	-227.8	-17.35	-212.5

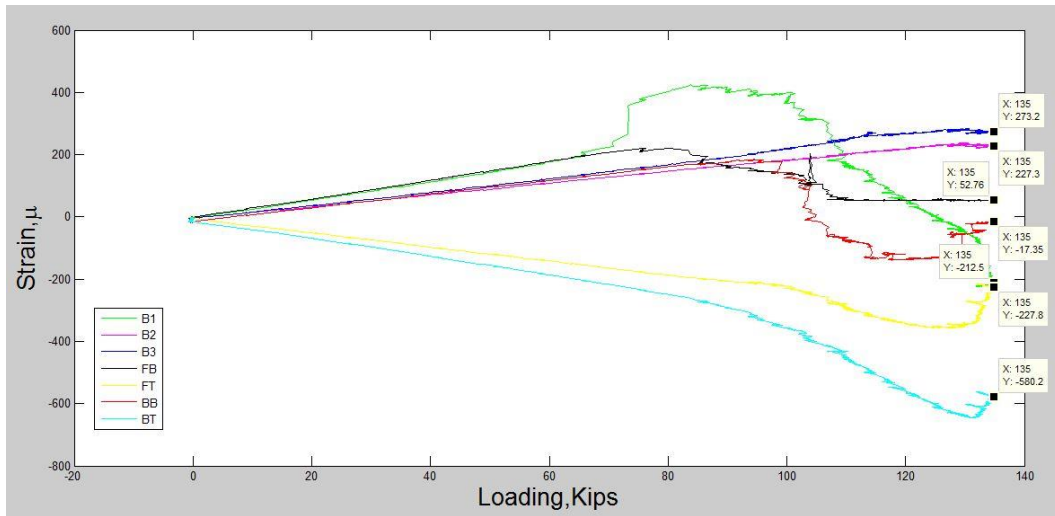


Figure 7-2 – Load versus Strain Curve GC

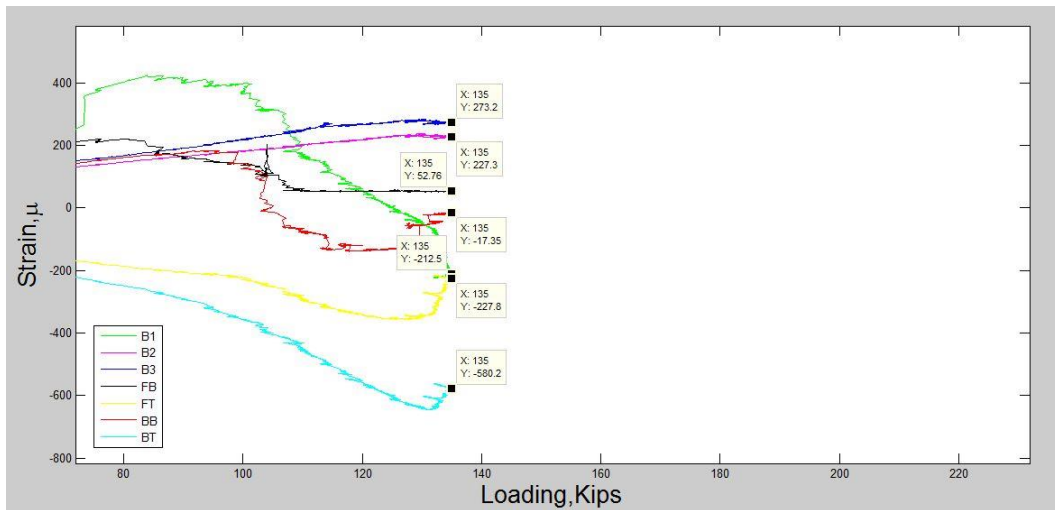


Figure 7-3–Magnified Load versus Strain Curve GC

7.2 Girder, Flexure 1 layer (GF1)

GF1 had one FRP layer at the bottom and 4 strips of U-wraps for flexure anchorage. This Girder gave very good results and shows increase in strength and deflection when compared to the control specimen. The maximum load at the point FRP debonded is 142 Kips.

Deflection at maximum load

Table 7-3 -Deflection at maximum load GF1

Loading lb, (N)	RS, in (mm)	CS in (mm)	CN in (mm)	LS in in (mm)
144380.9, (642238)	0.04, (1.24)	2.10, (53.42)	2.10, (53.34)	0.0043, (0.10)

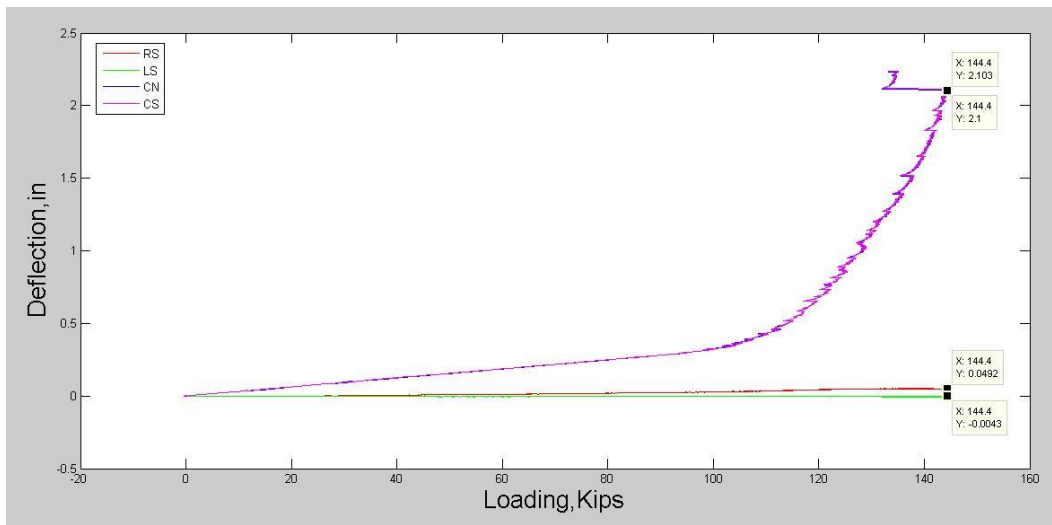


Figure 7-4 – Load Deflection plot GF1

Strain at Maximum Load

Table 7-4 -Strain at Maximum Load GF1

Loading	B1($\mu\epsilon$)	B2($\mu\epsilon$)	B3($\mu\epsilon$)	FB($\mu\epsilon$)	FT($\mu\epsilon$)	BB($\mu\epsilon$)	BT($\mu\epsilon$)
144380.9, (642238)	410.1452	6517.12	879.1586	-15.78	-609.495	62.9210	-356.353

