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## A Survey on Strengthening Steel Bridge Girders Using CFRP

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**ABSTRACT:** While traditional retrofitting methods for steel bridge girders could be time consuming and uneconomical, an alternative repair method is suggested using Carbon Fiber Reinforced Polymers (CFRP) laminate strips, providing engineers with a competitive solution that will increase the life-cycle of repaired bridges. This study investigated its feasibility as an option to strengthen and rehabilitate steel bridges. The main advantages of using CFRP laminates are their light weight and durability, which results in ease of handling and maintenance. The research conducted experimental and analytical work to evaluate the effectiveness of strengthening steel beams by the use of novel CFRP laminate strips configurations. The research involved the testing of five experimental composite beams, in addition to the development of approximately 100 finite element models. The results showed a significant gain in the beam's elastic and ultimate capacities. The conclusion is that there are specific sensitive parameters controlling the effectiveness of the CFRP laminate rehabilitation technique. An adequate AASHTO design of the rehabilitation method, which takes into consideration the effective parameters, would result in an effective bridge structure.

**KEYWORDS-**CFRP, Steel Beams, Bridge Girders, Rehabilitation, Strengthening, Finite Element Modeling

### I. INTRODUCTION

#### 1.1 Introduction of the Project Work

Throughout the India, there are thousands of steel bridges that are at various levels of advanced deterioration due to many years of service and exposure to the environment (Liu, Silva, & Nanni, 2001). Rehabilitation can involve various strategies and application methods. These strategies include adding steel plates to the girders in order to increase the girder capacity, adding new girders between the old ones (McRae & Ramey, 2003), or replacing the whole bridge superstructure. Moreover, load ratings decrease as bridges deteriorate, which affects truck routing and loading limits and in turn affects freight costs dramatically. CFRP materials have been predominantly used by the aerospace industry, where cost is generally a secondary consideration to weight (Jones R. , 1998). Carbon fibers were first used in civil applications at Swiss Federal Testing Laboratories (Burgoyne, 1999). The bridge collapse in Minnesota in 2007 was a wakeup call for bridge engineers and departments of transportation. Current bridge inspection is mainly visual and lacks in-depth inspection, such as strain and stress evaluation of different structural elements. Besides the rehabilitation method using carbon fiber reinforced polymers (CFRP) laminates discussed in the report, modeling techniques using FE to verify the usefulness of the method are also presented.

##### a. Motivation

During the recent decades, Carbon Fiber-Reinforced Polymer (CFRP) composite materials have proven valuable properties and suitability to be used in the construction of new buildings and in upgrading the existing ones. The objective of this paper is to review the previous work in this area and compare it with the current experimental results to show the design equations for CFRP strengthened steel structural elements. Research findings have shown that

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CFRP sheets and strips are not only effective in restoring the lost capacity of a damaged steel section, but are also quite effective in strengthening of steel sections to resist higher loads, extend their fatigue life and reduce crack propagation.

## b. Background

This paper investigates the effect of CFRP strengthening on dynamic and fatigue responses of composite bridge using finite element program ABAQUS. Dynamic and fatigue responses of composite bridge due to truck load based on AASHTO standard are investigated. Two types of CFRP strengthening techniques, CFRP sheets and CFRP deck, are applied to both the damaged and undamaged bridges. For the case of damaged bridge, two through-thickness crack sizes, 3mm and 6mm in depth, are assumed at midspan of the steel girders. Furthermore, effects of the number of steel girders on the dynamic and fatigue responses are also considered. The results show that the maximum responses of composite bridges occur for dual lane cases. By using CFRP as a strengthening material, the maximum stress and deflection of the steel girders reduce and consequently increase the fatigue life of the girders. After introducing initial crack into the steel girders of the composite bridges, the fatigue life of the bridges is dramatically reduced. However, the overall performance of the damaged composite bridge can be improved by using CFRP, albeit with less effectiveness. Therefore, if cracks are found, steel welding must be performed before strengthening the composite bridge by CFRP

## 1.2 Objectives

The objective of this research is to quantify the load improvement using novel CFRP configurations and develop design guidelines for using CFRP laminates to strengthen steel bridge girders.

