

## **Strategy for the Rehabilitation of R/C T Beam Bridges with Carbon Fiber Reinforced Polymer Sheets**

**Manuel Coll Borgo, Ph.D., P.E.**

Acting Director, Bridge Engineering Office, PR Highway and Transportation Authority, San Juan, PR  
mcoll@act.dtop.gov.pr

**Ildefonso Burgos Gil, M.E., P.E.**

Assistant to the Secretary, PR Department of Transportation and Public Works, San Juan, PR  
iburgos@act.dtop.gov.pr

**Hector Laureano Pagan, P.E.**

Assistant in Structures, Construction Area, PR Highway and Transportation Authority, San Juan, PR  
hlaureano@act.dtop.gov.pr

### **Abstract**

Six reinforced concrete T beam bridges have been rehabilitated with Carbon Fiber Reinforced Polymer (CFRP) in flexion and shear in Puerto Rico to improve their load capacity. The economy in initial cost was significant when compared to replacement. These bridges showed heavy flexural and shear cracking of its girders due to overloading and needed posting. As part of the rehabilitation of the mentioned bridges a static load test was performed on bridge 2028 in order to monitor the effectiveness of the CFRP system. Two sets of load test have been performed. Load Test #1 was performed before the girders were rehabilitated on November 21, 2002 and Load Test #2 was performed on August 5, 2005 after the rehabilitation took place. Computer models of the before and after behavior of the bridges were also developed and showed good correlation with the measured displacements and dynamic properties. The load test showed about a 10%-15% increase in stiffness of the bridge. In order to monitor the long term effectiveness of the CFRP rehabilitation system load test will be performed after five and ten years of service.

### **Keywords**

Bridge, Reinforced Concrete, Strengthening, CFRP, Load Test.

### **1. Introduction**

The Puerto Rico Highway and Transportation Authority (PRHTA) faces the challenge to keep the Island bridges in a good operating condition. Bridge ratings have been performed for the major routes and found the older reinforced concrete T beam bridges to have ratings substantially lower than accepted. This is a major problem in the Island due to the fact that the legal loads were incremented from 80,000 to 110,000 pounds in 1997 and we had to increase our design live loads from the HS-20 to an HS-30 Truck. Suddenly a lot of adequately designed bridges became under-designed for our legal loads.

Thirty-nine (39) reinforced concrete (R/C) T beam bridges exist in the main highways of Puerto Rico. Of those bridges only two of them have inventory ratings above 1.0 for the HS30 truck. Field inspections also confirm the deterioration of the T beam bridges due to overloading, considerable shear and flexural crack are visible in many of these bridges. These cracks expose the reinforcing steel and causes early corrosion and deterioration resulting in a shortened service life span for the bridge. Fifteen of the mentioned bridges have a condition rating of 5 or less, the condition ratings are established through visual inspection according to the Recording and Coding Guide for the Structure Inventory & Appraisal of the Nation's Bridges" [6]. Some of these bridges are in the bridge replacement program and twenty (20) are posted for load restrictions.

In other to eliminate posted bridges of the main highways of PR without the high cost of replacement, the PRHTA needs to implement a durable and economic strengthening alternative to replacement. The upgrading of reinforced concrete members using bonded steel plates has been proven in the field to be an effective, convenient and economic method of improving structural performance. However, disadvantage inherent in the use of steel have stimulated the use of fiber reinforced polymers (FRP) materials in its place, providing a non-corrosive, more versatile strengthening system; it can also be used for pre-stressed concrete [5]. FRP's are beneficial in improving bridge ratings either directly through strengthening deteriorated components or indirectly through replacing existing concrete decks with much lighter FRP decks. Studies on the behavior of concrete beams strengthened by bonding FRP plates to the tension zone have shown to increase member stiffness by 17 to 79 percent and member ultimate strength by 40 to 97 percent. The use of these materials for the rehabilitation of bridges is generally less costly than replacement and preferable to posting the bridge for lower loads. Strengthening with FRP shortens downtime for rehabilitation, which reduces inconvenience to traffic and economic loss to area served [5].

