

Strengthening of Steel Girder Bridges Using FRP

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ABSTRACT

This paper documents two projects funded through the Federal Highway Administration's Innovative Bridge Research and Construction (IBRC) program. The IBRC program was developed to assist bridge owners in applying emerging technologies in bridge engineering. In these projects, the Iowa Department of Transportation employed techniques for strengthening steel girder bridges using carbon fiber reinforced polymers (CFRP). Two bridges were strengthened using CFRP composite materials in an effort to improve the live load carrying capacity of the bridges. In one case, a bridge was strengthened using CFRP post-tensioning rods in the positive moment regions. In the other case, a bridge was strengthened by installing CFRP plates to the bottom flange of girders in the positive moment regions.

Key words: beam—carbon fiber reinforced polymer—strengthening

INTRODUCTION

Many state, county, and local agencies are faced with an ever-deteriorating bridge infrastructure composed in large part of relatively short to medium span bridges. In many cases, these older structures are composed of rolled or welded longitudinal steel stringers used as part of a continuous slab-on-girder bridge. Most of these bridges continue to serve as an integral part of the transportation system yet need some level of strengthening due to increases in live loads or loss of capacity due to deterioration. The bridges are usually not critical enough to warrant replacement so a structurally efficient, but cost-effective, means of strengthening needs to be employed. In the past, the use of bolted steel cover plates was a common retrofit option for strengthening such bridges. However, the time and labor involved to attach such a retrofit can be prohibitive.

Among various strengthening methods, the use of carbon fiber reinforced polymers (CFRP) composite materials is very appealing in that they are highly resistant to corrosion, have a low weight, and have a high tensile strength. In the last decade, the use of these composite materials has emerged as a promising technology in structural engineering (1). With this nationwide recognition, two projects, funded through the Federal Highway Administration's Innovative Bridge Research and Construction (IBRC) program, were initiated to investigate the effectiveness of using CFRP composite materials to strengthen existing steel girder bridges. Two bridges were strengthened using CFRP composite materials in an effort to improve the live load carrying capacity of the bridges. In one case, a bridge (Bridge 1) was strengthened using CFRP rods that had been post-tensioned in the positive moment regions. In the other case, a bridge (Bridge 2) was strengthened by installing CFRP plates to the bottom flange of girders in the positive moment region.

OBJECTIVES

The two primary objectives of these projects were to investigate the effectiveness of CFRP composite materials to strengthen existing, structurally deficient steel girder bridges and to identify changes in structural behavior due to addition of strengthening system and time. To accomplish these objectives, testing of the installations was coupled with theoretical calculations.

STRENGTHENING WITH CFRP POST-TENSIONING RODS

Description of Bridge 1

Bridge 1 (number 3903.0S 141) which was strengthened with post-tensioning (P-T) CFRP rods is a 210 ft x 26 ft three span continuous rolled shape steel girder-bridge in Guthrie County, Iowa, on State Highway 141. The bridge is currently rated with an HS 11.0 Inventory Rating and an HS 18.7 Operating Rating. The bridge has a total length of 210 ft consisting of two end spans of 64 ft and a center span of 82 ft with four beams spaced at 8 ft -3 in. on center. The roadway width is 26 ft allowing two traffic lanes and a narrow shoulder. This bridge is considered to be a borderline case which may soon require posting.



(a) Side view



(b) Road way

FIGURE 1. Photographs of the Bridge 1

Strengthening System

The strengthening system utilized was developed based on the strengthening recommendations of Klaiber et al (2) and material performance data provided by the manufacturer in an effort to increase the load carrying capacity of the bridge. CFRP rods (3/8 in. in diameter) were selected due to their outstanding mechanical characteristics and non-corrosive nature. Anchorage assemblies consisting of 5 in. x 5 in. x 3/4 in. stiffened angles 7 in. in length, 1 in. couplers, and steel tube anchors, were used to connect the P-T CFRP rods to the bridge. Each post-tensioning bracket (connected to the web of the steel beams with 1 in. diameter high strength bolts) connects four CFRP rods to the web of the beam near the bottom flange. Material properties of CFRP rods used are listed in Table 1.

