

# Fiber-optic Bragg Grating Sensors for Bridge Monitoring

R. Maaskant,<sup>a\*</sup> T. Alavie,<sup>a\*</sup> R. M. Measures,<sup>a</sup> G. Tadros,<sup>b</sup> S. H. Rizkalla<sup>c</sup>  
& A. Guha-Thakurta<sup>d</sup>

<sup>a</sup>University of Toronto, Institute for Aerospace Studies, 4925 Dufferin Street, Toronto, Ontario, Canada M3H 5T6

<sup>b</sup>Strait Crossing Incorporated, Calgary, Alberta, Canada

<sup>c</sup>University of Manitoba, Department of Civil Engineering, Winnipeg, Manitoba, Canada

<sup>d</sup>City of Calgary, Structures and Facilities, Calgary, Alberta, Canada

## Abstract

*Fiber-optic Bragg grating strain sensors hold a great deal of potential for structural monitoring because of their exceptional stability and demonstrated potential for long-term monitoring. This sensing technology takes advantage of a spectrally encoded signal which provides inherent immunity from signal intensity fluctuations which plague many other fiber-optic and electronic sensing techniques. This results in measurement stability and lead/interconnect insensitivity which permit long-term and intermittent monitoring with high resolution and accuracy. Fiber-optic grating sensors are intrinsic to the optical fiber, thus capitalizing on its extremely small size and inherent strength and durability. Recent results are provided from a sensor array installed in a road bridge. The strain sensors are attached to both steel and carbon-fiber-reinforced plastic prestressing tendons, which are embedded in the precast girders of the bridge. Measurements of traffic loads and the relaxation behaviour of the tendons are presented. The potential of fiber grating technology is briefly discussed including its application in long-gage strain-sensing and strain-distribution measurements. © 1997 Elsevier Science Limited*

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## INTRODUCTION

Fiber-optic sensors for the measurement of strain have been under development for a number of years and a number of sensing techniques have been established.<sup>1</sup> In all cases the goal has been to capitalize on the unique features of fiber-optic technology including extremely small physical size and its inherent immunity to electromagnetic interference. Here attention is focused on fiber-optic grating sensor technology, which possesses some unequaled characteristics which benefit strain-sensing applications. These sensors are intrinsic to the optical fiber, i.e. they are physically part of the optical fiber itself, and furthermore the sensor relies on the spectral content of the optical signal. These features provide high durability, the potential for inexpensive mass production, serial multiplexing of many sensors along a single optical fiber, and enhanced long-term measurement stability. This allows strain measurements to be made in situations where they were previously unattainable, or at best problematic for conventional strain-sensing techniques.

A significant amount of interest in fiber-optic sensing techniques has been generated in the civil engineering community with regard to instrumentation of bridges and similar structures. This interest has benefited from the recent maturation of fiber-optic sensing which has seen its emergence from the laboratory to field applications, and has coincided with a heightened concern about the state of the infra-

\*Presently with ElectroPhotomis Corporation, Unit 200, 7941 Jane St, Concord, Ontario, Canada, L4K 4L6.

structure, particularly in North America.<sup>2,3</sup> Along with the development of new materials, non-destructive and non-intrusive monitoring techniques are actively being sought in order to evaluate structural performance and assess both structural and material integrity in the short term, during and immediately following construction, as well as throughout the structure's service life. Since the service life of typical structures may be of the order of 50 years or more, this poses a serious challenge.

Techniques have been and continue to be developed for the purpose of structural monitoring and damage assessment in the field of civil engineering.<sup>4</sup> Fiber-optic sensors have been successfully embedded in a variety of polymer-based composite materials<sup>5</sup> as well as in concrete components.<sup>6-9</sup> In Canada a major initiative has recently been launched in the form of a national network center of excellence named *Intelligent Sensing for Innovative Structures* (ISIS). This network of researchers have as their mandate the development of a new generation of structures which employ new materials, innovative construction techniques and integrated sensing employing fiber-optic sensors.

Fiber-optic grating sensors possess a great deal of potential for structural-sensing applications and can be used in a variety of configurations including localized strain sensing, long-gage strain sensing, as well as configurations which allow the measurement of strain distribution. Field use of these sensors has been demonstrated by the installation of an array of fiber-optic grating sensors in a new road bridge in Calgary, Alberta, Canada in 1993.<sup>10,11</sup> These are currently being used to monitor the relaxation of prestressing tendons, both conventional steel-strand tendons and new carbon-fiber-reinforced plastic (CFRP) tendons.