Puerto Rico has already strengthened 6 bridges with Carbon Fiber Reinforce Polymer (CFRP) sheets, the average cost of the rehabilitation per bridge was \$300,000 without traffic disruption, while replacement would have cost approximately \$2,000,000 per bridge and would cause significant traffic disruption. The total savings in initial cost of the rehabilitation projects was of approximately 85%, however, the durability of the retrofit system needs to be assessed in order to validate the economic saving in the long-term.

## **2. Objective**

This study presents the benefits from a CFRP rehabilitation from an analytical stand point by comparing the increase in theoretical capacity with the rehabilitation. And in order to assess the performance of the CFRP technology in the long-term a health monitory plan needs to be implemented. The objective of this study was to record the properties of a R/C T bridge before and after the rehabilitation with CFRP sheets was performed. To monitor the long-term effectiveness of the CFRP rehabilitation system load test will be performed in five and ten years to monitor changes in the response of the structure.

## **3. Scope of Work**

Puerto Rico Bridge #2028 was selected for the long term monitory. This reinforced concrete T beam bridge showed heavy flexural and shear cracking of its girders due to overloading and was a good candidate to be rehabilitated with Carbon Fiber Reinforced Polymer (CFRP) for flexure and shear.

As part of the rehabilitation of the mentioned bridge a static load test and dynamic ambient vibration analysis were performed on the bridge before and after the rehabilitation to record the static and dynamic properties and estimate the effectiveness of the CFRP system. Load Test #1 was performed before the

girders were rehabilitated on November 21, 2002 and Load Test #2 was performed on August 5, 2004 after the rehabilitation took place. The findings of the test are presented herein.

