Intelligent Sensing for Innovative Bridges

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**ABSTRACT:** This paper discusses two types of fiber optic sensors used for monitoring highway bridges in Manitoba, Canada. The first, the Taylor Bridge, is the longest smart bridge built in North America and was completed in 1997. Four girders, large portions of the deck slab and the barrier wall are reinforced with carbon and glass fiber reinforced polymer (FRP) materials. The bridge is remotely monitored using fiber optic sensors embedded in the girders, the deck slab and the barrier wall to provide continuous information on the health and structural performance of the bridge. Signals obtained from the optical sensors are transmitted through a telephone line, thereby allowing an office-based engineer to monitor the stresses and strains via a computer anywhere in the world. The paper discusses the expert system program used to reduce the data collected from the bridge into engineering information which can be used to assess the performance of the FRP material and the behavior of the bridge.

The second, the Norwood Bridge, is another innovative bridge also built in Winnipeg, Manitoba. The bridge is a complex precast reinforced concrete structure including an innovative mechanical connection at the supports to provide continuity. Monitoring of the bridge was requested by the owner, the City of Winnipeg, to verify structural behavior during different stages of construction and operation. A different type of fiber optic system was used in this bridge. Both the Taylor and the Norwood Bridge projects were undertaken by the Network of Centres of Excellence on Intelligent Sensing for Innovative Structures (ISIS Canada) which was able to provide the valuable link between the emerging new technology in structural remote monitoring and the construction industry.

**INTRODUCTION**

ISIS Canada, a Network of Centres of Excellence, is a collaborative effort of Canadian universities specializing in civil, mechanical, materials, aerospace, and electrical engineering. It was established in 1995 to research and develop innovative uses of fiber reinforced polymers (FRPs) in concrete structures that are prone to deterioration because of corroding steel reinforcements. As a means of documenting the behaviour of FRP, ISIS Canada also researches and develops structurally-integrated fiber optic sensing (FOS) systems that allow engineers to monitor structures from remote locations. ISIS Canada’s FOS technology is the key to FRP’s ultimate acceptance in national international codes of practice. There are many different applications of ISIS Canada technology. Three attributes, however, remain constant:

1. Fiber Reinforced Polymers (FRPs)
2. Fiber Optic Sensing
3. Remote Monitoring

An integral part of ISIS Canada’s mandate is to transfer technology from the research laboratory to practice. This is done on an on-going basis by liaising with industry and infrastructure owners in the formulation and undertaking of major field demonstration projects. The projects are all geared to achieving a specific objective involving actual functioning structures. This paper describes the collaborative projects undertaken by ISIS Canada to incorporate fiber optic sensing and remote monitoring in two bridge structures built in Manitoba, Canada.

**FIBER OPTIC SENSING TECHNOLOGY**

Fiber optic sensors have been used in numerous field applications, including measuring strains, temperature, humidity and stresses in structures (Ansari, 1998). A portion of the light is sent through the fiber to the sensor and is modulated according to the amount of expansion or contraction. The sensor reflects back an optical signal to a demodulation device which translates the reflected light into numerical measurements representative of the change in sensor length. These measurements indicate precise amounts of strain of the structure, and compensatory calculations are made to eliminate the effect of temperature change on the strain measurements. Fiber optic sensors offer a series of unique advantages over their conventional electronic counterparts including stability, electromagnetic immunity, light weight, small size, low transmission loss and resistance to corrosion. A number of different fiber optic sensors have been devel-
oped in recent years. There are simple sensors which measure only an on/off state and multiplexed sensors which measure a range of frequencies. A variety of other fiber optic sensors have been demonstrated based on intensity, polarization and interferometric techniques. This paper discusses two commonly used optical sensors, the Fiber Bragg Grating (FBG) sensor and the Fabry-Perot (FP) sensor.