## GRATING SENSOR TECHNOLOGY

In-fiber optic Bragg grating technology has its origins in the discovery of the photosensitivity of optical fibers by Hill *et al.* in 1978.<sup>12</sup> Later, it was demonstrated<sup>13</sup> that a permanent periodic modulation of the refractive index in the core of a photosensitive optical fiber could be produced by transverse illumination with an interference pattern created by a pair of strong UV beams as shown in Fig. 1. This creates a Bragg grating

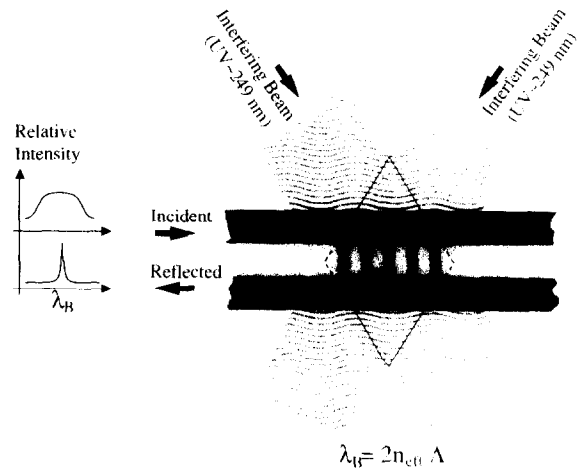


Fig. 1. Illustration of fiber-optic grating fabrication technique.

in the core of the optical fiber, which acts essentially as a wavelength-selective mirror. By virtue of its strain and temperature sensitivity, described in more detail below, the in-fiber Bragg grating is an effective sensor for many applications.

One of the most challenging tasks in the adaptation of fiber-optic sensing technology for engineering applications is the production of durable and consistent sensors at a reasonable cost. A major development in practical fabrication procedures for fiber-optic Bragg gratings employs a phase mask which simplifies the procedure considerably.<sup>14</sup> In another recent development it has been shown that Bragg gratings can be produced on the fiber draw tower during fabrication of the optical fiber.<sup>15</sup> This has the potential of reducing cost significantly and removes the need to handle the fiber during grating fabrication, thus improving the sensor's durability.

The fiber-optic grating acts as a wavelength-selective mirror for incoming light as is depicted in Fig. 2. The reflected portion of the light consists of a narrow spectral band while the remainder is simply transmitted through the grating. The transmitted light is simply lost or, as in the serial multiplexing schemes described below, it is used to interrogate gratings further along in the fiber. The centre wavelength  $\lambda_o$  of the reflected spectral band is defined by the *Bragg condition*:

$$\lambda_o = 2n_{eff} \Lambda$$

Fiber-optic grating sensor response arises from two sources, namely the induced change in pitch length ( $\Lambda$ ) of the grating and the pertur-

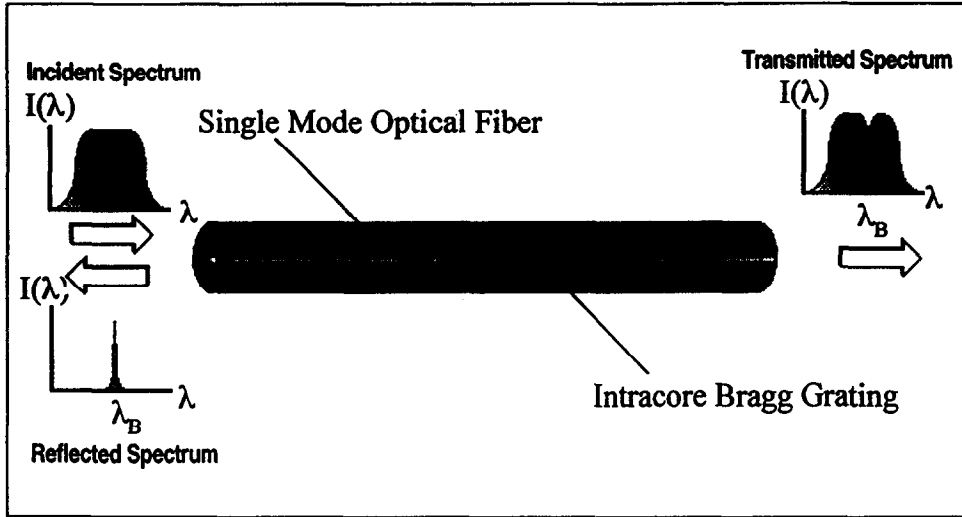


Fig. 2. Illustration of the principle of operation of fiber-optic grating sensors.

