EFFECTS OF A DEBONDING FLAW SIZE AND LOCATION

ON THE FLEXURAL PERFORMANCE OF CFRP

RETROFITTED STEEL SECTIONS

by

SHARAD C. CHOUDHARY

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

MAY 2007

ACKNOWLEDGEMENTS

I would like to express my immense gratitude towards my research advisor, Dr. Guillermo Ramirez, for his continued support, advice, and encouragement to me towards my accomplishing the completion of my research analysis of the problem. His thorough understanding of the many issues fundamental to the area of embedded processor code design, and his attention to the fine details and basics that very often govern the behavior of modern-day systems will always be remembered. I would like to thank Dr. Matthys and Dr. Hossain, members of my research committee for their valuable suggestions and advice. I dedicate this work to my parents and to my brother for their constant advice, prayers, encouragement and moral and financial support throughout the process of my research, as also all through my life. I would like to thank my brother shishir choudhary for his help and encouragement in proofreading this document and assisting me with formatting and graphics issues. I would like to thank all my friends at UTA for their assistance, wishes, support and encouragement throughout my research, and also throughout the course of my graduate study at UTA. Also, I express my thanks to the many other people whose faces pass through my mind as I reflect on   the wonderful period spent at UTA. It was a pleasure knowing

them all, and that, as much as anything else, made this entire journey of my life worthwhile.

May 10, 2007

ABSTRACT

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Sharad C. Choudhary, M.S.

The University of Texas at Arlington, 2007

Supervising Professor: Dr. Guillermo Ramirez

In US there are several thousand steel bridges at present. Out of them many bridges are at various level of advance deteriorations due to many years of service life and environmental factors. These bridges cannot be fully replaced so retrofitting is the best choice .Earlier steel plates were used. With introduction of FRP in 1960.It is replacing the steel plates as they are lighter in weight and can be made stronger than steel. While installation of these FRP some kinds of Flaws are encountered. The variation of strength of carbon fiber reinforced laminate used for structural repair or

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strengthening containing a flaw is a major concern due to the potential occurrence of strength reduction. This study investigates the variation in flexural strength, flexural stiffness and flexural deflections of carbon fiber laminate bonded to steel beams due to the presence of surface flaws in the laminate. To understand this behavior, a series of three point bending tests were performed on a steel I-section which was bonded on FRP laminate containing a flaw. The amount of flaw was the percentage of the un-bonded area of laminate.

Fifteen three point static tests were conducted on an American Standard (AISC) section S6X12.5 of A36 grade steel. The variables used in the study were two conditions of steel i.e. un-notched section, and a notched section, produced by cutting a 4inch (102mm) notch. The test setup consisted of the 36 grade S6X12.5 steel beam specimen, 400kip (181.4mt) Tinius Olsen compression testing machine, carbon fiber laminate, epoxy, strain gauges and three strain indicators.

Based on test results, it was shown that with 6% or lesser flaw for notched beam was critical flaw size.

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INTRODUCTION

1.1 Background

In September 2006, the Federal Highway Authority (FHWA) reported that there are 587,550 bridges in their inventory. Around 60,000 of these bridges are classified as structurally deficient. Out of these 60,000 bridges, approximately 50% are steel bridges. Due to costs and many other practical problems arising due to issues in their transportation, construction and design, the government is looking towards more economical and efficient alternatives to achieve some innovative solutions in making these bridges structurally adequate . The application of composites such as Carbon Fiber Reinforced Polymers (CFRPs) is one such alternative.

Composites have been used since the time of the Second World War. In 1950, the use of composites was restricted to only the aerospace industry. However, recently, the application of composites has been introduced in the area of civil engineering, especially in the strengthening and retrofitting of bridges.

Limited number of studies have been performed to verify the effectiveness of steel or concrete retrofit with CFRP. To our best knowledge, there has been no study

to date on the effect of surface flaws in the CFRP on the strength of the steel or concrete section.

Fiber Reinforced Polymer (FRP) is a combination of two or more materials joining to form a new system with enhanced properties. These composite materials have fibers embedded in a polymeric resin matrix. The role of the fiber is to enhance the load bearing capacity of the composite laminate. FRP materials are extensively used in the field of structural engineering as they are suitable for the rehabilitation of structures. FRP materials have excellent tensile strength in the direction of the fibers. They also show excellent compressive strength in the order of 7000Mpa (1015ksi) as mentioned in Busel et al [13]. They are orthotropic and brittle in nature. Composite materials are good at resisting corrosion. Hence, there exists the possibility that they may be the best replacement for some of the present day construction materials.

Commercially available Fiber Reinforced Polymer (FRP) laminates are shown in figure 1.1. They are typically made of glass (GFRP), Armid (AFRP) and/or carbon (CFRP) which are bonded with an epoxy. Some of the engineering properties of these Fiber are summarized in table 1.1.

The most important characteristics of FRP that are relevant for repair and strengthening applications are the ease and speed of installation. The parameter values of specialized labor, shut down cost, and site requirements are typically reduced when this FRP strengthening procedure is used, thus making this procedure very

competitive compared to presently used techniques like using steel plates, jacketing etc. The increased performance characteristics in terms of the parameters specified above are realized by a small increase in the overall cost due to the introduction of the FRP material.

Table 1.1 Typical properties of commercial fiber [14]

Types of fiber	Modulus of Elasticity		Tensile Strength		Ultimate elongation
	Msi	Gpa	Ksi	Mpa	
Carbon	42-58	290-400	350-830	2400-5700	0.3-1.8%
Glass	10-13	72-87	480-650	3300-4500	4.8-5.0%
Armid	9-21	62-142	350-460	2410-3150	1.5-4.4%

Figure 1.1: Some Commercial CFRP laminates by Degussa Buildings [15]

Quality control is a very important aspect for repair of structures. It starts at the time of installation and ends with non-destructive testing, typically performed after installation. The type of composite selected depends on the type of application for which it is to be used. The general criteria for composite selection are strength, stiffness and durability. Resins are selected based on the kind of environment to which the structure will be exposed. Quality inspection should be a continuous process during installations and should be done regularly to ensure proper installation.

1.1.1 Flaws in FRP

Flaws in FRP can be either process-induced or service related. Process-induced flaws generally occur at the time of molding the laminate due to lack of process control or even poor raw material quality, defective tool design and human error. The nature of the process-induced defects depends upon the particular process used for manufacturing the composite part. The service related defects are due to unintentional loading, excessive loading, or even due to low energy impacts (for example due to wrench drop or pebble impact), fatigue and environmental factors.

1.1.2 Common Types of Defects Encountered in FRP

The common types of defects encountered in FRP as mentioned in the FRP handbook [16] are as follows:

- Flaw in CFRP in form of cone shape propagation, Figure 1.2

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- Flaw due to presence of air voids, moisture or even excessive amount of solvent used in making pre-peg, Figure 1.3.

- Co Resin starved areas, due to bleeding of resin during resin transfer molding, Figure 1.4..

- Flaw due to scratching or cut in laminate, Figure 1.5.

- De lamination of FRP, due to the impact loading ,Figure 1.6

- Unbounded areas or lack of adhesive in adhesively bonded joints ,Figure 1.7)

- De-lamination or separation between laminates due to poor consolidation and under curing in the molding process., Figure 1.8

- Damage produced in FRP due to high impact ,Figure 1.9

- Resin starved or rich fiber, which can happen due to non uniform resin distribution in the pre-peg process.

- Fiber misalignment, which can be due to disorientations of fibers in the pre-peg, deviation from the pre-selected lay-up or filament winding.

- Flaw due to under-curing or non-uniform curing when proper temperature and time are not used in the molding process.

- Fiber waviness or kinking due to improper tensioning during pre-peg preparation, filament winding and pultrusion.

- Knit lines which occur in both injection and compression molding due to joining of two or more flow fronts.

- Flaw caused by ply overlap or ply gap which can occur in hand lay-up.

- Blisters, caused due to entrapment of air voids in compression molding.
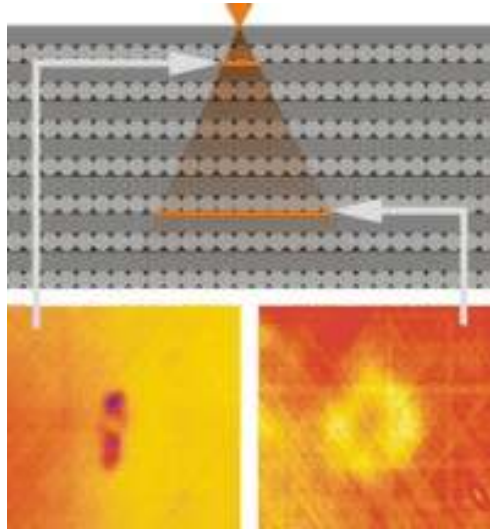
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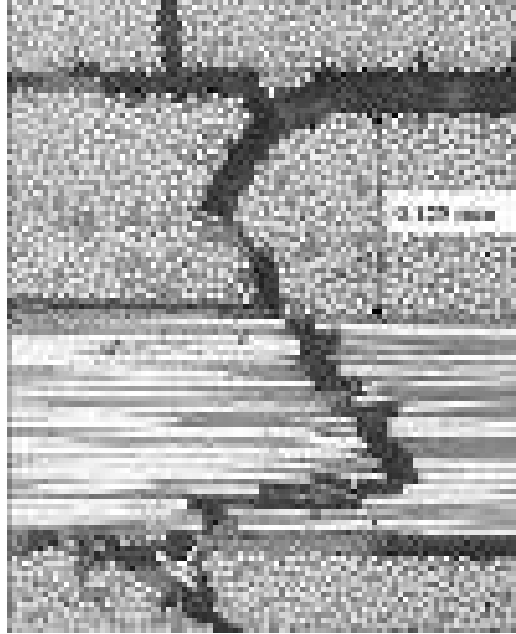
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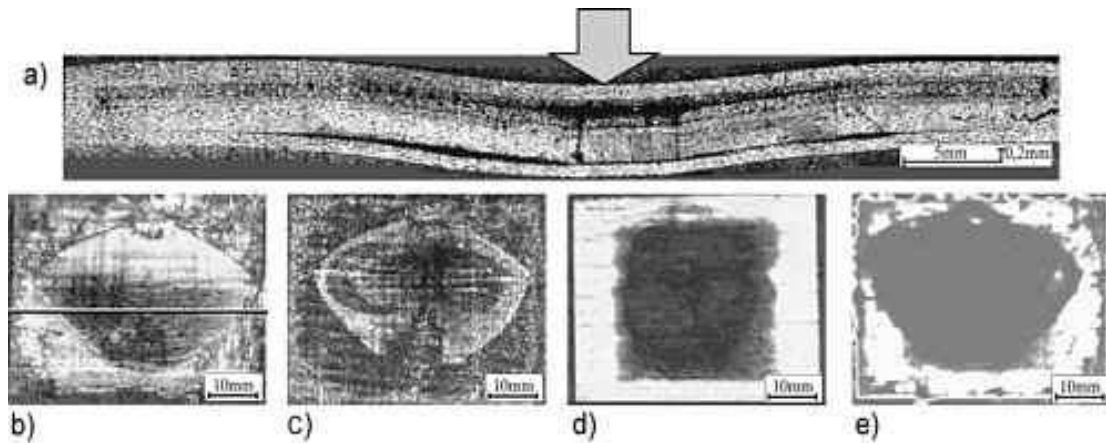
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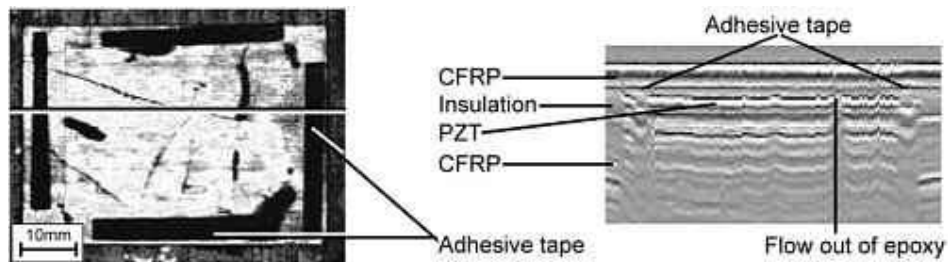
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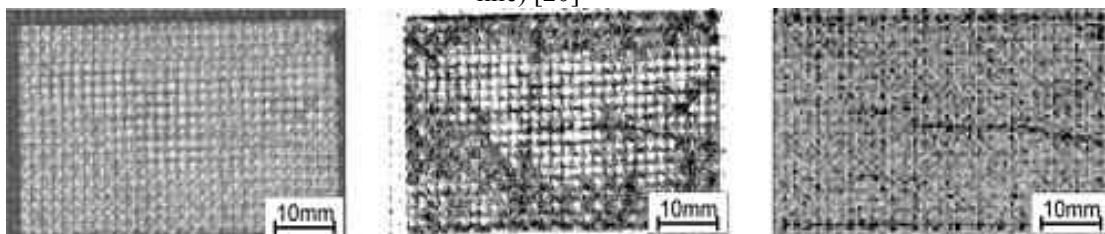
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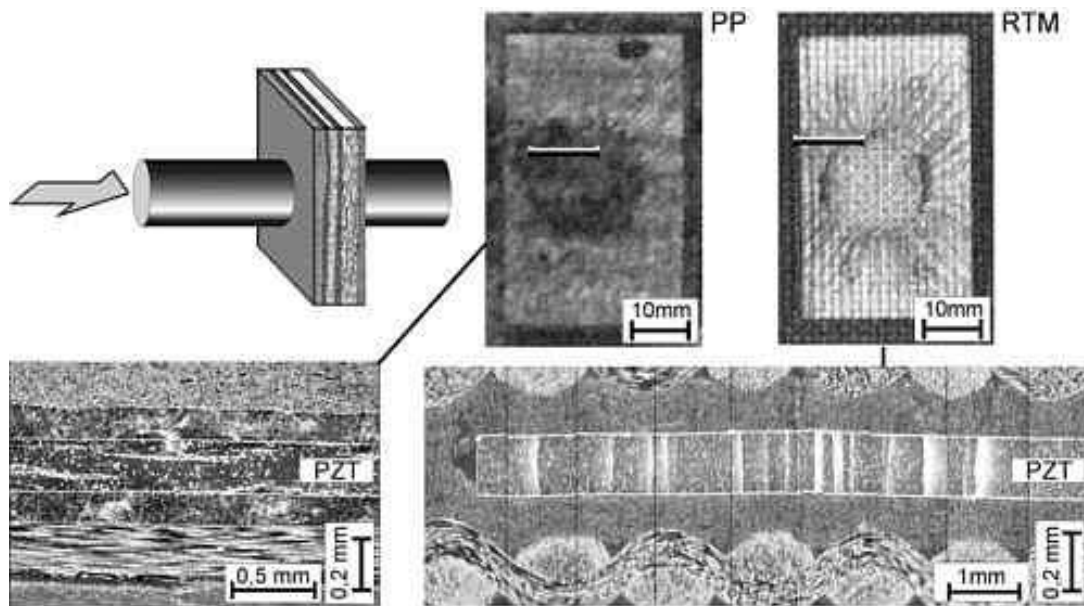
Figure 1.9: Damages in high speed impact tested specimens [20]

1.2 Objective and Scope of Research

1.2.1 Objective

The goal of this research was to determine how the strength of a steel I-section behaved due to the introduction of a surface flaw into the FRP laminate that was bonded to the steel I-section. There are no known published data describing how the strength of FRP varies with different percentages of bonding area. Therefore, the aim of this study was to perform a preliminary analysis of the variation of the strength of a

steel I-section with the introduction of surface flaws of varying percentages into the FRP laminate bonded to the steel I-section.

