KEYWORDS: Bridges, concrete, fibers, optic, polymers, prestress, reinforcements, sensors, strain, stress, structures.

ABSTRACT
Future generations of civil engineering structures and bridges will be constructed from materials that are significantly lighter, tougher and longer lasting. Structures and bridges will be continuously and remotely monitored to communicate their performance under environmental and loading conditions. An engineer could potentially check on a daily basis for a possible message of warning of damage that could have a cost in human lives.

This paper reviews the current research and development of the Canadian Network of Centres of Excellence on Intelligent Sensing for Innovative Structures (ISIS Canada) on using advanced composite material as construction material and the use of structurally integrated optic fiber sensors for monitoring from a central location remote from the site of the structures. The paper reviews some of the applications completed and in progress, as well as some of the products implementing this technology.

INTRODUCTION
ISIS Canada has undertaken the challenge of research and development for a new generation of civil engineering structures and bridges. These structures are classified as innovative through the use of a new structural system and/or the use of advanced composite materials in the form of fibre reinforced polymer (FRP) materials. These innovative structures are also smart by virtue of the use of integrated fibre optic structural sensing for continuous remote monitoring through links to a central monitoring station. The use of FRP has the advantage of being corrosion free with a high strength-to-weight ratio, has good fatigue behaviour and low relaxation, is electromagnetically neutral, and is easy to handle. Consequently, the structures have more service life.

STRUCTURAL MONITORING WITH OPTIC SENSORS
This paper briefly discusses the new technology of monitoring structures with optic sensors under development in a fashion similar to strain gauges with gauge lengths that can vary between 1 centimeters and 10 meters. These sensors are based on a new device formed within an optical fiber and called a Bragg grating. A fiber Bragg grating is a section of an optical fiber that has been modified by exposure to an intense pattern of ultraviolet laser radiation and subsequently behaves as a very special kind of mirror. This mirror reflects light that lies in a very narrow band centered at the Bragg wavelength. What makes this a valuable structural sensor is that changes in the strain imposed on the optical fiber are translated into shifts in this Bragg wavelength. The concept used for measuring the wavelength encoded by this sensor is shown in Figure 1.

![Bragg Reflection Spectrum](image)

*Figure 1 - Wavelength - Strain Response for Fiber Bragg Grating.*
The development includes several types of optic fibre sensors. The short gauge length fiber Bragg grating strain sensors (FBGSS) have already been used on a number of advanced bridges in Canada where they have been used to monitor both slow strain changes over time and simultaneously track the transient strains associated with the dynamic response of the bridges to vehicular traffic. These fiber optic sensors have a number of advantages over conventional sensors and are particularly well suited for pultruding within advanced composite material reinforcements and prestressing tendons. Furthermore, strings of such fiber optic grating sensors can be produced along a single optical fiber and interrogated from one end. Long gauge fiber optic strain sensors are ideal for incorporating into thin advanced composite material wraps used for rehabilitation and strengthening of corroded concrete columns. Such sensors allow the repaired column, as shown in Figure 2, to be subsequently monitored for possible build-up of corrosion induced pressure.

![Fiber Optic Monitoring System for Concrete Column Composite Rehabilitation/Strengthening Wrap](image)

Figure 2 - Long Gauge Fiber Optic Strain Sensors.

Clearly, this new form of structural sensing could greatly facilitate the introduction of new advanced composite materials for bridges and other structures by providing a built-in monitoring capability. Fiber optic Bragg grating technology also holds the promise of extremely compact, rugged and low-cost integrated optoelectronic microchip-based systems. The newly created “Network of Centres of Excellence on Intelligent Sensing for Innovative Structures” is a unique and major program with the mandate to develop and explore the application of both advanced composite materials and fiber optical structural sensing to civil engineering.

The merits of fiber optic Bragg grating sensors can be summarized as follows:

- Hair size, dielectric, embeddable in concrete or composites.
- EMI immune, non-conducting, remote monitoring ideal.
- Resistant to corrosion, or fatigue, long life.
Current development includes three types of fiber Bragg grating structural sensors. The short gauge, approximately 10 mm long, was used successfully in the first highway bridge in the world constructed with carbon fiber reinforced polymer (CFRP) reinforcements for prestressing four girders of the bridge. Recently, the same type of short gauges were used for the 13-km Confederation Bridge which opened to traffic on May 31, 1997.

The long gauges are convenient for rehabilitation and strengthening of existing concrete columns. These types of gauges are ideal for monitoring the changes in the hoop stresses within concrete columns that are rehabilitated and strengthened with thin wraps of fiber reinforced polymers sheets. This type of gauge has been used in parking garage columns in Hull, Quebec, and a highway bridge column on Highway 10 in Sherbrooke, Quebec.

