Fabry-Perot Sensors for the Monitoring of FRP Reinforced Bridge Decks

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ABSTRACT

The extensive use of deicing salts in Canada during winter times is identified as the main reason behind the deterioration of highway bridges and parking garages. To fight this infrastructure crisis, Fibre Reinforced Polymers (FRP) has become a very attractive alternative to traditional reinforcing steel due to their non-corrosive nature and light weight. The replacement of steel with Glass FRP bars in bridge deck slabs has been extensively researched in the last few years. This paper presents the first efforts to implement these bars in two highway bridges in Quebec, Canada, and Vermont, USA. These projects are aimed to prove the feasibility of using GFRP bars in bridge construction. GFRP bars were used as reinforcement for parts of the deck slabs in the two bridges while traditional steel was used in the remaining parts. Fibre Optic Sensors (FOS) were used to measure strains in the concrete, reinforcing bars and steel girders. The sensors were surface mounted on the bars or steel girders using standard glue, or embedded in concrete. Static and dynamic testing of the bridges was done using loaded trucks placed for maximum stresses. The design, construction, testing, and results obtained from the bridges are briefly outlined in this paper. The results indicated the accuracy of the sensors and their feasibility for bridge construction and remote monitoring.

Keywords: Monitoring, Fabry-Perot, Fibre optic sensors, Bridges, Fibre reinforced polymers, Deck slabs, Composites, Strain, Highway.

1. INTRODUCTION

Bridge decks deterioration is one of the most common deficiencies in a bridge system. Concrete bridge decks deteriorate faster than any other bridge component because of direct exposure to environment, de-icing chemicals, and ever-increasing traffic loads. The magnitude of deck cracking and delamination due to corrosion is a major problem when measured in terms of rehabilitation costs and traffic disruption. To overcome the corrosion-related problems, the steel reinforcement should be protected from elements causing corrosion, or be replaced with alternative non-corrosive materials. One of these alternatives, fiber reinforced polymers (FRP) composite reinforcement has been used successfully in many industrial applications and more recently has been introduced as concrete reinforcement in bridge decks and other structural elements. The use of the non-corrosive FRP composite bars as reinforcement for concrete bridge decks provides a potential for increased service life, cost-effectiveness, and environmental benefits.

The advancement in manufacturing of the FRP and the research performed to prove their performance in structural application has encouraged the Federal Highway Administration (FHWA) to focus on advancing FRP composite technology in order to rebuild, rehabilitate, and maintain the infrastructure through their Innovative Bridge Research and Construction (IBRC) (US DOT, 2002). The FHWA established the IBRC with the passage of TEA-21 (Twenty-First Century). The Congressional TEA-21 has established research funding to investigate the feasibility of using innovative materials in bridge construction in order to develop cost effective materials, reduce maintenance costs, extend service life, improve life-cycle cost efficiency, develop construction and monitoring techniques, and develop design criteria. The use of FRP reinforcing bars has been extensively researched to test their mechanical properties and durability. Several recognized design codes have included a new section for FRP reinforced concrete structures. Furthermore,

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several codes and design guidelines for concrete structures reinforced with FRP bars have been published recently (ACI 440.1R-01 2003, CAN/CSA-S806-02 2002, ISIS-M03-01 2001).

Through the NSERC research chair in FRP reinforcements for concrete structures, which started in 2000 at the Department of Civil Engineering, Université de Sherbrooke (Quebec, Canada), collaboration with the Ministry of Transportation of Quebec (MTQ) and different industrial partners was established to develop and implement the FRP reinforcements in concrete bridges. After the development/improvement of new carbon/glass composite bars and the satisfactory results obtained in the laboratory on concrete deck slab prototypes reinforced with these bars (Benmokrane et al. 2002; El Salakawy et al. 2003), field applications became a requirement to move forward with this technology. Successful field application of these new bars was Wotton Bridge (Benmokrane and El-Salakawy 2002, Benmokrane et al. 2003). This paper presents two more recent field applications where Fabry-Perot fiber optic sensors are used in the performance assessment of the different structures. Fabry-Perot sensors were used in different laboratory studies of civil engineering materials (Quirion et al., 2000, Zhang et al., 2003). In these projects, Fabry-Perot sensors are use for the dynamic testing of the bridges and, in the future, for the long term monitoring of their behavior. This paper presents part of the data collected from two highway bridges; Morristown Bridge on Route 100 in Vermont, USA, and Magog Bridge on Highway 55 North, Québec, Canada. The results prove the accuracy and capacities of the FOS as well as the integrity of the GFRP bars as reinforcement.

