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Researchers instrument sections of a reconstructed bridge in which carbon-fiber and glass-fiber reinforced polymer grids and bars replace some of the reinforcing steel.

Fiber-Optic Sensors Monitor FRP-Reinforced Bridge

BY B. BENMOKRANE, H. RAHMAN, P. MUKHOPADHYAYA, R. MASMOUDI, B. ZHANG, I. LORD, AND G. TADROS

Rebar corrosion in reinforced concrete bridge decks is a major problem. Most technical solutions for the problem attempt to slow the corrosion rate or prevent corrosion, but an alternate approach is replacing the steel with a more durable material such as fiber-reinforced polymer (FRP).

The University of Sherbrooke, Quebec, Canada, recently conducted a field project in which FRP rebar and grids were used to reconstruct portions of a concrete deck slab that had severely deteriorated when the reinforcing steel corroded. The project included analysis and design of the bridge structure, construction of the concrete deck slab, and field-performance monitoring of the completed construction using fiber-optic sensors (FOSs). The integration of FOSs to monitor long-term performance of RC structures is a fairly recent development that deserves more attention from practicing engineers and field personnel.

Project background

Built in 1950, the Joffre Bridge in Sherbrooke, Quebec, had deteriorated severely, due primarily to corrosion of reinforcement in the concrete deck and girders. The City of Sherbrooke and the Ministry of Transport of Quebec decided to reconstruct the deteriorated parts of the bridge, widen the deck, and use steel girders rather than the original concrete girders. The Province of Quebec accepted the proposal for reconstructing a significant part of the bridge deck, sidewalk, and traffic barrier using rebar made of carbon-fiber reinforced polymer (CFRP) and glass-fiber reinforced polymer (GFRP).[1]

Monitoring the performance of such a novel structure by using fiber-optic sensing technology would not only answer the safety concerns but also generate valuable data for further research and development of FRP technology

TABLE 1: MATERIAL PROPERTIES

Material	Compressive strength	Tensile strength	Elastic modulus	Elongation at failure (%)	Density
CFRP	—	1400 MPa (203.1 ksi)	90 GPa (1300 ksi)	1.55	1360 kg/m³ (84.90 lb/ft³)
GFRP	—	700 MPa (102 ksi)	42 GPa (6100 ksi)	1.70	—
Concrete	45 MPa (6.5 ksi)	—	37 GPa (5400 ksi)	—	—

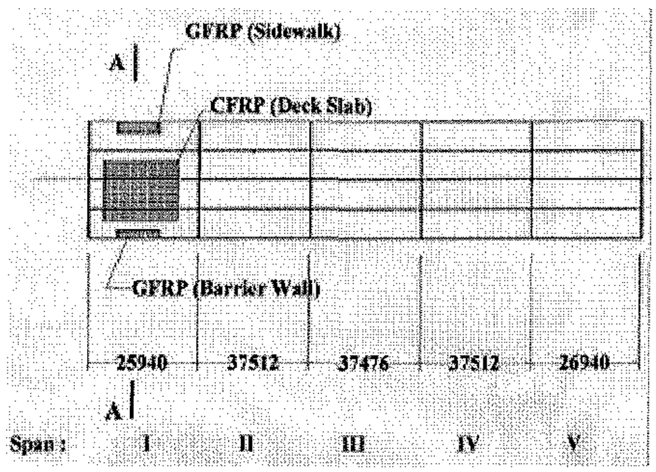

Fig 1a: Layout of Joffre Bridge plan view

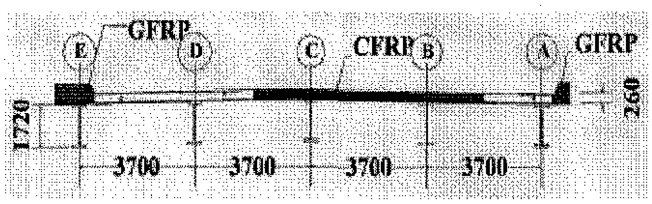

Fig 1b: Layout of Joffre Bridge Section A-A

To develop some basic understandings of the behavior of the FRP-reinforced concrete deck, we first carried out a brief but comprehensive laboratory test program at the University of Sherbrooke. We built and tested one conventional steel-reinforced and three FRP-reinforced concrete deck slabs, 3200 x 1000 x 260 mm (126 x 39 x 10 in.), under static and cyclic loading, and critically analyzed the results.[2] The experience gained from these tests in the laboratory helped us formulate the design and construction strategies for the real structure in the field.

