LONG-TERM BEHAVIOUR OF AN FRP-STRENGTHENED STRUCTURE: THE CASE OF THE SAINTE-ÉMÉLIE-DE-L’ÉNERGIE BRIDGE

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ABSTRACT

The Sainte-Émilie-de-l’Énergie bridge is a one-span structure with two traffic lanes supported by four reinforced concrete T-section beams. In 1996, the Ministère des Transports du Québec (MTQ) selected this 45-year old bridge as its first field application of FRP for structural strengthening. Prior to strengthening, this bridge was considered to be in good condition, but its capacity did not meet the most recent standards. Both the bending and shear strength had to be increased by the addition of external FRPs. The strengthening of the bridge was completed in 1998, using a configuration established on an analytical basis and by laboratory scale testing. The flexural strengthening of the four beams consisted of longitudinal strips of carbon fibre reinforced composites (CFRP) on their full length. U-shaped external stirrups of fibreglass reinforced composites (GFRP) were used to increase the shear strength of the beams and to improve the anchorage of the longitudinal CFRP strips. In order to evaluate the reliability and durability of the reinforcement, a variety of sensors was installed on the structure. The fibre optic strain sensors, conventional resistive strain gauges and thermocouples are still interrogated on a regular basis to assess the rehabilitation. Four loading tests have also been performed by the MTQ over a six-year period. The paper summarizes the testing program and discusses the behaviour of the FRP reinforcement in actual field conditions.

KEYWORDS

RC beams, FRP strengthening, structural repair, field application, long-term behaviour, monitoring.

INTRODUCTION

The need to repair and strengthen existing bridges seems to escalate at an ever increasing rate. The generalized degradation of civil infrastructure is accelerated by traffic loads that often exceed original design expectations. In northern countries, severe winter conditions combined with an extensive use of de-icing salts cause additional damage to many structures. In recent years, fibre reinforced polymer products (FRPs) have become increasingly popular for the rehabilitation and strengthening of damaged structures, and have also been introduced in the design of new structures. The ever expanding use of FRP products in bridge engineering is well documented in recent monographs (e.g. Keller, 2003), design recommendations (Neale and Demers, 2007; Rizkalla and Mufti, 2004), and international conference proceedings (e.g. COBRAE, 2005). However, there are few publications on the topic of long-term behaviour of actual field applications. This paper presents such information for an existing bridge that was externally strengthened with FRPs and was subsequently monitored to evaluate the performance of this reinforcement. Part of the data was obtained from fibre optic sensors that were installed at the same time as the FRPs. Although these monitoring devices were then quite new to the field of bridge engineering, they appeared to be particularly promising when used in long term field applications (IABSE, 2002; Ansari, 2005).

BRIDGE CHARACTERISTICS

The bridge over the Noire River on Route 131 near the village of Sainte-Émilie-de-l’Énergie is approximately 130 km northeast of Montréal. It is a one-span structure with two traffic lanes supported by four reinforced concrete T-section beams. In 1996, the Ministère des Transports du Québec (MTQ) selected this bridge for its first field application of FRP structural strengthening. Prior to this event, the bridge was considered to be in good condition, but its capacity did not meet the most current standards. Both the bending and shear strength were
increased by the addition of external FRP. A general view of the structure prior to the rehabilitation is shown in Figure 1.

Figure 1. General view of the Sainte-Émélie-de-l'Énergie bridge

The strengthening of the bridge was completed in 1998, using a configuration established on an analytical basis and corroborated by laboratory testing on 1:3 scaled specimens (Lapière et al. 1998, Lamothe et al. 1998, Labossière et al. 2000). The flexural strengthening of the four beams consisted of placing longitudinal strips of carbon fibre reinforced composites (CFRP) on their full length. U-shaped external stirrups, made of fibreglass reinforced composites (GFRP), were used to increase the shear strength and to improve the anchorage of the longitudinal CFRP strips. The repair work is documented in Labossière et al. (2000).

METHODS OF MEASUREMENT

Bridge Instrumentation

A variety of sensors was installed on the structure. Since their activation, the sensors have been interrogated on a regular schedule to assess the performance of the repair. Instruments include fibre optic strain sensors, conventional strain gauges and thermocouples. Eight resistive strain gauges (GS) were welded to the bottom reinforcing bars of the four beams, at midspan. Twenty additional resistive gauges (GC) were placed on the FRPs. Twenty-eight fibre optic sensors (FOS) were installed on the steel rebars and on the FRP. Two types of FOS were used: 20 Fibre Bragg Grating (FBG) sensors and eight Fabry-Pérot sensors. Positioning of gauges and FOS was determined to allow reading comparisons between both types of instruments. Ten thermocouples were also installed on the bridge to evaluate thermal effects. Four of them were placed on longitudinal steel rebars, and six were bonded to the surface of the FRPs. The cables of all the sensors were inserted in PVC pipes converging to an aluminium box in which the connectors are easily reachable. To the permanent instrumentation described above, other devices were added temporarily for load testing including displacement sensors to measure the mid-span deflection and accelerometers to measure vibrations during traffic load tests.