The third type of sensors are the multiplexed and distribute strain sensing with fiber gratings. This type, which was recently discovered, has the capability of measuring the strain profile which could be very convenient in measuring the strain transfer process within an anchorage system and the stresses within the development length of the FRP sheets.

ISIS Canada's research is currently also progressing towards building the first demodulation of a fiber Bragg grating sensor by an optoelectronic chip and tunable lasers to measure the wavelength.

INNOVATIVE STRUCTURES

Innovative Bridge Deck
This system was developed in collaboration with the Ontario Ministry of Transportation and Vaughan Engineering Association. The new innovative structural system for the bridge deck slab uses inexpensive non-ferrous fibres and is totally devoid of steel rebar. The deck acts in composite action with the steel girders by means of shear connections and interconnecting the top flanges of the steel girders immediately below the deck by transverse steel straps to provide the restraint necessary to develop the arch action within the slab under the effect of vehicle load. The design and construction of the first bridge built using this new innovative system, the Salmon River Bridge in Halifax, Nova Scotia, are shown in Figure 3.
Advanced Composite Materials for Highway Bridges (Headingley Bridge)

Due to the severe environmental conditions and the use of salt for de-icing of roads in several parts of North America, the use of fibre reinforced polymer (FRP) reinforcement for bridge girders, deck slabs and barrier walls is considered by ISIS Canada to be a promising solution for the deterioration of bridges due to corrosion.

Due to the lack of code standards for the use of FRP for structures and bridges, ISIS Manitoba has undertaken the challenge of testing several structural models, in some cases, full-scale models of bridge girders and slabs to examine their behaviour and provide safe design guidelines for the use of this material for field application. The main features of Headingley Bridge which is currently under construction in Manitoba are:

- Use of carbon fibre reinforced polymer (CFRP) straight and draped tendons for prestressing four, 31.2 metre span girders.
- Use of CFRP stirrups for shear reinforcements of two main girders.
- Use of CFRP for the deck slab.
- Use of glass fibre reinforced polymer (GFRP) reinforcements for the bridge curbs.
- Use of 64 fibre optic sensors and 16 conventional electric resistance strain gauges to monitor the bridge from a central monitoring station remote from the bridge.

Figures 4 and 5 show reinforcement detail and completed bridge girder of Headingley Bridge currently under construction in Manitoba.

This paper also reviews the research work conducted on a scale model of the bridge girder (Figure 6) and a full-scale model of a portion of the bridge deck (Figure 7) using the same type of reinforcements and sensors used for the bridge. The results were implemented in the design and construction of the bridge.

Figure 4 - Reinforcement details of one of the main girders of Headingley Bridge.

Figure 5 - Headingley Bridge girder totally reinforced and prestressed by CFRP.

Figure 6 - 1:3 Scale Model of Headingley Bridge Girder.
Preliminary results of other research projects currently in progress at the University of Manitoba to establish general design guidelines and codes for this material were also used in the bridge. These research projects include a program designed to evaluate the strength and performance of FRP stirrups for shear reinforcements\(^5\). The program included testing of specially designed specimens (Figure 8) and beams (Figure 9). In this study, the effect of bending of FRP rods to provide the appropriate anchorage for FRP stirrups and the development lengths required for these types of stirrups were investigated. Strength of the FRP stirrups as effected by the pattern of the diagonal shear cracks with an angle with the stirrups is also studied.

*Figure 7 - Full-Scale Model of a Portion of the Headingley Bridge Deck.*

*Figure 8 - Test Specimens for CFRP Stirrup.*

*Figure 9 - Beam Reinforced with CFRP.*
The research program at ISIS Canada also includes testing of two types of specimens to study bond characteristics, transfer length and development length for CFRP strands and rods for prestressing concrete structures as shown in Figure 10.

![Test specimens to examine bond characteristics of CFRP.](image1)

**New Concrete For GFRP**  
ISIS Canada is working closely with a research group of the Atomic Energy of Canada Limited (AECL) to examine the possibility of using a low-heat, high-performance concrete (LHHP) for construction of massive concrete structures reinforced by glass fibre reinforced polymer (GFRP) reinforcements, such as secondary containment structures for CANDU Reactors.

This new patent LHHP concrete has a very low cement content and, therefore, has very low heat hydration (15°C) which is of a great advantage for massive concrete structures where thermal cracking is considered to cause serious problem. LHHP has the advantage of having a low alkalinity (pH 9) which is suitable for structural members reinforced with GFRP where high alkalinity could cause deterioration of the glass fibers. The research currently in progress evaluates the structural behaviour of LHHP structural members reinforced by GFRP reinforcements. This includes flexural and bond behaviour and durability concrete reinforced by GFRP.