**Fiber Bragg Grating (FBG) Sensor**

A FBG sensor consists of a continuous fiber core made by germanium-doped silica; the grating portion itself consists of modulation in the index of refraction along a short length of the continuous fiber core. The operating principles of ideal FBG are illustrated in Figure 1, where light from either a broad band or a tunable laser source interacts with the grating. FBG sensors reflect light in a very narrow band centered about the Bragg wavelength enhancing precision of the measurement. The sensor acts as a selective wavelength "mirror" reflecting the light at the Bragg wavelength back down the sensor. The Bragg wavelength, \( \lambda_b \), is related to the grating pitch, \( \Lambda \), and the mean refractive index of the core, \( n \), by: \( \lambda_b = 2n \Lambda \). Both the fiber refractive index and the grating pitch vary with changes in strain or temperature, such that the Bragg wavelength shifts left or right in wavelength spectrum (Figure 1) in response to applied strain or temperature change. For a FBG bonded to the surface of a structural element, the strain is related to the change in the Bragg wavelength by:

\[
\frac{\Delta \lambda_b}{\lambda_b} = P_e \varepsilon + \left[ P_a (\alpha_s - \alpha_F) + \zeta \right] \Delta T
\]  
(1)

where \( \alpha_s \) and \( \alpha_F \) are the coefficients of thermal expansion of the structural material and fiber, respectively, \( \zeta \) is the thermal-optic coefficient, and \( P_e \) is the strain-optic coefficient (Ansari, 1998).

FBG sensors are particularly attractive for structural sensing since they offer wavelength encoded operation. A major advantage of the wavelength encoded operation is that it simplifies the process of multiplexing numbers of FBG sensors on a single strand of optical fiber. This type of FBG sensor is called a multi-Bragg grating optic sensor. Multi-Bragg fiber optic sensors have the capability to monitor distributed strain, as illustrated in Figure 2.

**Fabry-Perot (FP) Sensor**

A FP sensor consists of measuring a gap or cavity length between two facing fiber ends, contained in a glass capillary. The FP sensor is based on measurement of a dimensional gap shift, and uses a white light broadband source. The FP fiber sensor manufactured by RocTest™ is designed around a FP interferometer that consists of two optical fibers, 50/125 microns in thickness, facing each other. These two fibers are positioned inside a 200-micron diameter glass micropipette. Semi-reflecting coatings are deposited on the tip of each fiber, acting as mirrored reflectors. The space between these two reflective surfaces is the cavity length from which is derived the strain information. The range of cavity length is between nine and 26 microns. The operating principle is shown in Figure 3, where a white light of a broadband source is aimed at one arm of a 2×2 splitter, and directed toward the FP sensor along an incoming multimode optical fiber. After the wavelength is modulated by the sensor, the light signal is reflected back down the fiber and into a read-out unit. The light, at this point, travels through a white-light cross-correlator (a Fizeau interferometer) and into a linear CCD (Charge-Coupled Device) array with a pixel arrangement that allows for a 1:1,000 resolution. The incoming fiber, which transports light to the sensor, is mechanically de-coupled from the strain-sensing fiber. Strain in FP sensors is converted to cavity length variation as follows:

\[
\varepsilon \ (\text{strain}) = \frac{\Delta L_{\text{cavity}}}{L_{\text{sensor}}}
\]  
(2)

where \( \Delta L_{\text{cavity}} \) is the change in cavity length, and \( L_{\text{sensor}} \) is the gauge length (= 10 mm).

Depending on the construction of the FP sensor, the major advantages of the FP sensors are using dual-path lightwave allowing the measurement of temperature compensated or noncompensated strain and measuring the absolute strain as the change in the cavity length. One disadvantage of the FP sensor lies in the fiber discontinuity introduced by the cavity,
Figure 3. General concept of Fabry-Perot (FP) optic sensors.

which can lead to stress concentration at the cavity tip when the sensor is embedded in a structural material.