1.2.2 Scope of Research

Fifteen systematic experimental tests were conducted to study the variation of strength of CFRP bonded to steel due to the presence of surface flaws in CFRP. These experiments were conducted under static loading. To allow the transfer of stresses from steel section to CFRP, a four inch-long notch was created in tension flange at the center. A flaw was introduced by pasting wax paper to CFRP and not allowing it to bond with the steel I-section directly. Different percentages of flaw (6%, 12% and 25%) were achieved by varying the percentage of bonded area to study the variation of strength as shown in Figure 1.10.
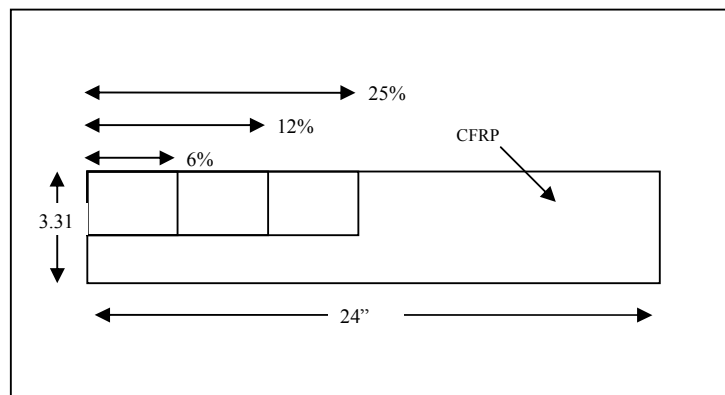
Figure 1.10: Different flaw size created in the FRP

1.3 Literature Search

A preliminary literature search was conducted in order to locate evidences of previous research work performed on this topic.

1.3.1 FRP Strengthening of Concrete Structures

Europe and Japan were the first ones to use FRP to strengthen concrete structures in the 1980's. The demand has been ever growing to several thousands today, as mentioned in Bakis et al [21]. Structural elements like beams, slabs, columns etc are strengthened with externally bonded FRP. The idea of externally bonded FRP to strengthen concrete structures is not new. Traditional retrofitting techniques like steel plates, column jacketing are gradually being replaced by FRP.

Europe, Japan and USA are still working on writing code language and guidelines for externally bonded FRP systems. The Japan Society of Civil Engineers and the Japan Concrete Institute organizations have published several documents related to the use of FRP materials in concrete structures. Europe has constituted the task group 9.3 of the International Federation for Structural Concrete (FIB) which has recently published a bulletin on design guidelines for externally bonded FRP to strengthen concrete structures .

The Canada Standard Association is also working on developing standard guidelines for FRP system. Recently Canadian Standard Association (CSA) and

Canadian Highway bridge design codes have approved the code for "Design and construction of building component with Fiber Reinforced Polymers" (CSA S806-02).

The US has published "Guidelines for design and construction of externally Bonded FRP system for strengthening Concrete Structures" (ACI 440.2R-02).

1.3.2 FRP Strengthening of Steel Structures

The review of existing literature reveals some of the previous attempts in strengthening of steel structures with CFRP describing the parameters investigated and the relevant results.

Edberg et al [23] investigated the rehabilitation of steel beams (W8X10 girders of A709 grade 36 steel) using composite materials (FRP). Four reinforcement schemes were designed to improve the flexural performance as expected. The first reinforcement scheme was a unidirectional CFRP bonded directly to the tension flange of the beam using two part epoxy adhesive. The second reinforcement scheme was the same, but with an aluminum honey comb structure. The thickness of the composite was 4.5mm. In the third scheme, a +/- 45 degree E-glass fabric was wrapped around the flange and the web cross section. Results was tested for service loads up to ultimate strength. Result showed an increase in stiffness by 11 to 30%, and the strength was increased by 37 to 71%.

Daniel N. Farhey [24] performed a diagnostic truck load test and micro structural analysis. The study was conducted on a steel truss bridge and rehabilitation design.

The feasibility and potential benefits of using advanced field experimental techniques within a structural identification framework were demonstrated. The integration of the experimental assessment technique permitted objective decision making and hence, a more rational approach to rehabilitation design.

X. Liu [25] investigated the effect of stiffness on the application of CFRP laminates to the tension flange of corroded steel members .They studied the stiffness by conducting tests on four W12x14 three (3) point tests with no retrofit or notch and FRP retrofit with 4inch (102mm) wide notch. First test was un-notched steel section without FRP. This was like control test specimen data. Second test was with 4" wide notch at the center to simulate reduction of strength due corrosion loss. Third specimen was with CFRP laminate for full length of the beam and fourth one only covering quarter span of the beam length. The failure mode of test one and two was Lateral torsion buckling. Third and fourth specimen failed in de lamination of laminate. Based on the experimental result they concluded that there is an increase in the stiffness and plastic load of corroded steel members.

Trent C. Miller [26] studied the feasibility of strengthening I-704 in Newark, Del. They conducted some preliminary laboratory tests for the effectiveness of bonding CFRP plates to the tension flange of the steel bridge girder to increase strength and stiffness. Analytical model for bond performance was done. The model was able to predict the force of transfer accurately. It was observed glass fiber is good in protecting as it prevents from galvanic corrosion. The result obtained from small scale

and large scale fatigue test was encouraging for cover plate detail. Based on this study they concluded that CFRP cover plates can be used to strengthen the deteriorated bridge girders, and demonstrated that a 10 to 37% increase in stiffness . They also conducted a diagnostic load test on I-704 and found an 11.6% increase in stiffness.

M. Tavakkolizadeh [27] studied the behavior of steel-concrete composite girders strengthened with CFRP sheets under static loading. Three large scale composite girders (W355x13.6) made of A36 grade steel and 75mm thick by 910mm wide (3inch thick x 36inch wide) concrete slabs were prepared and tested. Their thickness was kept constant while varying the number of layers in the specimen. They found that the test result of steel – concrete composite girders retrofitted with epoxy – bonded CFRP was very encouraging. All the retrofitted girders resulted in an increase in the ultimate load carrying capacity of up to 76% for odd number of layers. They also found that the effect of CFRP sheet bonding on the elastic stiffness of the girder was not significant due to the flexibility of the adhesive.

David Schnerch [28] investigated the strengthening of steel structures and bridges with high modulus carbon fiber reinforced polymers for different types of resin. He also fabricated a scaled monopole from A572 grade 60, similar to cell phone towers. The length of the pole was 6090mm (20'-0") and it had dodecagonal or twelve-sided cross sections. It was tapered uniformly along the length, starting at 457mm (18inch) at the base and ending at 330mm (13inch) at the tip. It was strengthened using wet

lay-up procedure for unidirectional dry fiber sheets for strengthening in longitudinal direction. They concluded that the deflection was reduced by 25 % at the middle by retrofitting the pole. When it was loaded for the failure it was observed that there was rupture of sheet on tension side underneath anchorage. They arrived at the promising conclusion by conducting tests on ten different types of resin for the wet lay-up.

Brent M. Phares [29] of the Iowa Department of Transportation strengthened two steel girder bridges using CFRP .The Bridge 1 (number 3903.os 141) was strengthened with post tension CFRP rods. It was a 210X26 feet three span continuous rolled shape steel girder in Iowa on State Highway 141. CFRP rods (3/8 in diameter) were selected for their outstanding mechanical characteristics. Bridge 2 (number 738.5S092) was strengthened with CFRP plates. It was a 150x30 feet three span continuous bridge at Iowa State Highway 92. The CFRP (E = 20,000 ksi) was selected due to its outstanding mechanical properties. It was concluded that although P-T does not significantly reduce live load deflection, it does increase the capacity by generating the strain opposite to those produced by dead loads. Using an HS-20 truck, it was determined that approximately 5 to 10 percent of the live load deflection was reduced by this method.

Strengthening of steel structures with FRP is a relatively new area where only limited numbers of tests have been conducted. Still no specific codes addressing analysis and design procedure and criteria are available. The only set of available guidelines is "ICE design and practice guides" published in UK [7]. It offers

recommendations for the strengthening or repair of metallic components of onshore structures using FRP. The recommendations cover different environmental aspects such as temperature, moisture, chemicals, UV radiation etc. For the design of composite materials, the strain compatibility method is used. The ultimate strength capacity is provided by the manufacturer.

Structural design from the first principles and design by finite element analysis are recognized by the guidelines. Further, it covers the main principles and important aspects of the strengthening and repair of metallic structures.

1.4 Flaws in FRP as per NCHRP

Our access to any relevant literature available on this topic for this civil engineering application is limited to the documents published as part of the NCHRP [30]. The NCHRP have presented the same set of recommendations as provided by the US aerospace industry. That was our prime motivation to pick this as our research topic, as a lot of research has to be done in this area pertaining to civil engineering structures. The aerospace industry is very conservative, while civil engineering structures have less stringent requirements. NCHRP 514 [30] has given some guidelines on how to deal with flaws found after NDT testing. The recommendations for different types of defects are summarized below:

1.4.1 Small Defects in FRP

Small defects are voids or surface discontinuities no larger than 6.4mm (1/4inch) in diameter. These shall not be considered major defects, and shall require no correction unless they are present at edges or there are more than five such defects in an area of 0.9sqm (9.70sft). Small defects sized between 6.4mm to 32mm (1/4 inch to 1 ¼ inch) in diameter shall be repaired using low pressure epoxy injections as long as the defects are local.

1.4.2 Minor Defects in FRP

Minor defects are those with diameters between 32mm and 152mm (1 ¼inch and 6 inch) and a frequency of less than five per any unit surface area of 3.0m (10ft) length and width. The area surrounding the defects to an extent of at least 25mm (1inch) on all sides are removed. The area is wiped clean and thoroughly dried. It is then patched by adding an FRP of the same type as the original.

1.4.3 Replacements of Large Defects in FRP

Defects larger than 152mm (6inch) in diameter shall be marked carefully and scraped out extending a minimum of 25mm (1inch) on all sides. Scraping should be progressive throughout the layers in case of multiple layers. In case a flaw is presented adjacent to the concrete, the entire thickness of FRP and primer shall be removed. The substrate should be prepared and primer reapplied after ensuring that both the surface and FRP are dry and clean.

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CHAPTER 2

EXPERIMENTAL PROGRAM

2.1 Introduction

Chapter 2 presents the experimental program of this research work consisting of three point load tests for a steel section bonded with CFRP having surface flaws. The epoxy was used as an adhesive between the steel flange section and the CFRP laminate. A total of fifteen I-steel section beams were tested in this study. The steel beams were S6x12.5 of grade 36. The CFRP laminate (courtesy Degussa Buildings) was 24inch long and 4.0inch wide (610mm x 84mm).Desired width of CFRP was obtained by cutting 4" (100mm) wide CFRP to 3.31"(84 mm) using machine saw. The bonding agent used was epoxy resin.

Two geometric configurations of beams were tested. The first group consisted of four un-notched steel sections shown in Figure 2.1, strengthened with CFRP laminate. The second group consisted of eleven steel I-Beams with a 4inch (102mm) long notch at the center of each of steel beam shown in Figure 2.2. It was

strengthened by adding the CFRP laminate with the help of a 10mm thick layer of epoxy bonded to the flange of the steel beam.

A-36 GRADE STEEL

36"
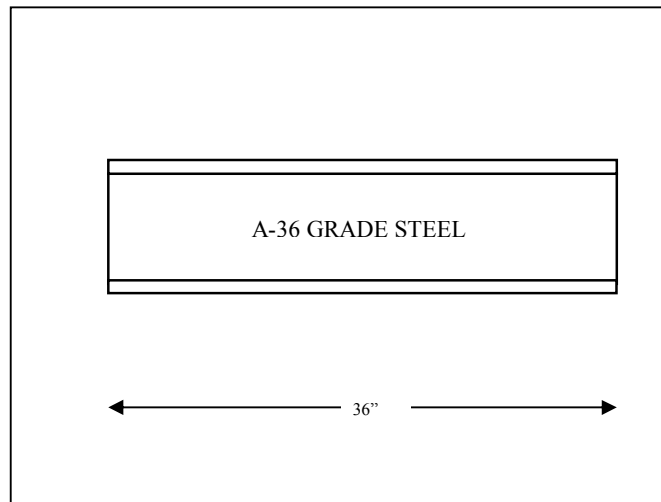
Figure 2.1: Un-notched steel section

A-36 GRADE STEEL

4" Notch

36"
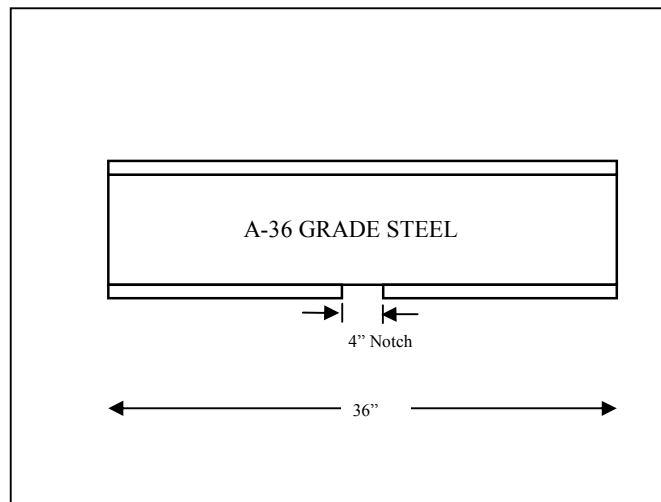
Figure 2.2: Notched steel section

In order to differentiate between the two types of specimens, the following notations were adopted: The first group starts with "UN" to describe that the steel section is un-notched . The second group starts with "N" to describe that the steel section is damaged. The number following UN and N is "X", where 'X' represents the percentage of flaw in CFRP. In our experiments, we have chosen 0, 6, 12, and 25 as experimental values of 'X'.

2.2 Material Properties

2.2.1 Steel Beams

Thirty six inch (914mm) long steel beams (S6x12.5) shown if Figure 2.3 were used in this investigation. The material properties of steel were provided by the supplier and were according to ASTM structural steel specifications for GR36. The yield strength values of the steel beam were 36ksi (2530kg/sqcm), which were determined by test.

