SHM technologies for civil engineering intelligent infrastructure

A.A. Mufti
President, ISIS Canada Research Network & Professor of Civil Engineering, University of Manitoba Agricultural & Civil Engineering Building, A250 - 96 Dafoe Road, Winnipeg, Manitoba, Canada, R3T 2N2, Telephone: (204) 474-7476; fax: (204) 474-7519; muftia@cc.umanitoba.ca

B. Bakht
President, JMBT Structures Research Inc., Toronto, Ontario, Canada

G. Tadros
President, SPECO Consultants Inc., Calgary, Alberta, Canada

ABSTRACT: Civil Engineers should develop innovative structures using advanced nanotechnology-based materials such as FRPs that utilize nano-clays. For these new structures to be accepted by the engineering community, it is mandatory that they be monitored and that the results are reported to the engineering community as well as being incorporated into civil engineering codes. ISIS Canada has been developing such structures and monitoring them through an innovative concept, which involves the development of the new discipline of Civionics where *Civi*l Engineering and Electrophot*onics* are being integrated. In this paper, some of the innovations that have been implemented will be described.

Keywords: civionics, Fibre Reinforced Polymers (FRPs), Fibre Optic Sensors (FOSs), structural health monitoring (SHM)

1 INTELLIGENT SENSING

For many years, engineers have been searching for ways to obtain information on how a structure is behaving in service by incorporating, at the time of construction or subsequently, sensing devices which can provide information about conditions such as strain, temperature, and humidity (Tennyson, 2001). The development of such structurally integrated fibre optic sensors (FOSs) has led to the concept of smart structures.

2 INTEGRATION OF INTELLIGENT SENSING WITH INNOVATIVE STRUCTURES

For infrastructure owners, one of the greatest values of ISIS Canada research lies in its practical application. Over the past year, there have been many new opportunities for applying ISIS Canada technology as is evidenced by the growing number of field demonstration projects underway. The projects range from a concrete steel-free bridge deck for the Salmon River Bridge in Nova Scotia (Newhook and Mufti, 2000), to the strengthening of a nuclear containment structure in Quebec (Demers et al. 2003).

At least fifty projects are currently being monitored for health in Canada. Several of those are described in the following sections.

2.1 Beddington Trail Bridge, Calgary, Alberta

In 1992, the Beddington Trail Bridge in Calgary (Rizkalla and Tadros, 1994), Alberta, as shown in Figure 1(a), was the first bridge in Canada to be outfitted with fibre reinforced polymer (FRP) tendons and a system of structurally integrated optical sensors for remote monitoring. The bridge opened in 1993, before ISIS Canada was formed. It is significant to the ISIS network because, for the group of researchers involved, it confirmed the need for an organization, like ISIS Canada, that could spearhead transferring this new technology to industry.

Figure 1(a). Accessing fibre optic junction box - 1999.

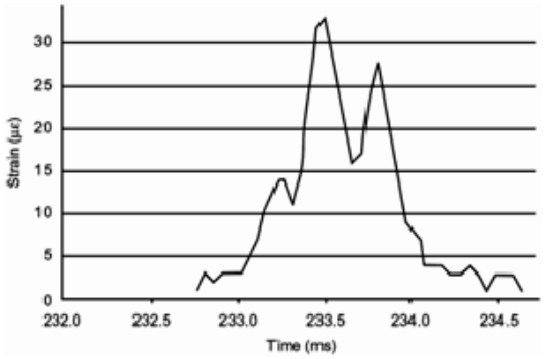

Figure 1(b). Dynamic FBG response to three-axle truck load - 1999.

Figure 2(a). Accessing fibre optic junction box - 2004.

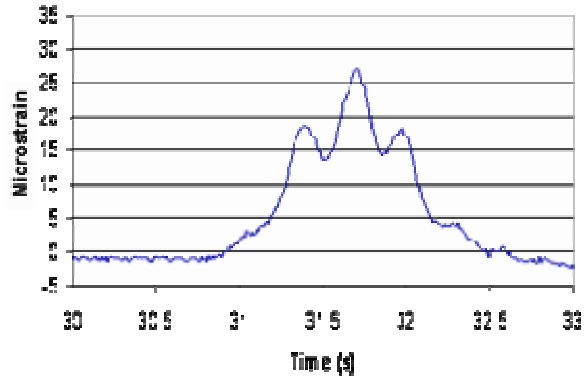

Figure 2(b). Dynamic FBG response to three-axle truck load - 2004.

The Beddington Trail Bridge is a 2-span, continuous skew bridge of 22.83 and 19.23-m spans, each consisting of 13 bulb-Tee section, pre-cast, prestressed concrete girders. Two different types of FRP tendons were used to pretension six precast concrete girders. Carbon fibre composite cables produced by Tokyo Rope of Japan were used to pretension four girders while the other two girders were pretensioned using Leadline rod tendons produced by Mitsubishi Kasei.

Fibre optic Bragg grating strain and temperature sensors were used to monitor structural behaviour during construction and under serviceability conditions. The four-channel Bragg grating fibre laser sensing system was developed for this purpose at the University of Toronto Institute for Aerospace Studies.

Before constructing the bridge, an experimental program was conducted at the University of Manitoba's W.R. McQuade Laboratory to examine the behaviour of scale model beams pretensioned by the same type, size, and anchorage of the two different tendons used for the bridge girders. The tests compared results using the same optic sensor as used for the bridge in addition to electric resistance strain gauges.

Prestressing of carbon FRP was adapted by coupling the carbon fibre composite cables and Leadline rods to conventional steel strands. Couplers helped to minimize the length of carbon FRP tendons, and were staggered to allow use of the same spacing for the conventional steel reinforcing tendons.

The Leadline rods were cut at the site and two rods were used for each tendon. The carbon fibre composite cables were delivered precut to the specified length with 300-mm die cast at each end to distribute the stresses at the anchoring zone. Construction of the bridge and handling of the girders at the site was typical.