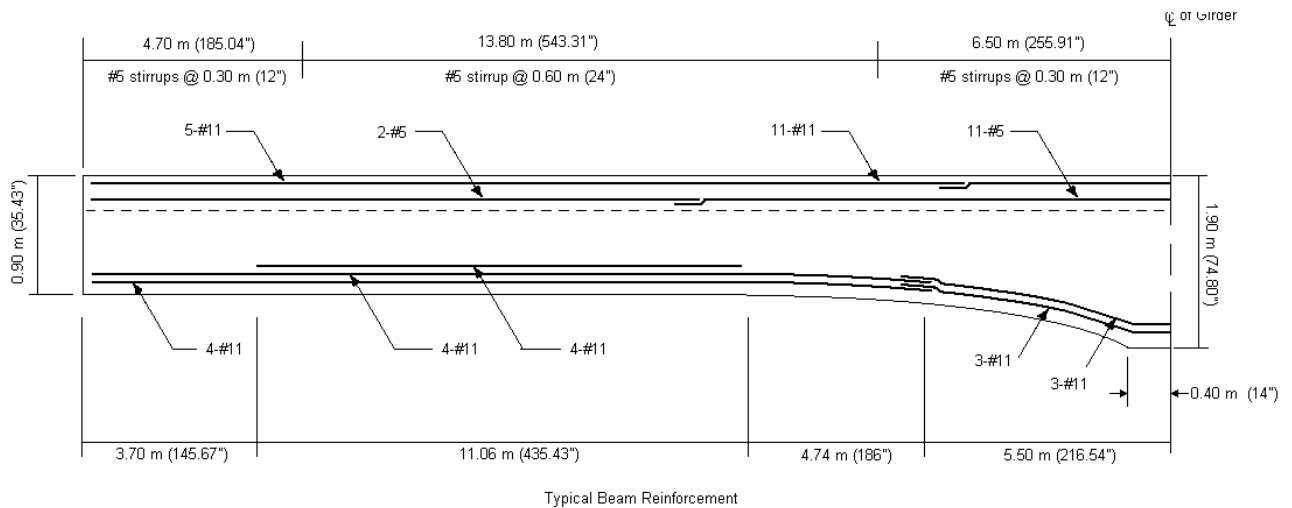


**Figure 1 Bridge 2028 After Rehabilitation with CFRP**

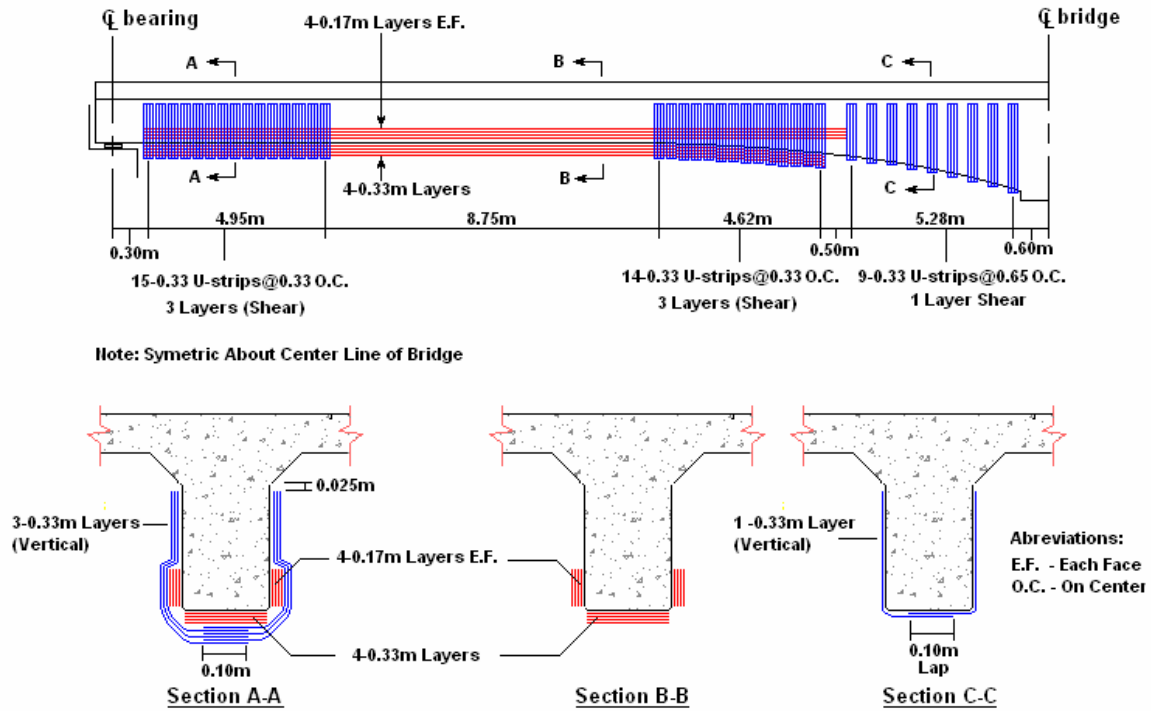
#### 4. Description of Bridge

Bridge 2028 is located in the PR-52 expressway, km. 38.75 over an access road to PR-1. The bridge represents an essential structure providing two traffic lanes in the Ponce to San Juan or northbound direction. Its twin bridge 2029 provides two traffic lanes in the San Juan to Ponce or southbound direction. The average daily traffic (ADT) of the two bridges was 48,400 vehicles by the year 1995. Both bridges have the same structural design but bridge 2029 have seven girders while bridge 2028 have nine since it have an additional lane which serves as an acceleration lane for an access ramp just before the bridge.

Bridge 2028 has two continuous 25 meter spans with parabolic T beams spaced at 1.73 meters, the web thickness and the slab thickness are 0.40 and 0.18 meters respectively. Figures #2 & #3 show the typical reinforcement schedule and retrofit scheme respectively.