2.2.2 CFRP Laminate (FRP)

The Laminate used in the current research was provided by Degussa. It was shiny black color as can be seen in figure 2.4.These were made of high strength carbon fiber. Some of the engineering properties of the laminate is tabulated in Table 2.1.

Figure 2.3: Steel beams of A-36 grade

Figure 2.4: CFRP laminate used in research

(CFRP plates are of standard thickness - 1.4mm (.055inch) with three different standard widths: 10, 50 and 100mm (3/8, 2.0, 4.0inch). For the present research, a 1.4mm thick and 100mm wide (0.055inch x 4inch) material was used. Its engineering properties are tabulated below).

Table 2.1 Standard engineering properties [15] of CFRP laminates

S&P Laminate	10/1.4 (NSM)	50 / 1.4	100 / 1.4
Fiber Type	Carbon	Carbon	Carbon
Matrix Resin Type	Epoxy	Epoxy	Epoxy
Fiber Volume Fraction	70%	70%	70%
Nominal Width in (mm)	3/8 (10)	2 (50)	4 (100)
Nominal Thickness in (mm)	0.055 (1.4)	0.055 (1.4)	0.055 (1.4)
Design Area (sq in)	0.0217	0.190	0.217
Modulus of Elasticity (psi)	23000,000	23000,000	23000,000
Tensile Strength Ultimate (psi)	390,000	390,000	390,000
Epoxy Resin Usage Rate (LF/Gallon)	150	180	90

2.2.3 Epoxy

The epoxy used in this research was provided by the same supplier. This epoxy is used for a CFRP laminate called Conc. Liquid LPL. The epoxy was a combination of two components A (white semi-liquid) and B (black semi-liquid) as shown in Figure 2.5, in the ratio of 2:1 by volume. The engineering properties of the epoxy are tabulated in Table 2.2.

Table 2.2 Engineering properties [15] of the epoxy

PROPERTY	RESULT	TEST METHOD
Tensile strength, Psi (Mpa)	4,400 (30.4)	ASTM D 638
Elongation at break (%)	1.49	ASTM D 638
Compressive Yield strength Psi (Mpa)	8,300 (57.3)	ASTM D 695
Compressive Modulus Psi (Mpa)	3.5X10^5 (2.4X10^3)	ASTM D 695
Slant shear Strength Psi (Mpa)	5,000 (34.5)	AASHTO T-237
Flexural Bond Strength, Psi (Mpa)	570 (3.9)	ASTM C 293

2.3 Specimen Preparation

The first step was to have the surface preparation process completed before applying the laminate. According to the supplier (Degussa buildings), the steel should be free from any grease, oil, paint, or rust that might affect the bond between the steel and the laminate. It was decided to remove paint, rust and grease off the top by using a hand grinder as shown in Figure 2.6. Then, the steel was cleaned with sand paper to make it totally free from any paint.

Figure 2.5: Epoxy used in research

Figure 2.6: Specimen preparation

2.4 Applying the CFRP Laminates

The two components of the epoxy were mixed as per supplier recommendations. The mix ratio was 2:1 by volume of component A to component B. First, component A was measured and was placed in a small plastic container to avoid any reaction. Component B was then added to component A, and was mixed at low speed drill (200 rpm) for approximately 5 minutes.

The epoxy was applied onto the surface of the CFRP laminate using a brush as shown in Figure 2.7. It was then spread using a paint brush. After applying the epoxy, the laminate was placed on a prepared area of steel and was pressed by hand. Later, some loads were placed over it to provide extra pressure. Then, it was left alone and allowed to cure for seven days at room temperature.

2.5 Test Set up

All fifteen I-beams were tested for three point static loading. The loading was applied using a 400kip (150mt) Tinius Olsen testing machine. The load was applied at the mid span of the beam, by a manually operated hydraulic pump. All the beams were loaded to 6000lb (2721kg) to counter the weight of the hydraulic slab that was used for our testing. Then, the entire additional load (in excess of 6000lbs) was used to test the I-beam. A typical load set up is shown in Figure 2.8.

Figure 2.7: Applying epoxy to CFRP laminate

All tests were controlled and data were collected using a computer which displayed the result in the form of a graph plotting the load vs. deflection under the specified parameter conditions.
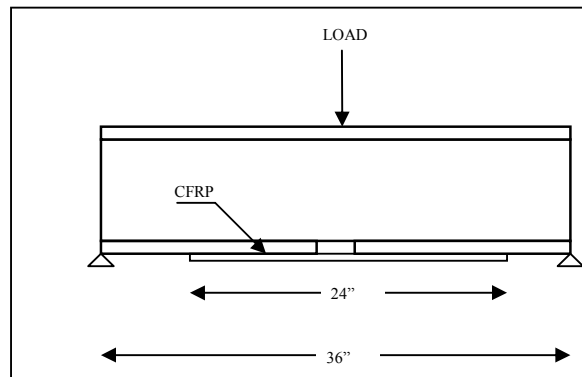
Figure 2.8: Test set up for the experiment

2.6 Instrumentation

The aim of the present research was to study the behavior of beams. Extensive instrumentation was utilized on the beams to study strains, loads, and deflection at desired locations more accurately. Further details elaborating this process will be provided below.

Strains in the steel section were recorded using a strain indicator. These strains were measured using strain gauge type C2A-06-250LW-350 from Vishay Micro-measurements shown in Figure 2.9a. The strains were placed at S1,S2 and S3 as shown in Figure 2.9b. Strain S1 was placed were the Surface flaw was created with help of wax paper. The strain gauge S2 was placed at he center of laminate and strain gauge S3 was placed at same location but in opposite side where there was no flaw. This was done to study how stain values changes with presence of flaw.

The vertical deflection was measured by using a dial gage and by using a Tinius Olsen Testing Machine, in separate iteration sets of the experiment for given parameter conditions.

Table 2.3 shows the matrix of experiments that were conducted in the present research. For un-notched beam single test were conducted. For notched beam ,three iteration was done to obtain the consistency in the result. Three bench mark were used.
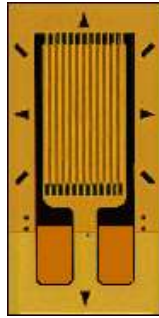
a)
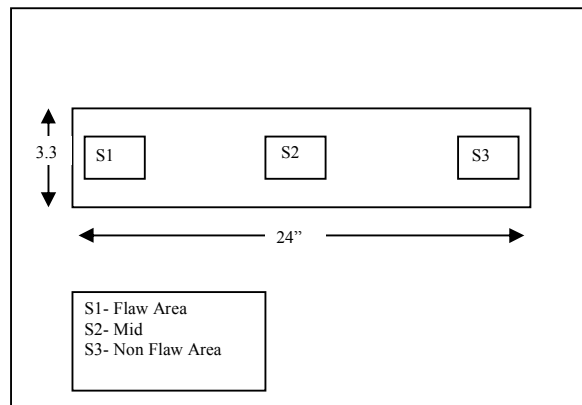
b)

Figure 2.9: Strain Gauges: a) strain gauge used by Vishay micro measurement   b) placement of strain gauge on FRP

Figure 2.10: System 5000 model 5100 Vishay strain sensor

Table 2.3 Matrix of experiments conducted

Flaw (% ages)	Un-notched	Notched
6%	1	3
12%	1	3
25%	1	3
Beam UN (BM1)	1	-
Beam N (BM2)	-	1
Beam N0 (BM3)		1

CHAPTER 3

EXPERIMENTAL RESULT

3.1 General

This chapter presents the results of three point bending tests conducted on un-notched and notched steel sections bonded with CFRP laminate. The variation of the beam samples for the present research were achieved by incorporating the presence and absence of a notch, and of different surface flaw sizes created in the CFRP laminate bonded to steel.

3.2 Bending Test Results

This section describes the results of the experiments conducted on the un-notched and notched steel sections, with varying amounts of surface flaw in CFRP bonded to steel beams. Steel beams (S612.5 of Grade 36) 36inch (914mm) long were used for the experiments. The dimension of the CFRP laminate used was 24 x 3.31 inch (610 x 79mm), and was bonded with epoxy provided by the manufacturer (as

described in section 2.2.3 of this thesis) to the tension flange of the steel sections. The steel beams were supported at one inch from each end. Two strain gauges were placed, one on top of the flaw area, a second on top of the non flaw area at the same position but on the opposite side as shown in Figure 2.9b. The point load was placed at the center, 17inch (432mm) from the supports. The load was applied hydraulically by rotating the knob of the Tinius Olsen machine .Deflection were recorded by two methods – digitally by software called MTESTW, and analog by using a dial gauge. Strain gauges were measured using the System 5000 Model 5100 Vishay Strain Sensor, which is shown in Figure 2.10.

3.2.1 Un-notched Steel Sections

The first group of bending tests was performed on un-notched steel beam with CFRP laminate bonded to the tension flange. The variable in these tests was the percentage of flaw created in the CFRP laminate interface to steel. The tests were performed on an un-notched steel beam (BM) with 0% flaw in CFRP, and then on a steel beam (UN6) with 6% flaw. It was observed that the results on the UN6 beam were identical to the BM results, and therefore the UN6 results were taken as the basis of the approach described from Section 3.2.1.1 onwards. Subsequently, experiments were conducted using flaw percentage values of 12% and 25%, as described in sections 3.2.1.2 and 3.2.1.3 respectively.

3.2.1.1 Beam UN (BM1)

The three point bending test was performed as a benchmark on an un-notched steel section without any CFRP. The steel section can be seen in Figure 2.1.
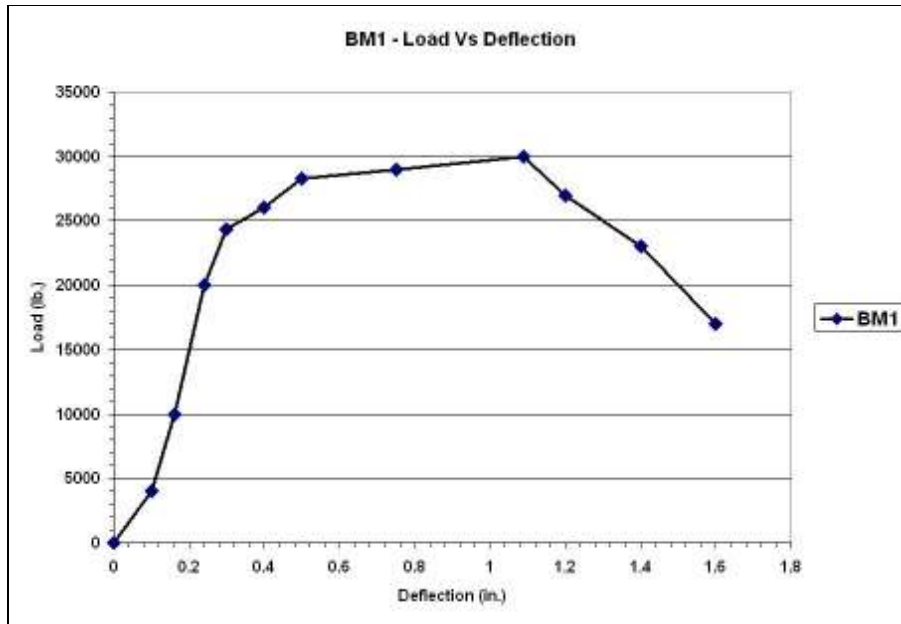
Figure 3.1: Load vs. deflection for un-notched 0 percentage flaw without CFRP

It was observed from the load vs. deflection graph shown in Figure 3.1 that the steel section failed at 30kips (13.60mt). This observation was used as a reference point to conclude that all the beam samples utilized for the purpose of this research are of A36 grade.

3.2.1.2 Beam-UN6

The three point bending test was performed on an un-notched steel section with a flaw of 6%. The reason for choosing 6 % flaw was, in practice 5% flaw of total area bonded is considered as acceptable flaw. This flaw was created by attaching a wax paper separator of dimension 2.7 x 1.66inch (69 x 42mm) to the corner of the laminate as shown in Figure 3.2. This laminate was then bonded to the steel section using the specified epoxy described in section 2.2.3 of this thesis. The load-deflection plot for this test is shown in Figure 3.3 of this thesis.

Figure 3.2: Showing 6 percentage flaw

It was observed that first indications of partial de-lamination occurred at 26000 lb (11792kg). The load was still increasing and full de-lamination took place at 46000lb (20864kg). The steel section failed in lateral torsion buckling.

De-lamination of the CFRP laminate from the steel section occurred, which resulted in a sudden failure in the form of lateral torsion buckling. This de-lamination and the resulting failure are suspected to be due to the presence of a small strip of laminate protruding out from the steel beam. Therefore it is not considered as valid test for data.
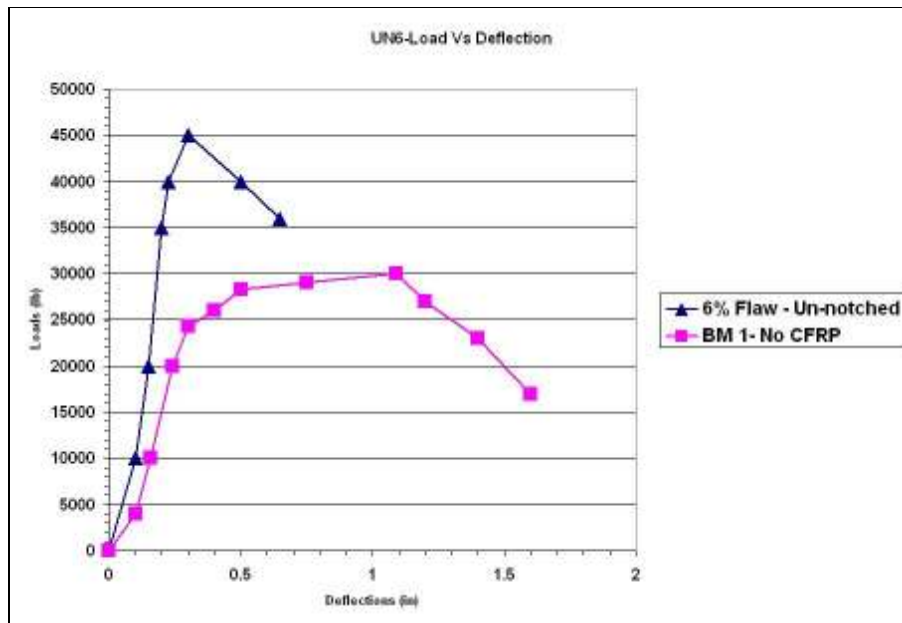
Figure 3.3: Load vs. deflection for 6 percentage flaw

Figure 3.4: Proper de-lamination of CFRP

The values of strain were recorded for increment of load. The strain values measured for both flaw and non flaw areas are shown in fig 3.5.
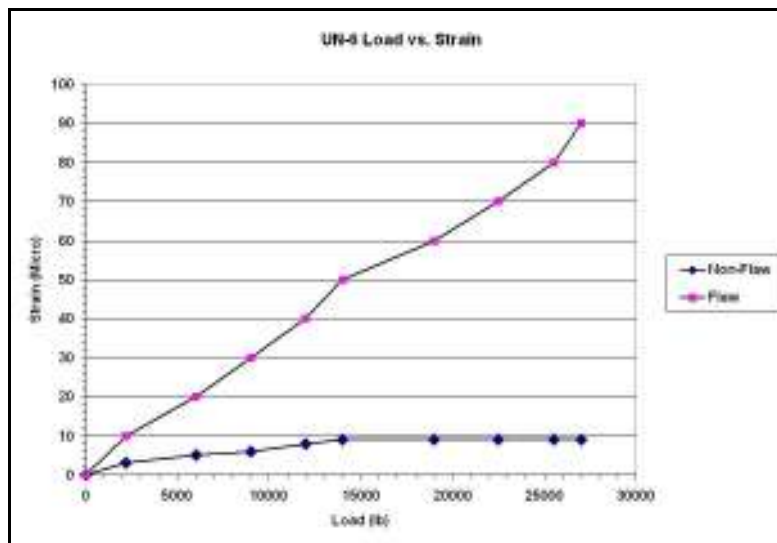
Figure 3.5: Load vs. strain graph for un-notched 6% flaw

3.2.1.2 Beam UN12

The three point bending test was performed on an un-notched steel section with a flaw of 12%. This flaw was created by attaching a wax paper separator of dimension 5.4 x 1.66inch (137 x 42mm) to the corner of the laminate as shown in Figure 3.6. This laminate was then bonded to the steel section using the specified epoxy.