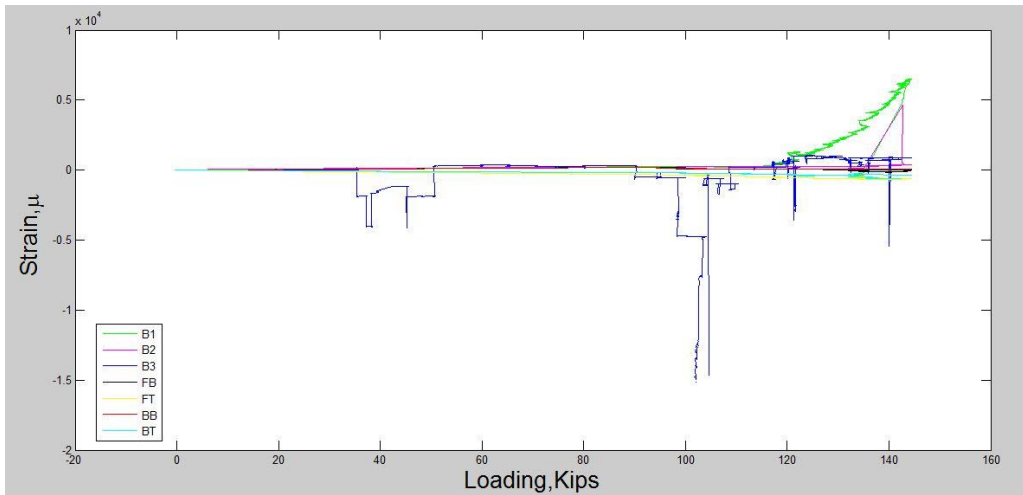


Figure 7-5 – Load versus Strain plot GF1

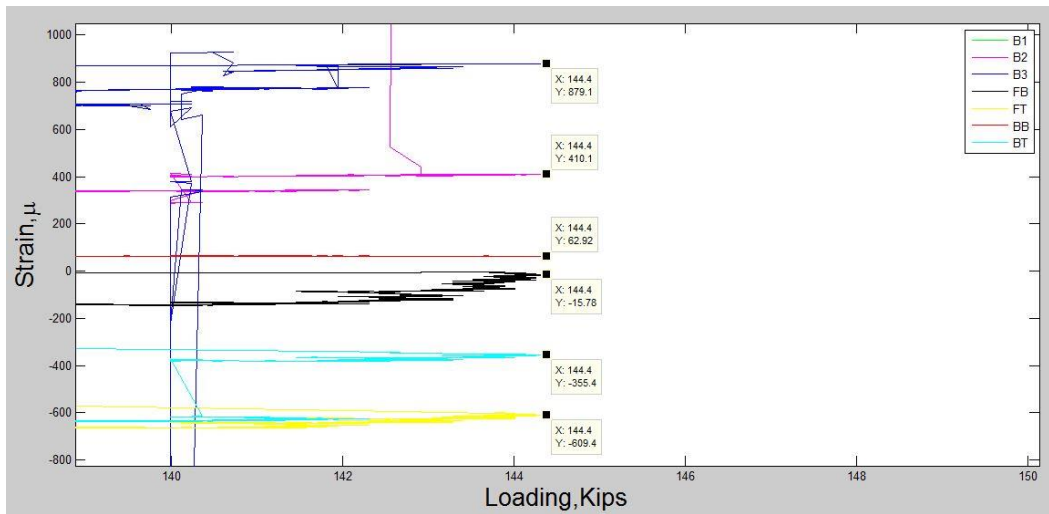


Figure 7-6– Enlarged Load versus Strain plot GF1

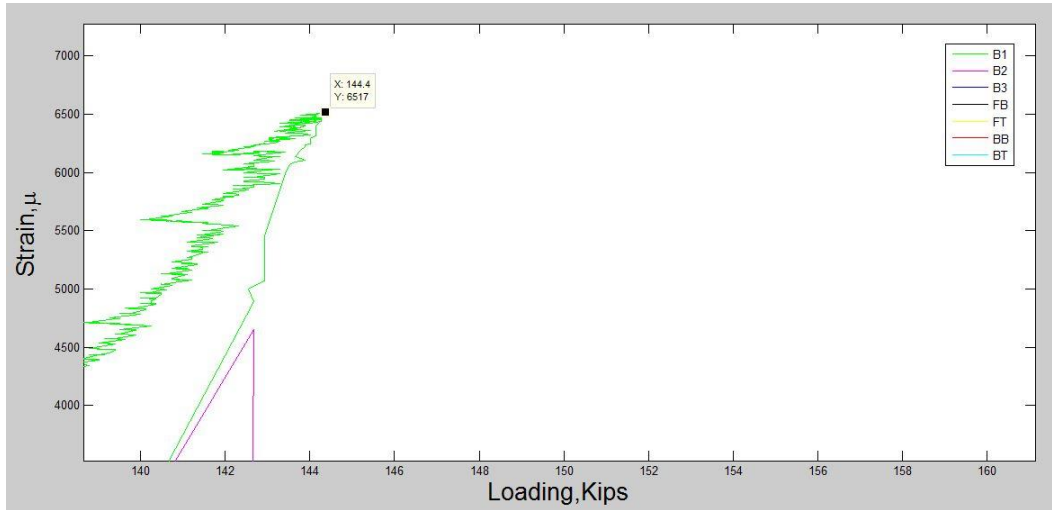


Figure 7-7–Enlarged Load versus Strain plot GF1

7.3 Girder, Flexure 2 layers GF2

GF2 had two FRP layers at the bottom and no flexure anchorage. One layer is 12 inch and the other layer is 11 inch at the midspan. The maximum load at the point FRP debonded is 142 Kips.

Deflection at maximum load:

Table 7-5 - Deflection at maximum load GF2

Loading	RS in (mm)	CS in (mm)	CN in (mm)	LS in (mm)
142433.1, (633573)	0.0508, (1.29)	1.6710(42.44)	1.6467, (41.82)	-0.0004, (0.01)

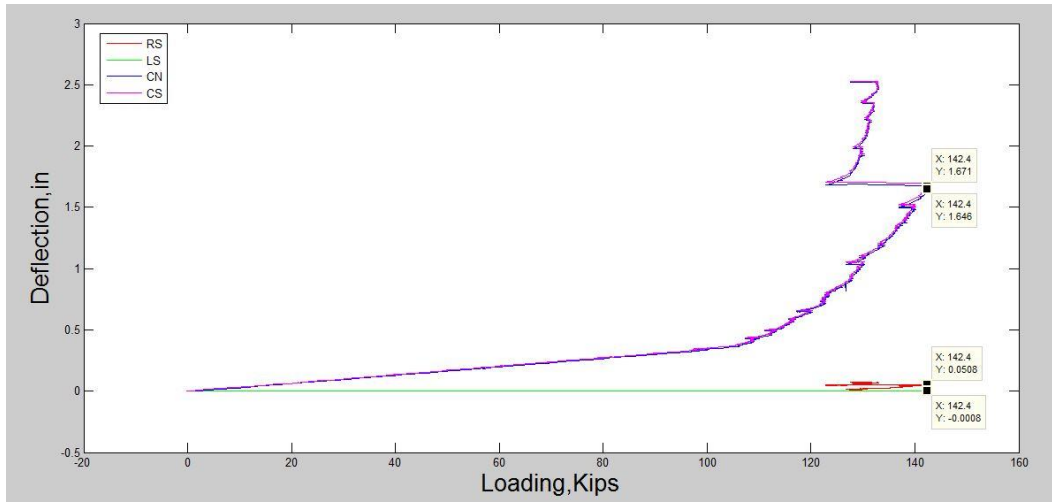


Figure 7-8—Load deflection plot GF2

Strain at Maximum Load

Table 7-6 -Strain at Maximum Load GF2

Loading, lb (N)	B1($\mu\epsilon$)	B2($\mu\epsilon$)	B3($\mu\epsilon$)	B4($\mu\epsilon$)	B5($\mu\epsilon$)
142433.1, (633573)	166	280.5125	5595.0649	348.0164	285.2345

Table 7-7 -Strain at Maximum Load GF2

Loading	FB($\mu\epsilon$)	FT($\mu\epsilon$)	BB($\mu\epsilon$)	BT($\mu\epsilon$)
142433.1	154.9213	- 438.3	61.1359	- 396.4

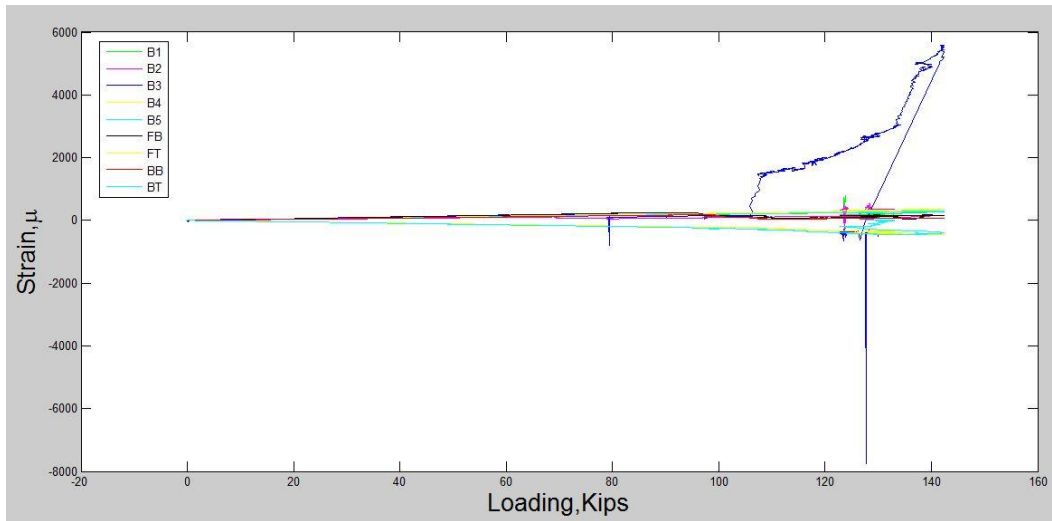


Figure 7-9 -Load versus Strain plot GF2

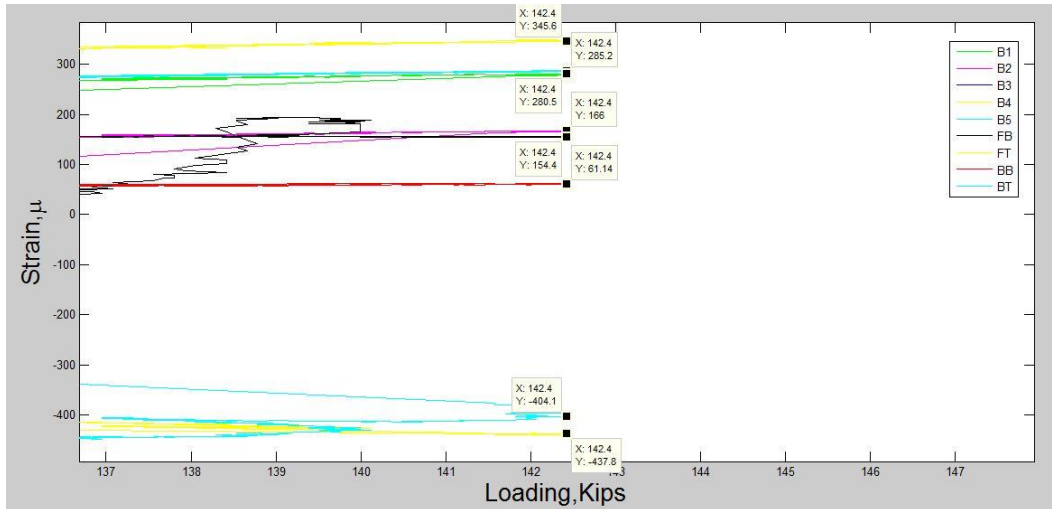


Figure 7-10 – Enlarged Load versus Strain plot GF2

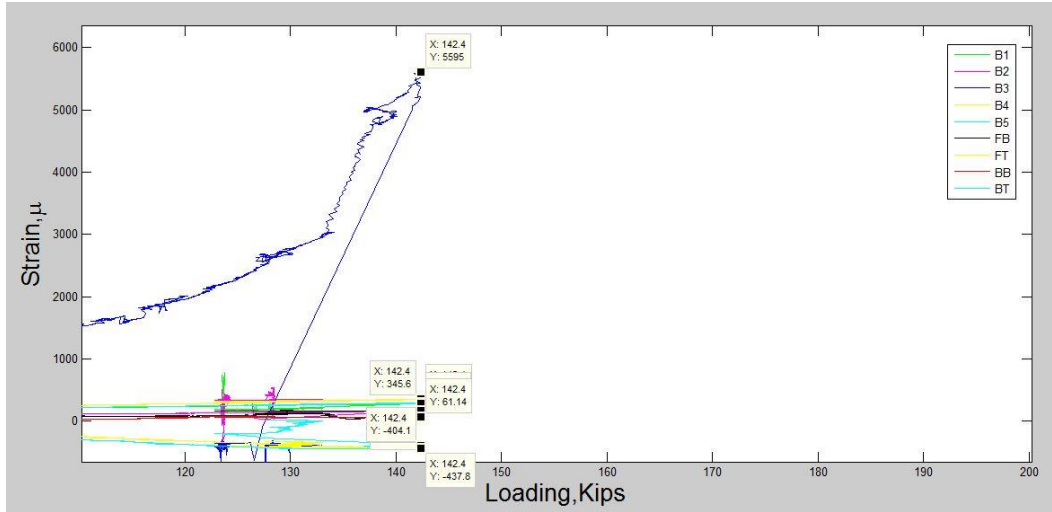


Figure 7-11–Enlarged Load versus Strain plot GF1

7.4 Girder, Shear 1 layer GS1

GS2 has four strips of U-wraps two on each end side by side. The capacity of loading hydraulic cylinder could not reach the capacity of the girder. Many cracks were observed during the test. The maximum load applied on the Shear strengthened girder is 380 Kips. The maximum capacity of the loading hydraulic cylinder is 400 Kips