TAYLOR BRIDGE

Due to a lack of codes and standards on the use of FRP as reinforcement and prestressing materials for concrete bridges, an extensive experimental program was conducted over the last four years. The program included testing of a large scale model of a bridge girder totally reinforced and prestressed with carbon FRP (Fam, Rizkalla and Tadros, 1997) and a full scale portion of the bridge deck slab reinforced with carbon fiber reinforced polymer (CFRP) under simulated traffic loads up to failure (Charleston et al., 1997). The results were used to design the Taylor Bridge which opened to traffic in October 1997. To obtain continuous information on the behavior and health of the bridge, as well as the performance of FRP as reinforcement and prestressing tendons, the bridge is monitored to provide data for long-term behavior. The Taylor Bridge is considered to be the world’s largest highway bridge reinforced by FRP and monitored using fiber optic sensors. The 165.1m-long bridge consists of 40 prestressed concrete AASHTO type girders, as shown in Figure 4. Four girders of the Taylor Bridge were prestressed by two different types of CFRP material using straight and draped tendons, as shown in Figure 5. The girders were also reinforced by CFRP stirrups protruded from the AASHTO type girders to act in composite action with the bridge deck. A portion of the deck slab is reinforced by CFRP reinforcement. Glass fiber reinforced polymer (GFRP) was also used to reinforce the barrier walls which are connected to the deck slab with double headed stainless steel bars.

Bridge girders prestressed and reinforced by CFRP were designed to have the same behavior as other girders of the bridge prestressed with steel strands under service loading conditions. The prestressing force and the eccentricity of the reinforcement were kept the same for all girders. The prestressing level was 60 percent of the guaranteed ultimate tensile strength for CFRP prestressing bars compared to 75 percent for steel strands. Several research projects were

Figure 4. Layout of "Taylor" Bridge.

Figure 5. Girder reinforcement of "Taylor" Bridge.
conducted by ISIS Canada to examine the performance of the bridge. Straight and draped CFRP reinforcements were also tested under axial tension. Performance of CFRP as shear reinforcement (Shehata, Morphy and Rizkalla, 1999), including effect of bend and orientation of the crack on the tensile strength, was investigated. Transfer and development lengths of the CFRP reinforcement were also evaluated and a theoretical model was introduced by Mahmoud, Rizkalla, and Zaghloul (1999). In addition, a research project (Maheu, and Bakht, 1994) was conducted at the Ministry of Transportation of Ontario (MTO) to examine the barrier wall and the deck slab for steel-free bridge decks.

Monitoring of Taylor Bridge

FBG sensors were used to monitor the strains in the CFRP reinforcement of the girders and the deck slab of Taylor Bridge, as well as the GFRP reinforcement of the barrier walls. Selective girders reinforced by conventional steel reinforcement were also instrumented using FBG sensors. The FBG sensors used in the Taylor Bridge were fabricated by E-TEK ElectroPhotons Solutions, Toronto, Canada, and had a full range of 10,000 microstrain (με).

Calibration of FBG Sensors

The FBG sensors were used in concrete structural models and calibrated in several tests at the W. R. McQuade Laboratory at the University of Manitoba.

A full-scale model of a continuous bridge deck slab, reinforced with CFRP bars, was fabricated and tested at the University of Manitoba (Charleson et al., 1997). The slab consisted of three continuous spans of 1.8 meters each and two cantilevers, with overall dimensions of 7.2 × 3.0 m and a thickness of 200 mm. Each of the spans and the two cantilevers were tested independently using a single concentrated load applied over a contact area equivalent to the area of a wheel, as specified by the AASHTO code for HSS 25 truck. The slab was loaded up to failure. The strain of the CFRP reinforcement was monitored using 64 electrical strain gauges (ESG) and eight FBG sensors. The slab failed due to punching shear at a load level of 1000 kN. The failure load is more than seven times the service load recommended by the AASHTO code. A typical load versus strain of the bottom CFRP reinforcement relationship is shown in Figure 6. Figure 6 shows good agreement of the load versus the strain measured by the fiber optic sensors and the electric resistance strain gauges. Agreement between the fiber optic sensors and the strain gauges was also observed in independent tension tests of CFRP bars and beam tests conducted at the University of Manitoba (Abdelrahman, Tadros, and Rizkalla, 1995).