Figure 3.6: Showing 12 percentage flaws

The measured increase in the ultimate capacity of the steel section of 49kips this could be attributed to the presence of CFRP. There was no de-lamination of the CFRP, and the final mode of failure was apparent in the form lateral torsion buckling.

From Figure 3.7 we observe that there was no influence of flaw over the ultimate capacity of the steel section as when compared to the values in the 6% flaw experiments of section 3.2.1.1 of this thesis.
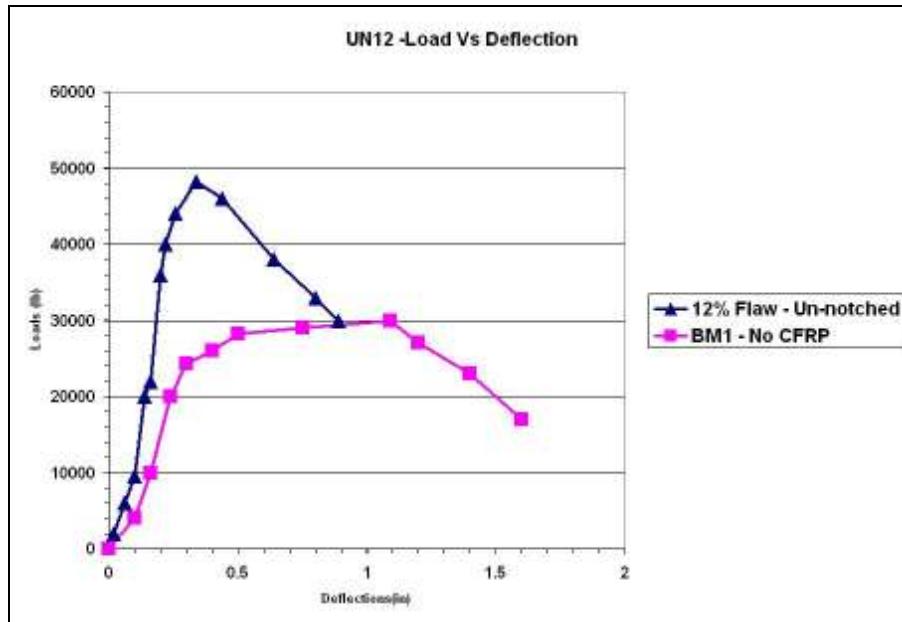
Figure 3.7: Load vs. deflection for un-notched 12 % flaw

There were a total of three strain gauges applied to CFRP one on top of the flaw area, a second on top of the non flaw area at the same position but on the opposite side, and third at the center of the beam as shown in Figure 3.8.

For every increase in load of the corresponding strain values were recorded.

Figure 3.8: Failures in lateral torsion buckling
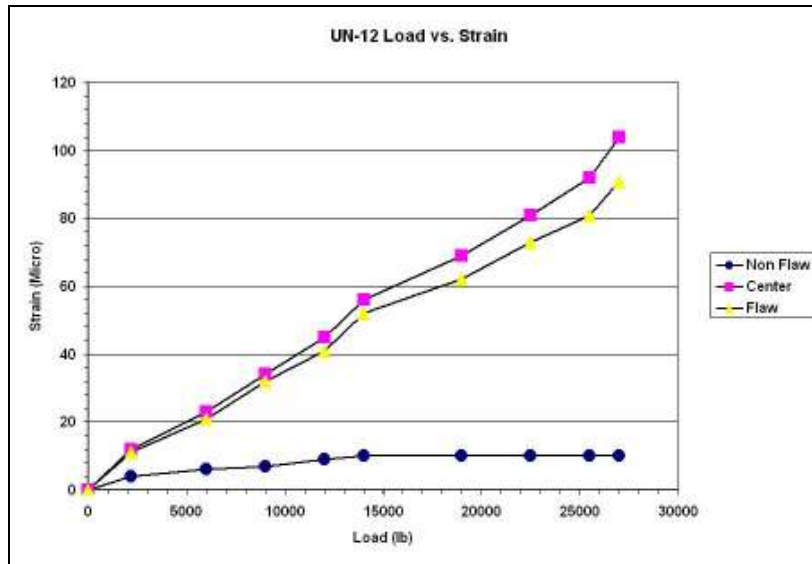
Figure 3.9: Load vs. strain graph for 12 percentage flaw

We can infer from the graph shown in Figure 3.9 that there are differences between strain in the flaw and non flaw areas as expected, but the difference is not

significant. At this point, there was a need to study how stresses on steel sections are transferred to the CFRP laminate, as shown in subsequent sections.

3.2.1.4 Beam UN25

The three point bending test was performed on an un-notched beam with a flaw of 25%. This flaw was created by attaching a wax paper separator of dimension 12 x 1.66inch (305 x 42mm) to the corner of the laminate as shown in Figure 3.10. This laminate was then bonded to the steel section using the specified epoxy.

Figure 3.10: Showing 25 percentage flaws

As seen in Figure 3.11, due to the presence of the flaw in the laminate, there was no variation in the ultimate capacity of steel sections as when compared to the previous experiments.
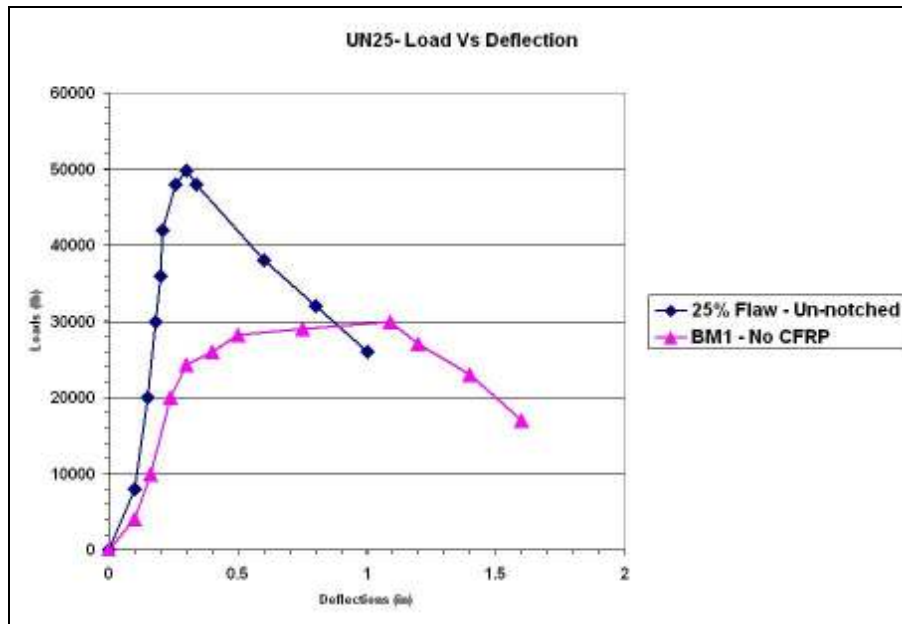
Figure 3.11: Load vs. deflection for un-notched 25 percentage flaw

It can be concluded from Figure 3.11 that the percentage of flaw created is not changing the ultimate capacity.

Figure 3.12: Failures in lateral torsion buckling

Strain gauges were placed this time at the CFRP and on the steel section as shown in Figure 3.12 to study the reason for no de-lamination.
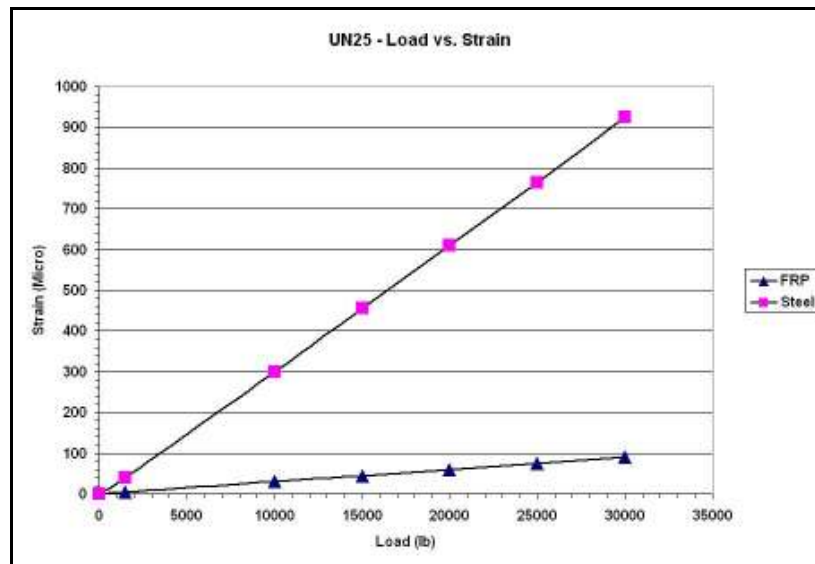
Figure 3.13: Load vs. strain graph for 25 percentage flaw

It was observed from the load vs. strain graph shown in Figure 3.13 that little stress is transferred from the steel section to the CFRP laminate as there is less strain . The strain in the steel section is much higher compared to the strain observed in the laminate. Hence, in the next experiment, it was decided to create a 4inch (102mm) notch section to allow proper transfer of stresses on the CFRP laminate.

3.2.2 Notched Steel Sections

The second groups of bending tests were performed on beams with a 4inch (102mm) notch at the center of the steel beams. The CFRP laminate was bonded to the tension flange. Again, the parameter variable in these tests was the different percentages of flaws namely 6%, 12 % and 25% that were created in the CFRP laminate.

3.2.2.1 Beam N (BM2)

The three point bending test was conducted on a notched steel section without any CFRP laminate. A 4inch (102mm) long notch was created at the center of the beam at the bottom of the flange of steel section to allow the transfer of stresses to the laminate, as shown in Figure 2.2 of this thesis.
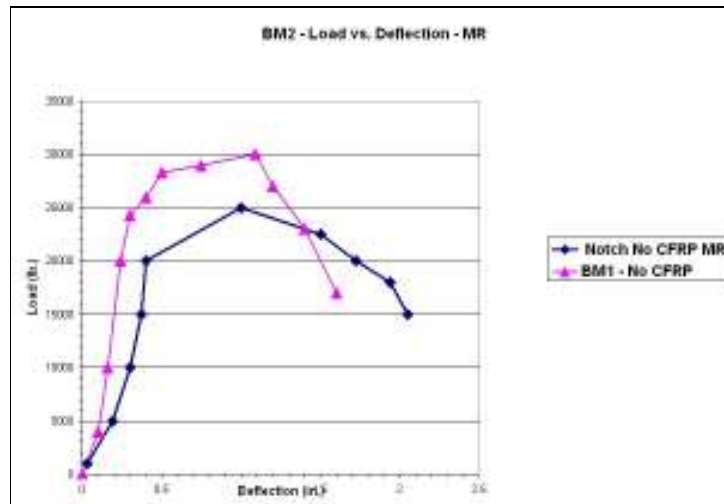
a)
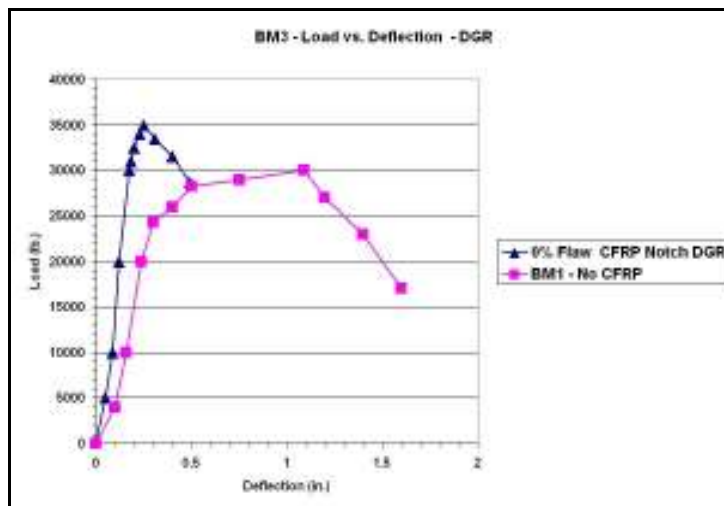
b)

Figure 3.14: Load vs. deflection for N-steel section without CFRP: a) machine reading b) dial gage reading

It was found the steel section failed at 25kip (11.34mt) in the experiment, there was reduction of strength due to presence of notch as expected. The load vs. deflection graph can be seen in Figure 3.14b.

Figure 3.15: Failures in tearing of beam

The aim of the experiment was to determine the ultimate capacity of steel section with notch. The failures in the form of tearing of the steel section can be see in Figure 3.15.

3.2.2.2 Beam N25

The three point bending tests were performed on a 4inch (102mm) notch with a 25 % flaw. The flaw was created in same way as it was created in earlier test and was glued at a quarter of the laminate as shown in Figure 3.16.

Figure 3.16: Showing 25 % flaw with notch

 For increase in load corresponding deflection values were recorded, and a set of three tests were performed to obtain more consistent values of load vs. deflection.