Deflection at maximum load

Table 7-8 -Deflection at maximum load

Loading, lb (N)	RS in (mm)	MD in (mm)	PL in (mm)	LS in (mm)
380000, (1690324)	0.02, (0.67)	0.7488, (18.79)	0.52, (13.20)	0.05, (1.27)

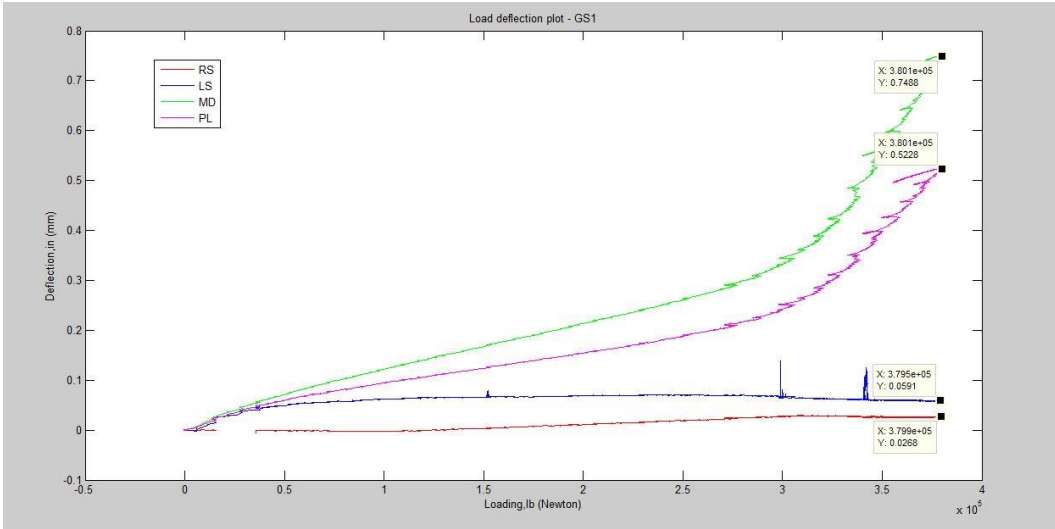


Figure 7-12 – Load deflection plot GS1

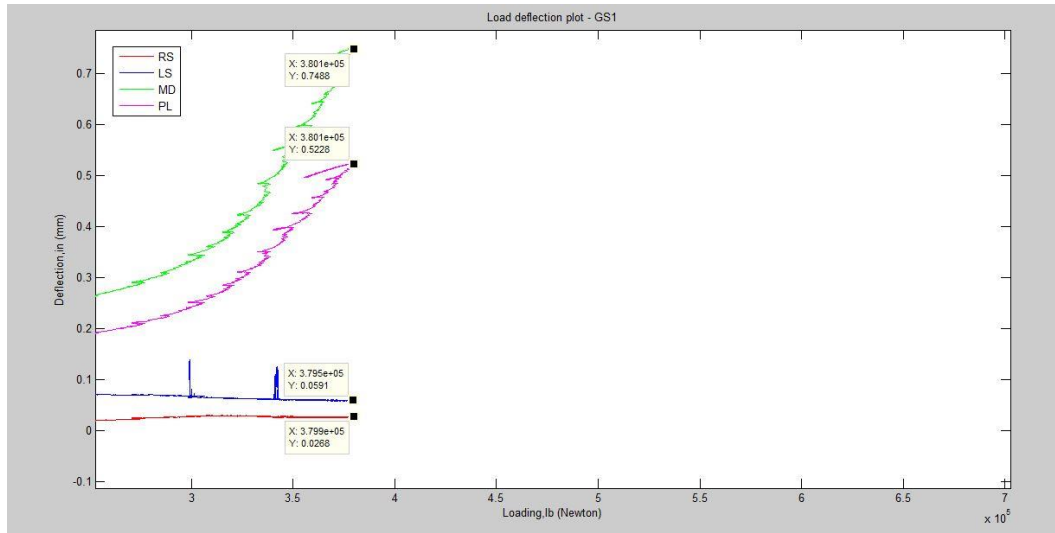


Figure 7-13–Enlarged Load deflection plot GS1

Strain at maximum loading

Table 7-9 -Strain at maximum load FB

Loading	FBH($\mu\epsilon$)	FBI($\mu\epsilon$)	FBV($\mu\epsilon$)	FBMP($\mu\epsilon$)	FBS($\mu\epsilon$)
380000	-2088	-53	59	450	3040

Table 7-10-Load versus Strain Plot GS1- FM

Loading	FMH($\mu\epsilon$)	FMI($\mu\epsilon$)	FMV($\mu\epsilon$)	FMMP($\mu\epsilon$)	FMS($\mu\epsilon$)
380000	36	11	40	65	55

Table 7-11 -Load versus Strain Plot GS1- FT

Loading	FTH($\mu\epsilon$)	FTI($\mu\epsilon$)	FTV($\mu\epsilon$)	FTMP($\mu\epsilon$)	FTS($\mu\epsilon$)
380000	-576	-137	245	244	822

Table 7-12 -Load versus Strain Plot GS1- BB

Loading	BBH($\mu\epsilon$)	BBI($\mu\epsilon$)	BBV($\mu\epsilon$)	BBMP($\mu\epsilon$)	BBS($\mu\epsilon$)
380000	-18	66	162	164	181

Table 7-13 - Load versus Strain Plot GS1- BT

Loading	BTH($\mu\epsilon$)	BTI($\mu\epsilon$)	BTV($\mu\epsilon$)	BTMP($\mu\epsilon$)	BTS($\mu\epsilon$)
380000	95	-118	-466	103	576

Chapter 8

Discussions

8.1 Introduction

Based on the experimental results analysis are done keeping in mind many parameters.

Each and every parameter like strength, deflections, strains, anchorage importance, and crack induced debonding are discussed in this section.

8.2 Analysis of Strength of Girders

The below graphs illustrates the comparison of strength of Control specimen with that of the FRP strengthened specimens.

8.2.1 Comparison of Strength of Control and GF1

Table 8-1- Load deflection comparison plot - % increase in strength

Girder	GC	GF1	%increase in Strength
Deflection in (mm)	2.102, (53.34)	2.102, (53.34)	
Loading lb (N)	133805 (595194)	144405, (642345)	7.92