Loading Tests

Loading tests were performed with technical support from the mobile testing laboratory of the MTQ. The tests were conducted before and immediately after strengthening of the bridge. They were repeated one year and six years later, for a total of four full-scale tests. For each test, the trucks travelled in the same direction along the bridge. Identical loading sequences were applied to the structure during the four test series. It first involved driving a single truck along each of four longitudinal paths and stopping it at eight predetermined positions. Trucks were also driven in double along parallel paths, or in triple with two trucks on one path and the third on a second path, stopping in each case at the same eight predetermined positions. Similar but not identical trucks had to be used for the four loading tests on the bridge. Prior to each series of tests, the weight supported by each axle of the trucks, as well as their widths and spacing were measured in order to precisely determine the applied loads. For the first, second and fourth tests, the loads were applied by three four-axle trucks weighing from 29.5 to 34.2 tons each. For the third test, which took place one year after completion of the repair, the load was applied by one four-axle truck that weighed 33.8 tons, and two three-axle trucks weighing, respectively, 26.3 and 26.6 tons.

The method used to compare the four tests is described further in this paper. It can be generally stated that a comparison of the readings showed that the strengthened bridge was in a good general condition and that the composites were performing efficiently.
RESULTS OF THE LOADING TESTS

A selection of typical readings taken since the repair of the bridge is presented here. Results include strains measured by the resistive gauges and fibre optic sensors during the loading tests, as well as Fabry-Pérot sensors and thermocouples data recorded periodically.

Reliability of the measuring instruments

The goal of the loading tests was not only to evaluate the bridge behaviour but also to verify the reliability of the fibre optic strain measuring devices. Two types of FOS relying on different technologies were installed on the structure: Fibre Bragg Grating (FBG) and Fabry-Pérot sensors. In the following, measurements taken with FOS are compared to the strains read by the resistive gauges. Figures 2(a) and 2(b) compare typical results obtained from the FBG to those from the resistive gauges.

The case illustrated corresponds to the loading path with three trucks identified as “ACA” (two trucks along loading lane “A” and one along “C”). Figure 2(a) shows strains measured by a pair of gauges (G111 and G112) welded to a reinforcing bar of the exterior beam as well as the readings of the corresponding Bragg sensor (B14). The strains indicated on Figure 2(b) were measured on the rebars of one interior beam for the same loading. It can be observed on these two graphs that the readings from the FBG sensors are systematically greater than those of the resistive gauges. Other loading paths produced similar results, also observed on the two other beams. Overall, the average variation between the measures taken with the two types of instruments was of 8%. Similar comparisons between resistive gauges and Fabry-Pérot sensors were undertaken. They did show more differences with respect to each other. For the “ACA” loading case, for instance, a comparison between the two types of instruments resulted in a 14% difference, on average. This discrepancy was later tracked down to the inaccuracy of the gauge factors specified by the manufacturer of the Fabry-Pérot sensors that were installed on the bridge.

Evolution of bridge behaviour under truck load

Strain measurements cannot be compared directly to each other because the four series of tests involved trucks that were not absolutely identical (different weights and axle spacing). In order to compare those measurements, we used the method of Savard and Laflamme (2005). It involves estimating the strains that would have occurred in testing series 2, 3 and 4, had the trucks from series 1 been used. We therefore supposed that the coefficients of the strain influence lines can be expressed with a polynomial $\varepsilon (x)$ having the following shape:

$$ \varepsilon (x) = Ax^4 + Bx^3 + Cx^2 + Dx + E $$

(1)

where the parameter $x$ defines the position of the load. If the latter equation is rewritten for five longitudinal positions taken by one of the trucks used for the first sequence of tests, we obtain:
with \( x_i \) being the longitudinal coordinate of axle \( i \) for the \( j \)th truck position, \( P_i \) the load associated to axle \( i \) and \( \varepsilon_j \) the value of the strain measured for the \( j \)th truck position. Inverting the matrix of Equation 2, we can calculate the coefficients \( A, B, C, D \) and \( E \), which define the strain influence line (equation 1). The value of the strain that would have been measured during loading tests 2, 3 and 4 with the truck used during loading test 1, taking position \( j \) (\( \varepsilon_j' \)), can be calculated with the following equation:

\[
\varepsilon_j' = \left( P_1' x_{ij}^4 + P_2' x_{ij}^2 + P_3' x_{ij}^4 \right) A + \left( P_1' x_{ij}^3 + P_2' x_{ij}^3 + P_3' x_{ij}^3 \right) B + \left( P_1' x_{ij}^2 + P_2' x_{ij}^2 + P_3' x_{ij}^2 \right) C + \left( P_1' x_{ij} + P_2' x_{ij} + P_3' x_{ij} \right) D + \left( P_1' + P_2' + P_3' \right) E
\]

where \( x_{ij}' \) is the coordinate of axle \( i \) for the \( j \)th truck position of loading test, and \( P_i' \) is the load associated to truck axle \( i \) of loading test 2, 3 or 4.