A four-channel Bragg grating fibre optic sensor system was used at different locations along the bridge girders that were pretensioned by the carbon FRP. Each fibre optic sensor was attached to the surface of the tendon after pretension to serve as a sensor. The sensors were connected, through a modular system, to a laptop computer used at the construction site to record the measurements at different stages of construction and after completion of the bridge. The optic sensor system measures the absolute strain rather than a strain relative to an

initial calibration value similar to electric resistance strain gauges and mechanical gauges.

In 1999, the bridge was tested statically and dynamically to assess the durability of fibre optic sensors (Fig. 1(a)). After six years, all FOSs were functioning (Fig. 1(b)). This finding validates the view that FOSs are durable and reliable for long term monitoring.

In November 2004, the bridge was tested again with the same vehicle and weight (Fig. 2(a)). Figure 2(b) indicates that the FBG sensors are durable and are providing accurate results and that the CFRP is performing as designed in 1993.

3 CIVIONICS

CIVIONICS (Mufti, 2003) is a new term coined from the integration of Civil-Electronics, which is derived from the application of electronics to civil structures. It is similar to the term Avionics used in the Aerospace Industry. For structural health monitoring to become part of civil structural engineering, it should include the new discipline of Civionics, which requires the development of formal definitions and guidelines to encourage its use as an academic discipline in the curriculum of Canadian universities and technical colleges. Civionics is integral part of the structural health monitoring process, which is shown in Figure 3.

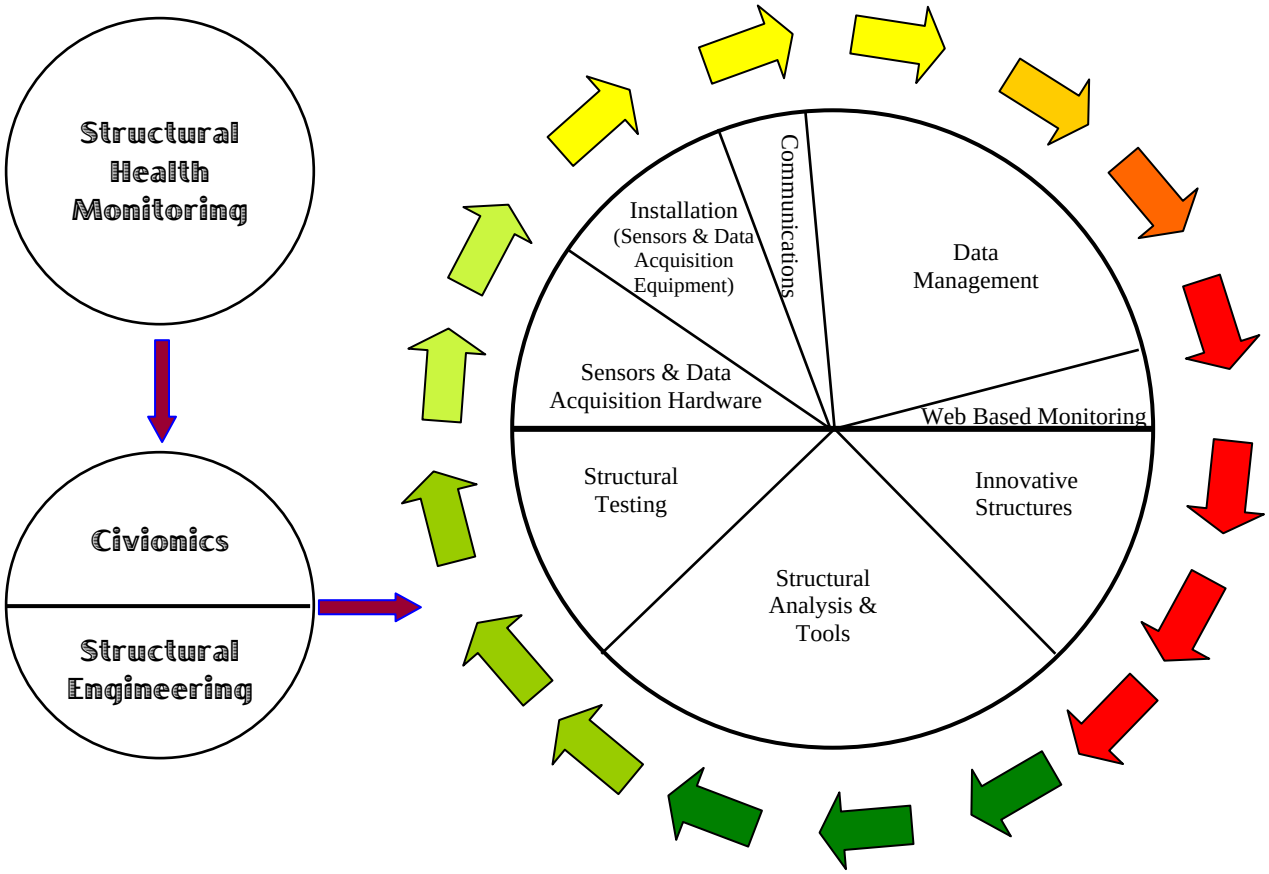

Figure 3. Various components of structural engineering and civionics.

The discipline of structural engineering is well established. Its various components such as analysis, design, computer programs and laboratory testing has been extensively developed. However, the development of innovative structures to include new materials such as FRPs has been slow due to the absence of the discipline of Civionics, which allows superimposing intelligent sensing on innovative structures leading to intelligent structures. The components of Civionics are shown in the Figure 3. Many of the individual components exist in the field of electronic engineering but to transfer these to civil engineering and integrate them into the construction process will be an interesting and demanding challenge that civil engineers of the future will face. Innovation in structural engineering will become much more rapid if the discipline of Civionics becomes an integral part of Civil Engineering.