Materials

The CFRP reinforcement used to reinforce the concrete deck—NEFMAC C19-R2 grids—is manufactured by Autocon Composites, Inc., in Ontario, Canada. The grids were 19 mm (3/4 in.) thick with rectangular openings measuring 100 x 200 mm (4 x 8 in.). The cross-sectional area of each bar element of the grid was about 200 mm² (0.3 in.²). We chose these grids because of local availability and cost-effectiveness. We used GFRP C-BAR rebars produced by Marshall Industries Composites, Inc., as reinforcement for a concrete sidewalk and traffic barrier.

Table 1 gives material properties for the CFRP grids, GFRP rebars, and ready-mixed normalweight concrete used for reconstruction of the bridge.

Structural details and design

As shown in Fig. 1, the Joffre Bridge consists of five longitudinal spans with lengths ranging from 26 to 37 m (85 to 121 ft), and four transverse spans, each 3.7 m (12.1 ft). The concrete deck is 260 mm (10 in.) thick. We selected the shaded areas of the concrete bridge deck, sidewalk, and traffic barrier shown in Fig. 1 for the application of FRP reinforcement. The structural design was carried out in accordance with appropriate guidelines available in the *Canadian Bridge Design Code Provisions for Fiber-Reinforced Structures* and other documented applications of FRP bar or grid reinforcements in bridge decks.

The selected part of the deck slab measured 7.3 x 11.5 m (24 x 38 ft), and was reinforced with CFRP grids near the top slab surface and steel rebars at the bottom (Fig. 2). During loading, top-steel reinforcement is typically less severely stressed than reinforcement at the bottom, but is more likely to be damaged by corrosion because it's closer to the road surface where deicing salts are applied. Replacing the top steel in the deck with FRP grids and the steel in the sidewalk and barriers with FRP rebars thus reduces the potential for corrosion-induced deterioration.

The main CFRP reinforcement consists of 10 CFRP grids each 3.6 m (11 ft) in length and 2.3 m (7.5 ft) in width. In addition, 12 CFRP grids (2.3 x 1.15 m [7.5 x 3.77 ft]) were used as laps in both the longitudinal and

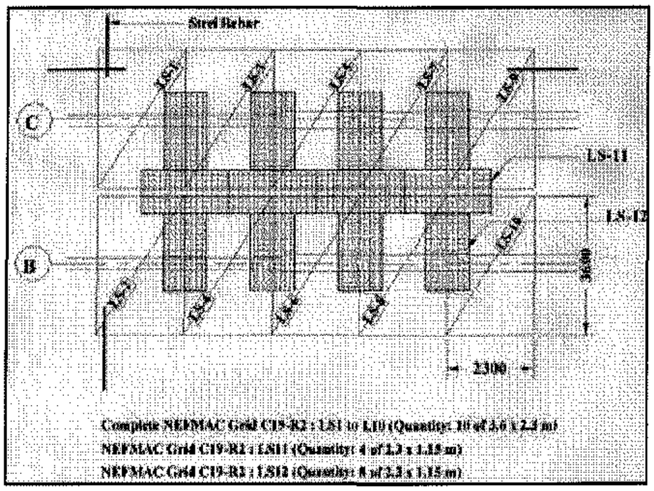

Fig. 2a: Structural details of bridge deck — plan view of CFRP grids used in the concrete deck slab