Figures 3(a) and 3(b) compare the four test series. Typical information from two loading cases with a single four-axle truck is illustrated. Figure 3(a) shows strain measured on internal rebars of an exterior beam during passage of a truck over path A; Figure 3(b) provides strain data from rebars of an interior beam during passage of a truck over path C. The illustrated beams are those that receive the most important load from the truck circulating along the identified path. For each strain curve, the value illustrated is the average of two gauges (G111 and G112 in Figure 3(a), and G131 and G132 in Figure 3(b)). The difference between the “Test 1” and “Test 2” curves in both figures demonstrates the beneficial effect of the CFRP strengthening. There is an approximate 5% decrease in strains after installation of the composites. This corresponds to the decrease in flexibility anticipated by the numerical model used to design the bridge strengthening. Tests 3 and 4 display little variation with Test 2. This confirms that the repair had preserved its integrity after six years of use. Only two cases are illustrated here but measurements along other loading paths and in other gauges gave similar results.

**Evolution of the Periodical Readings**

Among the three types of strain sensors installed on the bridge, the Fabry-Pérot sensors were the only instruments that allowed a regular follow-up throughout the years. Therefore, these sensors as well as the thermocouples are still being read periodically since their activation. The readings were taken approximately every six weeks until 2002, and then every three months until June 2004. Since then, the Fabry-Pérot sensors and the thermocouples have been read twice a year.
Figure 4 shows all readings taken by one of the Fabry-Pérot sensors after bridge strengthening. In this case, it gives the strains on the external CFRP strip attached to an interior beam and temperature readings from a thermocouple located nearby. The data points are identified by time period, each one producing a certain number of dots aligned on what appears to be a straight line. The curves obtained by a linear regression of the data for the time periods of “June 1999 to October 2001” and “January 2004 to July 2005” are also shown. The slope of these lines corresponds to a coefficient of thermal expansion used later to estimate thermal-related strains and to isolate them from the other mechanical effects causing strains. For instance, the coefficient for the illustrated sensor was calculated as 9.02 με/°C initially and changed to 8.33 με/°C afterwards. The strains recorded by the fibre optic sensors during the “January to May 1999” time frame and those recorded since June 1999 were measured with different readout units. The noticeable gap in the data between the first and subsequent periods is attributable to differences in the calibration of the two instruments used for the measurements. Figure 5 shows a typical correction of the strain for the same sensor. Three curves are drawn: (1) the strains actually measured; (2) the corrected strains, which are the measured strains minus the thermal component; and (3) the temperature measured near the sensor. The correlation between the measured strains and the temperature is obvious. The corrected strain of the sensor remained relatively constant until 2001. However, the important changes in corrected strain between October 2001 and January 2002, and again between September 2003 and January 2004 seem to indicate that permanent strains occurred in the beam at these times.

Figure 5. Typical correction of strains (Beam 2 CFRP)

The corrected residual strains with positive values indicate elongation, while negative values are associated with shortening. Some of the strain data for the beam located on the west side of the bridge, in particular, were not coherent with initial expectations and appeared at first incompatible with strains measured in other locations. In order to explain the data, the bridge was modelled with finite elements. The model showed that when the bridge is exposed to sun, the deck and one beam tend to elongate. The elongation is restricted by the three other beams. Moreover, an increase of the average temperature of the beams as well as a negative thermal gradient causes the deck to move upwards. This negative bending produces compression in the bottom fibres of the beams and
reduces the tension stresses induced in the beams other than the one directly exposed to the sun. It is important to note that the longitudinal stresses associated with thermal effects are present whether or not the beam supports are free to move. On the Sainte-Émélie-de-l’Énergie bridge, the horizontal displacements of the supports are not completely free and there is a partial restriction due to friction. This explains that the permanent strains seem to occur during summer or winter, when the thermal gradients and the average temperature reach their maximum levels.

CONCLUSIONS

The installation of instrumentation on the Sainte-Émélie-de-l’Énergie Bridge, combined with loading tests conducted four times over a period of six years, allowed a thorough evaluation of the reliability and durability of the technology of strengthening existing structures with composite materials. The results summarily presented in this paper demonstrate that the FRP-strengthened structure maintained its integrity since it was repaired and that the FRP has performed as originally anticipated. The tests conducted by the MTQ have allowed us to:
(1) Evaluate the contribution of the CFRP strips on the flexural stiffness of the beams. The results of tests before and immediately after strengthening showed that the bending stiffness was increased by up to 5%.
(2) Confirm that the flexural stiffness of the bridge remained constant in the six years that followed the FRP strengthening, thus indicating that the repair has not deteriorated.
(3) Establish the reliability of two types of fibre optic sensors. The tests have shown an average gap of 8% between the readings from the FBG sensors and those from the resistive gauges, while the average gap between measurements from the Fabry-Pérot sensors and those from the resistive gauges was 14%. An inadequate gauge factor of the Fabry-Pérot sensors was identified as the cause of the important gap between the two types of instruments. Once corrected, the precision of these sensors was judged adequate.
(4) The long-term monitoring carried out with Fabry-Pérot sensors and thermocouples showed that there was not any beam sag since the installation of the FRPs. One of the seven active sensors seems to indicate a high permanent strain at the extremity of one beam, but the relative incoherence of this reading can most likely be attributed to the instability of the sensor.

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