At the present, in order to develop new concepts or to use nanotechnology-based materials in structural engineering, sophisticated analysis tools based on the finite element method's theory of elasticity and structural mechanics are used. When a concept cannot be formulated by analytical tools, then it is established by laboratory testing. However, the acceptance of such innovations is slow in the construction industry due to the conservative nature of this industry. But, if it could be shown by monitoring innovative structures that the new materials and new concepts are functioning as predicted, then the acceptance of these new and innovative concepts will become much faster.

Realistically, it is true that consulting engineers and contractors will only invest in the development of the expertise created by graduates of the Civionics discipline when they can be assured that the prospects for business are good in this field. The ISIS Canada experience of integrating FOSs and FRPs into innovative structures that have been built across Canada demonstrates that these opportunities do exist. In Canadian Universities and Technical Colleges, research, academic and training courses are established or are in process of being developed (Bisby and Mufti , 2005). It is intent of ISIS Canada that future generations of structural engineers and technologists will be familiar with the requirements of industries related to Civionics. To that end, ISIS Canada has developed a Civionics Specifications Manual (Rivera et al. 2004), which is being utilized to assist in the training of highly qualified personnel (Fig. 4).

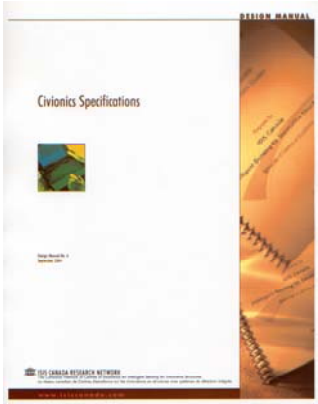

Figure 4: Civionics Specifications Manual.

3.1 Civionics application in a second generation steel free bridge deck

In the spring of 2004, research engineers at the University of Manitoba constructed a full-scale second generation steel free bridge deck. This bridge deck is the first of its kind to fully incorporate a complete civionics structural health monitoring system to monitor the deck's behaviour during destructive testing.

Throughout the construction of the bridge deck the entire installation of the civionics system was carried out by research engineers to simulate the actual implementation of such a system in a large scale construction environment. One major concern that has been raised by consulting engineers is the impact that a civionics system that uses conduit, junction boxes, and other electrical ancillary protection will have when embedded and installed externally on full-scale infrastructure. The full-scale destructive testing of the second generation steel free bridge deck that utilizes a civionics system designed and implemented using the Civionics Specifications Manual at the University of Manitoba will provide engineers with the information necessary to address the constructability and structural integrity issues.

The complete civionics system for the test bridge deck at the University of Manitoba includes rigid PVC conduit and junction boxes to provide protection for the network of sensors embedded within the deck and all of the sensors installed externally on the steel straps and steel bridge girders. The placement of the system of conduits and junction boxes is important because it should minimize its effect on the structural integrity of the bridge deck, as well as minimize the amount of conduit and exposed cable within the deck. In this case, the conduits were placed within the haunches of the deck (Fig. 5).

Figure 5 (a).

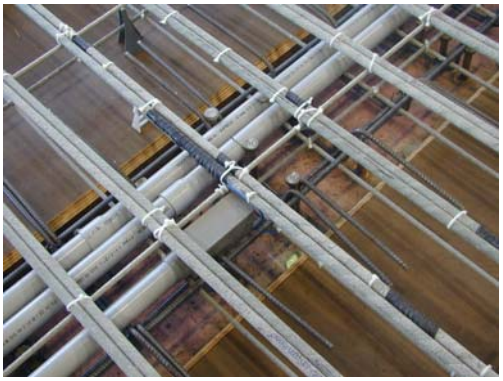

Figure 5 (b).

Figure 5. Rigid PVC conduit embedded with bridge deck haunches.

The sizing of the conduit was determined using the Civionics Specifications Manual. The conduit size and junction boxes required for this project were 1½" in diameter. It should be noted that for research purposes this bridge deck was equipped with several additional sensors and that the conduit was sized accordingly. A civionics system for an actual steel free bridge deck would contain a minimal number of embedded sensors, thus reducing the amount and size of conduit required. For a typical installation on an actual bridge the conduit would be placed by the local electrical contractor and all of the necessary wires would be terminated at the junction boxes. A short time prior to the casting of the bridge deck, and after all major placement of reinforcement has been completed, qualified personnel would be required to install the specified sensors and make the appropriate connections at the junction box to the wires already supplied and installed by the electrical contractor. Field installation of the sensors requires the application of several protective coatings and the exposed lead wires should be located in such a manner as to prevent damage during placement of concrete (i.e. wires should be placed on the underside of the reinforcement and properly secured - Fig. 6). The sensors embedded within the bridge deck on the reinforcing bars allow engineers to monitor live load stresses during and after construction.

Figure 6. Protected sensors complete with properly located and secured lead wires.

Surface mounted sensors located on the external steel straps and on the steel girders also provide engineers with pertinent information relating to the overall performance of a bridge. However, these sensors must also be properly protected from vandalism and local environmental conditions. Therefore, a system of rigid PVC conduits and junction boxes were permanently installed on the steel girders and steel straps. The conduit and lead wires would be installed by an electrical contractor after all of the formwork has been removed. The wires must be properly labelled to ensure that the correct locations of all sensors are known at a later date. Once again, qualified personnel perform the installation of the necessary gauges within the PVC boxes and splice all lead wires.

The size of the conduit and junction boxes on the straps were 1" in diameter to provide enough space in the junction box to install the sensor. The back of the PVC junction box had to be removed in order to facilitate surface mounting of the sensors (Fig. 7). Strain gauges installed on the straps will allow engineers to monitor live load strains. Flexible conduit measuring ¾" in diameter was used with the junction boxes on the top and bottom flanges of the steel girder (Fig. 7). The purpose of the gauges installed on the girders is to determine the live load stress ranges and to determine the transverse load distribution pattern. Also, the gauges will allow engineers at the University of Manitoba to determine exactly if placement of the conduit within the haunches has any significant effect on the composite action between the girders and the deck.