2. MORRISTOWN BRIDGE

The Morristown Bridge (BR 213) is located over the Ryder Brook on Route 100 in Vermont, USA. The bridge is subjected to heavy traffic of more than 7000 vehicles per day. The bridge is located on the south side of the town of Morristown (Vermont, USA). This area receives heavy snow fall in the winter season, and frequent wet-dry and freeze-thaw cycling. These conditions cause fast deterioration of the infrastructure and encouraged the authorities to search for innovative solution to the problem. The following are the main characteristics of the bridge

- Owner: Vermont Agency of Transportation
- Construction of the bridge: Started in May 2002
- Opening of the bridge to traffic: September 2002
- Structure category: Medium span (girder bridge)
- Spans: one span of 43.9 m.
- Width: 11.27 m
- Structural system: 5 steel girders continuous integrally cast with the two end abutments
- Deck slab: 230 mm thick concrete, entirely reinforced with glass FRP reinforcing bars in all directions.
- Start of monitoring: August, 2002
- Number of sensors installed: 12 fiber optic sensors – Classified as Smart Bridge -

The instrumentation of the GFRP bars was designed by the research team at the University of Sherbrooke, Sherbrooke, Quebec, Canada. This is the first bridge deck world wide, of this size and category, in which the concrete slab was fully reinforced with glass FRP reinforcing bars. The bridge is a girder type, with five main steel girders, integrally cast with the two end abutments over one span of 43.90 m. The deck is a 230 mm thickness concrete slab continuous over four spans of 2.36 m each with an overhang of 0.915 m on each side. Two identical glass FRP mats, No.19 @ 100 and 150 mm in the transverse and longitudinal directions, respectively, were used at top and bottom. Clear concrete covers of 38 and 64 mm at bottom and top, respectively were used

The purpose of the Morristown Bridge instrumentation is to monitor the bridge performance on a continual basis. Fabry-Perot fiber optic sensors (FOS) were used to monitor the strains in the Glass Fiber-Reinforced Polymer (FRP) reinforcing bars and concrete deck slab. Thermocouples were used to compensate for temperature effects.

2.1 Sensor Details

The fiber optic sensors (FOS) were distributed along the middle section of the bridge (midspan). A total of 12 Fabry-Perot fiber optic sensors (FOS) were used. Ten FOS were glued on reinforcing FRP bars. Five of them were glued on transverse top reinforcement at mid span of bridge at location of maximum stresses on top of supported girders. Three FOS were glued on transverse bottom reinforcement at mid span of bridge at location of maximum stress at mid way between girders. Figure 1 below shows the distribution of the FOS on the FRP bars in the bridge. The remaining two FOS were glued on top longitudinal reinforcement, one on middle bar on the top of middle girder and the other on end bar on the top of edge girder. Two FOS were embedded in concrete at the level of top and bottom reinforcements. Figure 2 shows a close-up of the GFRP reinforcement and the attached FOS.