## 1.3 Scope of the Project Work

The scope of this research is limited to the strengthening of steel beams in flexure only. No shear strengthening is included. Steel beams for the experimental work were chosen to have enough shear-carrying capacity throughout the loading process. The main focus was to increase the load carrying capacity of the beams using CFRP plates' configurations. Only laboratory strengthening was performed.

## II. LITERATURE REVIEW

### 2.1 Introduction

Many state and local agencies are faced with deteriorating bridge infrastructure composed of relatively short to medium-span bridges. In many cases, these older structures are hot-rolled or welded longitudinal steel stringers acting compositely with a reinforced concrete deck (Wipf T. J., Phares, Klaiber, & Lee, 2003). Bridge deterioration rates, durability and longevity performance have been discussed thoroughly during the last few decades. A factor that receives too little consideration in bridge work is durability (Ramey & Wright, 1997). This leads to the huge number of structurally deficient and functionally obsolete bridges all over the United States.

### 2.2 Common Rehabilitation Field Applications

Conventional rehabilitation, such as welding steel plates to structural members has been the traditional method for a long time but induces high thermal stresses in the steel members. The induced stress reduces the member fatigue resistance. A rehabilitation design using conventional methods is discussed by Farhey (Farhey, et al., 2000), as applied to an existing historic bridge crossing Sandusky River in Fremont, Ohio. Although the conventional restoration methods are still applicable and preferred in some structural elements, such as the gusset plates, the CFRP method is on the rise as a rehabilitation technique to be used with bridge elements, such as main girders.

When total replacement is not an option and traditional retrofit methods are uneconomical and time consuming, an alternative retrofit method using CFRP composite material provide engineers with an effective solution that can

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increase the life cycle of these bridges. Research recently conducted on the use of CFRP for strengthening and repair of steel beams has been investigated (Mertz & Gillespie, 1996), (Tavakkolizadeh&Saadatmanesh, 2003) and (Al-Saidy, Klaiber, &Wipf, 2004). A number of different approaches have been studied to assess the effectiveness of various CFRP materials for the strengthening and repair of steel bridges, including the repair of overloaded girders (Sen, Libby, & Mullins, 2001).

A proposed solution to strengthen the damaged reinforced concrete headstock of the Tenthill Creeks Bridge, Queensland, Australia, using FRP composites was presented by Nezamian (Nezamian&Setunge, 2007). A decision was made to consider strengthening the headstock using bonded carbon FRP laminates to increase the load-carrying capacity of the headstock in shear and bending. reliability analysis of reinforced concrete bridge girders strengthened by CFRP laminates was developed by Okeil (Okeil, El-Tawil, &Shahawy, 2002). A resistance model is used to calculate the probability of failure and the reliability index of CFRP-strengthened cross sections. The reliability method is employed to calibrate the flexural resistance factor for a broad range of design variables. The study shows that the addition of CFRP improves reliability somewhat because the strength of CFRP laminates has a lower coefficient of variation than steel or concrete.

The rehabilitation of an existing concrete bridge in Alabama through external bonding of FRP plates to the bridge girders was performed by Stallings (Stallings, Tedesco, El-Mihilmly, & McCauley, 2000). Field load tests were conducted before and after application of the FRP plates to evaluate the advance in structural response.

## 2.3 Guidelines of Using FRP Reinforcement in the United States

Design guidelines and testing protocols for FRP reinforcement are nationally defined for concrete structures. The American Concrete Institute (ACI) presents a number of technical reports for the design, construction, and repair of concrete structures using FRP reinforcement. Recommendations for the design and construction of FRP reinforcement based knowledge gained from worldwide research can be found in ACI 440.1R-03 (ACI Committee, 2003). Flexure and shear design procedures, and FRP reinforcement detailing are presented in this report. The report also includes material characteristics of commercially available FRP.

Although FRP design, construction, and rehabilitation guidelines are available for concrete structures, similar guidelines are not available for steel structures.