Figure 7. Rigid PVC conduit and junction boxes for externally installed gauges.

3.2 South Perimeter Bridge

The Red River Bridge is located on the South Perimeter Highway that encircles the city of Winnipeg, Manitoba. It is a 250 meter long, 7-span bridge, consisting of three simply supported spans and one continuous span. Over a period of two years, the entire bridge deck will be replaced with a second generation steel-free GFRP hybrid bridge deck. The installation of a civionics structural health monitoring system in this bridge will follow the requirements as outlined in the Civionics Specifications Manual. Preliminary plans involve a minimal number of sensors including fibre optic sensors, accelerometers, conventional sensors and weigh in motion sensors (Fig. 8).

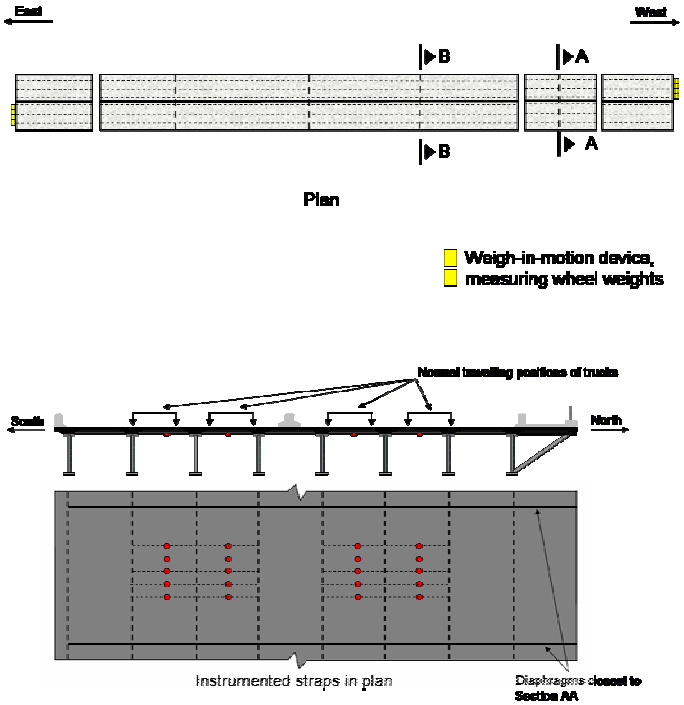

Figure 8. Location of weigh-in-motion sensors and electronic strain gauges on steel straps.

4 SMART FRP REINFORCED BRIDGE DECKS

4.1 Portage Creek Bridge - strengthening against earthquakes & field assessment, British Columbia

The Portage Creek Bridge (Mufti et al. 2003) (Fig. 9) in Victoria, British Columbia, was designed in 1982 by the British Columbia Department of Highways Bridge Engineering Branch. It crosses Interurban Road and the Colquitz River at McKenzie Avenue.

Figure 9. Portage Creek Bridge.

It is a 125 m (410 ft) long 3-span steel structure with a reinforced concrete deck supported on two reinforced concrete piers with abutments on steel H piles. The deck has a roadway width of 16 m (52 ft) with two 1.5 m (5 ft) sidewalks and aluminum railings. The super structure is supported at the ends and has two intermediate supports along the length of the bridge called Pier No. 1 and Pier No. 2.

The Portage Creek Bridge is a relatively high profile bridge that has been classified a Disaster-Route bridge. However, it was built prior to current seismic design codes and construction practices and

could probably not resist the potential earthquake forces, which are required by today's standards. Although some consideration was given to seismic aspects as evidenced in the original drawings, it required retrofitting to prevent collapse during a seismic event. The service life of the bridge can thus be increased to 475 years.

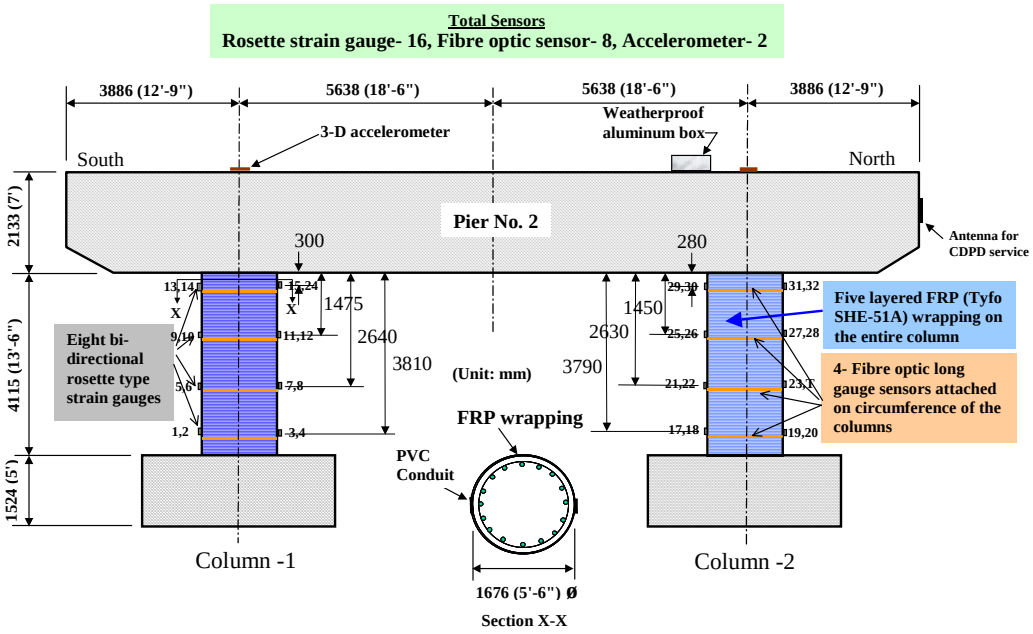

Figure 10. Portage Creek Bridge FOS location.