bation of the effective core refractive index ( $n_{\text{eff}}$ ). The sensor response is described by the linear relation

$$\frac{\Delta \lambda}{\lambda_0} = \left(1 - \frac{n_{\text{eff}}^2}{2} p_{12}\right) \varepsilon_1 - \frac{n_{\text{eff}}^2}{2} (p_{11} \varepsilon_2 + p_{12} \varepsilon_3) + \beta_0 \Delta T$$

In this relationship  $\varepsilon_1$  is the axial strain, and  $\varepsilon_2$  and  $\varepsilon_3$  are the principal strains in the cross-sectional plane at the core of the optical fiber. Together with the temperature change  $\Delta T$  and wavelength shift  $\Delta \lambda$ , these represent excursions from a reference condition corresponding to the center wavelength  $\lambda_0$ . The photoelastic coefficients  $p_{11}$  and  $p_{12}$  represent the elasto-optic effect and are commonly taken as  $p_{11} = 0.113$  and  $p_{12} = 0.252$ , although they are known to vary somewhat with fiber type. The coefficient  $\beta_0$  is the sum of both the thermo-optic component and the thermal expansivity of the optical fiber, and has the nominal value  $6 \times 10^{-6}/^\circ\text{C}$ .

In the above relationship it is tacitly assumed that the fiber grating response is axisymmetric. This is strictly only the case if the grating is non-birefringent and the strain field is axisymmetric. The gratings dealt with herein are written in nominally non-birefringent optical fibers. In fact these fibers typically possess a small degree of birefringence and the grating writing process can induce a small additional amount. However, this is very small and does not affect the grating response. Although the strain field in the host material is generally not axisymmetric, the strain transfer to the fiber is

generally very poor in the transverse direction so that the magnitude of the difference ( $\varepsilon_2 - \varepsilon_3$ ) at the fiber core is very small. For example, optical fibers possess a stiffness of 70 GPa and are typically bonded or embedded in an epoxy which has a stiffness in the range 1–5 GPa. In a surface-bonded configuration, illustrated in Fig. 3, the lateral stress in the fiber transmitted by the adhesive fillets to the sensor is closely approximated by the stress-free condition which prevails in the transverse direction. For practical purposes, the fiber-grating sensor response is well represented by the simplified expression

$$\frac{\Delta \lambda}{\lambda_0} = GF \cdot \varepsilon_1 + \beta \Delta T$$

wherein the strain gage factor,  $GF$ , is introduced. Further compensation for the thermal apparent strain contribution by the host material can be performed by applying

$$\beta = \beta_0 + GF(\alpha_{\text{host}} - \alpha_0)$$

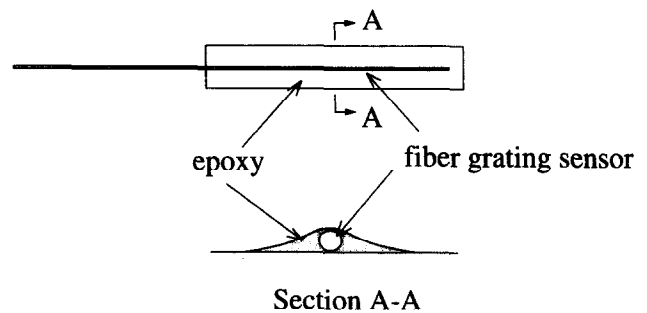


Fig. 3. Characteristics of surface-bonded fiber-optic grating sensors.