## 2.4 Guidelines of Using FRP Reinforcement Worldwide

Limited literature was found for design guidelines of FRP worldwide. Deeks and Hao, (2004) mention some design guidelines and safety factors. Based on BS 8110 (1997), the guidelines identify critical areas to be assessed along the length of the beam. These are the areas of maximum moment and the ends of the FRP. It is recommended that internal steel reinforcement yield before failure from either concrete crushing or FRP rupture. BS 8110 (1997) also recommends that the characteristic material properties be divided by appropriate partial safety factors. The partial safety factors for concrete in flexure,  $\gamma_c$ , and steel reinforcement,  $\gamma_s$ , are 1.50 and 1.15, respectively. The partial safety factor for strength of FRP is equal to the type of fiber,  $\gamma_{mf}$ , multiplied by the stage in the manufacturing route in which the FRP samples were taken for testing,  $\gamma_{mm}$ , (e.g. in-situ or factory). CFRP, GFRP, and AFRP (C: carbon, G: glass, and A: aramid) have  $\gamma_{mf}$  values of 1.40, 3.50, and 1.50, respectively, while  $\gamma_{mm}$  varies from 1.10 to 2.0. The recommended partial safety factors for modulus of elasticity,  $\gamma_{mE}$ , are 1.10, 1.80, and 1.80, for CFRP, GFRP, and AFRP, respectively. To avoid any possibility of brittle failure, the ultimate moment capacity may be increased by 1.15.

## 2.5 FRP Types and Applications

Fiber reinforced plastic (FRP), also known as fiber reinforced polymer, is a composite material consisting of a polymer matrix reinforced with fibers. Fibers are usually aramid, fiberglass, or carbon, while the polymer is usually a vinyl ester, polyester thermosetting plastic, or epoxy.

Figure 2-1 shows a stress-strain comparison between steel and various FRPs. It shows that CFRP have similar stiffness to steel, while AFRP and GFRP have lower stiffness compared to steel. Both CFRP and AFRP have high strength

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compared to GFRP. Comparing the FRP modes of failure against steel, it is clear that all FRP have a brittle failure mode, while steel has its well-known ductile behavior.

## 2.6 CFRP Structural Characteristics

The material properties of the CFRP laminates have been greatly improved over the last few years, with a wide variety of dimensions and strengths required to achieve significant stiffness increases. More recently, CFRP materials with a modulus of elasticity approximately twice that of structural steel have become available. Several researchers have indicated that these materials can be used to increase the strength and stiffness of steel-concrete composite beams. Consideration of the CFRP plate end debonding as critical failure mode should be avoided to prevent an undesirable failure of the system. Debonding strength of steel beams strengthened with CFRP plates were discussed by Lenwari (Lenwari, Thepchatri, & Albrecht, 2006) and Nozaka (Nozaka, Sheild, &Hajjar, 2005). Spliced connections were further discussed by other researchers (Schnerch D. , 2005) and (Dawood, 2005).

## 2.7 CFRP in Steel Beam Applications

Several researches were performed on strengthening steel beams and steel girders using CFRP. Due to the great development in CFRP material properties, and due to the development of epoxies used, the gain in stiffness and strength in steel structures is still in the research phase. Two main CFRP products are used by structural engineer researchers in strengthening steel structures. These are CFRP laminates (plates) and CFRP tendons. CFRP laminates are available in a wide variety of thicknesses, widths, and lengths. The coming sections will focus on both CFRP products and review some of the research performed using these products.

## 2.8 CFRP Bond Behavior

Similar to the way stresses develop in reinforcement bars or plates, high concentrated stresses develop at the reinforcement ends. Several details were investigated by Schnerch (2007) to help reduce the bond stress concentration near the ends of the splice plate, including increasing the length of the splice cover plate, implementing a reverse taper near the plate ends, and applying a transverse CFRP wrap around the splice plate. It was found that increasing the length of the splice plate beyond the maximum moment region did not significantly increase the total capacity of the CFRP system but may be necessary to avoid sequential failure in unreinforced regions. Similarly, the presence of the transverse CFRP wrap did not increase the ultimate capacity of the spliced connection.

The debonding strength of partial-length adhesively bonded CFRP plates that are used to strengthen steel beams was studied by Lenwari, Thepchatri, & Albrecht (2006). CFRP plates only covered a partial length of the steel beams. Bonded CFRP plates tend to debond under static and fatigue loadings because of the very high stress field at the plate ends. CFRP plate length was also studied, and research concluded that the hybrid beams had two failure modes: plate debonding in beams with short plates, and plate rupture at midspan in beams with long plates (Lenwari, Thepchatri, & Albrecht, 2005).