Most of the bridge is being strengthened with conventional materials and methods. The dynamic analysis of the bridge predicts the two tall columns of Pier No. 1 will form plastic hinges during an earthquake. Once these hinges form, additional shear will be attracted by the short columns of Pier No. 2. A nonlinear static pushover analysis indicates that the short columns will not be able to form plastic hinges prior to failure in shear. Therefore, it was decided that FRP wraps should be used to strengthen the short columns for shear without increasing the moment capacity. The bridge is instrumented with 16 foil gauges, 8 fibre optic sensors and 2 accelerometers (Fig. 10). The bridge is being remotely monitored and data collected with the datalogger and monitoring system shown in Figures 11 and 12. ISIS Canada is assisting with the structural health monitoring of this bridge.

Figure 11. Datalogger.

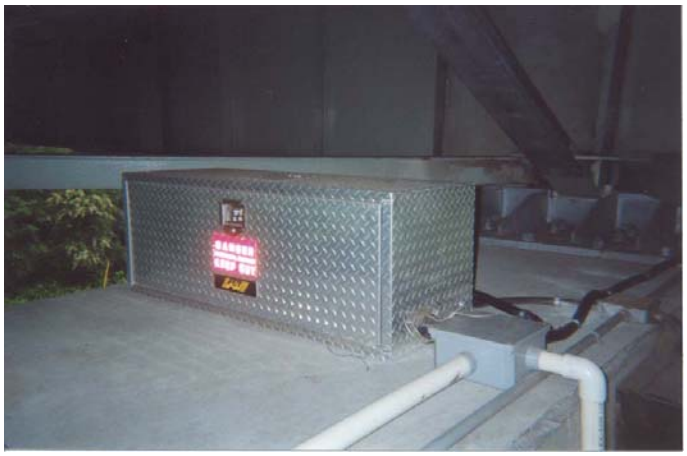

Figure 12. Monitoring System.

5 BROOKSIDE CEMETERY - LONG-TERM PERFORMANCE OF ANCHOR ASSEMBLY FOR MARKER IN CONCRETE AT VETERAN AFFAIRS

The rapid deterioration of the markers and the supporting concrete beams at Brookside Cemetery (Fig. 13) in Manitoba and other cemeteries across Canada has become a major issue of concern for Veterans Affairs Canada National and International Memorials, and Heritage Conservation Services, Public Works and Government Services Canada (Mufti and Onofrei, 2004).

Figure 13. Brookside Cemetery, Winnipeg, Manitoba, Canada.

Brookside Cemetery, located northwest of Winnipeg, is a very large cemetery with over 96,000 graves. A portion of the cemetery is designated for the graves of Canadian veterans from World Wars I and II and from the Korean War. The rest of the cemetery is designated for the graves of civilians.

5.1 Field Application of FRP Reinforced Smart Beam

5.1.1 Instrumentation

As part of the structural health monitoring system, a total of 12 sensors were installed at critical locations (Fig.14) in the reinforced concrete beam (Mufti et al. 2004). In order to gain a comprehensive representation of the condition of the beam and validate the theoretical calculations of mid-span deflection and natural frequency, three types of electrical sensors were selected. Each type of sensor will provide information on a different aspect of the concrete beam. Electrical strain gauges were used to provide strain measurements from the GFRP reinforcing bars. These strain readings can then be used to determine the deflection of the beam at the mid-span. Thermocouples were also installed to measure the temperature inside the beam. Finally, an accelerometer was installed in the beam to measure the frequency response of the beam to an applied load.

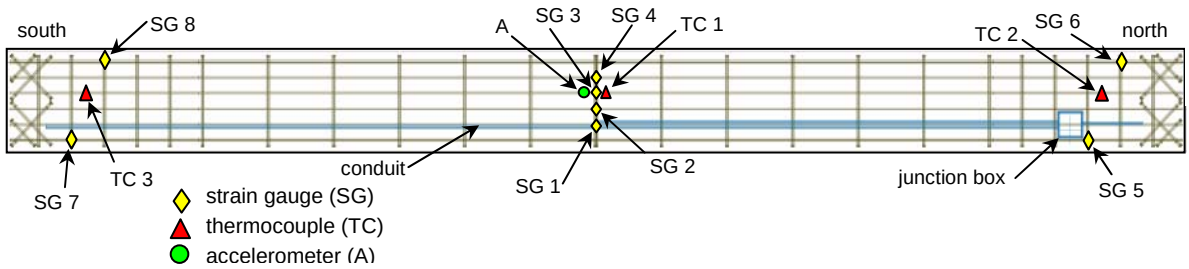

Figure 14. Sensor locations on 24 ft (7.32 m) field trial beam.

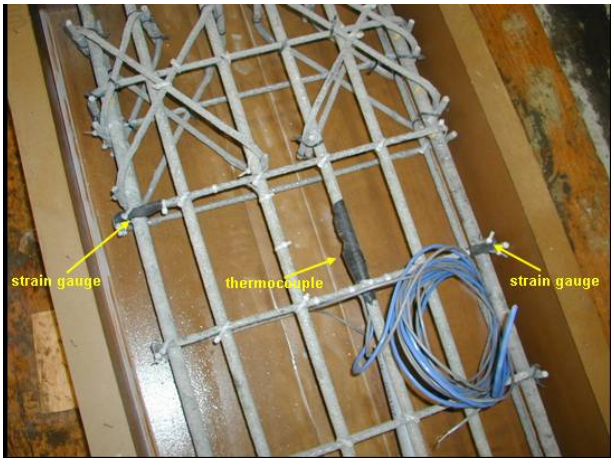

Figure 15. Strain gauges and thermocouple installed on north end of 24 ft (7.32 m) field trial beam.