where  $\alpha_o = 0.5 \times 10^{-6}/^\circ\text{C}$  is the typical value for the thermal expansivity of optical fibers. For sensors with center wavelengths in the neighborhood of 1535 nm, the nominal value for the gage factor  $GF^{16}$  is 0.8 based on free fiber response. The transverse sensitivity of the sensor response for typical surface-bonded conditions is less than 2%. For bonding onto steel, for example, this amounts to a gage factor correction of approximately 0.5%. The above relationship bears a strong resemblance to that of the foil strain gage. In fact, the analogous gauge factor for a foil strain gage in a quarter-bridge configuration is 0.5. However, fiber-grating sensors employ a spectrally encoded signal which constitutes a significant advantage for long-term monitoring. The sensor wavelength signal is not sensitive to fluctuations in optical power due to light source variations, and optical loss along the fiber or at connection points. In fact, the instrumentation need only receive light levels sufficient to make an effective measurement of wavelength and is otherwise completely independent of intensity. This inherent independence of signal intensity provides for immunity to measurement interruption and long-term stability without the requirement for special provisions. With respect to more conventional electrically based systems, it is the analog of the vibrating wire technique which has attained widespread acceptance in long-term field monitoring due to its frequency-encoded form of electrical signal.<sup>17</sup>

Successful implementation of fiber-optic Bragg grating based sensor systems is highly dependent on practical demodulation of the strain data from the wavelength-encoded signal. A scheme initially developed at the University of Toronto Institute for Aerospace Studies is based on splitting the back-reflected Bragg spectrum into two beams. The first of these is passed through a wavelength-dependent transmission filter and the second serves as a reference. The ratio of the two signals represents the decoded strain or temperature information.<sup>18</sup> This approach has proved to be accurate and sufficiently robust for field application. It has been used for early field work<sup>19</sup> and has since been developed into a commercial system. In addition to single-point measurement applications, in-fiber grating sensors are inherently suited for serial multiplexing in applications where multi-point measurements are appropriate or desirable. A single optical

fiber can contain many grating sensors which are interrogated independently. This can be achieved by essentially two schemes: time-division multiplexing and wavelength-division multiplexing.<sup>20</sup> The former employs time-of-flight to evaluate where the interrogated sensor is located while the second requires sensors which are separated in wavelength.

Long-term stability of fiber grating sensors is enhanced by their geometric profile which enables the sensor to be effectively shielded from high bond-stress zones. For a bonded (or embedded) sensor in a zone of relatively uniform host strains, the stress distribution along the fiber is illustrated schematically in Fig. 4. High shear stresses only occur near the ends of the bonded regions and over a development length of the order of a few millimetres in accordance with the relative stiffness and geometry of the adhesive and the fiber. The effects of creep or bond degradation are limited to this zone and will not affect the sensor response until this zone reaches the sensing region itself. Provision of adequate bonding length can therefore protect the sensor from the vagaries of bond mechanics.

In strain-sensing applications such as those under consideration here, the high strain demands relative to those in the telecommunications industry requires that particular attention be paid to the issue of long-term strength of the optical fiber. Optical fiber produced for telecommunications is routinely

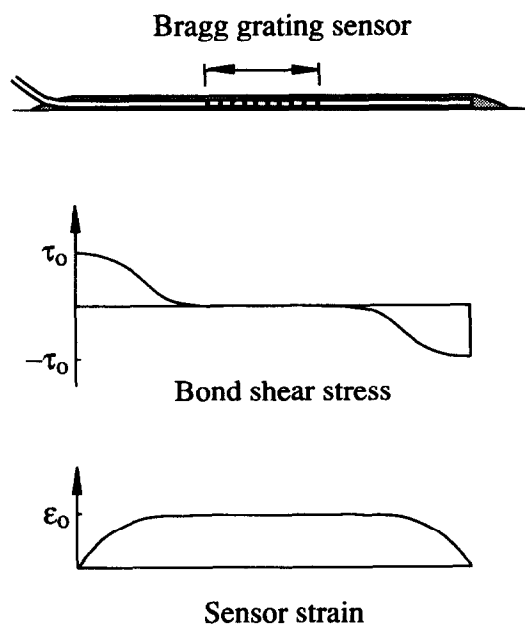


Fig. 4. Sensor bond-stress distribution.

proof-tested to a strain of  $5000\ \mu\epsilon$  and, for special applications, up to strain levels of  $10000\ \mu\epsilon$ .<sup>21</sup> In order to ensure 20–40 years of service, it is generally recommended that service strain be limited to approximately 30% of this level.<sup>22</sup> However, for prestressing tendons the sustained tensile strain can be as high as  $8000\ \mu\epsilon$ . Obviously, for such applications the proof-test levels must be increased and efforts must be made to improve the prediction of the long-term strength of optical fibers.