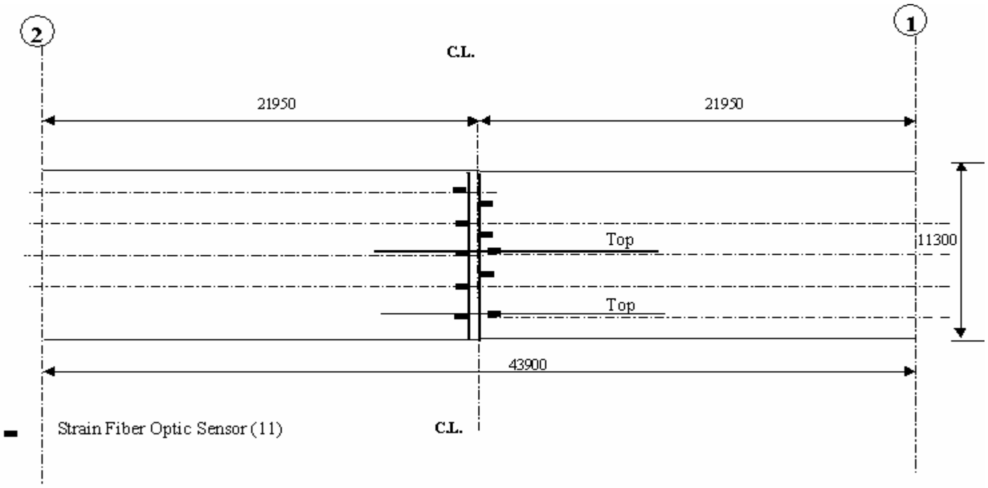

Figure 1: Distribution of FOS for strain monitoring in FRP bars.

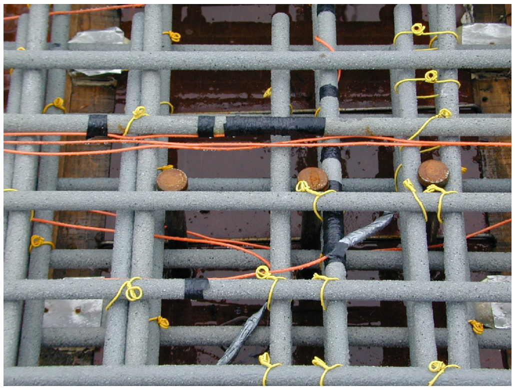

Figure 2: Fiber optic sensors on glass FRP bars.

Figure 3: Field testing of Morristown Bridge.

In addition to the instrumentations used in the bridge and described above, the authors are currently preparing to launch a second phase starting 2005. Additional 21 surface mounted FOS will be installed on the steel girders to measure the strains with time. The sensors will be connected to DMI 32-channels readout unit permanently installed beneath the bridge. This phase will establish the first smart bridge of its size in North America where the state of strains in the critical points of all the bridge elements will be continuously and remotely monitored.

2.2 Results

The bridge was tested for service performance (October 2003) under static loads using two calibrated truckloads with three axles each as show in Figure 3. Four paths, two in each direction, corresponding to the direction of each with seven stations (truck stops) were marked along the longitudinal direction of the bridge to give critical loading cases and influence lines at the instrumented section of the bridge (mid-span). The test was carried out using a single truck over the four paths and the two simultaneously along one path for a total of 35 (7 stations × 5 paths) readings were recorded for each gauge. Results were presented in a strain position-plot shown in Figure 4 below for two FOS on transverse bars. The maximum value on the horizontal axes represents the location on the bridge that contains the gauge under consideration (mid-span). In case of one truck, the maximum measured strains in bottom and top FRP bars were 31 and 4 micro-strains, respectively. These values show the sensitivity of the FOS and their ability to function under low strains. In addition, the sensors were proven to be rugged enough to withstand the conditions of concrete cast, placing, and curing. Attaching the FOS to GFRP bar surface was also proven to be a valid procedure. The bridge was then tested for dynamic response under real traffic conditions. The maximum-recorded strain values in FRP reinforcement were in the same order as for the static tests as shown in Figure 5. Further details of the interpretation of the static and dynamic data of the Morristown Bridge are provided by Benmokrane et al. (2003).

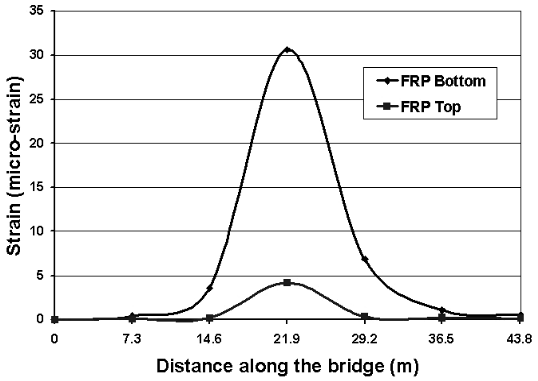

Figure 4: Strains in FRP bars under static loading.