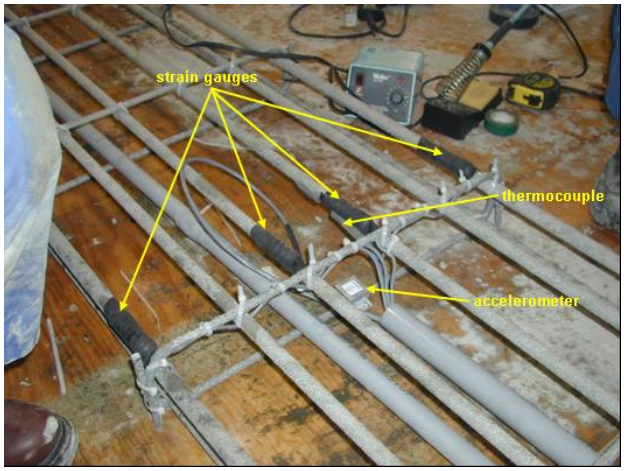

Figure 16. Strain gauges, accelerometer, and thermocouple installed at mid-span of the 24 ft (7.32 m) field trial beam.

At each end of the beam, two strain gauges on the stirrups and a thermocouple on the reinforcement bar were installed as shown in Figure 15. At the mid-span, four strain gauges, a thermocouple and an accelerometer were installed on the bottom reinforcement bars (Fig. 16). The majority of the sensors were placed at the mid-span since it will experience the greatest amount of deflection and strain.

A 24 ft beam has been designed and instrumented as shown in Figure 17 to demonstrate the performance of FRPs in a field application.

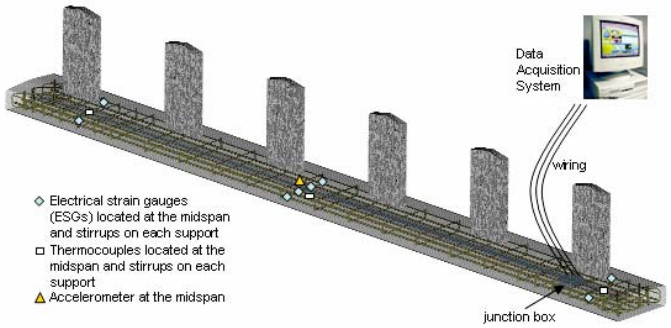

Figure 17. Schematic diagram of a 24 ft beam and SHM system.

5.1.2 Frequency Response of Beam

Following the successful execution of the installation of the beam at Brookside Cemetery (Mufti et al. 2004), the static and dynamic response of the beam was recorded using a data acquisition system. The accelerometer embedded in the mid-span of the beam was used to determine the frequency of the beam. After the beam was placed on the piles, the beam was excited at the mid-span with a 68 kg mass. The accelerometer responses of the beam before and after installation of the markers are presented in Figures 18 and 19.

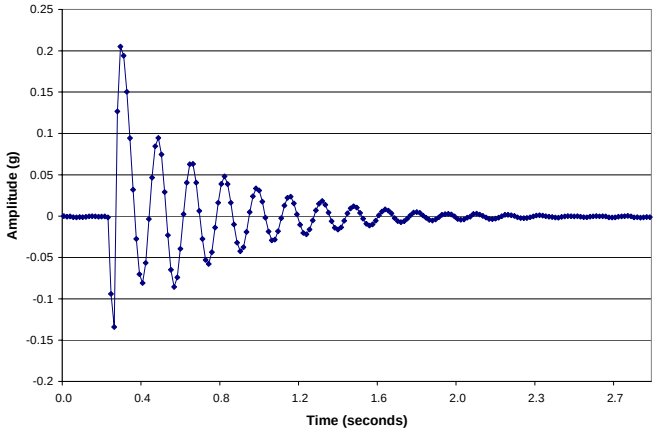

Figure 18. Accelerometer response to a load applied at mid-span of beam *before* installation of the markers.

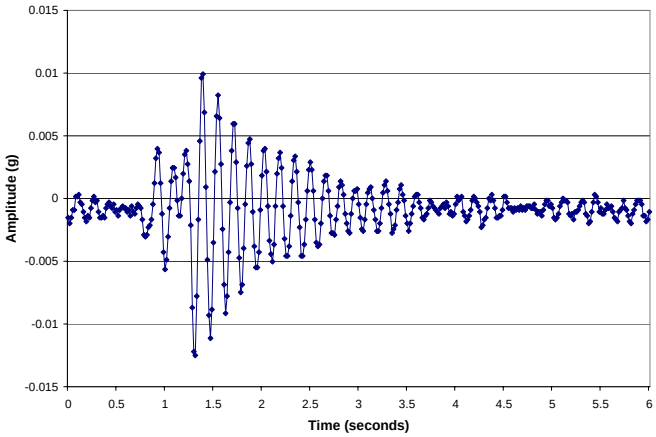

Figure 19. Accelerometer response to a load applied at mid-span of beam *after* installation of the markers.

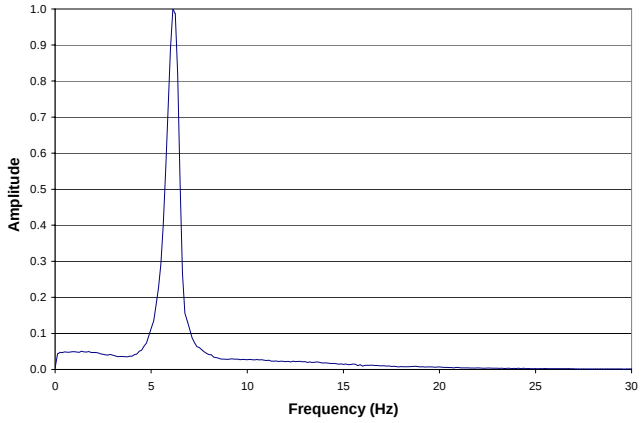

Figure 20. Frequency of the concrete beam *before* installation of the markers.

The frequency of the beam is determined by taking the fast Fourier transform (FFT) of the accelerometer response. The FFT is shown in Figure 20. The frequency was approximately 6.3 Hz.