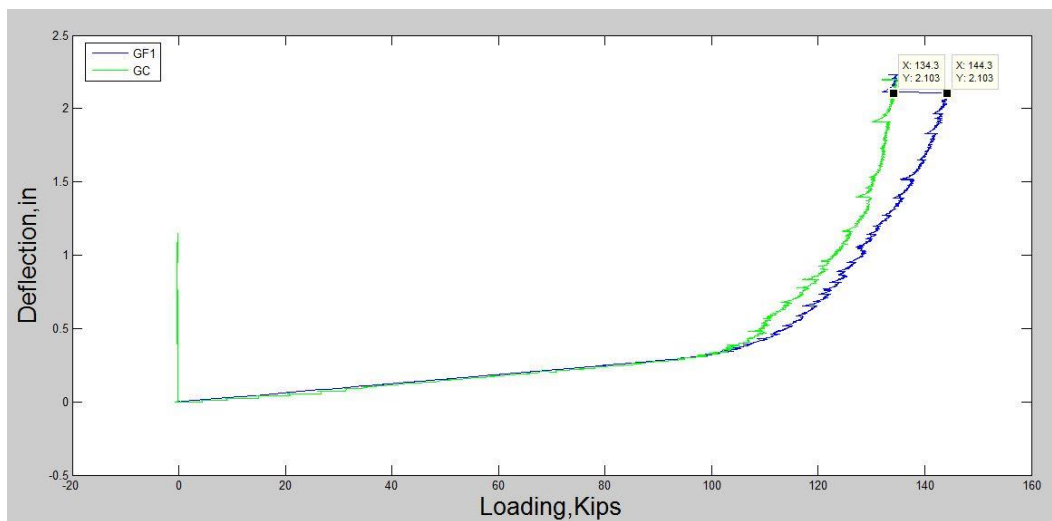


Figure 8-1 – Load deflection comparison plot - % increase in strength

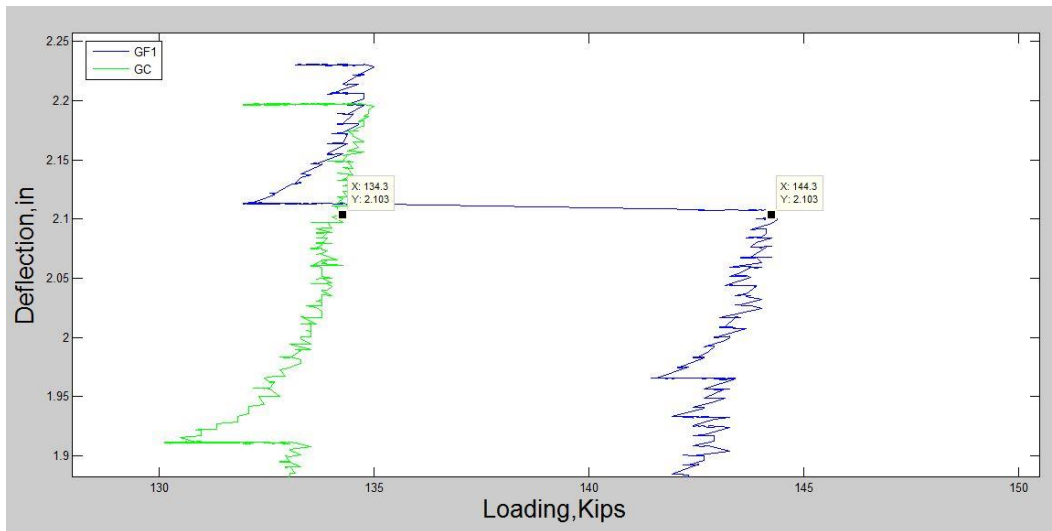


Figure 8-2 -Load deflection comparison plot - % increase in strength

Observing the strain results of the GF1, it is clear that the pre-stressing steel is not yielded. Since we were more concerned with the failure of the FRP, we did stop loading the girder as soon as we could see the debonding of FRP. Because once the FRP is debonded, it cannot resist or provide more strength to the girders for the loading applied. So the best way analysis would be the point at which the specimens faced same deflection. At the point when both the girders faced the same deflection is the point which is taken as the comparison of strength.

The above graph and table shows that the maximum deflection of GF1 is 2.102 and the corresponding loading is 144405 lb. when the deflection and strength of GF1 is compared with that of the GC, where GC read 2.102 in of deflection for 133805 lb. This shows there is been 7.92 % increase in the capacity. During the experiment the control girder reached the strain hardening state at around 125 kips after which only deflection is seen to rise up for very low increment of the load. So if we consider that point of strain hardening in GC we can see more increment in the strength from 125 Kips to 144 Kips.

8.1.2 Comparison of strength of control and GF2

Table 8-2 - Comparison of strength of control and GF2

Girder	GC	GF2	%increase of strength
Deflection, in (mm)	1.641, (41.65)	1.641, (41.65)	
Loading, lb (N)	131605, (585408)	142405(633449)	8.20

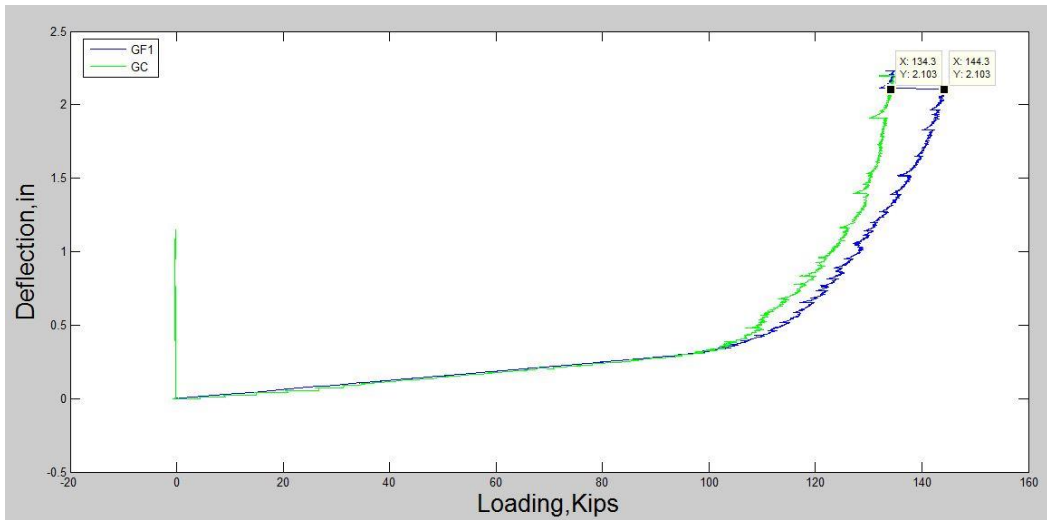


Figure 8-3- Comparison of strength of control and GF2

Considering the same criteria for comparison as we did previously for GC and GF1, here the strength is compared between GC and GF2.

The above graph and table shows that the maximum deflection of GF2 is 1.641 and the corresponding loading is 142405 lb. when the deflection and strength of GF2 is compared with that of the GC, where GC read 1.641 in of deflection for 131605 lb. This shows there is been 8.20% increase in the capacity.

When we compare the capacities of GF1 and GF2 it is very evident from the experimental results that the strength of both the girders is almost same and shows the same % increase in strength when compared with the control girders. GF1 shows 144405 Kips and GF2 shows 142405 Kips at FRP debonding. This behavior of GF1 taking more

capacity that the GF2 is because of the flexure anchorage. Flexure anchorage has a great influence on the strength of the FRP strengthened girders. Without the FRP flexural anchorage the girders are going to show debonding soon than that with the flexure anchorages.

8.2 Analysis of Deflections

The graph below illustrates the comparison of deflections between the control girder and the CFRP strengthened specimens. Since we were more concerned with the failure of FRP, once the FRP debonding occurred we noted the deflections at that point. The point after the FRP debonding showed a drastic drop in load with the same deflection. This show the girders are not taking any more loads with the increase in deflection. It is clear from the graph that the CFRP strengthened girders takes more load for less deflection which in turn means that the tensile strength of the CFRP in utilized to increase the capacity of the girders. The FRP application on the girders makes them more stiff and reduces the deflection,

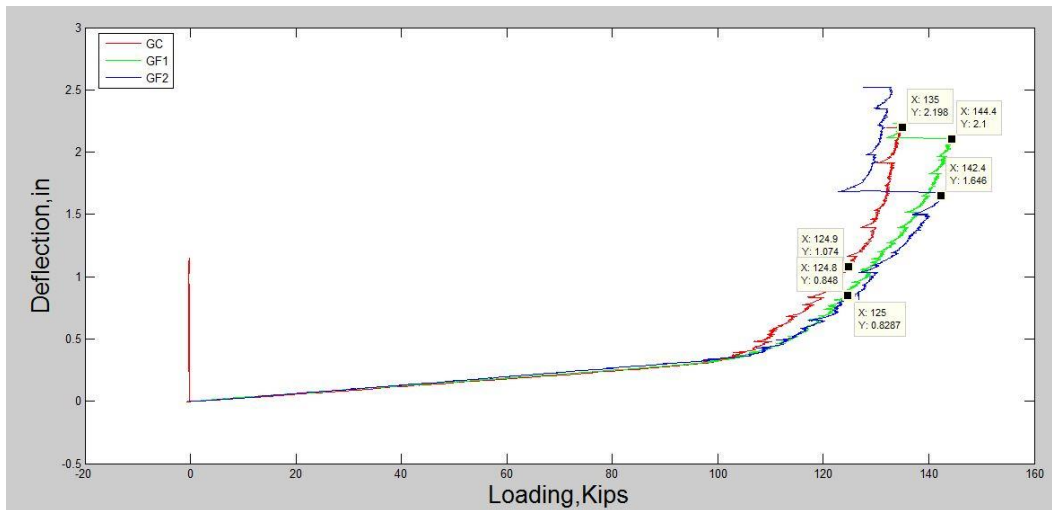


Figure 8-4 – Load deflection comparison plot

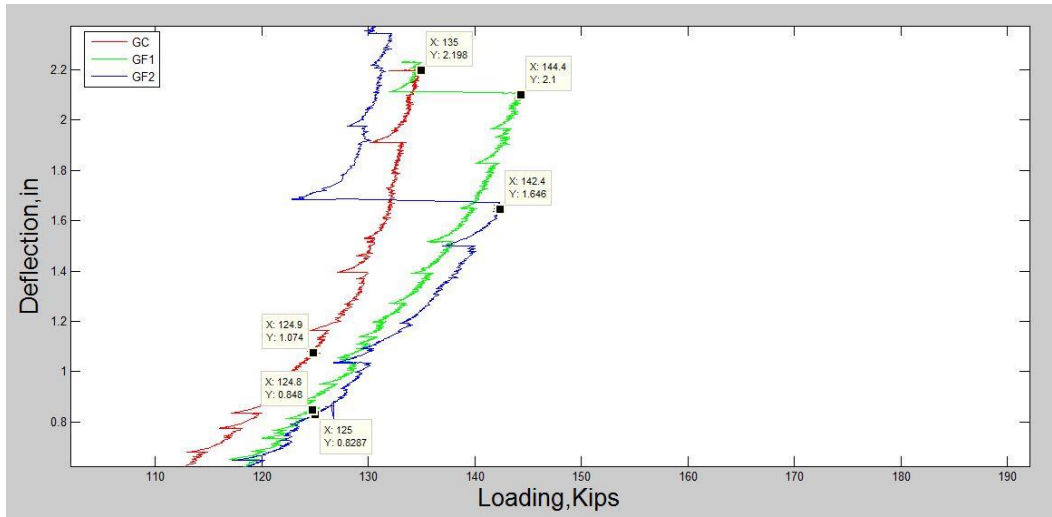


Figure 8-5– Magnified Load deflection comparison plot

8.3 Importance of Anchorage

The transverse U-wraps cover the width of the FRP and extend all along the width of the girder. These are the flexure anchorages to prevent the premature debonding of FRP before its full tensile strength is utilized. In this research GF1 is tested with the anchorages but GF2 is without the anchorages. It is clear from the experimental results and the below graphs illustrates the same, that even though GF2 had two CFRP flexure layers since it was not provided with the flexure anchorage, it shows very low deflection and CFRP debonded at around 1.6 in. Whereas on the other hand the GF1 With just one layer of FRP and Flexure anchorages shows that the girder can take more deflection before the debonding and it slows down the FRP debonding. This makes the girder stiffer. At 1.6 in the GF2 shows more strength when compared to GF1. In case GF2 is also provided with the flexure anchorages, it shows more deflection than the GF1 did in this case. So providing the flexure anchorages is very necessary to utilize the FRP strength and unexpected debonding.