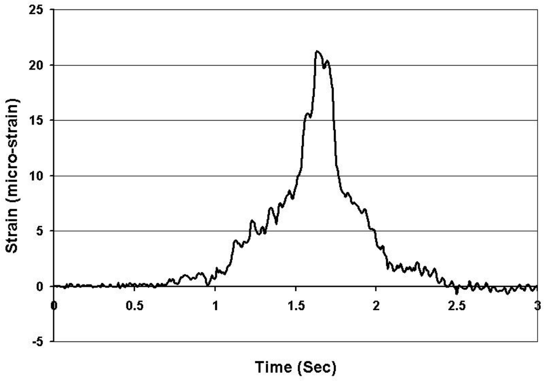

Figure 5: Strain in bottom FRP bars under dynamic loading.

During static tests, deflections of concrete slabs and steel girders were measured by a theodolite using a system of rulers installed at the mid-span as shown in Figure 6. The maximum measured deflection on the steel girders at the mid-span of the bridge due to truckloads at different paths as shown in Figure 7. In case of one truckload, the two intermediate girders directly underneath the truckload carry 55 to 60% of the total load, while the other three girders away from it carry 40 to 45%

Figure 6: Rulers installed on steel girders to measure deflection.

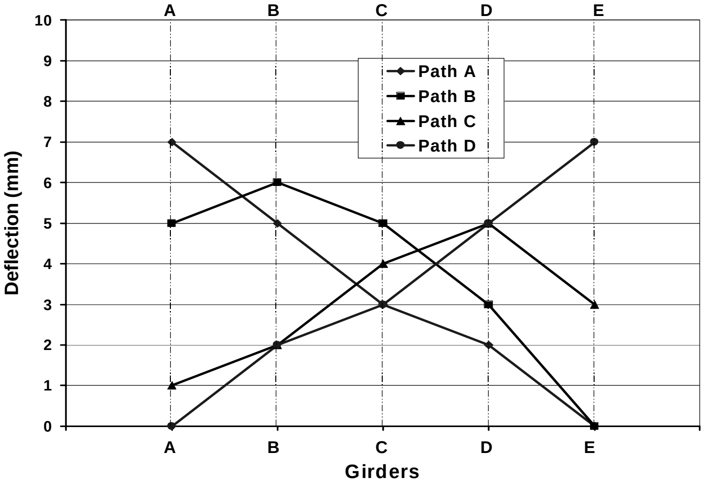

Figure 7: Maximum measured deflection of steel girders (Truck at bridge mid-span)

3. MAGOG BRIDGE

The Magog Bridge opened in October 2002. It is built over the Magog River on Highway 55 North, in the province of Québec. The bridge is located at 45 km north of the US-Canadian borders, which makes it plays a major role in transportation of goods between Canada and USA. The bridge is located just outside the city of Magog, near Sherbrooke City, Québec, Canada. Following are the main characteristics of the bridge:

- Owner: Ministry of Transportation of Québec
- Structure category: Medium span (girder bridge)
- Spans: 3 spans: 2 end spans of 26.0 m each and middle span of 32.0 m.
- Structural system: 5 steel girders continuous over 3 spans supporting concrete slab.
- Deck slab: 220 mm thick reinforced concrete. For one end span, the slab was reinforced with CFRP bars in bottom and GFRP bars at top. Galvanized steel was used in the other two spans.
- Start of SHM: October, 2002
- Number of sensors installed: 35

The instrumentation of the GFRP bars was designed by the research team at the University of Sherbrooke, Sherbrooke, Quebec, Canada.

The bridge is a girder type with a total length of 83.7 m and five main steel girders continuously supported over three spans as shown in Figure 8. The two end spans are 26.2 m each and the middle one is 31.3 m. The deck slab is continuous over four spans of 2.845 m each with an overhang of 1.352 m on each side as shown in Figure 9. Clear concrete covers of 35 and 60 mm at bottom and top, respectively were used. One full end span of the deck slab was reinforced with FRP bars. The other two spans were reinforced with galvanized steel. The concrete deck slab was designed according to Section 8 of the Canadian Highway Bridge Design Code (CHBDC, 2000) for steel reinforcement, which was then replaced with FRP bars according to Section 16 of the same code in one end span. The resulting FRP reinforcement was glass FRP (GFRP) bars (No.16 at 15.9 mm) in all directions, except the short direction at the bottom, where carbon FRP (CFRP) bars (No.10 at 9.5 mm) were used. The bridge is well instrumented with fiber-optic sensors at critical locations to record internal temperature and strain data. These sensors have monitored deck behavior since bridge construction (September 2002) and will continue to do so for several years. Also, the bridge was tested for service performance using standard truckloads as specified in the new CHBDC (2000).