**Figure 2: Typical Beam Reinforcement**



**Figure 3: Rehabilitation of Girders with CFRP**

## 5. Reasons for the CFRP Rehabilitation

The main reason to do the CFRP rehabilitation on bridge 2028 was because of the heavy flexure and shear cracks present on the bridge girders (see Figure 4) which gave the bridge a poor condition rating. From an analytical standpoint we increased our legal loads up to 110,000 pounds in the year 1997 and thus adopted the HS30-44 live load model for design, so automatically the bridge (designed for HS20-44) was under-designed at the Inventory Level (INV). Analysis shows (see live load envelopes and capacity envelopes in the charts) that even at Operating Level (OPR) the bridge was under-designed. INV and OPR refer to levels of safety for evaluation of structures used by AASHTO [1]. INV is the same level of safety used in design of new structures and OPR is a lower level of safety used when evaluating existing structures. In LFD this translate in a live load factor of 1.67 at INV and 1.00 at OPR.



**Figure 4: Crack in Exterior Girder**

Since the bridge is part of an important route that connects the two main cities in PR (San Juan and Ponce) and was in such bad shape, the alternative of CFRP rehabilitation without having to close the bridge to traffic was selected to improve the condition and increase the rating capacity of the bridge up to the HS30-44 live load. Because CFRP has its limitations in how much it can increase the section capacity, the HS30-44 live loads at the OPR level was accepted as suffice for the rehabilitation design, although the effort was made to increase the capacity to HS30-44 loads at the INV level.

**Table #1: Rating Factors for HS30-44 Life Load (LFD)**

	INV		OPR	
	Before	CFRP	Before	CFRP
SHEAR	<b>0.27</b>	0.61	<b>0.44</b>	1.02
POSITIVE MOMENT	0.61	0.88	1.03	1.88
NEGATIVE MOMENT	0.53	<b>0.53</b>	0.89	<b>0.89</b>

Rehabilitation for the Negative moment capacity of the beams would have required closing the bridge at some point for strengthening with CFRP bars at the top of the girders. Although the analytical negative moment capacity was not the HS30-44 at the OPR, they were close enough (ORP rating of 0.89 the lowest), and the bridge did not show sings of distress due to negative moments. So it was considered to costly and not necessary to retrofit the bridge to increase its analytical negative moment capacity by just a few percent.

On the other hand, the capacity at the OPR was adequate for positive moment capacity, but because the bridge showed sings of distress in the positive moment regions it was decided to rehabilitate the bridge for positive moments. The analytical rating of the bridge increased from 0.61 to 0.88 for the HS30-44 live loads at the INV. The CFRP Sheets for shear capacity was increased from a rating of 0.44 to 1.02 at the OPR level for the HS30-44 live load model.

## 6. Instrumentation Scheme

To monitor the response of the bridge due to static loading a total of 35 gauges were installed on the bridge for the test before the rehabilitation (load test #1) and eight more added for the test after the bridge was rehabilitated (load test #2) for a total of 43 gauges. Figure 5 shows the location of the LVDT's placed on the bridge.

The gauges included the following:

- 8 quarter bridge weldable strain gauges to measure strain in the bottom steel reinforcement.
- 17 clip gauges to measure strain in concrete.
- 10 lineal variable displacement transducers (LVDT's) to measure vertical displacement at different points of the girders.
- 8 additional quarter bridge bondable gauges to measure strain in the CFRP sheet reinforcement were added for the second load test.

The load consisted of two dump trucks for a total weight of 171 kips on the first test and 150 kips on the second test. The loads were placed at eleven different locations on the bridge. The gauges were placed on the bridge strategically so there would be gauges at the points of maximum strains and displacement for each of the load cases. In all, the eleven load cases should give an overall record of how the bridge was behaving before and after the rehabilitation. Figure #6 show the truck positions for three load cases.

The load test was performed with personal of the PRHTA and a team of researchers from Drexel University of Philadelphia working under the supervision. The Drexel University Researchers also performed ambient vibration analyses of the bridge by installing accelerometers on top of two girders (girders #1 and #2) and recording accelerations with normal traffic for about 6 hours and able to identify the natural frequencies of the first nine modes of the structure [7].