There was no increase in strength of steel section due to 25%, and average failure occurred at 25kip (11.34mt) as shown in Figure Set 3.17.

Strain gauges S1, was placed on laminate where surface flaw of 25% was created . The strain gauge S2 was placed at center of laminate. The Strain gauge S3 was placed at same location but in opposite side where there was no flaw. The main objective of this was to study the variation of strain in laminate due to presence of flaw. The geometrical placement of these strain gauges can seen in Figure 2.9b.
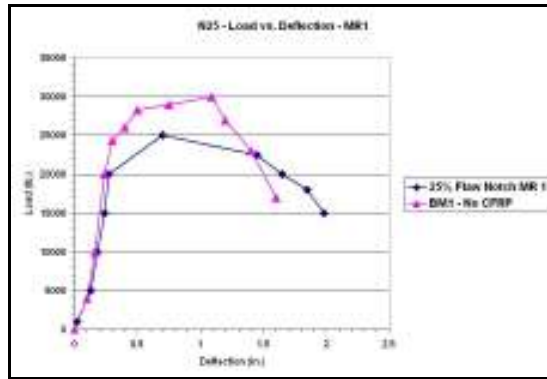
a)
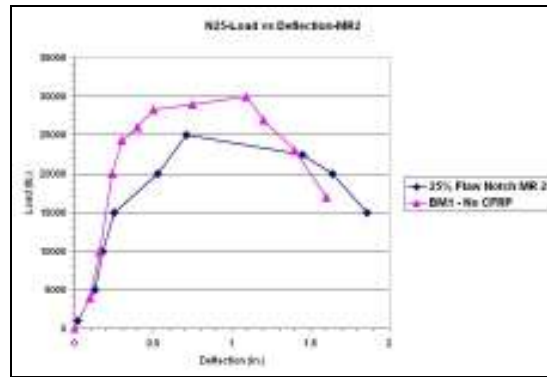
b)
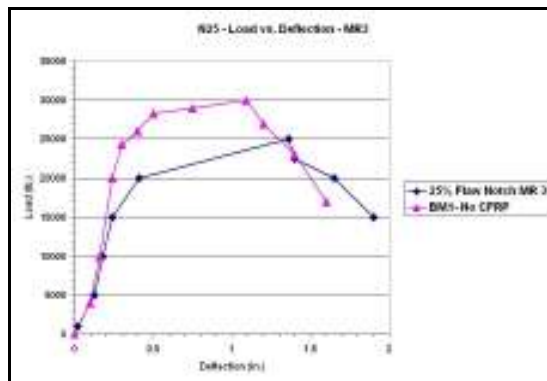
c)

Figure 3.17: Load vs. deflection N 25 % flaw with machine readings: a) specimen 1 b) specimen 2 c) specimen 3
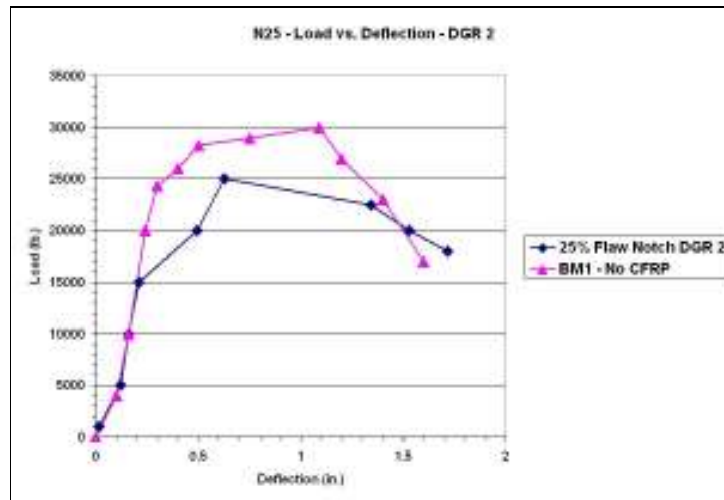
a)
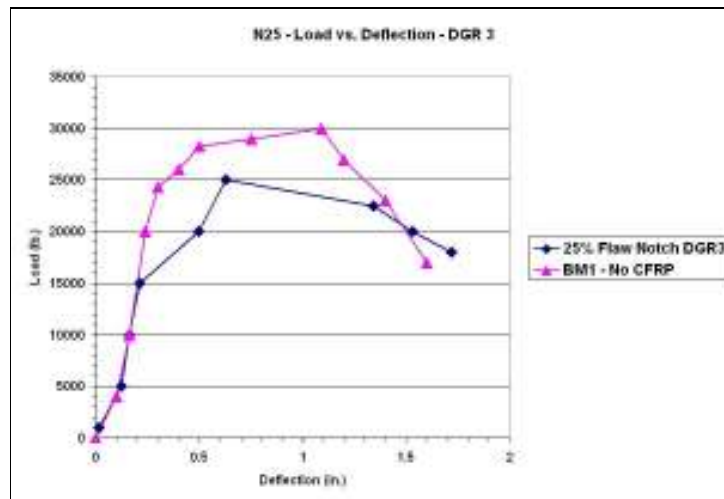
b)

Figure 3.18: Load vs. deflection N 25 % flaw with dial gauge readings:
a) specimen 2 b) specimen 3

The section failed in de lamination of laminate and tearing of steel section where notched was created . This can be clearly seen in Figure 3.19.

Figure 3.19: Failures with de-lamination and tearing of beam

Strains in flaw and non-flaw area are shown in Figure Set 3.20. Based on the slopes of the load vs. strain plots shown in Figure Set 3.18, it was seen that the graph, proper transfer of stresses was taking place from steel to laminate as there is considerable amount of strain present in the laminate. Still the stress in steel was much higher than laminate, this can attribute to more stiffness of steel compared to CFRP.
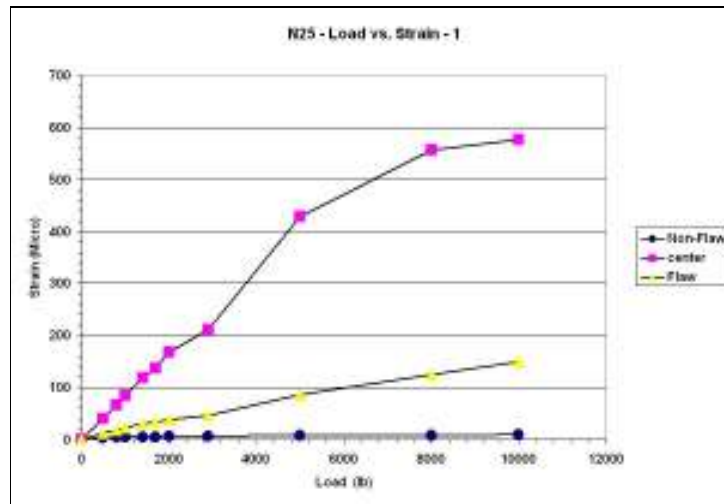
a)
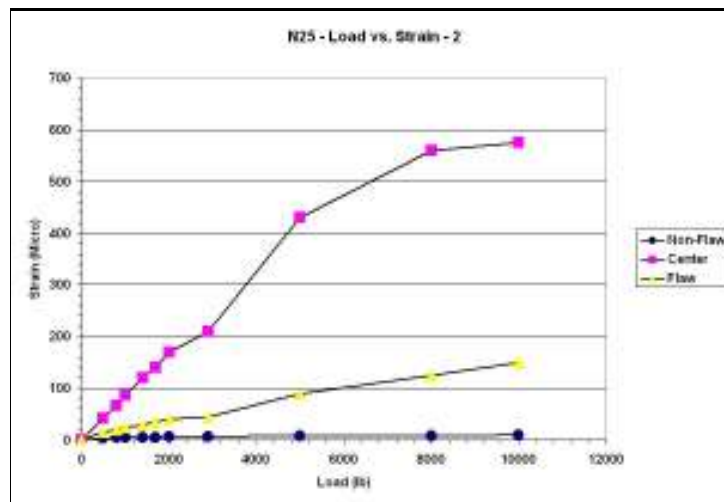
b)

Figure 3.20: Load vs. strain graph for N 25 % flaw:
a) specimen 1   b) specimen 2

3.2.2.3 Beam N12

The three point bending test was conducted on a 4inch (102mm) notch with 12% flaw. The flaw was created in the same way as mentioned in earlier tests. Figure Set 3.21 shows the load vs. deflection for the beam with 12% flaw for the three beams tested.

Strain gauges S1, was placed on laminate where surface flaw of 12% was created . The strain gauge S2 was placed at center of laminate. The Strain gauge S3 was placed at same location but in opposite side where there was no flaw. The main objective of this was to study the variation of strain in laminate due to presence of flaw. The geometrical placement of these strain gauges can seen in Figure 2.9b

The failure of this beam manifests itself in the form of de lamination of CFRP and tearing of steel section were the notch was created . The beam failed at maximum load of 25kip (11.34mt), thus indicating that both the beams, i.e., one with 12% and one with 25% flaw failed at 25kip (11.34mt). Presence of flaw doesn't change the ultimate strength of the notched steel section. The load vs. strain set for this beam is shown in Figure set 3.23.From the graph we find there is large difference in strain values at flaw and non flaw area. As expected the maximum strain at the center then flaw and least non flaw area.
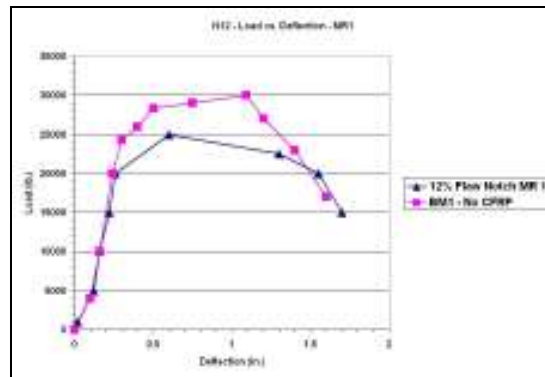
a)
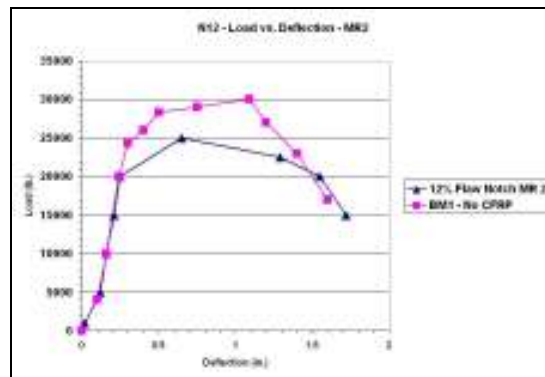
b)
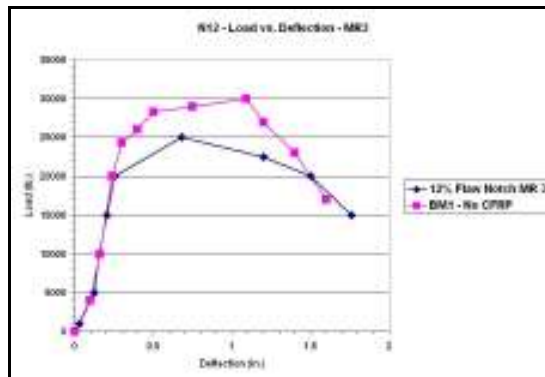
c)

Figure 3.21: Load vs. deflection N 12 % flaw with machine readings:
a) specimen 1 b) specimen 2 c) specimen 3

a)
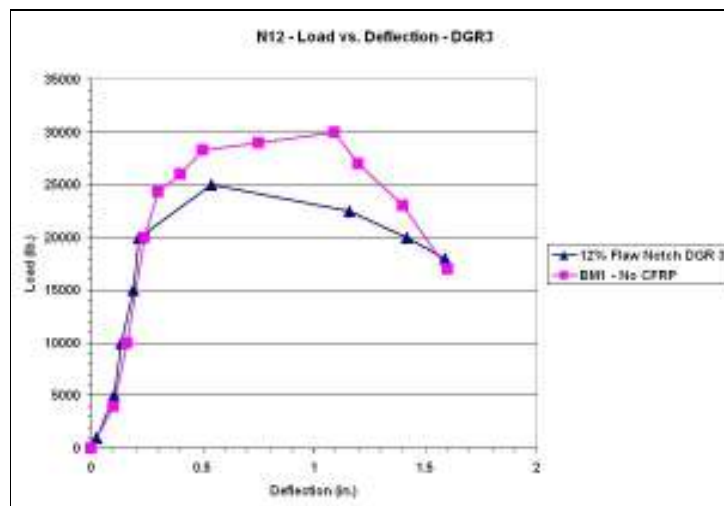
b)

Figure 3.22: Load vs. deflection N 12 % flaw with dial gauge readings:
a) specimen 2 b) specimen 3
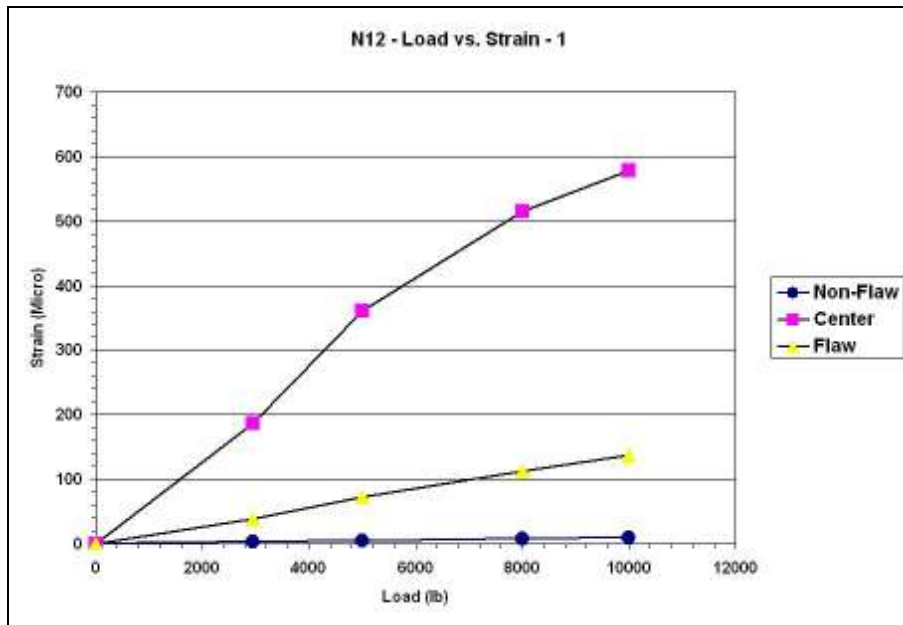
a)
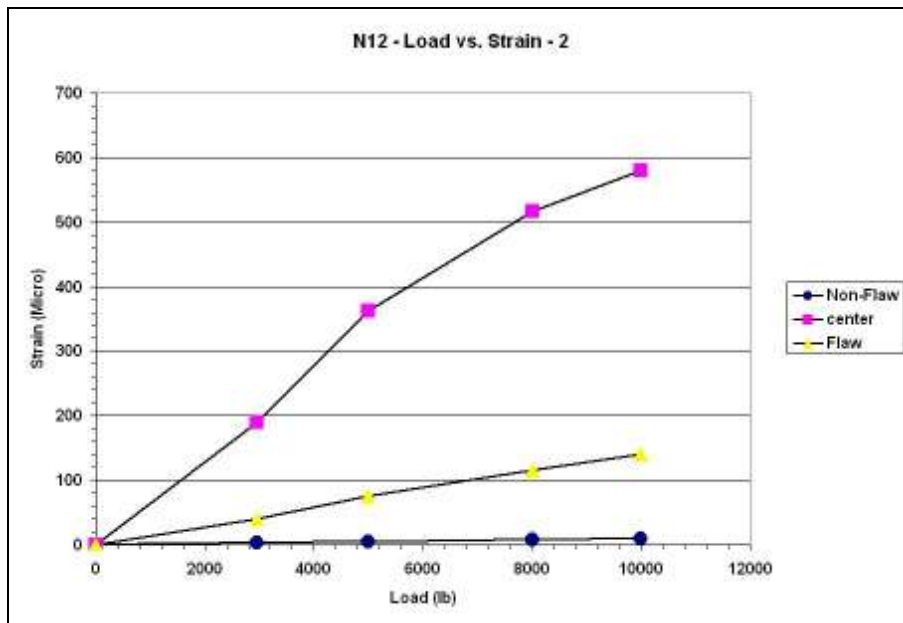
b)

Figure 3.23: Load vs. strain graph for N 12 percentage flaw:
a) specimen 2 b) specimen 3

3.2.2.4 Beam N6

The three point bending test experiment was performed on a notch of length 4inch (102mm), with a 6 % flaw in the laminate. The flaw was created in the same way as it was created in previous tests, at a location shown in Figure 3.24. The hydraulic load was applied at the center of the beam.