Optical fibers comprise fused silica which is designated as a brittle material, i.e. failure occurs as a result of rapid crack propagation. As such, this material is susceptible to surface flaws which serve as initiation sites for this failure process. In addition, moisture adsorption on the surface of the glass can significantly reduce life expectancy, particularly in the presence of high strains.<sup>23,24</sup> These fibers generally possess a protective coating, generally a UV-cured acrylate material or a polyimide coating, which is applied directly after the optical fiber is drawn. Such coatings dramatically increase fiber strength in as much as they protect the glass from surface damage and prevent contact with moisture. However, the coating must be removed prior to the photoinduction of the Bragg grating. The coating is then replaced and often must be removed again prior to installation as a strain sensor. This procedure has the potential for introducing minor surface damage which can interact with available moisture and tensile stress to reduce the stress-corrosion-induced time to failure to unacceptable levels. This difficulty can be alleviated, however, by extreme care in handling the bare optical fiber, surface conditioning, enhanced proof-testing and proper environmental protection of the installed sensor.

Concrete is highly alkaline, and in its cured condition can contain a highly alkaline pore solution. Glass is susceptible to alkaline attack and hence unprotected optical fibers are less than ideal for direct embedment in concrete. In the concrete construction industry there is little motivation to address the high alkalinity since it contributes to the protection of reinforcing steel from corrosion. These problems were also faced by developers of glass-fiber-reinforced concrete<sup>25</sup> who have developed special alkali-resistant glass reinforcing fibers. However, alkali-resistant optical fibers are not currently available so that direct measurement

of concrete strains must be accomplished by means of sensor packaging which provides adequate protection of the optical fiber from the surrounding environment.

## BRIDGE MONITORING PROJECT

A fiber-optic Bragg strain sensor array has been installed in the Beddington Trail Bridge in Calgary (Alberta, Canada) to monitor the use of three types of prestressing tendon<sup>11,26</sup>: conventional steel strand; Tokyo Rope Carbon Fiber Composite Cable (CFCC) (Tokyo Rope Manufacturing Co. Ltd, Japan); and Leadline Rod (Mitsubishi Chemical, Japan). The three-lane two-span skew bridge consists of 26 precast prestressed girders, six of which contain the CFRP prestressing strands.<sup>10</sup> The fiber-optic grating sensors were attached to prestressing tendons of each type which were subsequently embedded in the concrete girders. In this project, an important motivation for the use of strain sensors was the desire to monitor the long-term characteristics of the tendon/concrete bond and the relaxation behavior to allow an assessment of the appropriateness of the new CFRP materials in the present context. In addition, monitoring of traffic usage, extreme load events and the load history of structures is possible with such a strain-sensor array. This information is useful in assessing bridge designs, comparing actual loading with the loads used in the design and specified in bridge design codes, and may prove to be helpful for diagnostics and assessments with regard to bridge maintenance or retirement when structural damage has been sustained.

The sensors used in the Calgary bridge were surface-bonded onto the prestressing tendons. Since the tendons were to be prestressed to levels of approximately  $8000\ \mu\epsilon$ , long-term strength was ensured by bonding the sensors after the application of prestress so that subsequent destressing and relaxation would place the sensors in compression, a very favorable state for protection from stress-corrosion mechanisms.

Prior to the bridge installation, a 1:3.3 scale test model of the bridge girder was tested at the University of Manitoba.<sup>27</sup> Fiber-optic grating sensors were installed alongside foil strain gages on the prestressing tendons and the beams were subjected to quasi-static and cyclic loading. The

optical-fiber grating strain sensors remained operational until failure of the beam as indicated in Fig. 5. Their ability to sustain the rigors of cyclic loading were further demonstrated by a simulation of the bridge loading performed at University of Toronto Institute for Aerospace Studies.<sup>28</sup> The test was performed on a fiber-optic grating sensor bonded to a prestressed  $\pm 45^\circ$  carbon/PEEK composite specimen. The test consisted of 320 000 load cycles in which the sensor was strained in the interval 0 to

–2000  $\mu\epsilon$ . Traces of the grating spectrum before and after the test revealed no degradation in the sensor response and a sample of the strain readings indicated a small amount of creep commensurate with expected microcracking damage in the composite.