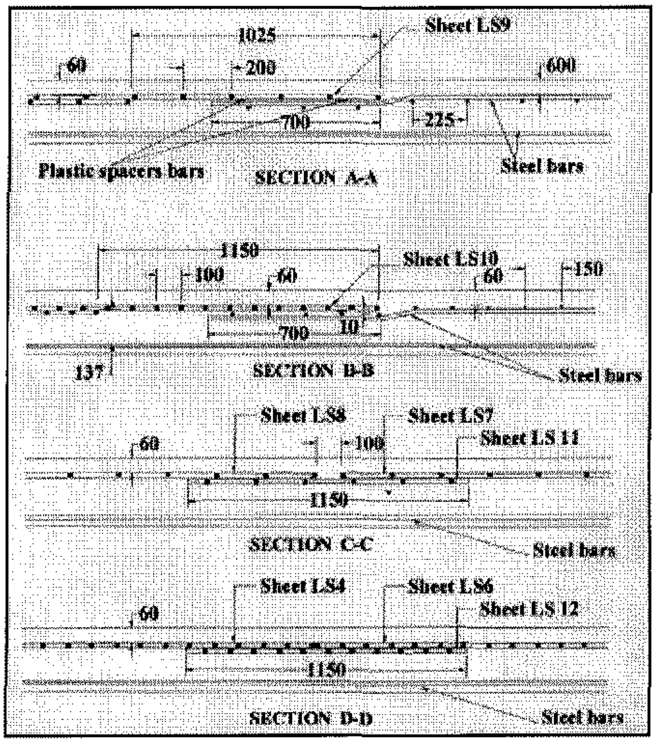

Fig 2b: Structural details of bridge deck — cross section for CFRP grid reinforced concrete deck slab

transverse directions, and at the joints of the main CFRP reinforcement grids (Fig. 2a). Workers placed the grids with the CFRP grid bar spacing of 200 mm (8 in.) running parallel to the length of the bridge and the CFRP grid bar spacing of 100 mm (4 in.) running perpendicular to the length of the bridge.

To keep the lightweight CFRP grids in a fixed position and resist flotation during vibration of fresh concrete, workers tied the grids to plastic chairs that were attached to the bottom steel bars at 2000 mm (79 in.) intervals. The lap splice length between CFRP grid and

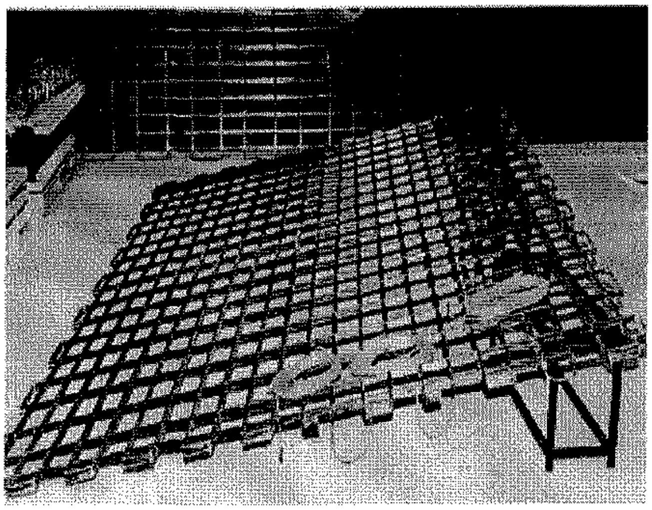

Fig. 3: Overview of Fabry-Perot SFO sensors integrated in CFRP grid reinforcement

steel rebar was 700 mm (27 in.), and the lap splice length between CFRP grids was 525 mm (21 in.) (Fig. 2b). Plastic spacer bars at the reinforcement splice laps between the CFRP and steel rebars prevented any contact between steel rebars that might cause galvanic current flow (Fig. 2b).