Figure 3.24: Showing 6% flaw in notched section

For every increase in load , the corresponding deflection values were recorded, and a set of three tests were performed to obtain the consistent values of load vs. deflection shown in Figure Set 3.25.

 Strain gauges S1, was placed on laminate where surface flaw of 6 % was created . The strain gauge S2 was placed at center of laminate. The Strain gauge S3 was placed at same location but in opposite side where there was no flaw. The main objective of this was to study the variation of strain in laminate due to presence of flaw. The geometrical placement of these strain gauges can seen in Figure 2.9b

The failure of this beam manifested itself in the form of de-lamination of CFRP and tearing of the notch in the beam. The beam failed at maximum load of 25kip (11.34mt), thus indicating that all the beams, i.e., one with 6%, one with 12% and one with 25% flaw failed at 25kips.The presence of flaw of 6% only still there was no increase in strength of notched steel section. At this point, a major interest in our direction of approach lay in the behavior of a notched beam with 0% flaw, and further tests were conducted, as shown in subsequent sections, in the light of the abovementioned findings.

The load vs. strain graph set for this steel section is shown in Figure Set 3.27.
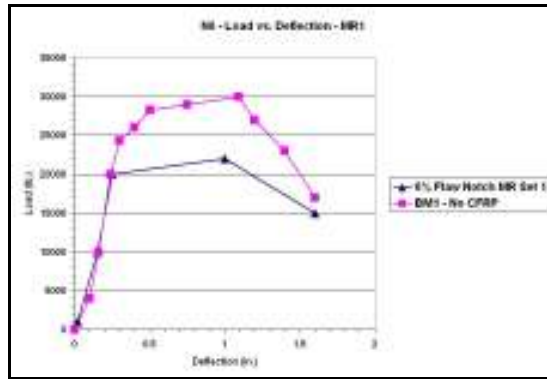
a)
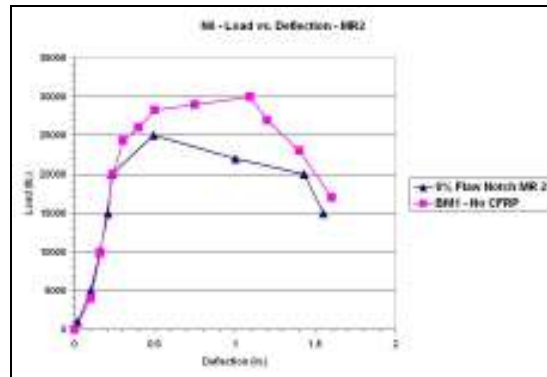
b)
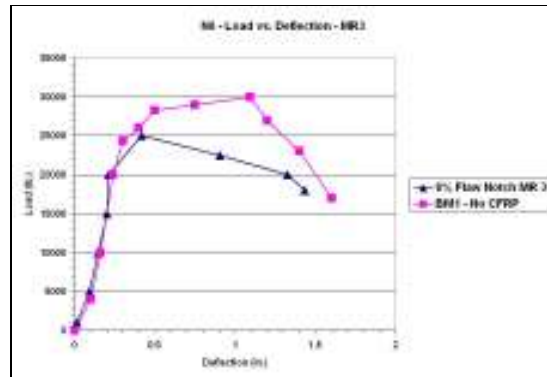
c)

Figure 3.25 Load vs. deflection N 6 % flaw with machine readings:
a) specimen 1 b) specimen 2 c) specimen 3
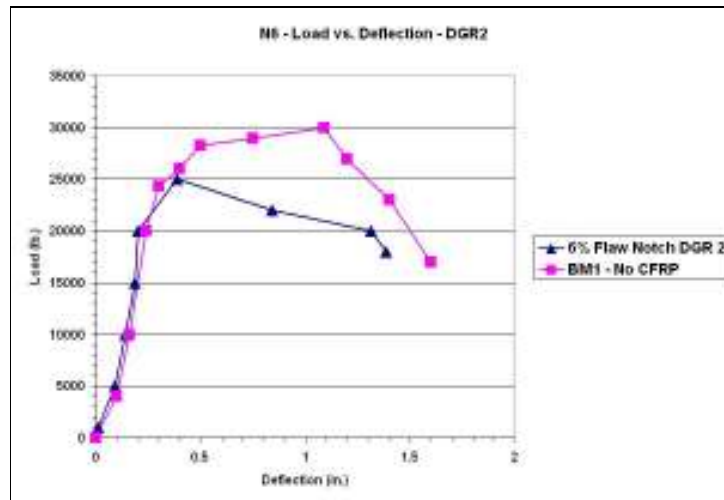
a)
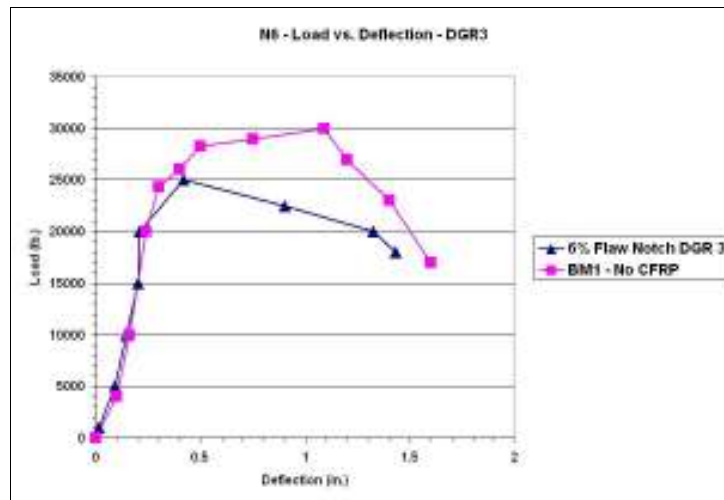
b)

Figure 3.26: Load vs. deflection N 6 % flaw with dial gauge readings:
a) specimen 2   b) specimen 3
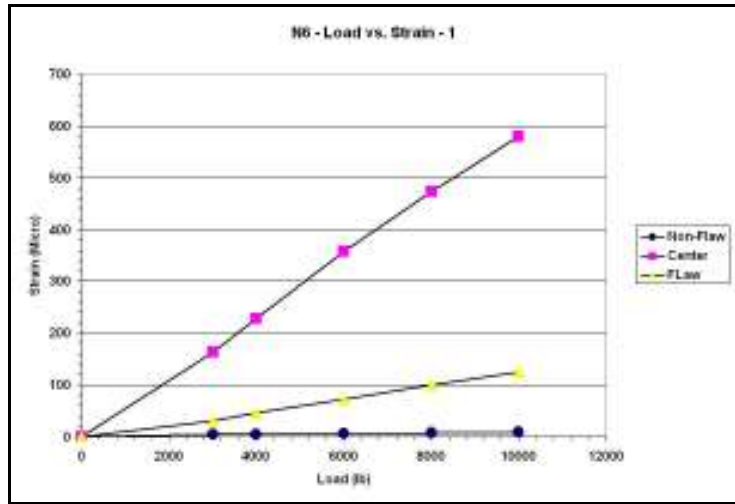
a)
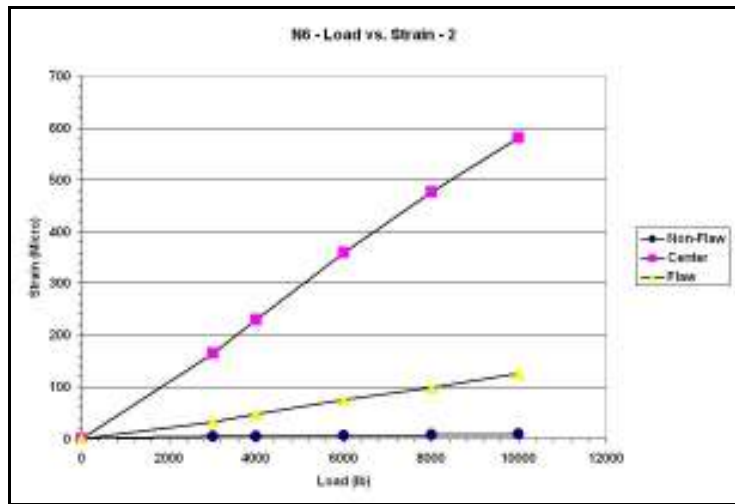
b)

Figure 3.27: Load vs. strain graph for N 6 percentage flaw:
a) specimen 1 b) specimen 2

3.2.2.5 Beam N0 (BM3)

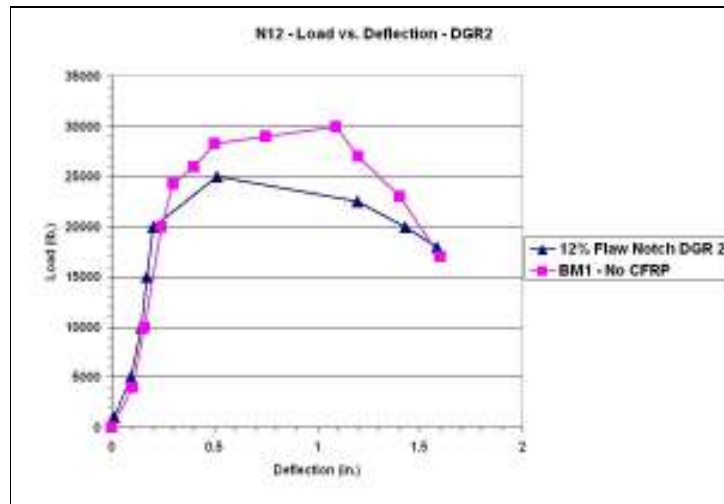The last three point bending test experiment was performed on a 4 inch notch with a 0 % flaw. This was achieved by bonding the pure CFRP laminate to the steel section, with the specified epoxy resin, and without the addition of any flaws, as shown in Figure 3.28.

Figure 3.28: Notched steel section with 0% flaw.

For every increase in load, the corresponding deflection values were recorded, and a set of three iterations were performed to obtain the consistent values of load vs. deflection shown in Figure Set 3.29.

The failure of this beam manifests itself in the form of de-lamination of CFRP and tearing of the notch in the beam. The beam failed at 35kip (15.90mt), indicating that the critical flaw occur between at 6 % flaw
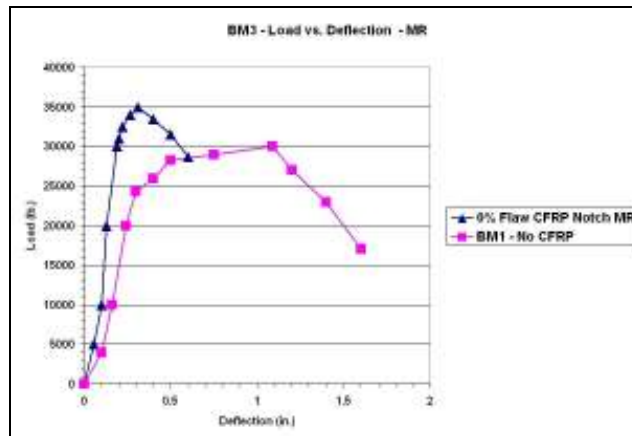
a)
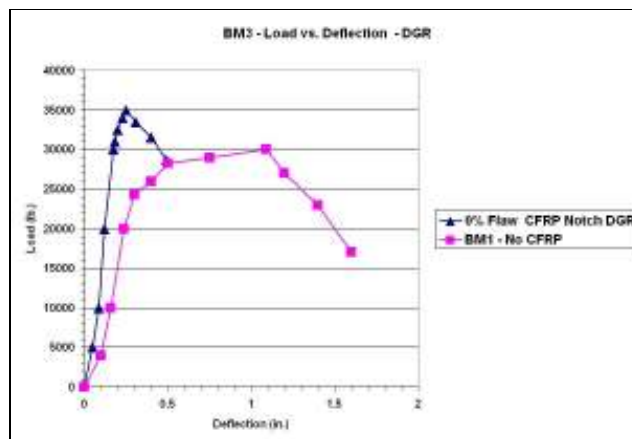
b)

Figure 3.29: Load vs. deflection N 0 % flaw by:
a) machine readings b) dial gauge readings

CHAPTER 4

ANALYSIS AND DISCUSSION OF RESULT

4.1 Introduction

Two kinds of test were conducted to study the relationship of percentage of flaw with change in strength. In this chapter, analysis of specimen tested and discussion of the research is carried out to develop an understanding of the relationship between the flaw percentages and the strength and efficiency of the CFRP reinforcement in the steel sections.

In our experiments, the deflection recorded was used as the reference-points in establishing this relationship. Four experiments were conducted for un-notched and eleven experiments on notched steel sections. In each type, separate sets of experiments were conducted on beams with different flaw percentages to obtain the deflection readings. Each such set of experimental readings for the deflection values were obtained first by machine readings, and by dial gauge readings for better accuracy and proper verification. The load vs. deflection graphs were plotted

separately, and the consistent readings were used as the baseline for the analysis of

beam properties, and in the computation of the corresponding load vs. strain graphs.