Figure 8: Magog Bridge – on Highway 55 North, Québec, Canada

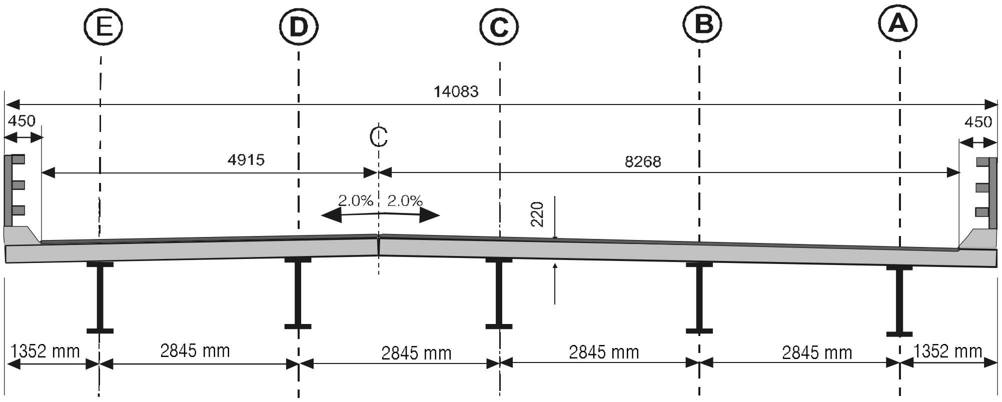

Figure 9: Cross-section of the Magog Bridge

3.1 Sensors Details

The bridge was well instrumented at critical locations to record internal temperature and strain data. Instrumentation was distributed in four sections on the bridge, namely, Sections 1-F and 2-F at quarter span and mid-span of the FRP-reinforced end span, respectively, and identically in Sections 1-S and 2-S at quarter span and mid-span of the steel-reinforced end span, respectively. A total of 39 FOS and 32 electrical resistance strain gauges were installed in the bridge deck to measure strain in concrete, FRP and steel bars, and steel girders. The objective of using FOS gauges is to allow for long-term monitoring of the bridge, while electrical strain gages have been selected only for the purpose of the short-term testing. They were placed as follows:

- Twenty-three FOS were glued on transverse reinforcing bars at all 4 sections (21 gauges for FRP bars, and 2 gauges for steel bars). These FOS were glued on transverse top reinforcement at location of maximum stresses on top of supporting girders, on transverse bottom reinforcement at locations of maximum stress at mid span between girders, and on top longitudinal reinforcement at the top of middle girder.
- Ten FOS were glued on the of steel girders surface at sections 2-F and 2-S at top and bottom flanges.
- Two FOS were embedded in concrete at section 2-F at the level of the transverse top and bottom reinforcements; one FOS is located on the top of the girder C at the level of the transverse bottom reinforcement, and the other halfway between girders C and B at the level of the transverse top reinforcement.
- Four FOS thermocouples were embedded in the concrete at the top and bottom of the slab at Sections 2-F and 2-S to measure temperature changes.

All 32 electrical resistance strain gauges were glued on transverse top and bottom reinforcing bars (12 gauges for FRP, and 20 gauges for steel bars). The locations of the electrical strain gauges installed on each bar type were identical to those of FOS glued on the same bars to allow for direct comparison between strains collected from these two types of gauges during live-load tests.

3.2 Results

The bridge was tested on October 2002 under both static and dynamic loads traveling in five transverse positions and two combinations of truckloads. Results were presented in a strain position-plot shown in Figure 10. The zero value on the horizontal axes represents the location on the bridge that contains the gauge under consideration. In case of two trucks (maximum expected load at most critical position), the maximum measured change in strain in bottom and top FRP bars due to truck load were18 and 9 micro-strains, respectively.