TABLE 1. Material Properties of CFRP Rods

Diameter, in.	Tensile Strength, ksi	Tensile Modulus, ksi	Elongation at ultimate	Fiber Content
3/8	300	20,000	1.5 %	65% by Volume

Installation of CFRP Post-Tensioning Rods

The P-T system was installed in the positive moment region of the exterior girders in all three spans. The anchorage assemblies were bolted to the webs of the beams with 1 in. diameter A325, high-strength bolts torqued in accordance with the manufacturer’s recommendation (Figure 2a) at locations based on design calculations and field measurements. The CFRP post-tensioning rods were then placed in position between each pair of anchorage assemblies on both sides of the web (Figure 2b). Application of the post-tensioning force was completed in several steps at each location (subsequently referred to as “events”). A nominal force of 12 kips was applied to all rods (four rods per location) in a symmetrical manner. Photographs of the application of P-T force in West and Center span are shown in Figure 2 (c) and (d) while the location of the post-tensioning system and photographs of the completed installation are presented in Figures 3 and 4, respectively.



(a) Installation of anchorage assembly



(b) Placement of CFRP rod



(c) Application of P-T force in West-end span

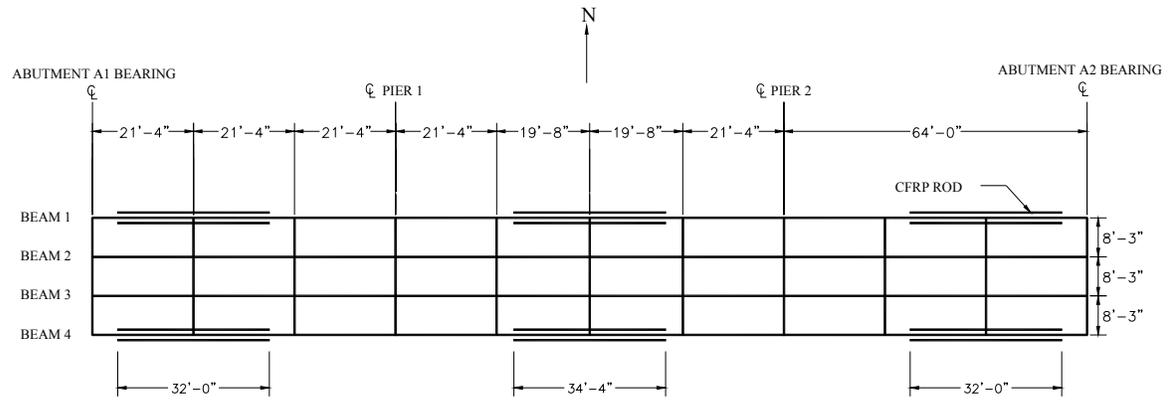


(d) Application of P-T force in Center span.

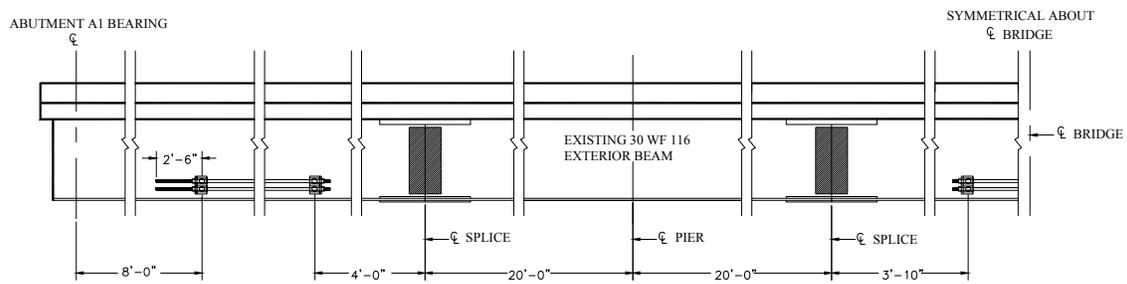
FIGURE 2. Photographs of the Installation of the P-T System on Bridge 1

Load Testing

The bridge was instrumented to measure the strains at strategically selected locations and tested before installation of the post-tensioning system, immediately following post-tensioning, and after approximately one and two years of service to assess changes in performance resulting from the addition of the P-T system and time. Standard 3-axle dump trucks, driven at a crawl speed, were used in the load tests and data were collected continuously as the trucks crossed the bridge. Data were collected for four different load paths with two test runs being conducted for each path. The locations of strain gages and the truck paths used are shown in Figures 5 and 6, respectively.