## 2.9 Fatigue Behavior of Steel Beams Reinforced with CFRP

Repairing fatigue cracks in older structures especially, with bridges designed prior to the AASHTO fatigue detailing provisions, is an ongoing problem. The use of CFRP has shown significant promise in bridge rehabilitation and strengthening. In addition to all of the previously mentioned advantages, CFRP has a very good resistance to fatigue in fiber-dominated materials (Jones &Civjan, 2003). Researchers proved that composite laminates can extend the fatigue life of aluminum specimens (Baker, 1997). An investigation of the use of prestressed CFRP to repair fatigue cracks and prevent future cracks from propagating showed a good impact on structures (Basetti, 2000). An experimental and analytical study was conducted to investigate the effectiveness of applying CFRP overlays to steel fatigue tension coupons to prolong fatigue life (Jones &Civjan, 2003). Specimens were either notched or center hole specimens and tested in uniaxial tension. Variables studied were CFRP system, bond length, bond area, one and two sided applications, and applications prior or subsequent to crack propagation. Two-sided applications were very effective, prolonging fatigue life by as much as 115%. The method

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## III. METHODOLOGY

In order to achieve the outlined objectives, a detailed plan was developed. Five steel beam specimens having CFRP laminate configuration variations were tested. Bending testing was conducted on the simply supported beams via four-point loading. Nonlinear finite element analysis software, ABAQUS (Abaqus Analysis User Manual, 2007), was used to verify the experimental results. The report describes the tasks performed and the design process of steel beam strengthened using CFRP. Discussion of the FE models built to simulate the experimental beams is also presented. Evaluation of the rehabilitation technique is performed utilizing FE models.

The list of tasks accomplished is as follows:

1. Experimental plan for the steel beams: this task was mainly focused on the preliminary design of steel beams to choose a suitable beam for laboratory experimentation given certain restrictions of the laboratory testing frame and equipment, such as length, depth, weight, and load capacity.
2. Excel design spreadsheet utilizing Visual Basic programming: an Excel spreadsheet that incorporated Visual Basic programming was developed to predict the failure load of various experimental beams. The experimental beam was chosen using this spreadsheet.
3. Steel beam purchase / fabrication: steel beams were fabricated and purchased from Garrison Steel Company. The bottom flange of the steel beams was sand blasted for proper attachment of the CFRP plate. Steel specimens for the tension tests were also provided.
4. Experimental setup and testing: tension testing was performed on steel and CFRP specimens. Test setup for the beams involved the attachment of the CFRP laminates to the steel flange. The beam was equipped with strain gages at various locations, and a load cell and LVDT were placed at the midspan of the beam. All instruments were then connected to the data acquisition system, and testing followed. Analysis of experimental results: this task included graphing load deflection, load strain, and strain variation along the depth of the beam for all tested beams. Comparison of the results was performed.
5. Parametric study using finite element (FE) analysis: a parametric study was conducted to test several parameters, such as CFRP laminate length, thickness, configuration, and material properties, and the steel beam section. ABAQUS was the software package used for the FE modeling, which involved special bonding elements, contact surfaces, constraints, and material properties.
6. Analysis of parametric study results: load-deflection graphs were plotted to compare the effect of various parameters. A tabular form was then utilized to calculate elastic and plastic percentage gains.
7. Performing structural evaluation of bridges strengthened using CFRP: FE models were developed using SAP2000 software.
8. Developing design guidelines for rehabilitating bridges using CFRP laminates.

Five scaled steel beams were tested in the lab to investigate the effectiveness of using different configurations of CFRP laminates to increase the strength and stiffness of steel highway bridge girders. The details of the testing program are presented in Table 3-1. All of the beams had a length of 4.3 m and were loaded monotonically to failure using a four-point bending configuration separated equally. A schematic diagram of the cross-section of a typical test beam and the corresponding strain gages location is shown in Figure 1.