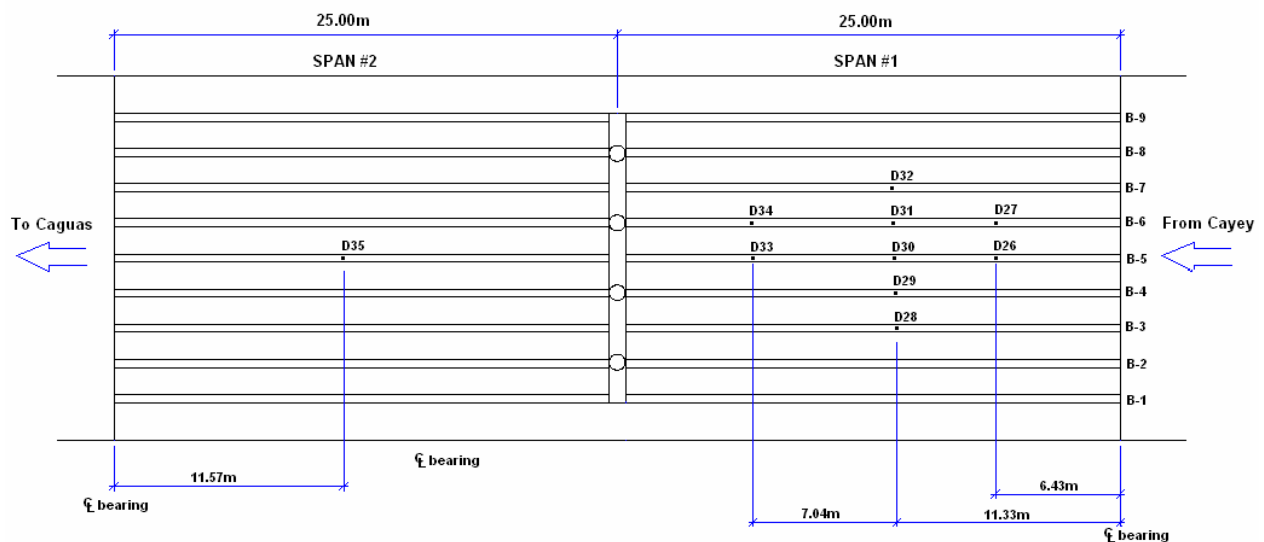
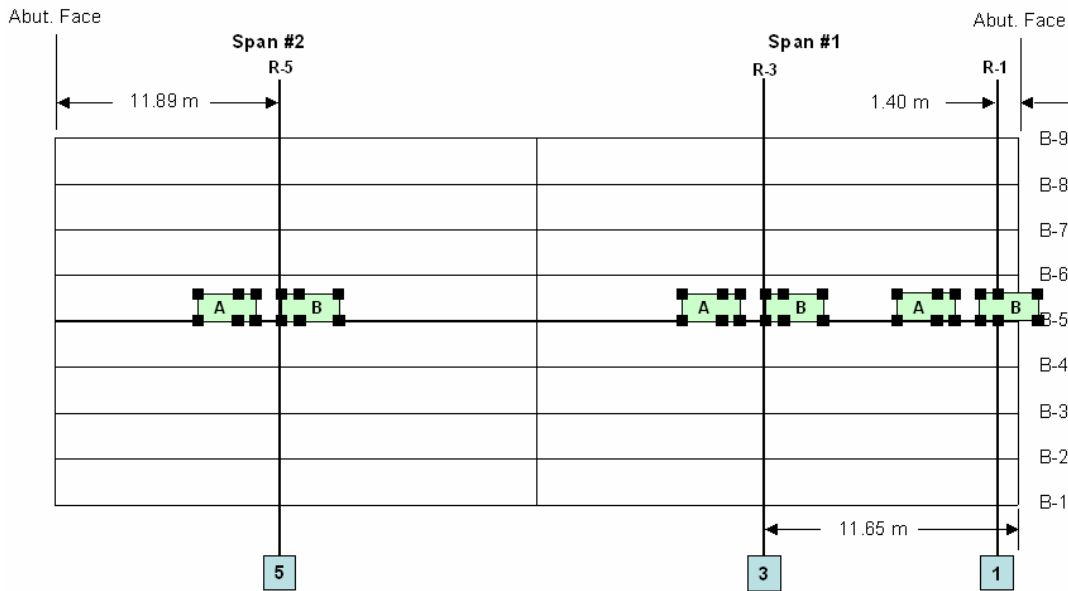