(a) Plan view



(b) Side view

FIGURE 3. Location of the Post-Tensioning System



(a) CFRP Rods on West-end span



(b) CFRP rods on Center span

FIGURE 4. Photographs of the Completed CFRP P-T System on Bridge 1

Results

Typical bottom flange strain data at the center span from each load test are presented in Figure 7. The increase of strain due to the P-T force applied on Beam 1 in the Center span is illustrated in Figure 8 where each “event” defines a specific step of the overall P-T process.

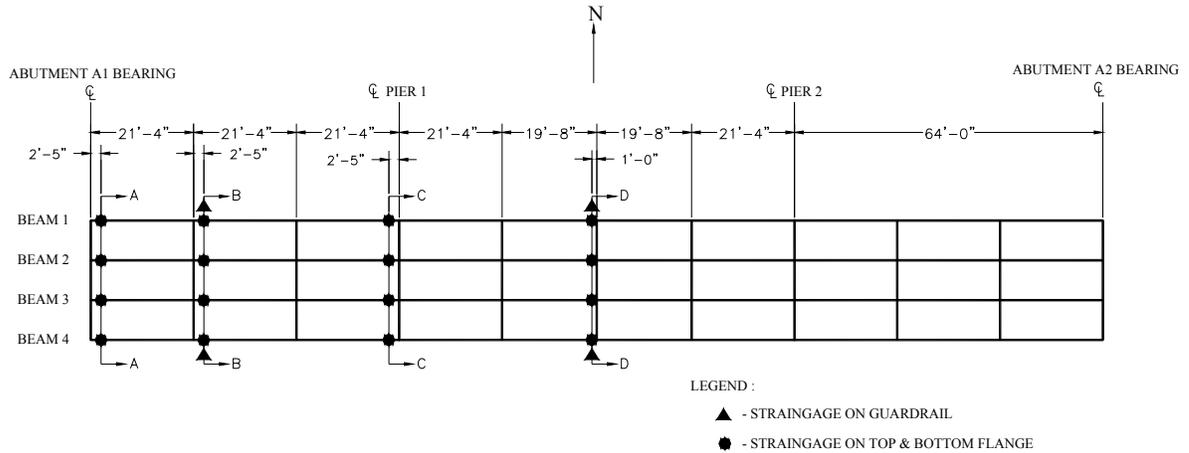


FIGURE 5. Location of Strain gages on Bridge 1

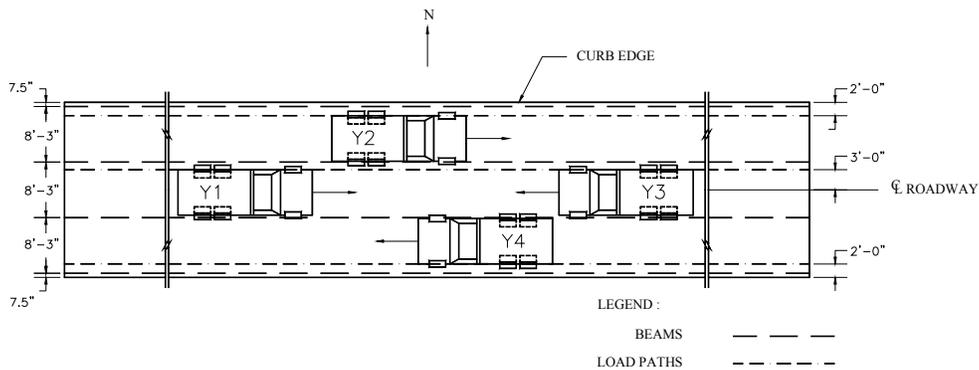


FIGURE 6. Truck paths used on Bridge 1

Each load test produced fairly consistent strain readings. This consistency in strain is informative in that it indicates that the P-T system did not alter the behavior of the bridge over the two years of service. Although it is not possible to precisely account for all the sources of strain, it is evident from the consistency of the strain data that the installation of the P-T system had negligible impact on changing the stiffness of the bridge. In general, good agreements in strain data were observed.