One of the more daunting tasks in the instrumentation of concrete structures is avoiding destruction of the sensor and the leads during concrete placement and compaction, as is recognized by all who have endeavored to install sensors in such structures. Proper cables need to be used which both protect the optical fibers from moisture and the surrounding alkaline environment, and minimize pinching and microbending which can compromise the integrity of the lead fiber and lead to loss of optical signal strength. The lead fibers need to be properly routed so as to be protected from the vibrating probes which are used to distribute the concrete through the maze of reinforcement bars. It must be recognized that the operators of these tools of potential destruction see as their mission the prevention of the formation of voids and honeycombing in the finished product. It is therefore ill advised to depend on careful placement of concrete and sensitive operation of compaction equipment by the concrete placement crew.

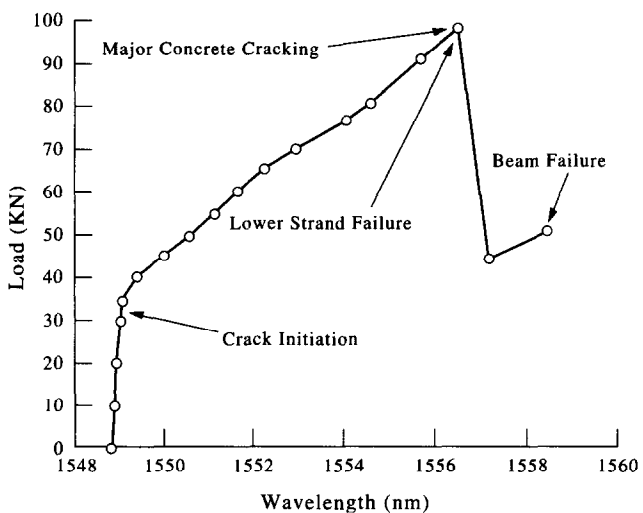


Fig. 5. Fiber-optic grating measurements in scale-model girder prestressed with Tokyo Rope CFCC.

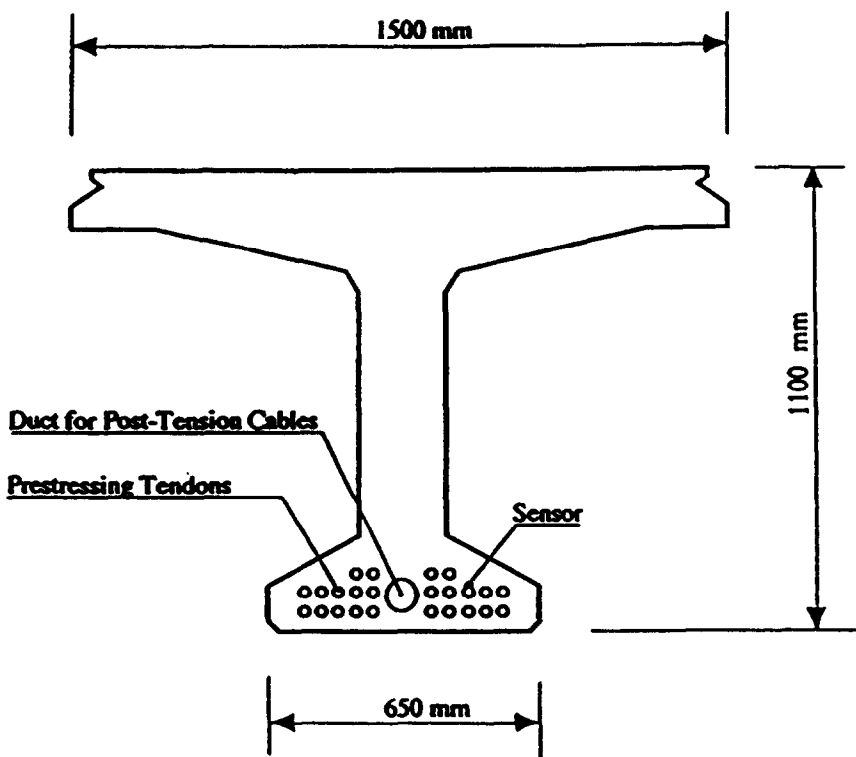


Fig. 6. Cross-sectional view of bulb-T girder.