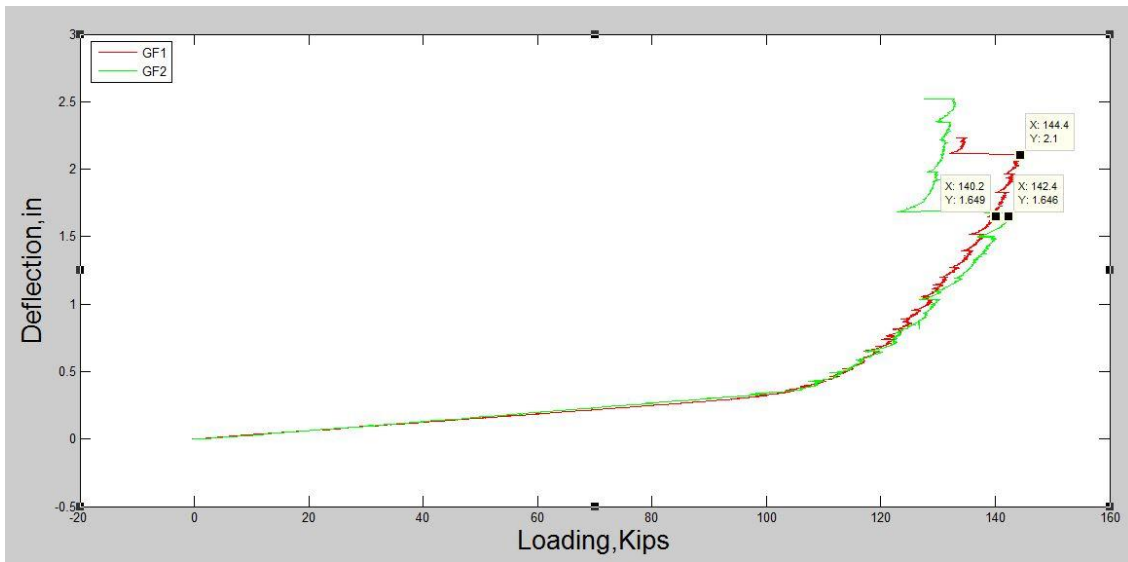


Figure 8-6 -Load deflection comparison plot for anchorage importance

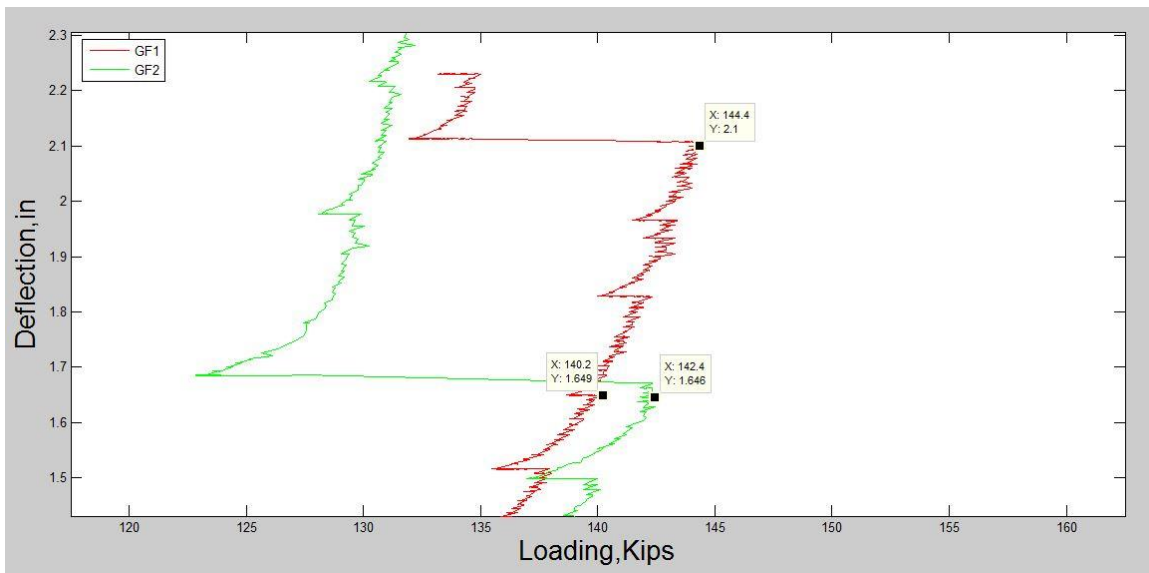


Figure 8-7– Magnified Load deflection comparison plot for anchorage importance

8.4 Analysis of Strains of the experimental results

Comparison of strain is the most critical part in the FRP strengthening. ACI 440 has a standard procedure for Flexure strengthening of FRP laminates. Refer Appendix A. Following the standard procedure we come across with strain due to debonding and strain due to rupture.

The strain due to debonding is calculated from the following expression:

$$\varepsilon_{fd} = 0.083 \frac{\sqrt{f'c}}{\sqrt{ntfE_f}} \leq 0.9 \varepsilon_{fu}$$

The rupture strain is given by the following equation:

$$\varepsilon_{fu} = CE * \varepsilon_{fu}''$$

The effective strain is expressed by:

$$\varepsilon_{fe} = \varepsilon_{cu} \frac{(df - c)}{c} - \varepsilon_{bi} \leq \varepsilon_{fd}$$

From the design of FRP strengthened Girders (Appendix A) the rupture strain is 0.01 and debonding strain is 0.01741. So the effective strain is the least one that is the rupture strain that controls.

Comparing both, the strain due to rupture and strain due to debonding, it is clear that the strain due to rupture controls and the failure should be due to the rupture of FRP.

Here is the right point where we need to discuss the different failure modes described by ACI 440. There are five failure modes as described by ACI 440

- Crushing of compression in concrete before the yielding of the steel
- Yielding of steel in tension before the rupture of FRP laminate
- Yielding of steel in tension before the concrete crushing
- Shear or tension de-lamination of concrete cover
- Debonding of FRP from the concrete surface.

Concrete crushing is seen when its compressive strain reaches its maximum usable strain of 0.003. Rupture of externally bonded FRP is seen when the strain the FRP reaches its design rupture strain before concrete reaches its maximum usable strain of 0.003. FRP debonding is seen when the force of the FRP cannot be sustained by the substrate bonding. The main reason beyond this FRP debonding is the cracks that are seen after the maximum usable strain of concrete. Once the flexure starts to show up, there induced the downward pulling that pulls the FRP against the substrate bonding

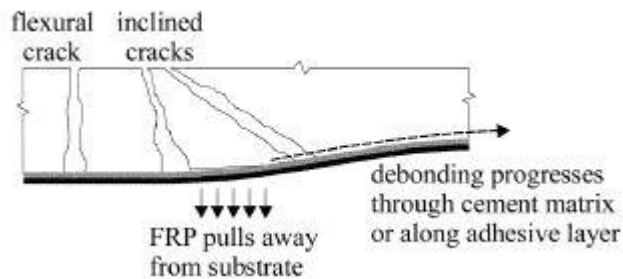


Figure 8-8 – Crack induced debonding

The solution to prevent this debonding is also given in this report as Flexure anchorage. Debonding is usually seen on the layer of FRP where the layer ends or terminates. ACI 440 suggests limiting the effective level of FRP reinforcement, to the debonding strain. From all the previous and this research it is proved that the FRP debonding is the only criteria that act major FRP failure. This shows the strain level that is obtained from the equations following the ACI 440 is very high and need to more research on that to verify the equations of Debonding strain, Rupture strain and Effective strain level. All the strain values at different locations of the girders and the FRP surface are listed in Chapter 7.

8.5 Comparison of GS1 FRP strengthened with the un-strengthened

Following the ACI 440 Design standards the shear capacity of the girder which is strengthened is increased by 33.4 Kips. Refer Appendix B

Chapter 9

Conclusions

9.1 Research Conclusions

Based on all the test results and analysis of this research work the following conclusions are made:

- There is appreciable increase in strength of FRP strengthened specimens from the controlled specimens.
- The GF1 specimen shows 7.92% increase in strength when compared to the GC
- The GF2 specimen shows 8.2% increase in strength when compared to the GC
- The flexure anchorage slows down the debonding of FRP.
- The FRP strengthened specimens are more stiff when compared with the control
- GF2 is more stiff when compared to GF1
- The bonding between the concrete and FRP showed good agreement, proved by pull off test.
- FRP debonding was the failure criteria for the FRP strengthened specimens.
- Full strength of the Fibers cannot be utilized.
- The test results show good agreement with the hand calculations.

9.2 Recommendations and Future Work

- From the conclusions we can see that the failure is FRP debonding and full strength of the FRP cannot be utilized. Further research can be done on many other types of epoxy and the bonding behavior of the FRP and Concrete surface to utilize the full strength of the fibers.
- The research can be done to provide proof and verify the expressions debonding and rupture strain as the level of these value obtained from the ACI 440 seems very high.