Post-tensioning the positive moment region generates strain opposite in sign to those produced by dead and secondary load. During the application of the P-T system, strain was measured to investigate the response of the structure due to the application of the P-T force. When the force was applied to a certain location on the exterior beam, that beam would experience more strain than other location. For example, when the north exterior beam (Beam 1 in Figure 5) on the Center span was post-tensioned (between the events 48 and 64 in Figure 8), the strain due to the P-T force increased significantly compared to other locations where the increase in strain were minimal.

A classic analysis was performed on the post-tensioned bridge utilizing an HS-20 truck as a live load. Depending on the location, it was obtained that approximately 5 to 10 percent of the live load moment was reduced by the P-T moment.

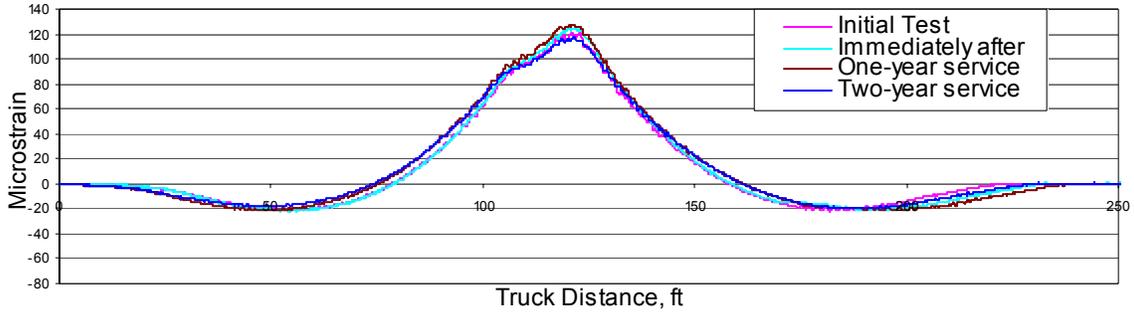


FIGURE 7. Bottom Flange Strain Data (Path Y2, Beam 1 on Center Span of Bridge 1)