Bridge Sensing System

A total of 63 FBG sensors and two multi-Bragg sensors were glued to the reinforcing CFRP bars of the structural members of Taylor Bridge. The number of sensors installed on each member is given in Figure 4. The FBG sensors were installed at different locations along the girders. FBG sensors located at the midspan were designed to monitor the maximum strain in the reinforcement due to applied loads, while FBG sensors located at the girder ends were designed to evaluate the transfer length of prestressing tendons. Due to the relatively high initial prestressing strain (~8800 microstrain) and the limited full range of the FBG sensors, most of the sensors were installed after tensioning the prestressing tendons. Some of the FBG sensors were installed before prestressing to measure the initial prestressing strains of the CFRP and steel tendons. FBG sensors were installed according to the installation manual prepared by the University of Toronto Institute for Aerospace Studies (UTIAS) for ISIS Canada (Tennyson, 1998).

Twenty-two AD590 electric-based temperature sensors, produced by E-TEK ElectroPhotons Solutions, were installed for the purpose of compensation for thermal apparent strain. Temperature sensors provide representative temperature measurements among different girders and at various locations along and through the depth of the girder and the deck slab. The reading of a FBG sensor, ε_{sensor}, was used to estimate the temperature-compensated strain, ε_{comp}, as follows:

$$\varepsilon_{comp} = \varepsilon_{sensor} - \frac{1}{P_e} [P_e(\alpha_f - \alpha_e) + \xi] \Delta T$$  \hspace{1cm} (3)

where \(\Delta T = (T_i - T_o)\) is the temperature variation, \(T_i\) is the temperature reading as recorded by the temperature sensor co-located with the FBG sensor under consideration, \(T_o\) is the reference temperature (=23.5°C), and \(\alpha_e\), \(\alpha_f\), \(\xi\), and \(P_e\) are defined in Equation (1).

A total of 26 electric strain gauges were also used at locations as close as possible to some of the FBG sensors. The electric strain gauges were installed on the CFRP tendons prior to pretensioning to monitor the prestressing strain. Even though the strain gauges were properly sealed, more than 60 percent of the electric strain gauges malfunctioned.
due to the excessive moisture resulting from steam curing of the concrete girders. None of the FBG sensors were found to be affected by the moisture content.

The strains were recorded using a fiber grating strain indicator (FLS3500R™), a 32-channel multiplexing unit for quasi-static strain measurements and a 24-channel multiplexing unit for temperature measurements, as schematically shown in Figure 7. The FLS3500 is a stand-alone unit with programmability and strain measurement from either the front panel display or the back panel analog/digital output ports. The FLS3500 handles input from ADS90 temperature sensors and FBG optical sensors, with digital output through an RS232 digital port. The FLS3500R™ strain indicator is connected to a resident computer which can be accessed by modem for data logging and downloading. Correction for thermal apparent strain may be performed either in real time within the FLS3500R™ device, or by post-processing after the data has been logged. The monitoring devices and the computer are housed in a heated enclosure mounted in the abutment of the bridge, as shown in Figure 8. The bridge will also be monitored with a camera to provide video information synchronized with the optic sensors’ signals.