A cross-sectional view of the bulb-tee precast prestressed girder is provided in Fig. 6, which shows the location of the prestressing tendons, the duct for post-tensioning, and the site of the fiber-optic Bragg grating sensor installation. The fiber leads were routed along the reinforcement to a sealed junction box which was attached by screws to the inside of the form. Prior to stripping the form work, the screws were removed, resulting in a junction box flush with the wall of the girder web. It is important to ensure that the junction box is properly sealed prior to steam curing in order to avoid embrittlement of the fiber leads.

The fiber-optic sensor array consists of a total of 18 strain and temperature sensors mounted on prestressing tendons in various locations. The fiber leads are routed to a single junction box placed at the top of one of the abutments. The sensors were placed in the span of the respective girder at a position approximately

37.5% of the girder length from the abutment end. This yields the position of maximum sensitivity to bridge loads. For the CFRP tendons, a sensor was also placed near the stress transfer zone, 1 m from the abutment or pier end as indicated in Fig. 7.

Static strain measurements from the Beddington Trail Bridge sensor array are provided in Fig. 8. These readings were obtained using a grating-fiber/laser system<sup>29,30</sup> in conjunction with a Burleigh Jr Wavemeter arranged as in Fig. 9. The measurement precision of this configuration is about  $\pm 40 \mu\epsilon$ , limited primarily by the wavemeter. The sensor measurements are designated by the tendon type (SS: steel strand; TR: Tokyo Rope CFCC; LL: Mitsubishi Chemical Leadline Rod), girder identification number (#) and sensor location identified by the number 1 to 4 as depicted in Fig. 7.

The measurements of September 1993 were taken immediately following post-tensioning of