Appendix A

Flexural Strengthening of Pre-stressed concrete Tx-28 Girder with CFRP sheet

Information about the Girder

Note: these calculations are done without considering any reduction factors

Material properties specifications

$E_c = 4768962$ Psi	Modulus of elasticity of concrete, Psi (Mpa)
$E_p = 28500000$ Psi	Modulus of elasticity of prestressing steel, Psi (Mpa)
$E_f = 8.2E+06$ Psi	Tensile modulus of elasticity of FRP, Psi, (Mpa)
$f'_c = 7$ Psi	Specified compressive strength of concrete, Psi (Mpa)
$f_y = 60000$ Psi	Yield strength of existing steel reinforcement, Psi (Mpa)

Section Properties:

$h = 28$ in	Height of the girder, in (mm)
$b_w = 7$ in	Web width, in (mm)
$h_f = 3.5$ in	Flange height, in (mm)
Area = 585 in ²	Cross sectional area of the girder, in ² (mm ²)
$I_x = 52772$ in ⁴	Moment of inertia along X axis, in ⁴ (mm ⁴)
$I_y = 40559$ in ⁴	Moment of inertia along Y axis, in ⁴ (mm ⁴)
$S_t = 3513.44$ in ³	Section modulus, in ³ (mm ³)
$S_b = 4065.63$ in ³	Section modulus, in ³ , (mm ³)
$Y_b = 12.98$ in fiber, in (mm)	Distance from the centroidal axis of section to extreme bottom fiber, in (mm)
$Y_t = 15.02$ in fiber, in (mm)	Distance from the centroidal axis of section to extreme top fiber, in (mm)
$e = 10.48$ in	Eccentricity of pre-stressing strands with respect to the centroidal axis of the member in support, in (mm)
$d_p = 25.5$ in	Distance from extreme compression fiber to the centroid of pre-stressing reinforcement, in (mm)

Strand Properties:

$E_p = 28500$ Ksi	Modulus of elasticity of prestressing steel, Psi (Mpa)
$e = 10.48$ in	Eccentricity of pre-stressing strands with respect to the centroidal axis of the member in support, in (mm)
$f_{pu} = 270$ Ksi	Specified tensile strength of the pre-stressing tendons, Psi, (Mpa)
$f_{py} = 243$ Ksi	Yield strength of Prestressing steel, Psi (Mpa)
$f_{pe} = 167.72$ Ksi	Effective stress in prestressing steel. Psi (Mpa)
$A_{ps} = 1.836$ in ²	Area of prestressing steel, in ² (mm ²)
$\epsilon_{pe} = 5.855E-03$	Effective strain in prestressing steel, in/in (mm/mm)
FRP Properties:	
$E_f = 8.2E+06$ Psi	Tensile modulus of elasticity of FRP, Psi, (Mpa)
$f^*_{fu} = 1.05E+05$ Psi	Ultimate tensile strength of FRP material as reported by the manufacturer, Psi (Mpa)
$\epsilon^*_{fu} = 0.01$	Ultimate rupture strain of FRP reinforcement, in/in (mm/mm)
$t_f = 0.02$ in	Thickness of FRP, in (mm)
$w_f = 24$ in	Width of FRP, in (mm)
$n = 1$ layer	Number of FRP layers.

Procedure: [For 1 layer FRP]

Step1:

FRP Material design material properties :

$$f_{fu} = 1.05E+05$$

$$\epsilon_{fu} = 0.01$$

Step 2:

Preliminary calculations

$$\beta_1 = 0.7$$

$$A_f = 0.48 \text{ in}^2$$

$$r = 9.49 \text{ in}$$

Step 3

Strain at the bottom of the girder before the application of FRP

$$\epsilon_{bi} = 0.000247$$

Step 4

Design strain of FRP

$$\epsilon_{fd} \leq 0.9 * \epsilon_{fu}$$

$$\epsilon_{fd} = 0.017148$$

$$0.9 * \epsilon_{fu} = 0.009$$

$$\text{Therefore } \epsilon_{fd} = 0.9 * \epsilon_{fu} = 0.009$$

Comment [Since the second expression from the ($\epsilon_{fd} \leq 0.9 * \epsilon_{fu}$) governs, it states that the FRP Rupture governs over the FRP debonding]

Step 5

Estimate the depth of neutral axis C

$$\text{Assume the initial } C = 0.1h = 2.8 \text{ in (mm)}$$

Step 6

Effective level of strain in the FRP

$$\epsilon_{fe} \leq 0.9 * \epsilon_{fu}$$

$$\epsilon_{fe} = 0.026753$$

$$0.9 * \epsilon_{fu} = 0.009$$

$$\text{Therefore } \epsilon_{fe} = 0.9 * \epsilon_{fu} = 0.009$$

Comment [So the effective strain will be 0.009]

Step 7

The strain in the existing prestressing steel

$$\epsilon_{pnet} = 0.00923$$

$$\epsilon_s = 1.536E-02$$

Step 8

The force in the existing prestressing steel

$$f_{ps} = 2.652E+02$$

$$f_{fe} = 8.2E+01$$

Step 9

Equivalent concrete stress block

$$\epsilon_c = 1.14E-03$$

$$\epsilon_c' = 0.002495$$

$$\beta_1 = 0.6970$$

$$\alpha_1 = 0.5526$$

Step 10

Compute C

$$C = 5.4248$$

Step 11

Adjust C for equilibrium

The adjusted C for equilibrium is 3.928

Therefore the Equivalent concrete stress block for Equilibrium C is

$$\epsilon_c = 0.001672$$

$$\epsilon_c' = 0.002495$$

$$\beta_1 = 0.714608$$

$$\alpha_1 = 0.743514$$

Step 12

Calculate the flexural strength components

$$M_n = 977.68 \text{ Kft} - M_d$$

$$M_d = 74.6 \text{ Kft}$$

Therefore $M_n = 903.08 \text{ Kft}$

FRP contribution to bending

$M_{nf} = 87.23 \text{ Kft}$

Design Flexural strength of Girder:

$M_n = 990.31 \text{ Kft.}$

Following the same procedure from ACI 440 for 2 layers of FRP Flexural strengthening

$M_{nf} = 174.05 \text{ Kft}$

Contribution of FRP to flexural strength

$M_n = 1074.563 \text{ Kft}$

Flexural strength of FRP strengthened Member

Appendix B

Shear Strengthening of Pre-stressed concrete T_x-28 Girder with CFRP sheets

Material properties specifications

$E_c = 4768962$ Psi	Modulus of elasticity of concrete, Psi (Mpa)
$E_p = 28500000$ Psi	Modulus of elasticity of prestressing steel, Psi (Mpa)
$E_f = 8.2E+06$ Psi	Tensile modulus of elasticity of FRP, Psi, (Mpa)
$f'_c = 7$ Psi	Specified compressive strength of concrete, Psi (Mpa)
$f_y = 60000$ Psi	Yield strength of existing steel reinforcement, Psi (Mpa)

Section Properties

$h = 28$ in	Height of the girder, in (mm)
$b_w = 7$ in	Web width, in (mm)
$h_f = 3.5$ in	Flange height, in (mm)
$Area = 585$ in ²	Cross sectional area of the girder, in ² (mm ²)
$I_x = 52772$ in ⁴	Moment of inertia along X axis, in ⁴ (mm ⁴)
$I_y = 40559$ in ⁴	Moment of inertia along Y axis, in ⁴ (mm ⁴)
$S_t = 3513.44$ in ³	Section modulus, in ³ (mm ³)
$S_b = 4065.63$ in ³	Section modulus, in ³ (mm ³)
$y_b = 12.98$ in	Distance from the centroidal axis of section to extreme bottom fiber, in (mm)
$y_t = 15.02$ in	Distance from the centroidal axis of section to extreme top fiber, in (mm)
$e = 10.48$ in	Eccentricity of pre-stressing strands with respect to the centroidal axis of the member in support, in (mm)
$d_p = 25.5$ in	Distance from extreme compression fiber to the centroid of pre-stressing reinforcement, in (mm)

Strand Properties

$E_p = 28500$ Ksi	Modulus of elasticity of prestressing steel, Psi (Mpa)
-------------------	--

$e = 10.48$ in	Eccentricity of pre-stressing strands with respect to the centroidal axis of the member in support, in (mm)
$f_{pu} = 270$ Ksi	Specified tensile strength of the pre-stressing tendons, Psi, (Mpa)
$f_{py} = 243$ Ksi	Yield strength of Prestressing steel, Psi (Mpa)
$f_{pe} = 167.72$ Ksi	Effective stress in prestressing steel. Psi (Mpa)
$A_{ps} = 1.836$ in ²	Area of prestressing steel, in ² (mm ²)
$\epsilon_{pe} = 5.855E-03$	Effective strain in prestressing steel, in/in (mm/mm)

FRP Properties

$E_f = 8.2E+06$ Psi	Tensile modulus of elasticity of FRP, Psi, (Mpa)
$f^*_{fu} = 1.05E+05$ Psi	Ultimate tensile strength of FRP material as reported by the manufacturer, Psi (Mpa)
$\epsilon^*_{fu} = 0.01$	Ultimate rupture strain of FRP reinforcement, in/in (mm/mm)
$t_f = 0.02$ in	Thickness of FRP, in (mm)
$w_f = 24$ in	Width of FRP, in (mm)
$n = 1$ layer	Number of FRP layers.