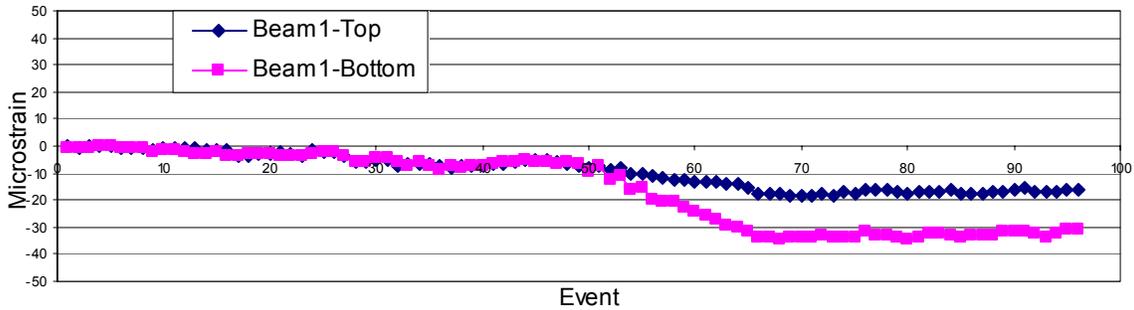


FIGURE 8. Increase of Strain Due to the Post-Tensioning Force on Bridge 1

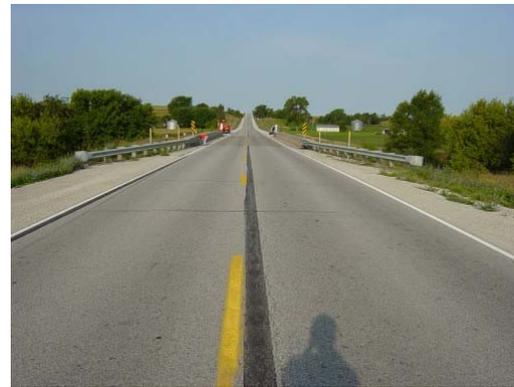
STRENGTHENING WITH CFRP PLATES

Description of Bridge 2

Bridge 2 (number 7838.5S092) strengthened with CFRP plates is a 150 ft x 30 ft three-span continuous I-beam bridge in Pottawattamie County, Iowa, on State Highway 92. Originally the bridge was a non-composite structure. In 1965, the bridge was widened with the addition of exterior girders that were made composite with the deck. The bridge has a total length of 150 ft consisting of two end spans of 45.5 ft and a center span of 59 ft and is supported by six beams: two W27x84 exterior I-beams installed in 1967, two W27 x91, and two W27x98 interior I-beams. The roadway width is 30 ft allowing two traffic lanes and a narrow shoulder.



(a) Side View



(b) Road way

FIGURE 9. Photographs of Bridge 2

Strengthening System

Previous research by Al-Saidi (3) at Iowa State University Bridge Engineering Center established the effectiveness of CFRP plates for improving the strength of steel composite beams. With this foundation study available, the next step was taken to implement this strengthening method on an existing steel girder bridge. The material used for strengthening is a pultruded carbon fiber reinforced polymer consisting of continuous unidirectional carbon fiber in an epoxy matrix, specially designed for flexural strengthening. The CFRP plates were selected due to their outstanding mechanical characteristics, non-corrosive nature, and relative ease of application. The material properties of the CFRP plates used are listed in Table 2. The strengthening system consists of preparation of the bonding surface and installing the CFRP plates to the beam surface with a high strength epoxy adhesive for the transfer of force to the high strength CFRP plates. The design of the CFRP plates was completed for the Iowa legal load utilizing the Load and Resistance Factor Design (LRFD) approach. Calculations indicated that the overstressed beams could be adequately strengthened by the addition of CFRP plates bonded to the bottom flange of the beams.

TABLE 2. Material Properties of CFRP Plates

Ultimate tensile stress, ksi	Modulus of elasticity, ksi	Ultimate strain
300	20,000	1.5 %

Installation of CFRP Plates

The CFRP plates were installed on both interior and exterior beams in the positive moment region of all three spans. A successful installation is highly dependent upon careful surface preparation and maintenance of adequate bond conditions. The steel beam surface to which the CFRP plates were to be bonded was roughened to a ‘coarse sandpaper’ texture by sandblasting with high-pressure air jets to remove the paint and any unsound materials on the bonding surface. Both the sandblasted beam surface and bonding surface (sanded side) of the CFRP plates were cleaned with acetone to remove all dirt and debris. The prepared beam surface was treated with a thin layer of primer to prevent potential galvanized corrosion induced by a galvanic reaction between the beam surface and carbon fibers and to provide an improved substrate for the epoxy adhesive. After the primer was set and tack-free, an appropriate amount of epoxy was applied evenly across

the surface of both the beam and the sanded side of the CFRP plates. Finally, the CFRP plates were placed on the designated surface and then pressed and rolled thoroughly to remove any trapped air pockets in the epoxy adhesives. Some of installation procedures are illustrated in Figure 10, and a detailed layout of the plates used can be seen in Figure 11.

A different number of CFRP plates were used on each span to investigate the effect of varying amount of CFRP plates, to compare the response of the different scheme used in different conditions, to investigate the ease of construction of multiple layers, and to evaluate the durability of the installation. In the West end span, a pair of 20 ft long CFRP plates (1 layer) were installed, side by side with a space of approximately $\frac{1}{2}$ in. in between, in the positive moment regions of Beams 1, 3, and 4. Three layers of CFRP plates 20 ft in length were installed on East end span. The center span was strengthened with two layers of CFRP plate 25 ft in length. Beam 6, in all spans, had half of the plates installed on the bottom of the bottom flange and half on the top of the bottom flange. This was done to investigate the performance and in-service durability under detrimental environmental conditions (i.e., direct exposure to sunlight, rain, etc.).