**FRP Transmission Poles**  
ISIS Canada’s innovation includes the development of a new generation of transmission poles using fibre reinforced plastic materials that are corrosion free and lighter in weight for easier handling. ISIS Canada is presently working with Faroex of Gimli, Manitoba, on the design and fabrication of these poles using a filament winding process. The new 32 foot, three axis computer controlled filament winder, which is now operational (Figure 11), necessitated devotion of an entire building provided by Faroex. This machine has an unmodified maximum diameter of 60 inches. Scale test poles are currently being tested at the structural laboratory of the University of Manitoba under static loading conditions. Test results will be compared to the finite element model. The scale models are tested to evaluate the resin properties, angle geometries, fibre properties and winding path configurations. The cost of the equipment was in the range of $200,000 and was shared by ISIS Canada, Faroex and Manitoba Centre of Excellence Funds. Success of the project will have a significant impact on Canada’s economy through sales of the product and job creation.

![Faroex Transmission Pole Facility in Gimli, Manitoba.](image2)
Smart Reinforcements
ISIS Canada is currently developing smart reinforcements for innovative structures. The research facilities required modification of the pultrusion manufacturing technology to allow for the incorporation of fibre optic sensors with different types of fibres to produce smart FRP reinforcements for concrete structures and bridges. The research includes evaluation of different coating processes for the pultrusion process to provide complete product specification and manufacturing guidelines. The pultrusion equipment required to process smart FRP reinforcements has been designed and built at ISIS Canada, Smart Composites Processing Laboratory, at Dalhousie University. The first generation of the smart FRP, including Fabry-Perot optical sensors, is currently being tested. Bragg grating optical sensors will also be embedded for carbon and glass fibre polymer reinforcements. Smart reinforcement will have significant economical savings on monitoring of bridges and structures by eliminating the need for the tedious and sensitive work related to installation of sensors and the required wiring at the construction site.

Corrosion Free Masonry Structures
A major area of concern with prestressed masonry is the corrosion of steel prestressing tendons and, therefore, extreme care must be taken to protect the steel and the anchorage to the masonry. The problem is alleviated by the use of FRP. Due to the unidirectional characteristics of FRP, anchorages could cause significant reduction of FRP strength due to a weakness of the FRP tendons perpendicular to the fibres. ISIS Canada has succeeded in inventing a new anchorage that satisfies the requirements for a post-tensioning anchorage system. The new anchorage is resin-free and easy to assemble in the field. The new anchorage system has made it possible to develop the full strength of the CFRP tendon. The anchorage is made of stainless steel with an outer diameter of 50 mm and 80 mm in length. The anchorage is made of three parts: an outer steel cylinder which has a smooth and greased conical hole; a four-piece wedge with a central hole; and an inner sleeve of steel or copper which has a small wall thickness. The assembly process is straight forward: the tendon is threaded through the conical housing, the copper sleeve is slipped onto the tendon followed by the wedges. The wedges can be inserted into the housing and the whole assembly moved down the tendon to the desired location for anchoring. At this location the wedges are seated with a hydraulic jack before tensioning. This process is very similar to the standard jacking process currently used for steel tendons. The size of this anchorage is also similar to the standard steel tendon anchorage and, therefore, there is no major differences to site practice.

Figure 12 - New Anchorage for CFRP Strands and Rods.

Innovative Ground Anchors
Steel tendons used for ground anchors are vulnerable to corrosion when exposed to aggressive environments. ISIS Canada is currently developing a new generation of corrosion-free ground anchors using CFRP (Figure 13). A characteristic of this new material is the structural integration of optic fibre sensors for continuous monitoring which could be used as spot check of the performance of a group of ground anchors for a particular project of prime importance, such as the repair of hydro dams or electric power generation stations. The current research work at ISIS Canada includes evaluation of the short and long-term properties, effect of climates and environmental conditions, and the load carrying capacity.
FRP for Concrete Pavements
ISIS Canada is working closely with Manitoba Highways and Transportation to investigate the possibility of replacement of steel dowels used in concrete pavement joints with fibre reinforced plastic dowels. The advantage of the new dowels will solve the traditional problems related to corrosion of the steel dowels leading to deterioration of the concrete pavement and continuous replacement of the joints. The research includes testing of specially designed specimens to examine the behaviour of the new dowels under the effect of various loading conditions due to traffic and truck loads. The experimental program is currently in progress in the R. W. McQuade Laboratory at the University of Manitoba.

Figure 12 - Test specimens for FRP dowels for concrete pavement.
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