Procedure

Step 1:

Compute the design material properties

$$f_{fu} = 1.05+05$$

$$\epsilon_{fu} = 0.01$$

Step 2

Calculate the effective strain level in the FRP reinforcement

$$L_e = 2.36 \text{ in} \quad \text{Active bond length of FRP laminate}$$

$K_1 = 1.45$ Modification factor applied for concrete
 $K_2 = 0.90$ Modification factor applied for FRP scheme
 $K_v = 0.6651$
 $\epsilon_{fe} = K_v * \epsilon_{fu} \leq 0.004$
 $\epsilon_{fe} = 0.0066511 > 0.004$
 $\epsilon_{fe} = 0.004$

Step 3

Calculate the contribution of FRP reinforcement to the shear strength

$A_{fv} = 0.96$ Area of FRP Shear reinforcement with spacing S
 $f_{fe} = 32.8$ Effective stress in FRP
 $V_f = 33.4$ Shear contribution from FRP
 $V_c = 148$ Kips Shear contribution from Concrete
 $V_s = 183$ Kips Shear contribution from Steel
 $V_n = 291$ Kips Shear Strength of the girder
 $V_n = 324.4$ Kips Shear strength of the FRP strengthened girder

References

- Agapay, A., & Robertson, I. N. (2004). Test of Prestressed Concrete T-Beams Retrofitted for Shear and Flexure using Carbon Fiber Reinforced Polymers. *Report*, (August).
- America, C. (2001). MoDOT Research , Development and Technology Repair and Strengthening of Impacted PC Girders on Bridge A4845 Jackson County , Missouri.
- Astm, A., Low, S. U., & Strand, R. (n.d.). S PECIFICATIONS FOR, 95205.
- Atadero, R. a., & Karbhari, V. M. (2006). Development of Load and Resistance Factor Design for FRP Strengthening of Reinforced Concrete Structures, (59).
- Bank, L. C. (2006). *Composites for Construction*. <http://doi.org/10.1002/9780470121429>
- Barros, J. a O., Dias, S. J. E., & Lima, J. L. T. (2008). Analytical and numerical analysis of the behaviour of RC beams flexural strengthened with CFRP, 22–24.
- Bending Behavior of Concrete Beams. (1998), 6(January), 3–10.
- Bozdana, T. (n.d.). ME 215 – Engineering Materials I, (Part I).
- Brayack, D. A., Virginia, W., Case, T. B., & Davalos, A. J. F. (2006). Technical and Economic Effectiveness for Repair with FRP of Concrete T-Beam Bridges : Case Study for.
- By, D., Pti, T. H. E., Committee, E., Author, L., & Hamilton, T. (n.d.). SECTION 3 DESIGN OF POST- TENSIONED COMPONENTS FOR FLEXURE CONVENTION.
- Cerullo, D. (2006). Digital Commons @ Ryerson Strengthening full-scale damaged prestressed concrete bridge girders with CFRP sheets.

- Cerullo, D., Sennah, K., & Azimi, H. (2013). Experimental Study on Full-Scale Pretensioned Bridge Girder Damaged by Vehicle Impact and Repaired with Fiber-Reinforced Polymer Technology. ... *of Composites for ...*, 6(October), 662–672. [http://doi.org/10.1061/\(ASCE\)CC.1943-5614.0000383](http://doi.org/10.1061/(ASCE)CC.1943-5614.0000383).
- Chen, J. (2004). Shear using CFRP L-Shaped Plates COLLEGE OF ENGINEERING, (June).
- CIVL 1112 Strength of Reinforced Concrete Beams CIVL 1112 Strength of Reinforced Concrete Beams. (n.d.), 1–11.
- Committee, a C. I. (n.d.). *Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures*.
- Concrete, P., & Rosenboom, O. A. (n.d.). ABSTRACT ROSENBOOM , OWEN ARTHUR . Behavior of FRP Repair / Strengthening Rizkalla .) BEHAVIOR OF FRP REPAIR / STRENGTHENING SYSTEMS FOR PRESTRESSED CONCRETE By.
- Contacts, M. E., Number, P., Hazards, E., & Hazards, S. (2002). SikaWrap Hex 117C SikaWrap Hex 117C.
- Czaderski, C., & Motavalli, M. (2007). 40-Year-old full-scale concrete bridge girder strengthened with prestressed CFRP plates anchored using gradient method. *Composites Part B: Engineering*, 38(7-8), 878–886. <http://doi.org/10.1016/j.compositesb.2006.11.003>
- Delaney, J. C., & Karbhari, V. M. (2006). THE ASSESSMENT OF ASPECTS RELATED TO DEFECT CRITICALITY IN CFRP STRENGTHENED CONCRETE FLEXURAL MEMBERS by, (59).

Design Step 5 – Design of Superstructure Design Step SHEAR DESIGN Prestressed Concrete Bridge Design Example Shear design in the AASHTO-LRFD Specifications is based on the modified compression Figure S5 . 8 . 3 . 4 . 2-1 - Illustration of Shear Parameters. (n.d.), 7, 82–110.

Di Ludovico, M., Prota, a., Manfredi, G., & Cosenza, E. (2010). FRP Strengthening of Full-Scale PC Girders. *Journal of Composites for Construction*, 14(5), 510–520. [http://doi.org/10.1061/\(ASCE\)CC.1943-5614.0000112](http://doi.org/10.1061/(ASCE)CC.1943-5614.0000112)

Documents, R., Included, W., Work, R., Repair, C., Injection, E., & Standards, R. (n.d.). Strengthening of Concrete with FRP (Fiber Reinforced Polymer) Reinforcement, 72(03742).

Education, P. (n.d.). *Types of Strain Tensile-Test. Education.*

Evaluation of FRP Repair Method for Cracked Bridge Members. (2005).

Fathelbab, F. a., Ramadan, M. S., & Al-Tantawy, a. (2011). Finite Element Modeling of Strengthened Simple Beams Using Frp Techniques," a Parametric Study. *Concrete Research Letters*, 2(June), 228–240. Retrieved from http://www.iifc-hq.org/proceedings/CICE_2012/01_FRP Strengthening of Concrete Structures, Historic Structures, Masonry Structures, Timber Structur/01_505_Ali, Shawky, Al Sayed_FINITE ELEMENT MODELING OF STRENGTHEN.pdf

FDOT_BC354_55_v1.pdf. (n.d.).

Fe, S. (2008). Innovation in Transportation Strengthening Reinforced Concrete Bridges in New Mexico Using Fiber Reinforced Polymers : Report, (March).

- Godat, A., Neale, K. W., & Labossière, P. (2007). Numerical Modeling of FRP Shear-Strengthened Reinforced Concrete Beams. *Journal of Composites for Construction*, 11(6), 640–649. [http://doi.org/10.1061/\(ASCE\)1090-0268\(2007\)11:6\(640\)](http://doi.org/10.1061/(ASCE)1090-0268(2007)11:6(640))
- Grace, N. F., & Singh, S. B. (2003). Design Approach for Carbon Fiber-Reinforced Polymer Prestressed Concrete Bridge Beams, (100), 365–376.
- Harries, K. a, Ph, D., Eng, P., & Aktas, C. J. (2009). Repair Method for Prestressed Girder Bridges. *Techniques*, (June).
- Higgins, C., Williams, G., & Elkins, L. (2006). Capabilities of Diagonally-Cracked Girders Repaired with CFRP. *Report*. Retrieved from <http://ntis.library.gatech.edu/handle/123456789/2925>
- Hii, A. K. Y. (2005). Torsional strengthening of reinforced concrete beams using CFRP composites.
- Holloway, L. C., & Leeming, M. B. (n.d.). Strengthening of reinforced concrete structures.
- Huang, P. C., Tumialan, G., Faults, S., Forde, M. C., & Press, E. T. (2001). Nanni, A., P.C. Huang and G. Tumialan, “Strengthening of Impact-Damaged Bridge Girder Using FRP Laminates,” 9.
- Hutchinson, R. L., Donald, D. R., & Rizkalla, S. H. (n.d.). Frp for shear strengthening of aashto bridge girders.
- Instruments, N. (1998). National Instruments, Application Note 078, Strain Gauge Measurement – A Tutorial, (August), 1–12.

- Interferometric, H. (2000). Strain Measurement Full Field Measurements • Useful to see macroscopic effects before looking into details, *3145*(Spring), 1–17.
- Jeremy, B., Chad, M. G., Daniel, R. B., & Dolan, C. W. (1998). DEVELOPMENT OF FRP REINFORCEMENT GUIDELINES, (15087), 131–139.
- Joseph, B., Yost, R., Goodspeed, C. H., & Schmeckpeper, E. R. (2001). Flexural Performance of Concrete With FRP Girders, (February), 18–25.
- Kansara, K., Ibell, T., Darby, A., & Evernden, M. (2010). Interpreting conservativeness in design criteria for flexural strengthening of concrete structures, *4*(1), 25–36.
<http://doi.org/10.4334/IJCSM.2010.4.1.025>
- Karabinis, A. I., Rousakis, T. C., & Manolitsi, G. E. (2008). 3D Finite-Element Analysis of Substandard RC Columns Strengthened by Fiber-Reinforced Polymer Sheets. *Journal of Composites for Construction*, *12*(5), 531–540.
[http://doi.org/10.1061/\(ASCE\)1090-0268\(2008\)12:5\(531\)](http://doi.org/10.1061/(ASCE)1090-0268(2008)12:5(531))
- Karbhari, V. M. (n.d.). Structural Response of Near Surface Mounted CFRP Strengthened Reinforced, (November 2008).
- Karbhari, V. M. (2006). Assessment of FRP Composite Strengthened Reinforced Concrete Structures At the Component and Systems Level Non-Destructive Evaluation, (59).
- Kasan, J., & Harries, K. (2009). Repair of Impact-Damaged Prestressed Concrete Bridge Girders With Carbon Fiber Reinforced Polymers. *iifc-Hq.Org*, (December 2005), 157–162. Retrieved from http://www.iifc-hq.org/proceedings/APFIS_2009/PAPER/T2A4.pdf

Kasan, J. L. (2009). No Title.

Kasan, J. L., Harries, K. a., Miller, R., & Brinkman, R. J. (2013). Repair of Prestressed Concrete Girders Combining Internal Strand Splicing and Externally-Bonded CFRP Techniques. *Journal of Bridge Engineering*, 130131233718002. [http://doi.org/10.1061/\(ASCE\)BE.1943-5592.0000475](http://doi.org/10.1061/(ASCE)BE.1943-5592.0000475)

Kim, Y. J., Green, M. F., & Fallis, G. J. (2008). Repair of Bridge Girder Damaged by Impact Loads with Prestressed CFRP Sheets. *Journal of Bridge Engineering*, 13(1), 15–23. [http://doi.org/10.1061/\(ASCE\)1084-0702\(2008\)13:1\(15\)](http://doi.org/10.1061/(ASCE)1084-0702(2008)13:1(15))

Klaiber, F. W., Wipf, T. J., Kempers, B. J., & Way, L. (n.d.). Repair of Damaged Prestressed Concrete Bridges Using CFRP, (August 2003).