A general view of FRP reinforcements installed in the deck slab can be seen in Fig. 3. The cross section of a CFRP grid was about 2000 mm^2/m (0.9 $in.^2/ft$) in the transverse direction of the slab (reinforcement ratio of 1%). Reinforcement used at the bottom consisted of 15M high-yield rebars spaced 150 mm (6 in.) center to center, which yields a reinforcement ratio of 0.66%. To ensure maximum protection of the steel, and because of the concreting technique, engineers chose a concrete cover of 60 mm (2.4 in.) for this project. The cover wasn't changed for the part of the concrete deck reinforced with CFRP grids.

A portion of the traffic barrier and the sidewalk (4.75 m [15.6 ft]) were reinforced with GFRP straight and bent reinforcing bars. Under field conditions, a lot of deicing salts are sprayed on the sidewalks and splashed on the concrete barriers. The use of GFRP bars in this situation can be a cost-effective way to prevent corrosion damage.

Instrumentation and construction

We instrumented the bridge with several types of gages at 180 critical locations in the concrete deck and on the steel girders. Workers installed fiber-optic sensors, vibrating-wire strain gages, or electrical strain gages at those locations. Four types of Fabry-Perot FOS, including SFO, SFO-W, EFO and TFO gages, were used in this project. These sensors have been extensively evaluated for strain monitoring of engineering materials and structures in the laboratory and showed good response to thermal variations and both static and

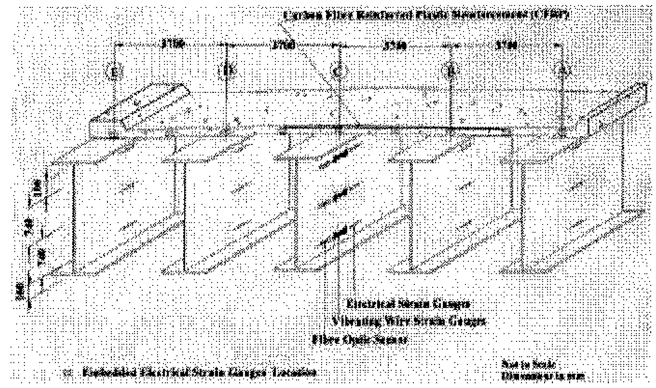

Fig. 4: Layout of fiber-optic sensors (SFO-W), vibrating wire strain gages and electrical strain gages on the steel girder

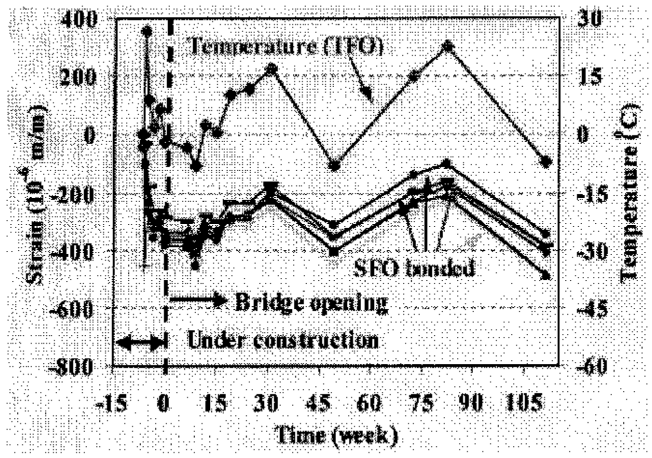

Fig. 5: Typical data recorded by Fabry-Perot SFO sensors bonded on CFRP grid (#LS6) during service conditions

dynamic loading conditions.[3] We used the vibrating-wire and electrical resistance strain gages were used for comparison. Embedded electrical strain gages measured the strain inside the concrete of the bridge deck slab. More details on the gages and evaluation results can be found in Benmokrane et al.[3]

The FOS units were installed during manufacture of the CFRP reinforcement grids. The sensors were installed at the time of the production of the FRP grids. This was the first attempt in Canada to use FOS to monitor the performance of FRP reinforcement inside the concrete in a bridge structure. Figure 4 shows the schematic depiction of installed gages on the steel girders and the nine locations of the embedded strain gages placed inside the concrete. Fabry-Perot SFO-W sensors, together with vibrating-wire strain gages and resistance strain gages, were bonded at the three positions of the top, middle, and bottom of the web of the central steel girder. It is expected that the gages will provide information about any hidden structural damage to the concrete deck.