A summary of the experiments conducted on the steel beams is shown in Table 4.1.

Table 4.1 Matrix of ultimate load for experiments conducted

FLAW (% age)	Un-notched Max Load(lb)	Notched Max Load(lb)
6%	45,000	25,000
12%	50,000	25,000
25%	50,000	25,000
Beam (BM1)	30,000	-
Beam(BM2)	-	25000
Beam (BM3)	-	35000

4.2 Verification of the Steel Section Grade

The steel section provided by the manufacturer was tested to confirm

the grade of the steel material. The beam section is shown in Figure 4.1.

$\emptyset M_n$ = bending strength of the steel section

$\emptyset$ = factor (0.9, for bending)

F_y = yield strength of the steel section (36ksi)

S_x = section modulus (8.45 for S6 X 12.5)

The value of the parameter $\emptyset M_n$ is given by the following equation

$$\text{ØM}_n = \text{Ø F}_y \text{ S}_x = 0.9 \text{ X } 36 \text{ X } 8.45 = 273.4\text{kip-inch (315mt-cm).}$$

Mmax = ØM_n = PL/4; for a span of length (L) 34 inches, P = 31 kip. The steel sections considered in this thesis failed at 30 kip (13.6mt). Hence, the grade of steel is at least A36.
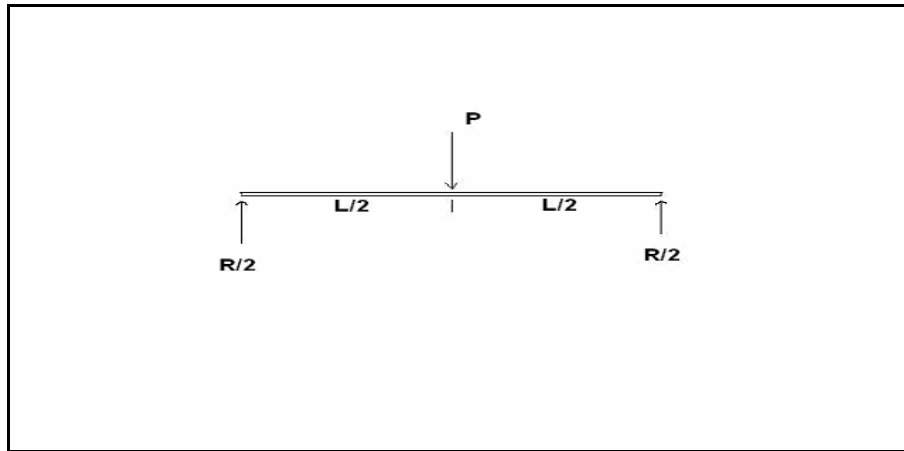
Figure 4.1: Beam section

4.3 Un-notched Steel Sections

Three point bending tests were conducted to study the relationship between the percentage flaw (Surface flaw created artificially described in earlier sections) and the variation in strength of the steel beams. The Load vs. Deflection comparison is shown in Figure 4.2. It consists of results for all the un-notched steel section test data in one graph.

63
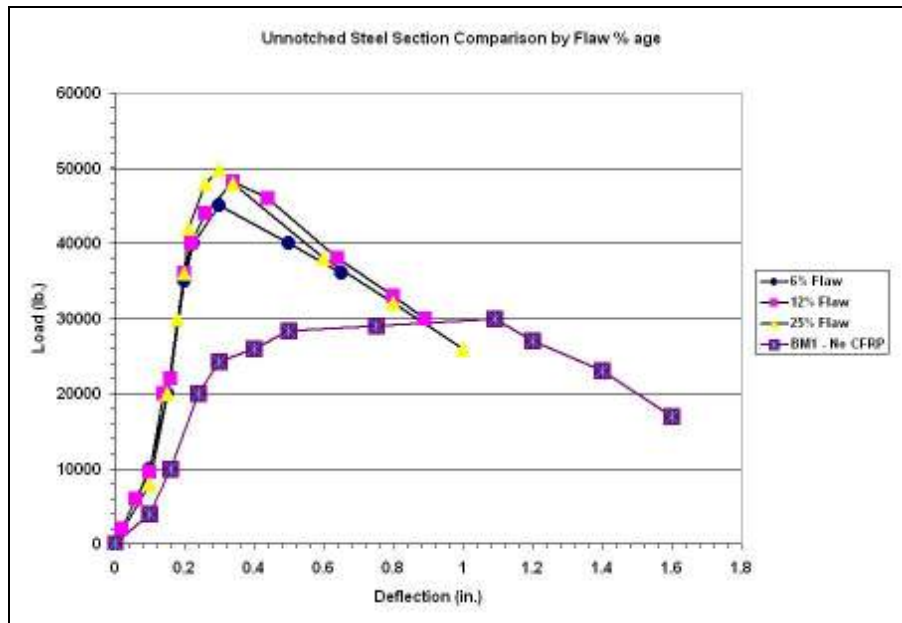
Figure 4.2: Un-notched steel section comparison

Three-point bending test was performed on an un-notched steel section with no CFRP, and the ultimate capacity of the steel section was observed to be 30 kip (13.6mt) indicating that the grade of steel is indeed 36 kips, as specified by the manufacturer. With 30 kip as a benchmark, and conducting the three-point bending tests on the un notched steel beams with varying flaw percentages as mentioned above, it was observed that there was an increase in the strength of steel section from 30kip to 49kip (13.60mt to 22.22mt). It was observed that there is a significant improvement in the strength of the steel sections with the introduction of the CFRP laminates. However, all the un-notched steel beams with various flaws failed at 49kip, irrespective of the magnitude of flaw percentages. Hence, we can safely infer that the

flaw percentages introduced in the CFRP of the steel beams in our experiments were not sufficient for us to reach the critical flaw percentage, beyond which the introduction of a CFRP laminate would not result in any increase in the strength of the steel section.

The slope of the load vs. deflection graph of the benchmark steel section Beam BM1 (no CFRP, un-notched) provided by the manufacturer was used as the benchmark stiffness of the steel beam. Subsequent to this, the slopes of the load vs. deflection graphs of the steel beams with 6%, 12% and 25% flaw values gave us their respective stiffness parameter values. It was observed that there was an increase in stiffness with respect to our benchmark steel section, leading us to infer that this increase can be attributed to the introductions of the CFRP laminate onto the steel beams. However, at this point, it is uncertain if the full potential of increase in the stiffness of the steel beams was achieved, with our selected percentage flaw values.

During the course of our experiment after testing the 6% flaw and 12% flaw beams respectively, it was decided to compare strain values for steel sections and the CFRP at the same location. Therefore, in the subsequent experiment on the steel section with 25% flaw, the strain gauges were placed at the center of the composite beam, both at the CFRP laminate, and on the tension flange of the steel section simultaneously. From the graph shown in Figure 3.13, we observed that the strain values in the CFRP laminate were very low compared to those in the steel section.

This indicated that the transfer of stresses from the steel section onto the CFRP laminate is not uniform. Therefore, in order to ensure efficiency in this transfer of stresses, it was decided to create a 4 inch notch at the center of the beam, as described in section 3.2.2 of this thesis.

After performing the three point bending tests on the original manufacturer-provided benchmark steel section (un-notched, no CFRP), it was seen that the mode of failure of the beam was a yielding failure. This observation motivated us to compare the failure modes in the steel sections of the subsequent experiments having varying flaw percentages. It was observed that the failure modes for the un-notched beams with 6%, 12% and 25% flaw percentages failed in lateral torsion buckling as when compared to the yielding failure previously observed. Hence, it might be concluded that the introduction of CFRP laminates to the steel sections changed the mode of failure from that of a yielding failure (i.e. ductile failure) to that of a lateral torsion buckling (i.e. non-ductile failure). However, further research needs to be conducted to establish the precise relationship between the flaw percentages in the steel sections and the ductility of the composite beams.

Lateral Torsional Buckling For Un-notched Beam

The limiting un-braced length, Lp is as follows
For I shaped member including hybrid section and channels:

Lp =1.76*r*Sqrt(E/Fy)

66

E= Modulus of elasticity of steel, 29000 Ksi.

Fy=Yield stress of steel, 36 Ksi

r= Radius of gyration, Sqrt. (Ixx/A)=0.702

Therefore Lp = 1.76*0.702*Sqrt (29000/36)

$\quad\quad\quad\quad\quad$ = 35.06"

4.4 Notched Steel section

From the results of the experiment conducted on the un-notched steel sections, it was decided to create a notch, as described in Sections 3.2.2 and 4.3 above. In this phase of our experimental research, experiments were conducted for the steel beams with the same flaw percentage values as for un-notched specimen. A total of 11 tests were conducted in this phase – 3 each for the 6%, 12% and 25% flaw beams respectively, one for the no-flaw notched steel section with CFRP and one for the notched steel section without CFRP. The 6%, 12% and 25% tests were performed with 3 iterations a piece to obtain the consistency in the readings, even taking into account all possible sources of experimental errors. This phase of work there were two more benchmark experiments in order to accommodate the notched steel section, namely – the no-flaw notched steel section with CFRP and notched steel section without CFRP.

In this phase, the deflections of the notched steel beams were recorded using the machine readings, as well as the dial gauge readings. Dial gauge readings are more accurate as when compared to machine readings.

The following graphs shown in Figure Set 4.3 depict the comparison of the load vs. deflection characteristics of the notched steel beams with various flaw percentages, captured both by dial gauge and machine readings.

The graphs in Figure Set 4.3 were plotted for the average values of the readings in the iterations of the experiments on the notched beams with respective flaw percentages.

Three-point bending test was performed on a 4inch (102mm) notched steel section , and the ultimate capacity of the steel section was observed to be 25 kips (11.34mt) indicating that the strength of the manufacturer-provided steel section was reduced due to the introduction of the notch. The 4inch (102mm) notch was created also to visualize, model and simulate the reduction in the strength of the steel section due to other environmental factors such as aging, corrosion, etc. This test was performed as a benchmark for further studies of the properties of steel sections with varying flaw percentages.
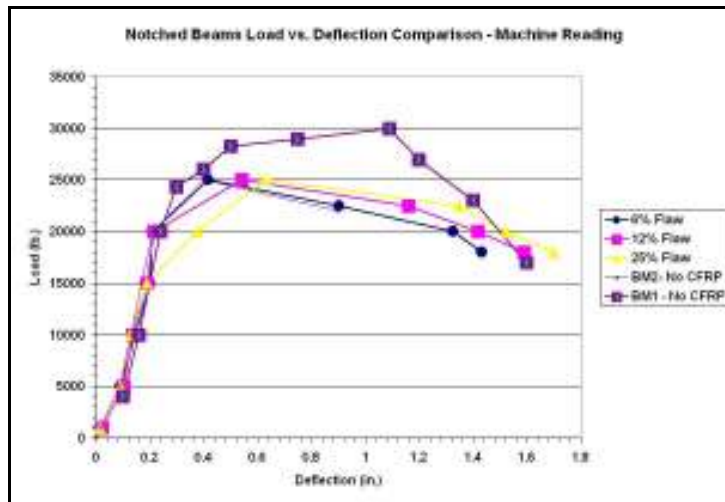
a)
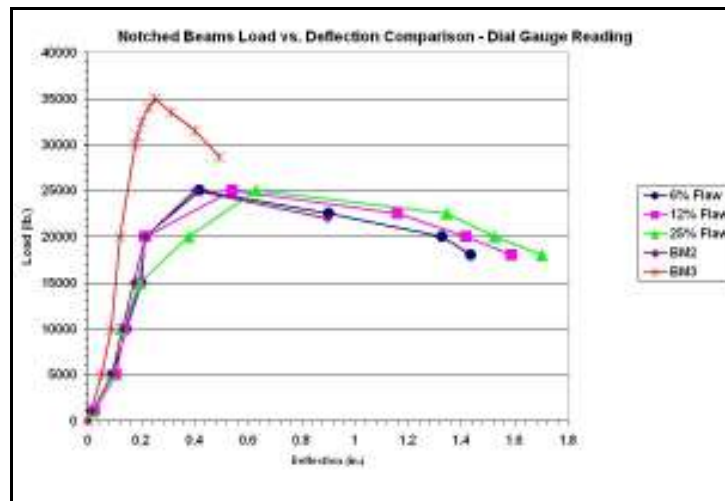
b)

Figure 4.3: Load vs. deflection of N-steel section for 6%, 12% & 25% flaw:
a) machine readings b) dial gauge readings

With this as a benchmark, and after conducting the three-point bending tests on the notched steel beams with varying flaw percentages as mentioned above, it was observed that there was no significant increase in the strength of steel sections due to the presence of the CFRP laminates having 6, 12& 25 flaw.).Hence, it could be concluded that the strength of the steel sections remained independent of the introduction of the CFRP laminates. All the steel beams with flaws failed at 25kip (11.34mt) uniformly in all cases, irrespective of the magnitude of the flaw percentages. At this point, the behavior of a notched steel section with 0% Flaw in the CFRP laminate bonded to the steel section became a topic of interest, and therefore, the experiment described in Section 3.2.2.5 of this thesis was conducted on the notched steel section with 0% flaw in the CFRP. It was observed that the strength of the steel section increased from 25kip to a value of 35kip (11.34 to 20.40mt), thus indicating that the introduction of CFRP laminate to the notched steel section improves its strength. This observation was consistent with the observations of previously conducted experiments. It was thus observed that even with a flaw of 6% in our experiment, the critical flaw percentage value was exceeded.

A possible reason for the non-increase in the strength of the notched steel sections can be attributed to improper bonding of the epoxy resin with the steel section, the epoxy resin provided by the supplier have been used for bonding concrete.

The slope of the load vs. deflection graph of the benchmark steel section (no flaw, no CFRP, notched) indicated the stiffness of the pure notched steel beam. Subsequent to this, the slopes of the load vs. deflection graphs of the notched steel beams with 6%, 12% and 25% flaw values gave us their respective stiffness parameter values. It was observed that there was an increase in stiffness with respect to our benchmark notched steel section, leading us to infer that this increase can be attributed to the introductions of the CFRP laminates onto the notched steel beams. However, at this point, it is uncertain if the full potential of increase in the stiffness of the notched steel beams was achieved, with our selected percentage flaw values.