Lammert, K. A. N. N. (2003). STRUCTURAL EVALUATION OF IMPACT DAMAGED PRESTRESSED.

Lee, L. S., M., V. K., & Charles, S. (2004). INVESTIGATION OF INTEGRITY AND EFFECTIVENESS OF RC BRIDGE DECK REHABILITATION WITH CFRP by Investigation of Integrity and Effectiveness of RC Bridge Deck Rehabilitated with CFRP Composites, (59), 1–319.

Lin, L. (2010). College of Engineering, (September).

Ludovico, M. Di. (n.d.). Center for Infrastructure Engineering Studies Experimental Behavior of Prestressed Concrete Beams Strengthened.

Measurement, L. D., Variable, L., Transformers, D., & Measurement, L. (2006). Measuring Position and Displacement with LVDTs, 3–6.

- Miller, A. D. (2006). Repair of Impact-Damaged Prestressed Concrete Bridge Girders Using Carbon Fiber Reinforced Polymer (CFRP) Materials. *Thesis Master*, 155. Retrieved from <http://www.lib.ncsu.edu/resolver/1840.16/752>
- Mohanamurthy, M., & Yazdani, N. (2015). Flexural Strength Prediction in FRP Strengthened Concrete Bridge Girders, 2(3), 59–68.
- Moral, T. H. E., & Worth, M. (1911). University of Missouri., (December 1999), 352–353.
- Murphy, M., Belarbi, A., & Bae, S. (2012). Michael Murphy, Abdeldjelil Belarbi, and Sang-Wook Bae.
- Murphy, M. S., & Belarbi, A. (2010). Shear Design Equations for Concrete Girders Strengthened with FRP.
- Narmashiri, K., & Jumaat, M. Z. (2010). Numerical study on strengthening composite bridges. *Challenges, Opportunities and Solutions in Structural Engineering and Construction*, 241–246. <http://doi.org/10.1201/9780203859926.ch37>
- Neale, K. W., Godat, A., & Abdel, H. M. (n.d.). Approaches for Finite Element Simulations of Frp-Strengthened Concrete Beams and Slabs, 59–72.
- No, R., For, P., & Submitted, D. (2010). REPAIR OF CONCRETE GIRDER ENDS AND GIRDER COLLISION Prepared For :, (January).
- Of, E., & Stallings, E. B. J. M. (2000). OF, (May), 107–113.
- Ormulas, B. D. F., Shear, W., & Grams, D. I. a. (2005). With Shear and Moment. *Design*.

- Pellegrino, C., Tinazzi, D., & Modena, C. (2008). Experimental Study on Bond Behavior between Concrete and FRP Reinforcement. *Journal of Composites for Construction*, 12(2), 180–189. [http://doi.org/10.1061/\(ASCE\)1090-0268\(2008\)12:2\(180\)](http://doi.org/10.1061/(ASCE)1090-0268(2008)12:2(180))
- Ramadass, S., & Thomas, J. (2011). Flexure-Shear Analysis of Concrete Beam Reinforced with GFRP Bars, 5(2), 27–30.
- Rasheed, H. a., Larson, K. H., & Peterman, R. J. (2006). Analysis and Design Procedure for FRP-Strengthened Prestressed Concrete T-Girders Considering Strength and Fatigue. *Journal of Composites for Construction*, 10(5), 419–432. [http://doi.org/10.1061/\(ASCE\)1090-0268\(2006\)10:5\(419\)](http://doi.org/10.1061/(ASCE)1090-0268(2006)10:5(419))
- Report, F., Elsafty, A., & Graeff, M. K. (2012). The Repair of Damaged Bridge Girders with Carbon-Fiber-Reinforced Polymer “ CFRP ” Laminates, (October).
- Research , Development and Technology Strengthening of an Impacted PC Girder on Bridge A10062 , St . Louis County , Missouri. (2001). *Exposure*.
- Resins, V. P. (n.d.). MBrace ® Composite Strengthening Systems.
- Riggs, H. R., Park, S., & Robertson, I. N. (2004a). D c e e, (December).
- Riggs, H. R., Park, S., & Robertson, I. N. (2004b). Final Report: Use of Advanced Composites for COLLEGE OF ENGINEERING, (December).
- Rizkalla, S. H., Rosenboom, O., & Miller, A. (2006). Value Engineering and Cost Effectiveness of Various Fiber Reinforced Polymer (FRP) Repair Systems, (June 2007). Retrieved from <http://trid.trb.org/view.aspx?id=878423>

- Rosenboom, O., Hassan, T. K., & Rizkalla, S. (2007). Flexural behavior of aged prestressed concrete girders strengthened with various FRP systems. *Construction and Building Materials*, 21(4), 764–776. <http://doi.org/10.1016/j.conbuildmat.2006.06.007>
- S, T. M. L. P. E.-. (n.d.). Introduction Changes in Specifications Dimensions Prices.
- Sagan, E. I., Rasheed, H. a., & Hawileh, R. a. (2013). An efficient design procedure for flexural strengthening of RC beams based on ACI 440.2R-08. *Composites Part B: Engineering*, 49, 71–79. <http://doi.org/10.1016/j.compositesb.2013.01.006>
- Set, N. (n.d.). Design of Isolated Square and Rectangular Footings (ACI 318-02). *Design*.
- Sharma, B., & Robertson, I. N. (2006). Debonding Failure of Fiber Reinforced Polymers. *Report*, (August). Retrieved from <http://www.cee.hawaii.edu/reports/UHM-CEE-06-03.pdf>
- Sheet, P. D. (2011). SikaWrap ® Hex 117C, 3.
- Sheet, P. D., & Sikadur, D. (2014). Sikadur ® Hex 300.
- Single-axis, N. R. R. (n.d.). TECHNICAL TERMS GAUGE LENGTH GAUGE RESISTANCE GAUGE FACTOR FATIGUE LIFE Single element, (mm).
- Stallings, J. M., & El-mihilmy, M. (1998). No Title, (March).
- States, U. (2007). Repair of Prestressed Concrete Bridge Girders With, 1–10.
- Strain Gauges Analysis Strain Gauge Measurement Calculation for 3-Element. (n.d.), 3.
- Systems, S., & Karbhari, V. M. (2009). Durability Data for Frp, (February).

- Thomas, J., & Ramaswamy, a. (2006). Nonlinear analysis of shear dominant prestressed concrete beams using ANSYS. *International ANSYS Conference* Retrieved from <http://www.ansys.com/staticassets/ansys/staticassets/resourcelibrary/confpaper/2006-int-ansys-conf-30.pdf>
- Thomsen, H., Spacone, E., Limkatanyu, S., & Camata, G. (2004). Failure Mode Analyses of Reinforced Concrete Beams Strengthened in Flexure with Externally Bonded Fiber-Reinforced Polymers. *Journal of Composites for Construction*, 8(2), 123–131. [http://doi.org/10.1061/\(ASCE\)1090-0268\(2004\)8:2\(123\)](http://doi.org/10.1061/(ASCE)1090-0268(2004)8:2(123))
- Tml. (2011). Strain Gauge Coding system.
- Wikipedia. (2013). Strain gauge. http://en.wikipedia.org/wiki/Strain_gauge.
- Wipf, T. J., Klaiber, F. W., Rhodes, J. D., Kempers, B. J., Division, H., & Highway, I. (2004). Effective Structural Concrete Repair Volume 1 of 3 Repair of Impact Damaged Prestressed Concrete Beams with CFRP Department of Civil , Construction and. *Environmental Engineering*, 1.
- Wolanski, A. J. (2004). Flexural Behavior of Reinforced and Prestressed Concrete Beams Using Finite Element Analysis. *Marquette University*.
- Yang, D., Merrill, B. D., & Bradberry, T. E. (n.d.). Texas ' Use of CFRP to Repair Concrete Bridges, 39–57.
- Yang, X. (2001). Concrete Beams Strengthened with Misaligned CFRP Laminates, (1996), 79–85.

- Ye, L. P., Lu, X. Z., & Chen, J. F. (2005). Design Proposals for the Debonding Strengths of Frp Strengthened Rc Beams in the Chinese Design Code, (Bbfs), 7–9.
- You, Y., Ayoub, A., Asce, M., Belarbi, A., & Asce, F. (2011). Three-Dimensional Nonlinear Finite-Element Analysis of Prestressed Concrete Beams Strengthened in Shear with FRP Composites, (December), 896–907. [http://doi.org/10.1061/\(ASCE\)CC.1943-5614.0000226](http://doi.org/10.1061/(ASCE)CC.1943-5614.0000226).
- Zhang, Z., & Hsu, C.-T. T. (2005). Shear Strengthening of Reinforced Concrete Beams Using Carbon-Fiber-Reinforced Polymer Laminates. *Journal of Composites for Construction*, 9(2), 158–169. [http://doi.org/10.1061/\(ASCE\)1090-0268\(2005\)9:2\(158\)](http://doi.org/10.1061/(ASCE)1090-0268(2005)9:2(158))

Biographical Information

Rakesh B Jayanna was born in Arsikere, India in 1991. He graduated from University Visvesvaraya College of Engineering; Bangalore India with bachelors' degree in civil engineering in may 2013. Later he started his masters in civil engineering/Structures and applies mechanics at University of Texas at Arlington. He graduated from Master in Summer 2015. His future plan to work in FRP strengthening industry and obtain professional license and start his own construction company.