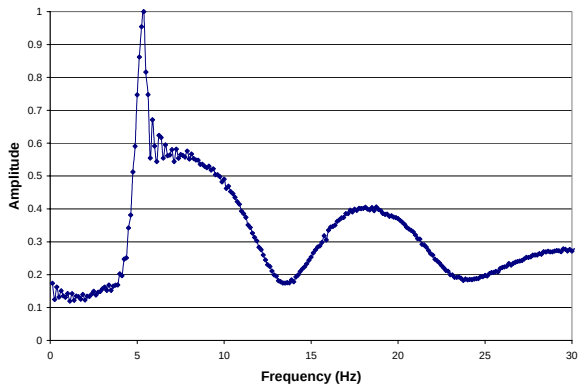

Figure 21. Frequency of the concrete beam *after* installation of the markers.

The FFT of the accelerometer response after the installation of the markers is shown in Figure 21 and the frequency was approximately 5.375 Hz. This drop in frequency is a result of the additional weight of the markers.

6 STRUCTURAL HEALTH MONITORING DATA ON WEB SITE

For the structures that have been instrumented with remote monitoring capabilities, data is constantly collected at varying frequencies. As the data grows daily, so does the need for a sophisticated archival management system. It becomes one of the most vital aspects of structural monitoring. ISIS is developing an on-line archiving system whereby authorized researchers submit raw data that will be accessible to users. In a user-friendly, world wide web interface, the site will offer access to sensor characteristics and locations, and response measurements from static and dynamic load tests. The archive will enable interested parties to browse the content, view the relevant documentation and down load data for analysis.

Several different strategies are being used for data collection. In some cases, the sensors are triggered manually at selected intervals of time, and the sensor data is stored on computer disks. In other cases sensor data is collected continuously at a specified scan rate and automatically transmitted to a remote location, where it is stored on a computer.

7 STUDIES OF CONCRETE REINFORCED WITH GFRP SPECIMENS FROM FIELD DEMONSTRATION PROJECTS

The methods used in this study (Mufti et al. 2005) to investigate the degradation of GFRP reinforced concrete are Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray (EDX), Light Microscopy (LM), Differential Scanning Calorimetry (DSC) and Infrared Spectroscopy. To obtain reliable information from the results/observations using such methods, special attention was given to sample preparation. During specimen preparation, the glass fiber can be scratched and microcracks can be induced into the matrix and concrete; the glass fiber can be debonded and the glass and matrix polished surfaces can be contaminated with elements from each other and with elements from the concrete. When such events take place, the interpretation of the results / observations become laborious.

Details on sample preparation, presentation of the results obtained on the entire set of GFRP reinforced concrete specimens removed from the five structures and an extended discussion of the results were presented in the ISIS Monograph on GFRP durability at the 7th International Symposium on Fiber Reinforced Polymer Reinforcement for Reinforced Concrete Structures in New Orleans, Lousiana, USA (Mufti et al. 2005).

The following is a brief excerpt of the main findings suggested by the results obtained to date from the analysis performed in 2005 at the universities of British Columbia, Saskatchewan, Sherbrooke and Manitoba on the randomly selected core specimens from the field demonstration projects using the SEM and EDX analyses. The cores were taken from five structures across Canada. Figure 22 shows the extraction of cores from the Waterloo Creek Bridge on Vancouver Island, BC.

Figure 22. Waterloo Creek Bridge - Core sample extraction.

Examples of SEM micrographs and EDX spectra on GFRP specimens cored from the Joffre Bridge and Hall's Harbor Wharf as well as for a set of control (unexposed specimens) GFRP specimens are presented in Figures 23 and 24. It should be noted that, although the entire surface of each specimen was examined, the attention was focused on areas close to the concrete/GFRP rod interface, where any degradation could be expected to take place, from which the micrograph presented in Figures 23 and 24 has been taken.

Data from SEM analyses suggests that that there are no visible signs of any degradation taking place on the reinforced bars/grids. The individual fibers are intact with no gaps between fibers and the matrix (Fig. 23). There is also good contact between the concrete and the matrix (Fig. 24).

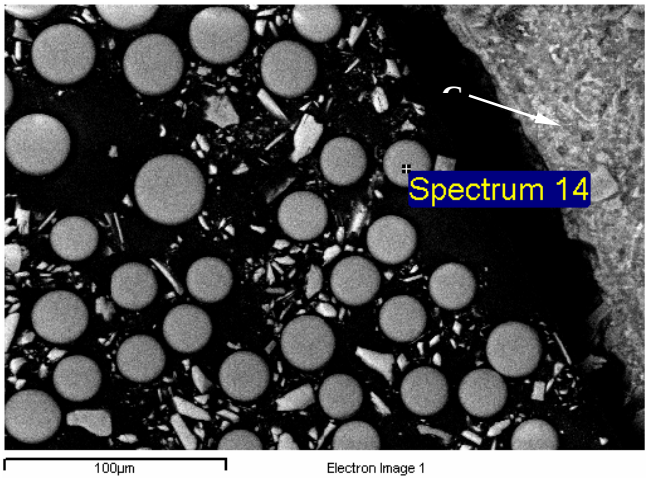

Figure 23. SEM photomicrograph - Cross section of core specimen from Joffre Bridge - EDX spectrum.

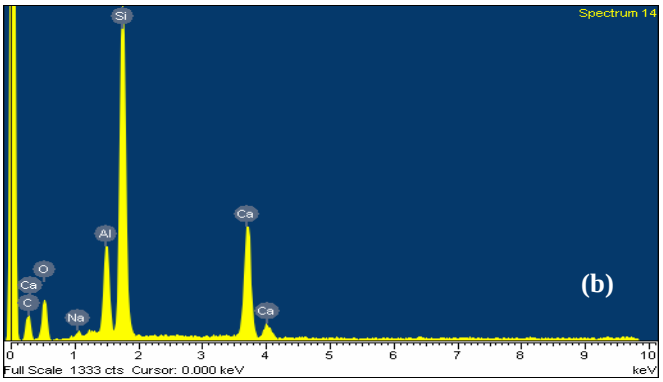

Figure 24. SEM photomicrograph - Shows the chemical composition of the glass fiber - magnification factor is 500X.