According to construction workers, the lightweight FRP bars and grid reinforcements were easily handled and placed during construction.

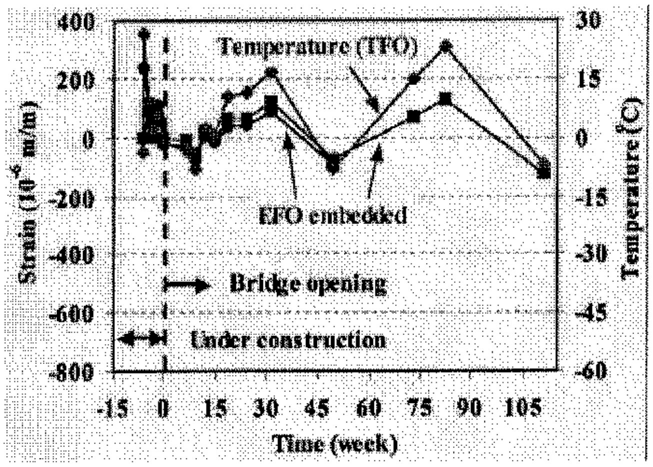

Fig. 6: Typical data recorded by Fabry-Perot EFO sensors embedded in the concrete of the bridge deck slab during service conditions

Structural performance

Following the successful execution of the construction, the bridge was opened to traffic on December 5, 1997. Since then, we have been regularly recording static and dynamic responses of different components of the bridge computer-aided data logging systems. It's too early to draw conclusions about the long-term overall serviceability or performance of the structure. But the interim results have helped to build confidence in the performance of FRP-reinforced concrete structures and the use of state-of-the-art instrumentation for continuous long-term structural performance monitoring.

Figures 5 and 6 show typical data recorded by FOS installed on the CFRP grid reinforcement and in the concrete of the bridge deck. The variation of recorded strain with time and temperature clearly indicates that it is possible to obtain meaningful and consistent results from FOS. Temperature is the most prominent factor influencing the strain variation in the bridge deck. The conclusive analysis of all such collected data is currently in progress and will be reported later.

Controlled field tests

To evaluate the stress level in FRP reinforcement, the concrete deck, and steel girders, we conducted field dynamic and static tests using calibrated heavy trucks one year after the bridge was opened to traffic. The truck loads were applied to bridge Deck Spans I (reinforced with CFRP), II, and III (Fig. 1). This was done with the realization that loads on Spans IV and V would not create any additional critical stress effects on the CFRP reinforcements used in Span I. The maximum combined load from the front wheels of a truck was 8 tons (79 kN) and was 19 tons (187 kN) for rear wheels. Four critical pathways were selected along the span of the bridge deck and the truck positions were chosen to create the maximum possible stress condition in the bridge deck. More details on the designations of pathways can be found in Benmokrane et al.[3]

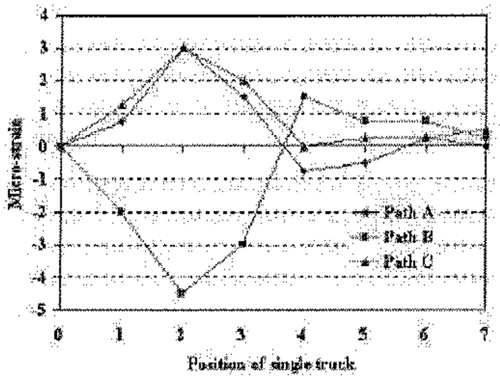

Fig. 7: Typical strain recorded by Fabry-Perot SFO sensor integrated in CFRP grid reinforcement of the concrete deck slab (LS7-1C) during static calibrated load testing