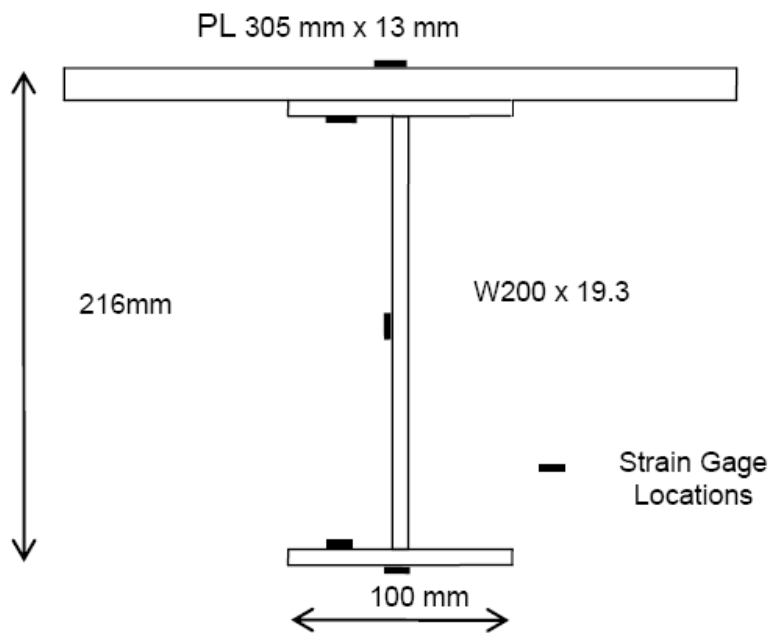


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**Figure 1. Beam dimensions and strain gage locations.**

The beam's cross-section was chosen based on several factors and limitations. The first factor was that the span-to-depth ratio had to be representative of a typical bridge girder. Due to laboratory restrictions, the beam's length was limited to a maximum of 4.5 m, which affected the design of the beam's depth. The CFRP laminate was designed accordingly. Furthermore, the weight of the beam was restricted to the lightest possible section for ease of handling in the lab using the mechanical crane. Through the development of an Excel spreadsheet, various W-shaped steel beams were evaluated. The W200 x 19.3 (W8 x 13) steel beam proved to be the most appropriate, based on the limitations and design criteria. Bridge decks are commonly composed of steel girders attached by shear connectors to an overlaying concrete slab. In this experimental setup, the concrete deck was replaced by a steel plate to avoid the results from being influenced by varying concrete strength produced by different batches for each beam. This would insure a controlled experiment with the CFRP laminates being the only variable. The steel plate was designed to have the neutral axis at the top flange of the steel beam, therefore causing the beam to be mainly in tension and the plate in compression. The steel plate's width provided the beam with sufficient lateral support to avoid any lateral torsional buckling. A top plate with cross-sectional dimensions of 305 mm by 13 mm was welded to the I-beam (Figure 3-1). The arc-weld strength used was 483 MPa, with a size of 9.5 mm (3/8 in) and length 76 mm (3.0 in) at 152 mm separation center-to-center (6.0 in). Steel beams were purchased from Garrison Steel, a steel manufacturing company in Pell City, Alabama. Figure 3-2 shows the steel beam and steel plate before welding in the manufacturing yard of Garrison steel. Figure 3-3 shows the spot welding size being requested from the technician and measurement mark-ups on the beam. The automatic arc-welding machine used to weld the steel beam to the plate is shown in Figure 3-4, and the welding process is shown in Figure 3-5. Beams were then transported to the UAB structural laboratory.

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## IV. CONCLUSION

Conclusions drawn from this research study can be summarized as follows:

1. Steel beams reinforced with CFRP laminates showed a significant increase in flexural capacity reaching 62%, and the beams exhibited satisfactory ductile behavior before laminate debonding.
2. Debonding occurred after yielding of the steel beam signifying that bonding was effective during the elastic stage (in the design range of beams and girders).
3. At debonding (in the plastic region) it was observed that the beam did not develop a plastic hinge at the point of maximum moment, rather it behaved like the control beam (unreinforced by CFRP) with similar strength and ductility.
4. Proper CFRP laminate configuration is essential for maximum gain in enhancing the beams, behavior. Increasing the CFRP laminates does not necessarily enhance the steel beam behavior.
5. Substituting the concrete slab with a steel plate is a valid assumption for the experimental work and was verified by FE models.
6. FE models using ABAQUS were accurate in predicting the load deflection curve and debonding load.
7. The FE models were able to predict the strain versus depth curves for all tested beams.
8. The parametric study using the FE model developed showed that the sensitive parameters affecting steel beams reinforced by CFRP laminates are CFRP laminate thickness, CFRP Young's modulus, and CFRP ultimate laminate strength.
9. The CFRP laminate length is not an effective parameter as long as the maximum moment zone is covered and appropriate development length is satisfied.

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