Sensors’ Expert System Program

A full-featured software package “ESPA” has been developed by the researchers in ISIS Canada for analyzing FBG sensors’ data downloaded from the Taylor Bridge computer (Maalej et al., 1998). The main features of the “ESPA” software are:

1. Interactive visualization of measurements
2. Estimation of natural frequencies and damping ratios
3. Spectral analysis of records using a collection of algorithms
4. Mode shapes
5. Strain profiles
6. Moment profiles
7. Estimation of the coefficient of thermal expansion of sensor substrate materials
8. Image viewing of diagrams or photographs of the structure
9. Estimation of vehicle velocities
10. Graphical user interface driven interaction
The "ESPA" software is portable in the sense that it can run on any major platform (operating system) including Windows’98 and Unix. In addition to the Taylor Bridge, the software was successfully used to process the sensors' data of the Salmon River Bridge in Nova Scotia (Maalej et al., 1998). A detailed description of the features of “ESPA”, along with hardware and software requirements, manuals and other instructions, are provided by Maalej et al. (1998).

**Monitoring Results**

Preliminary results recorded address the following stages:

1. Construction stage
2. Load testing of the bridge
3. Long-term behavior due to the temperature effect

**Construction Stage:** Most of the available research on bond behavior of CFRP reinforcement was obtained by testing specimens reinforced with single CFRP bars or strands; therefore, it is important to assess the behavior in case of multiple CFRP tendons used for the bridge girder. FBG sensors were installed on the CFRP tendons at the end of the bridge girders to measure the effective stress level in the tendons after release of the prestressing force. Figures 9 and 10 show the effective-to-initial prestressing ratio along five meters at the end of the bridge girders prestressed by two different types of CFRP tendons. It can be seen that the transfer lengths, \( L_p \), are 600 mm (60 \( d_b \)) and 340 mm (22.3 \( d_b \)) for CFRP tendons type 1 and type 2, respectively, where \( d_b \) is the bar diameter. Based on an independent research program conducted to investigate the bond characteristics of CFRP tendons (Mahmoud, Rizkalla, and Zaghoul, 1999), transfer lengths in the bridge girders were recommended as 66 \( d_b \) and 22.5 \( d_b \) for the same CFRP tendons type 1 and type 2, respectively. The observed values for transfer lengths showed good agreement with the values determined based on the equations proposed in (Mahmoud, Rizkalla, and Zaghoul, 1999).

The strain in the CFRP prestressing tendons was monitored during transportation of the girders to the bridge site. The strain signal of a selective sensor at the midspan of the girder was recorded at 14 intermediate stations along the trip from the pre-casting plant to the bridge site. Figure 11 shows the variation in the CFRP strain relative to the effective prestressing strain at different stations during the trip.

**Load Testing:** The output signal of a FBG sensor installed on a CFRP prestressing tendon at midspan was recorded every 0.24 second during a test loading conducted using a slow moving truck and trailer, as shown in Figure 12. The
36-ton truck made several passes over the girder span, forward and backward. The FBG sensor was able to record the strain change experienced by the CFRP tendon as shown in Figure 13. The figure clearly identifies both the truck and the trailer loading as two distinct peaks in the response curve even though the magnitude of the strains are quite small. The direction of travel can also be detected by the relative magnitudes of the peaks since the truck load is larger than the trailer load. Hence, the first event in Figure 13 represents a backward pass and the subsequent one is a forward pass over the span.

**Temperature Effect:** The strains in CFRP reinforcement are being continuously monitored to detect any loss in the prestressing forces. Since the long-term monitoring initially commenced, no significant loss in the prestressing force has been observed. Sample data is given in Figure 14 showing the variation in the strain and the temperature of a CFRP prestressing tendon over a period of seven days. The signals from the FBG sensors and the temperature sensors were recorded every five minutes. The strain variation is attributed to the difference in the coefficient of thermal expansion of CFRP reinforcement ($\alpha_{\text{CFRP}}$) and the concrete ($\alpha_{\text{Concrete}} = 12 \times 10^{-6}/\degree C$). The strains in the FRP and steel reinforcement are continuously monitored to investigate the temperature and creep effects on the structural performance of the bridge structure.