In this phase of experiments, a strain gauge called 'flaw' was placed at the top of the CFRP laminate area where the flaw was created. Simultaneously, at the other end of the CFRP laminates, a strain gauge was placed at a location congruent to the flaw location, and was called 'non-flaw'. A third strain gauge was placed at the center of the CFRP laminate, and was called 'center'. This setup was implemented on the steel sections with 6%, 12% and 25% flaws, in order to analyze the behavior of the strain in the notched beams with changing flaw.
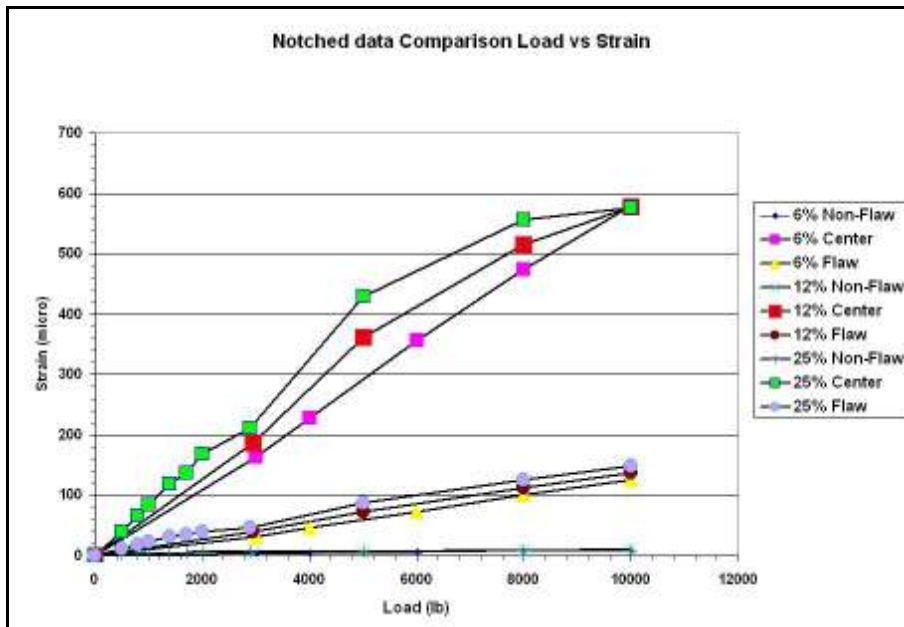
Figure 4.4: Load vs. strain plot for notched steel section for 6%, 12% and 25% flaw

The graphs in Figure 4.4 were plotted for the average values of the readings in the iterations of the experiments on the notched beams with respective flaw percentages.

From the above graphs, a trend can be observed in the strain values of the CFRP laminate at different flaw locations. As expected, the strain gauge values were the highest at the center, next at the flaw areas, and the lowest at the non-flaw areas. This trend was observed in the steel sections with all the selected flaw percentage values – namely 6%, 12% and 25%. It was also observed that the highest strain magnitudes for each of the respective strain gauge locations were observed in the steel

section with 25% flaw, next in the steel section with 12% flaw, and lowest in the steel section with 6% flaw. Also, there was an occurrence of partial de lamination of the CFRP laminate bonded to the steel section. There was partial de lamination seen at 10 kip in all the experiments of this phase. We suspect this to be due to the fact that the epoxy resin (bonding agent) used for this experiment and supplied by the provider was originally intended for use in bonding with concrete. It was observed that full de-lamination for 6% .12% and 25% was 17 kip, 14 kip and 12 kip respectively. This indicates there might be linear relationship between for percentage of flaw vs. strength. Still more extensive test need to be conducted to find the exact relationship.

After performing the three-point bending tests on our benchmark steel section (notched, no CFRP), it was seen that the mode of failure of the beam was a yielding failure. This observation motivated to compare the failure modes in the notched steel sections of the subsequent experiments in this phase having varying flaw percentages. It was seen that the failure modes for the notched beams with 6%, 12% and 25% flaw percentages also failed by yielding (ductile mode of failure). It is seen from the tests that there is an improvement in the ductility of the notched steel sections with the introduction of the CFRP laminate, unlike in the case of the un-notched steel sections. Also, it was observed that with an increase in the percentage of flaw, there is a distinct reduction in the ductility of the notched steel beams. Therefore, we might conclude that the ductility of the notched steel beams decreases with an increase in the flaw percentages.

Lateral Torsional Buckling for Notched Beam

The limiting un-braced length, Lp is as follows
For I shaped member including hybrid section and channels:

Lp =1.76*r*Sqrt(E/Fy)

E= Modulus of elasticity of steel, 29000 Ksi.

Fy=Yield stress of steel, 36 Ksi

Ixx = Moment of inertia (notch)=9.11

   r= Radius of gyration, Sqrt. (Ixx/A)=0.66

Therefore Lp   = 1.76*0.66*Sqrt (29000/36)

                 = 33"

CHAPTER 5

CONCLUSION AND SCOPE OF FUTURE WORK

This study focused on determining how the strength of CFRP bonded to steel I section behaves due to the presence of flaws. An extensive literature review was conducted regarding this area, but there was no data describing how the variation occurs with different flaw percentage. The works presented in this research try to address the issue and to understand the behavior.

- All un-notched beams with various flaw size failed at same load of 49kip (22.22mt). Hence flaw size up to 25% flaw was not critical.

- All un-notched beams with different flaw size shows similar stiffness up to load of 40,000lb (18142kg).

- All un-notched beams with different flaw size show linear variation up to 40,000lb (18142kg).

- All un-notched beam shows increase in strength compare to bench mark Beam BM1

- It was observed there was increase in stiffness for un-notched beam compare to bench mark Beam BM1.

- Very negligible stresses were transferred during the test from steel section to CFRP laminate in un-notched beams. Hence there was no de-lamination of CFRP.

- All un-notched steel sections failed in LTB. This may be due to small eccentricity in the loading.

- Yield line is steeper with increase in percentage of flaw in CFRP for all un notched steel sections.

- All notched beams with different flaw size shows similar stiffness up to load of 15,000lb (6803kg).

- All notched beams with different flaw size shows linear variation up to 15,000lb (6803kg).

- There was clear de-lamination of CFRP from steel in notched steel section. Hence the stresses are getting transferred to CFRP laminate from steel.

- De-lamination of CFRP took place first where flaw was created for notch beam with 25% flaw. Hence strain are more in the flaw area compared to the non flaw area.

- The failure mode of notched steel section was symbolized by the tearing of the beam at the corner of notch. The failure was ductile and not brittle.

- The strain in CFRP at flaw and non flaw area for notch and 25% flaw was of the order of 10 times. Still, the strain in steel was more than flaw area.

- It was also seen that full de-lamination for notched beam with 6% .12% and 25% flaw was 17kip, 14kip and 12kip (7.7mt, 6.35mt and 5.44mt) respectively. This indicates there might be linear relationship between for percentage of flaw vs. strength.
- All beams with different flaw size (6, 12, & 25%) there was no increase in ultimate capacity as it failed at 25kip (11.34mt) same as benchmark Beam BM2. This could be explained as 6% flaw was critical flaw size.

The present research has dealt only with flaws related to un-bonded CFRP to steel sections. Further research has to be done in this field. More experiments have to be conducted in order to see how this variation of flaw below 6% changes the strength. More experiments have to conducted on position of flaw. To check if the result remain same if the flaw was in center and not on the edge. Some test should include the envoi mental effects, heat , impact etc

APPENDIX A

GLOSSARY

Some of the common definitions   that are extensively used in the field of Composites are listed below for easy reference. Some of these definitions are used above at appropriate places.

Air-bubble Void: Air entrapment within and between the plies of reinforcement; non interconnected, spherical in shape.

Air Vent: Small outlet to prevent entrapment of gases.

Anisotropy of Laminates: The difference of the properties along the directions parallel to the length or width into the lamination planes; or parallel to the thickness into the planes perpendicular to the lamination.

Aspect Ratio: The ratio of length to diameter of a fiber.

Binder: A resin soluble adhesive that secures the random fibers in chopped strand mat or continuous strand roving.

Bond Strength: The amount of adhesion between bonded surfaces; a measure of the stress required to separate a layer of material from the base to which it is bonded.

Burst Strength: (1) Hydraulic pressure required to burst a vessel of given thickness, commonly used in testing filament-wound composite structures. (2) Pressure required breaking a fabric by expanding a flexible diaphragm or pushing a smooth spherical surface against a securely held circular area of fabric. The Mullen expanding diaphragm and Scott ball burst machine are examples of equipment used for this purpose.

Casting: The process of pouring a mixture of resin, fillers and/or fibers into a mold as opposed to building up layers through lamination. This technique produces different physical properties from laminating.

Catalyst: Technically considered an initiator, catalyst is the colloquial name given to the substance added to the resin or gel coat to initiate the cure

Composite: A reinforcing fiber in a resin matrix whose cumulative properties are superior to the individual materials.

Compressive Strength: The stress a given material can withstand when compressed. Described in ASTM D-695.

Cure: The completion of the cross-linking process during which a composite develops its full strength.

Cure Temperature: Temperature at which a cast, molded, or extruded product, a resin-impregnated reinforcement, an adhesive, etc., is subjected to curing.

Cure Time: Time between introduction of catalyst or initiator to a polymer and final cure.

Curing Agent: A catalytic or reactive agent which when added to a resin causes polymerization; synonymous with hardener.

De-laminating: The separation of composite layers from each other.

E-glass: Originally formulated for use in electric circuitry, E-glass is the most common glass formulation used in fiberglass reinforcements.

Epoxy Resin: A polymer resin characterized by epoxies molecule groups.

Fiber: Reinforcement material which is a major component in a composite matrix.

Fiber Diameter: The measurement (expressed in hundred-thousandths) of the diameter of individual filaments.

Fiberglass: Glass which has been extruded into extremely fine filaments. These filaments vary in diameter, and are measured in microns. Glass filaments are treated with special binders and processed similar to textile fibers. These fibers come in many forms such as roving, woven roving, mat and continuous strands.

Fiber Orientation: Fiber alignment in a non-woven or a mat laminate where the majority of fibers are in the same direction, resulting in a higher strength in that direction.

Fiber Pattern: Visible fibers on the surface of laminates or moldings; the thread size and weave of glass cloth.

Filament: A single thread-like fiber of extruded glass, typically microns in diameter.

Fillers: Usually inert organic or inorganic materials which are added to plastics, resins or gel coats to vary the properties, extend volume, or lower the cost of the article being produced.

Flexural Modulus: An engineering measurement which determines how much a sample will bend when a given load is applied, Described in ASTM D-790.

Flexural Strength: The resistance of a material to being broken by bending stresses; the strength of a material in bending, expressed as the tensile stress of the outermost fibers of a bent test sample at the instant of failure. (With plastics, this value is usually higher than the straight tensile strength.)

Flow: The movement of resin under pressure, allowing it to fill all parts of a mold; flow or creep - the gradual but continuous distortion of a material under continued load, usually at high temperature.

FRP: Fiber Reinforced Plastics, also known as GFRP (Glass Fiber Reinforced Plastic), GRP (Glass Reinforced Plastic), FRP (Reinforced Plastic) and Composites.

GRP: Glass reinforced plastics. Generally based on polyester resin. See Fiberglass, FRP.

Hand Lay Up: The process of manually building up layers of fiberglass and resin using hand rollers, brushes and spray equipment.

Hardener: A substance or mixture added to a plastic composition to promote or control the curing action by taking part in it. Also, a substance added to control the degree of hardness of the cured film.

Impregnate: To saturate with resin. The most common application is saturating fiberglass with a catalyzed resin.

Inhibitor: An additive to polyester resin or styrene used to slow the chemical reaction which leads to curing.

Insert: A piece of material put into a laminate during or before molding to serve a definite purpose.

Inter-laminar Shear Strength: The maximum shear stress existing between layers of a laminated material.

Laminant: The product of lamination. A composite consisting of a layer or layers of thermo set polymer and fiber reinforcement.

Laminate: To place into a mold a series of layers of polymer and reinforcement. The process of applying FRP materials to a mold. To lay up.

Lamination: Applying layers of glass and resin to a mold. Also used to describe a single ply of laminate.

Matrix: The liquid component of a composite or laminate.

Modulus of Elasticity: An engineering term used to describe a material's ability to bend without losing its ability to return to its original physical properties.

Pattern: The initial model for making fiberglass molds. See <u>Plug</u>.

Polymer: A chain molecule composed of many identical groups, commonly found in plastics.

Pot Life: The time during which the catalyzed resin remains liquid or "workable." See <u>Gel Time</u>.

Resin: A liquid polymer which when catalyzed cures to a solid state.

Resin Content: The amount of resin in a laminate expressed as either a percent of total weight or total volume.

Resin-Rich Area: Space which is filled with resin and lacking reinforcing material.

Resin-Starved Area: Areas of insufficient resin, usually identified by low gloss, dry spots or fiber show.

Resin Tearing: Separation of pigments in a gel coat affecting cosmetic appearance.

Stiffness: The relationship of load and deformation; a term often used when the relationship of stress to strain does not conform to the definition of Young's modulus.

Strands: A primary bundle of continuous filaments (or slivers) combined in a single compact unit without twist. These filaments (usually 51, 102 or 204) are gathered together in the forming operations.

Tenacity: The term generally used in yarn manufacture and textile engineering to denote the strength of a yarn or of a filament of a given size. Numerically it is the grams of breaking force per denier unit of yarn or filament size; grams per denier, gpd. The yarn is usually pulled at the rate of 12 inches per minute. Tenacity equals breaking strength (grams) divided by denier.

Tensile Load: A dulling load applied to opposite ends of a given sample.

Tensile Elongation: An engineering term referring to the amount of stretch a sample experiences during tensile strain. ASTM D-638.

Tensile Strength: A measurement of the tensile load a sample can withstand. ASTM D-638.

Thermoplastics: A group of plastic materials that become elastic or melt when heated, and return to their rigid state at room temperature. Examples are PVC, ABS, polystyrene, polycarbonates, nylon, etc.

Ultimate Tensile Strength: The ultimate or final stress sustained by a specimen in a tension test; the stress at moment of rupture.

Unidirectional: Strength lying mainly in one direction. A glass reinforcement in which the fiber is oriented in one direction.

Void Content: The percentage of voids in a laminate.

Void Free: A molding containing no entrapped air cavities, blisters, or voids.

Water Absorption: The amount of water which a laminate will absorb.

Wet Lay-up: The reinforced plastic which has liquid resin applied at the reinforcement is laid up. The opposite of "dry lay-up", "prepreg".

Yield Strength: The stress at which a material exhibits a specified limiting deviation from the proportionality of stress to strain; the lowest stress at which a material undergoes plastic deformation. Below this stress, the material is elastic; above it, viscous.

Young's Modulus: The ratio of tensile stress to tensile strain below the proportional limit.

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BIOGRAPHICAL INFORMATION

Sharad Chandra choudhary was born in Bihar, India in January of 1977. He earned his Bachelor of Engineering in Civil Engineering from Bangalore University in 2001. After that he worked as structural engineer in Delhi for two years. He decided to pursue his master's degree in Civil Engineering (Major in structural engineering) at University of Texas at Arlington. He finished his research in "Effects of de bonding flaw size and location on flexural performance of cfrp retrofitted steel section" under supervising professor Dr Guillermo Ramirez .He was awarded civil engineering scholarship from University of Texas at Arlington.