Figure 5: Location of Displacement Gauges (LVDT's)

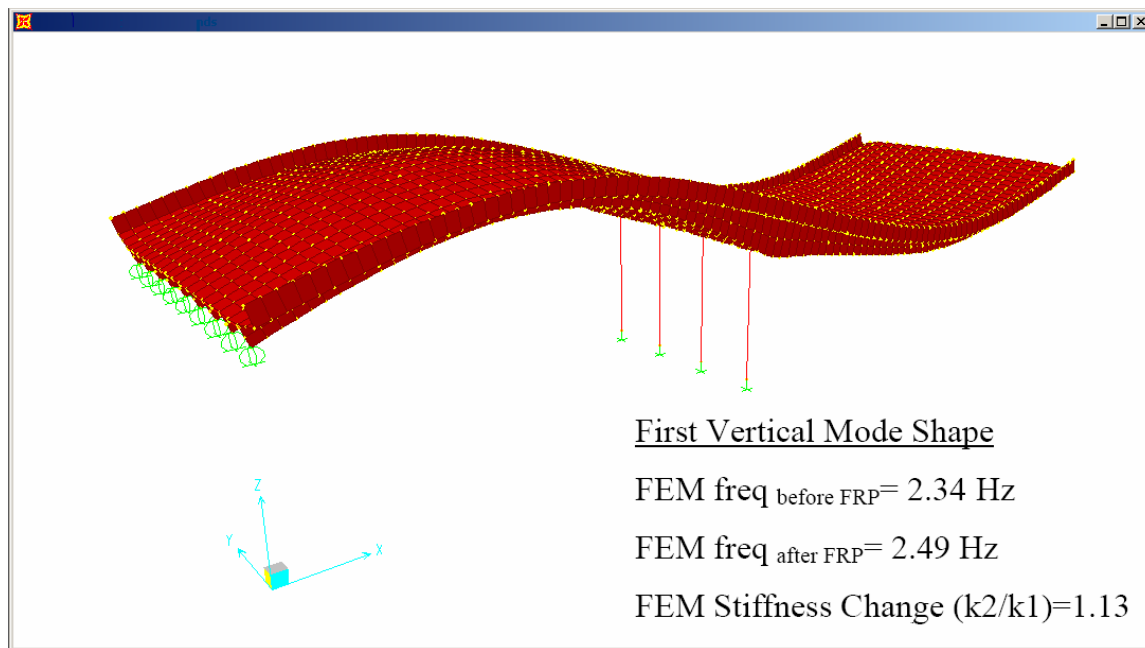


**Figure 6: Truck Locations for Load Cases #1, #3 & #5**

## 7. Simulation of the Load Test

A simulation of the load test performed in a non-calibrated elastic 3D FEM was performed assuming gross properties of the bridge. The model was used to estimate the level of accuracy required in measuring deformations and strains. It showed maximum deflections at 15.8 mm for the first load test and 11.3 mm for the second load test, with an average decrease on displacements of 28%. The results showed that LVDT's capable of recording to a precision of +/- 0.1 mm would be adequate.

Also the frequencies of the Vertical Mode Shapes were estimated with the 3D FEM. They varied between 2.34 and 8.05 Hz for the first nine modes of vibration. Figure 7 shows the mode shape for the first vertical mode of vibration of the 3D-FEM.