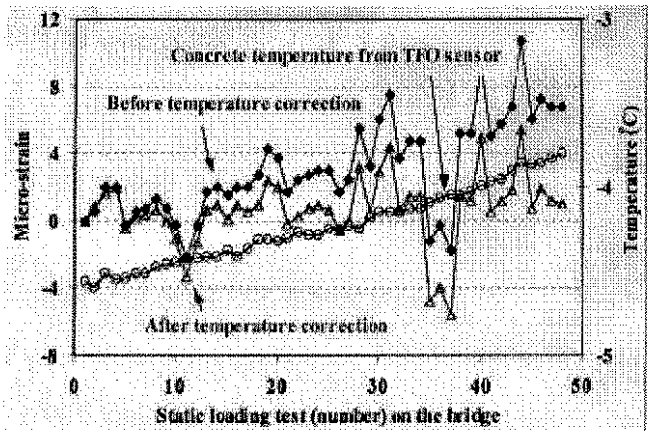

Fig. 8: Typical data recorded by Fabry-Perot SFO sensors installed on CFRP grid reinforcement of the concrete deck slab during static-calibrated load tests

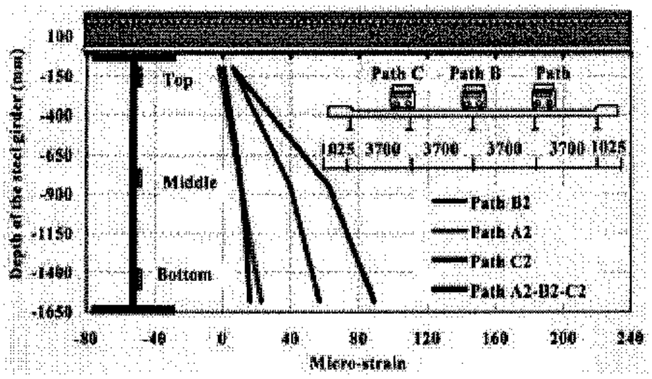

Fig. 9: Typical strain profile recorded by Fabry-Perot SFO-W sensors microwelded on the web of steel girder (#C) during static-calibrated load tests

The striking similarity between recorded data at the middle of the steel girder obtained from two similar tests, and the higher values of strain recorded at the bottom of the beam justify the reliability and rationale of the instruments used in this program.

Figure 7 shows typical monitoring results of FOS instruments on the CFRP reinforcement under the static calibrated load test. The CFRP reinforcement strains at the location of instrumented FOS vary with the loading position of the truck. For given calibrated loads, the CFRP reinforcement strain variation is small for similar tests, as shown in Fig. 8. The measured strains in the FRP grid are very low, less than 20 microstrains. Figure 9 depicts the variation of strain along the depth of the steel bridge girder due to a truck at position A2 (on Path A), B2 (on Path B), and C2 (on Path C), and the combined effect A2-B2-C2.

Figure 9 also reflects two interesting facts. First, the presence of tensile strain throughout the section depth and at the top of the girder suggests that effective composite action between the concrete deck and steel girder did exist. Second, the strain profiles produced by the truck position A2 and C2 were very similar, which reflected the fact that Paths A and C were symmetrical pathways. Figure 9 also shows that the combined load of three trucks on positions A2, B2, and C2 produced strain values at the top, middle, and bottom of the steel girder that were approximately the summation of the effects of three individual truck loads. The measured girder steel strains resulting from static calibrated load tests are less than 120 microstrains. Additional analyses of the calibrated load results are in progress and will be published later. Subsequent calibrated load tests on the bridge will also be carried out at regular intervals.

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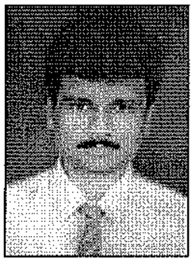

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