(a) Primer application



(b) Cleaning CFRP plates



(c) Epoxy application on CFRP plates



(d) Epoxy application on beam



(e) Placement of CFRP plate



(f) CFRP plate installed.

FIGURE 10. Installation of CFRP Plates on Bridge 2

Load Testing

A diagnostic initial load test was conducted prior to the installation of CFRP plates to establish a baseline static behavior of the unstrengthened bridge. The second field-testing will take place in August 2003 followed by two other tests in two years of period (one in 2004 and one in 2005) to assess any change in performance and behavior resulting from the installation and over time.

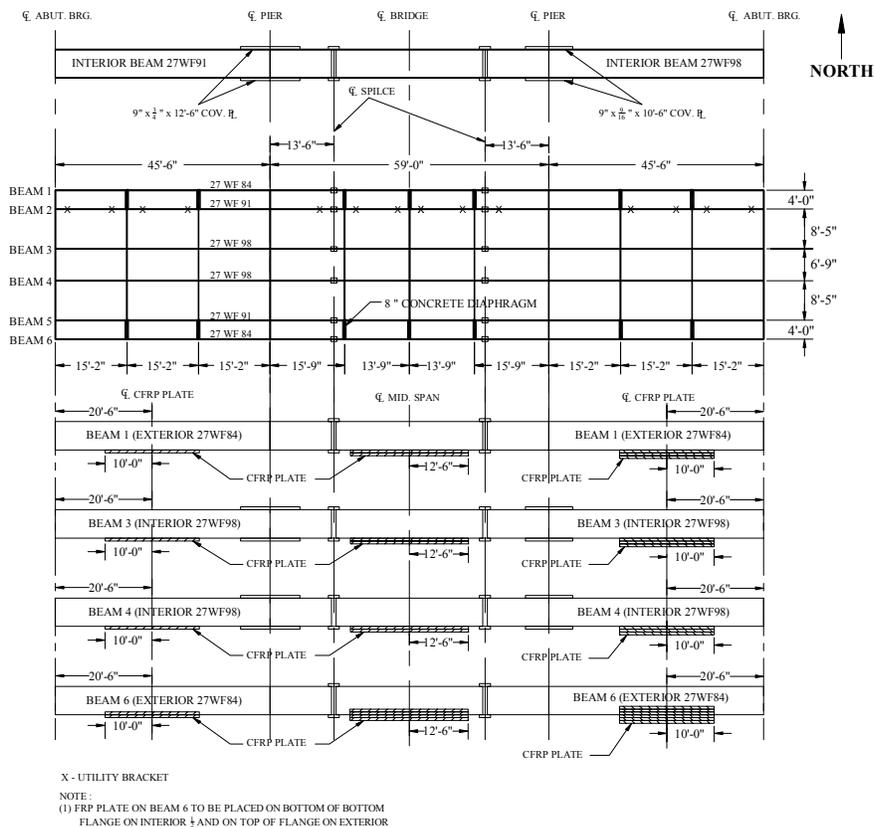


FIGURE 11. Detailed Layout of CFRP Plates on Bridge 2

SUMMARY

As has been described, two existing, structurally deficient steel girder bridges were strengthened utilizing CFRP composite materials. These innovative, yet economical strengthening methods appear to be effective strengthening solutions. Although P-T does not significantly reduce live load deflections, it does increase the live load carrying capacity of the bridge by generating strain opposite to those produced by dead load and, thus, allows the bridge to carry additional traffic live loads. Based on classic analysis utilizing an HS-20 truck, it was determined that approximately 5 to 10 percent of live load moment was reduced by the P-T moment. Finally, the overstressed beams of Bridge 2 were strengthened to enhance their capacity through the addition of CFRP plates attached to the tension flanges. Conclusions on performance and behavior of Bridge 2 will be made as follow-up test takes place.

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