**NORWOOD BRIDGE**

The five-span, 180-meter Norwood Bridge consists of 85 precast reinforced concrete girders, as shown in Figure 15. The precast girder is designed as a simple beam to carry the dead loads of the bridge structure, while the continuity of the girders provided by means of the innovative system, illustrated in Figure 16, carries the live loads. A typical 28.5m-long variable-depth precast girder of the bridge is shown in Figure 17.

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**Figure 13.** Truck passage data.

**Figure 14.** Strain and temperature data—February 1998.

**Figure 15.** Layout of “Norwood” Bridge.

**Figure 16.** Schematic drawing of girder continuity.
Monitoring of Norwood Bridge

Due to the complex nature of the bridge structure and the slenderness of the girders used, officials of the City of Winnipeg required monitoring of the girders during transportation and erection, as well as monitoring of the entire structure after completion. A total of 51 strain sensors were used to instrument the reinforcement in six girders similar to the one shown in Figure 15, the reinforcement in the concrete overlay at the pier locations, and the Dywidag bars used to connect the girders. Three types of strain sensors, shown in Figure 18, were used:

1. Spot weldable fiber optic sensors
2. Bondable fiber optic sensors
3. Spot weldable vibrating wire strain gauges

The sensors were produced by RocTest™ and installed according to the installation manual prepared by the UTIAS for ISIS Canada (Tennyson, 1998). FP sensors have been evaluated for strain monitoring in concrete structures at the University of Sherbrooke through an extensive research program (Nicole and Benmokrane, 1997).

The working principle of the vibrating wire strain gauge is based on measuring the natural frequency of a wire under tension, and then correlating this value to the strain in the member to which the gauge is attached. The vibrating wire strain gauge consists of two end blocks between which a length of steel wire is clamped under initial tension. Vibrat-
ing wire strain gauges are characterized by their high resolution and accuracy, long-term reliability, easy installation, corrosion resistance, and stable frequency signal unaffected by cable lengths.

The lead wires of the vibrating wire and fiber optic sensors were pulled through PVC conduits to junction boxes, where they were spliced to the main cable running to the read-out devices. The data acquisition system is designed to be remotely accessed from anywhere around the world through a telephone line. ISIS Canada, in collaboration with Reid Crowther and Partners, are currently working on the design and specifications of the data acquisition system.

Preliminary Monitoring Results

Two precast girders were monitored during transportation to the bridge site using long-gauge extensometers mounted on the top and bottom surfaces at the midspan of the girder, as shown in Figure 19. The girders were supported at two intermediate points during transportation, as shown in Figure 17, to minimize the probability of inducing tensile cracks in the bottom surface. The signals from the extensometers were recorded at 52 intermediate stations along the trip from the pre-casting plant to the bridge site. Figure 20 shows the variation in the bottom strain at different stations during the trip. It was observed by Figure 20 that the measured tensile strain was less than the cracking strain of the concrete. The remote monitoring phase of the project is expected to be complete in summer 2000.

CONCLUSION

Two types of FBG sensors have been deployed in the Taylor Bridge, Headingley, Manitoba, and the Norwood Bridge, Winnipeg, Manitoba. The optical sensing system is used to remotely monitor the bridge structure, giving the bridge engineer a warning signal if abnormal conditions should occur. These projects provided a practical application for the use of these types of sensors during construction, transportation and long-term structural monitoring under operating conditions. The fiber optic sensors, calibrated through several load tests, showed good performance as compared to the conventional electric strain gauges. When embedded in concrete members, FBG sensors are more durable than electric strain gauges. Preliminary data collected from the Taylor Bridge show that such a monitoring system is a very effective tool for the bridge engineer. Monitoring of the Taylor Bridge provides essential data related to the short-term and long-term performance of FRP material used to reinforce the bridge members. In summary, the monitoring system can provide a profile of the bridge, with detailed information on its structural behavior, as well as health due to applied loads and environmental effects.

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