**Figure 7: First Vertical Mode Shape**

## 8. Results from the Load Test

To compare the results before and after the rehabilitation a factor of  $171 \text{ kip}/150 \text{ kip} = 1.14$  was included in the results of the second load test to account for the lighter loads applied on the test. For Load Case #3 which recorded the largest deflections, the maximum deflection was recorded in gauge D30 at 11.38 mm and  $9.02 \text{ mm} \times 1.14 = 10.24 \text{ mm}$  for a 10% reduction in the displacement. On the average displacements were reduced by 13%. Figure 7 shows a plot of the deflections of the Girders on Load Case #3 before and after the rehabilitation. Maximum Strains on rebar were about 9% of yield (60 ksi) and a decrease of 13% on the average was also noted.

The simulation predicted in average about double the stiffness increase with the CFRP rehabilitation, and it also predicted larger displacements than measured on site. But in general the displacements were close enough to what we had expected based on the simulation.

In the second load test an additional proof load test was performed with four dump trucks for a total weight of 286 kips and a maximum displacement of 15.4 mm was recorded without any sign of distress and thus an OPR rating of 1.4 was determined using the rating procedure through proof load testing specified in the NCHRP Manual for Bridge Load Rating Through Load Testing [2]. This procedure was accepted by AASHTO and adopted in the new Manual for Condition Evaluation and Load and Resistance Factor Rating of Highway Bridges [3] published in 2003.

The dynamic monitoring performed by the Drexel Team showed a change in frequency of about 7.2% in the first mode of the structure (2.64 hz to 2.83 hz) for a 15% change in stiffness [7]. This is very similar to the change in stiffness of 13% that was reflected in the static load test. The 3D FEM also gave a good prediction of the estimated frequencies for the principal three vertical mode shapes.



## 9. Conclusions and Recommendations

The rehabilitation of the bridge increased the load rating capacity of the bridge to 0.89 due to flexure in the negative moment region at the OPR level. Because the bridge does not show sign of distress in that region, according to the AASHTO Manual for Condition Evaluation of Bridges [1], it would not have to be posted for load restrictions. But, taking advantage of the closure of the bridge for the second load test a proof load rating was performed with four dump trucks, which gave a load rating factor 1.40 at the OPR level to confirm the structural adequacy of the rehabilitated bridge.

The load test showed an increase in stiffness of about 13% in the static load test and about 15% in the dynamic test performed by the researchers from Drexel University. It was also found that the non-calibrated elastic 3D FEM gave good predictions of the expected results of the load test. This data was very useful in the selection of the appropriate gauges for the test.

It is recommended that the bridge be tested in 5 and 10 years to establish the durability of the CFRP rehabilitation and be able to confirm the economy of the rehabilitation system in the long-term.

## 10. References

1. Manual for Condition Evaluation of Bridges American Association of State Highway And Transportation Officials (AASHTO), 1994.
2. Manual for Bridge Rating Through Load Testing, Research Results Digest, National Cooperative Research Program (NCHRP), November 1998 – Number 234.
3. Manual for Condition Evaluation and Load and Resistance Factor Rating of Highway Bridges. American Association of State Highway And Transportation Officials (AASHTO), 2003.
4. Standard Specifications for Highway Bridges 17<sup>th</sup> Ed., Association of State Highway And Transportation Officials (AASHTO), 2003.
5. Holloway L.C., Leeming M.B., “Role of Bonded fibre-reinforced composites in strengthening of structures”. Strengthening of Reinforced Concrete Structures – Using externally-bonded FRP Composites in Structural and Civil Engineering. CRC Press LLC, 2000. Pages 1-10.
6. Recording and Coding Guide for the Structure Inventory & Appraisal of the Nation’s Bridges. Federal Highway Administration, Report No. FHWA-PD-96-001, December 1995.
7. F.N. Catbas, K.A. Grimmelsman, S. K. Ciloglu, I. Burgos-Gil and M. Coll-Borgo, “Static and Dynamic Testing of a Concrete T-Beam Bridge Before and After Carbon Fiber Reinforced Polymers (CFRP) Retrofit”, To be published at the Journal of the Transportation Research Board, 2006.