For the dynamic testing, the trucks traveled at four different speeds of 5, 30, 50, and 70 km/hr. The maximum-recorded change in strain in FRP reinforcement due to truck load was in the same order as for the static tests. The peak strains measured on the steel girders were very similar, if not exactly the same, for FRP-reinforced and steel-reinforced spans for the same truck speed and path. Figure 18 shows the tensile strains measured in steel girder C against time for the two trucks traveling simultaneously on Path C-E at a speed of 50 km/h. In this figure, the two graphs represent the response of the same girder (C) measured at the middle of the two end spans while the truckloads were moving across the bridge. Note that the measured peak strains on the steel girders were -25 and +73 micro-strains. For Truck No. 2 with the trailer traveling on Path C at a speed of 5 km/h and 50 km/h, the strain values were -20 to +35 and -15 to +35 micro-strains, respectively. These strains correspond to stresses of - 4, 7, - 3, and 7 MPa. Further details of the interpretation of the static and dynamic data of the Magog Bridge are provided by El-Salakawy and Benmokrane (2003).

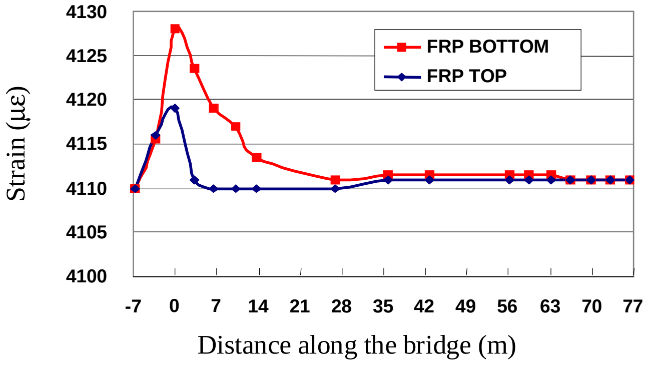

Figure 10: Change in strains in FRP bars due to truck load (static testing).

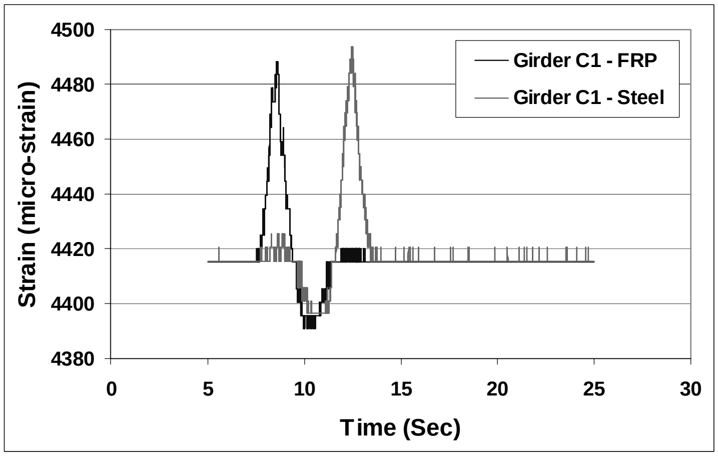

Figure 11: Change in strains in steel girders (Two trucks over Path C-E - 50 km/hr).

4. CONCLUSIONS

This paper summarizes the design, construction, and testing of two highway bridges in Canada and The United States where glass fiber reinforced polymer (GFRP) bars were used as reinforcement of the deck slab and fibre optic sensors (FOS) were used to measure strains in the reinforcement and concrete. Surface mounting technique to attach the FOS to the GFRP bars was feasible using appropriate glue. The sensors and their lead wires were rugged enough to withstand the hardship of concrete casting, placement, curing procedure and hydrating heat. The sensors were sensitive to changes in strains in the GFRP bars under truck loading.

The current state of the FOS technology and cost enables the expansion of the smart structures concept. Real-time monitoring of stresses and strains in buildings and bridges can be made using remote monitoring of the FOS. The ability of the sensors to provide high frequency output (100 readings/sec and above) makes dynamic testing and monitoring of bridges more feasible and reliable.

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