It can be concluded that for the range of conditions of field demonstration projects included in this study there is no degradation of the GFRP reinforcement. Since the pH of the concrete pore water solution is expected to decrease further with time, it is quite probable that for all practical problems the degradation of GFRP can be considered to be insignificant.

The results obtained to date in this study do not support the results obtained in the laboratory studies that report GFRP degradation in various degrees. There are several reasons for this disagreement. First, in the present study, the specimens under investigation were from real life engineering structures, whereas in laboratory studies that observed GFRP degradation, the conditions were very different from the real systems. The lab studies are usually conducted in alkaline solutions that are kept at constant high pH values and/or high temperatures, the GFRP is generally kept in contact with infinite leachant volume or a very large effective surface area of the road is exposed to the solution. With the exception of special projects, such conditions do not really exist in real life. For most practical engineering projects, it is quite probable that the degradation of GFRP reinforced concrete in most cases is not significant. The full details have been published in Mufti et al. (2005).

8 CONCLUSIONS AND RECOMMENDATIONS

As mentioned earlier, ISIS Canada intends to significantly change the design and construction of civil engineering structures. For changes in design and construction to be accepted, it is necessary that innovative structures be monitored for their health. To assist in achieving this goal, ISIS Canada is developing a new discipline, which integrates Civil Engineering and Electrophotonics under the combined banner of Civionics.

The new discipline of Civionics must be developed by Civil Structural Engineers and Electrophotonics Engineers to lend validity and integrity to the process. Civionics will produce engineers with the knowledge to build "smart" structures containing the SHM equipment to provide much needed information related to the health of structures before things go wrong. This discipline will, thereby, assist engineers and others to realize

the full benefits of monitoring civil engineering structures.

9 ACKNOWLEDGMENTS

Veterans Affairs Canada National and International Memorials, Heritage Conservation Services, Public Works and Government Services Canada and the ISIS Canada Research Network have jointly funded the research on the veterans' grave markers. Their financial support was greatly appreciated. The authors also gratefully acknowledge the support of Specialty Construction Products Ltd., Pultrall Inc., and Larsen Memorials, as well as the contributions of Dr. A. Bagchi, who initiated the SHM design, Mr. Moray McVey, Mr. Aaron Kroeker and Ms. Evangeline Rivera for their technical assistance. In addition, the administrative support provided by Ms. Nancy Fehr, Executive Assistant to the President of the ISIS Canada Research Network is gratefully acknowledged.

REFERENCES

Bisby, L .A and Mufti A. A. 2005. SHM in the Class room: A Unique Educational Opportunity. *Proceedings of the Second International Conference on Structural Health Monitoring of Intelligent Infrastructure (SHMII-2).* Shenzhen, P.R. of China.

Demers, M., Popovic, A., Neale, K., Rizkalla, S. and Tadros, G. 2003. FRP Retrofit of the Ring-Beam of a Nuclear Reactor Containment Structure. *ACI Special Publication*. SP-215: 303-316.

Mufti, A.A. and Onofrei, M. 2004. Long-Term Performance of GFRP and Steel Anchor Assemblies for Markers in Concrete at Veteran Affairs Brookside Cemetery. ISIS Canada Technical Progress Report. Winnipeg, Manitoba, Canada.

Mufti, A.A. (2003). Integration of Sensing in Civil Structures: Development of the New Discipline of Civionics. *Proceedings for the First International Conference on Structural Health Monitoring and Intelligent Infrastructure (SHMII-1 '2003)*: 119 - 129. Tokyo, Japan.

Mufti, A.A., Neale, K., Rahman, S., Huffman, S. 2003. GFRP Seismic Strengthening and Structural Health Monitoring of Portage Creek Bridge Concrete Columns. *Proceedings for the fib2003 Symposium - Concrete Structures in Seismic Regions*. Athens, Greece.

Mufti, A., Onofrei, M., Benmokrane, B., Banthia, B., Boulfiza, M., Newhook, J., Bakht, B., Tadros, G. and Brett, P. 2005. Durability of GFRP Reinforced Concrete in Field Structures. *Proceedings of the 7th International Symposium on Fiber Reinforced Polymer Reinforcement for Reinforced Concrete Structures (FRPRCS-7).* New Orleans, LA, USA.

Mufti, A.A., Onofrei, M., Rivera, E., Klowak, C., and Bindiganavile, V. 2004. Structural Health Monitoring of Field Trial Beam at Veteran Affairs Brookside Cemetery. ISIS Canada Technical Progress Report. Winnipeg, Manitoba, Canada.

Newhook, J.P., and Mufti, A.A. 2000. A Reinforcing Steel Free Concrete Bridge Deck Slab for the Salmon River Bridge. *Concrete International*: 18(6): 81-90.

Newhook, J.P., Bakht, B., Mufti, A.A., and Tadros, G. 2001. Structural Health Monitoring of Innovative Bridge Decks. *Proceedings, Annual Conference of the International Society for Optical Engineering*. Newport, California, USA.

Rivera, E., Mufti A.A. and Thomson, D. 2004. Civionics Specifications. Design Manual, ISIS Canada Research Network. Winnipeg, Manitoba, Canada.

Rizkalla, S.H., and Tadros, G. 1994. A Smart Highway Bridge in Canada. *Concrete International*: 42-44.

Tennyson, R. 2001. Installation, Use and Repair of Fibre Optic Sensors. ISIS Canada Research Network. Winnipeg, Manitoba, Canada.

www.isiscanada.com. 2003. ISIS Canada Research Network Web Site. Winnipeg, Manitoba, Canada.