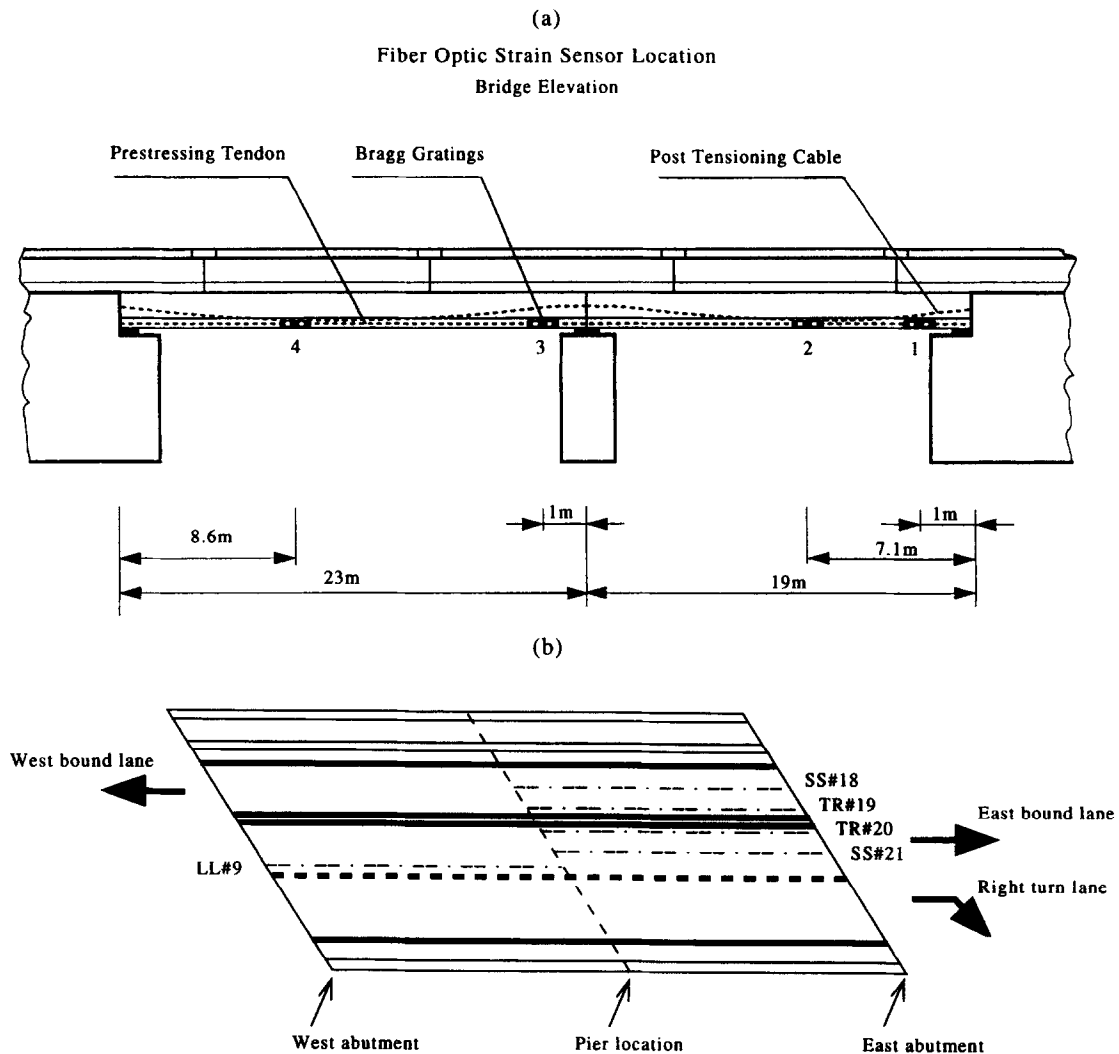


Fig. 7. Sensor location in Beddington Trail Bridge (Calgary, Alberta, Canada): (a) elevation view; (b) plan view.

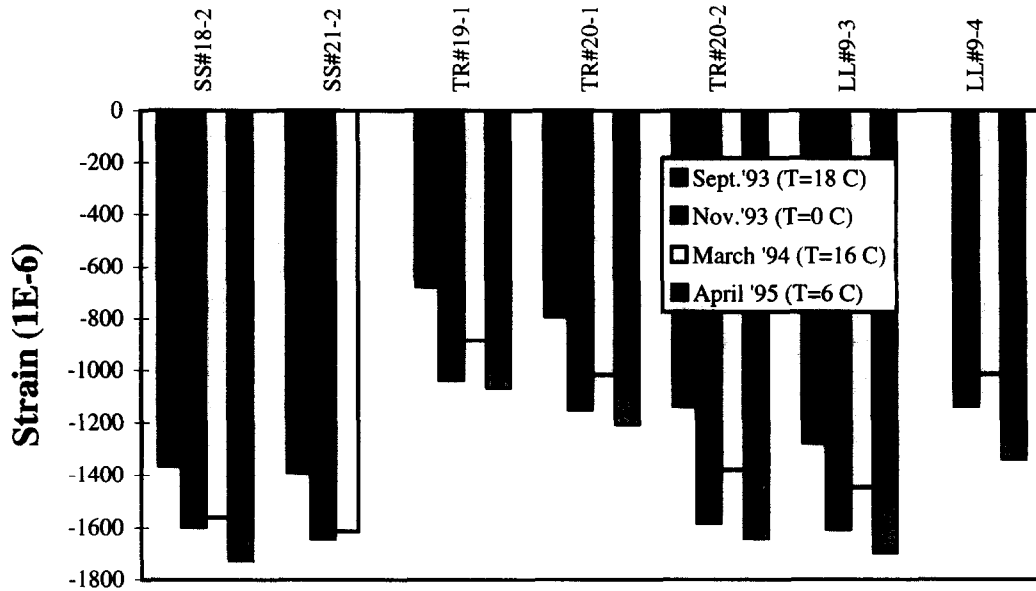


Fig. 8. Static strain-relaxation measurements; Beddington Trail Bridge (Calgary, Alberta, Canada).

the girders. These measurements represent the stress relaxation in the tendons from the combined effects of destressing, concrete shrinkage and creep, the dead loading of the bridge deck, and the post-tensioning applied across the two spans. Subsequent measurements began approximately 1 month after the bridge was opened with the last recorded measurement occurring in April 1995, 18 months later. Unfortunately, early measurements during and immediately following sensor installation in the girders are unavailable owing to equipment

malfunction. Hence it must be noted that the datum for the measurements has been assumed to coincide with the measured centre wavelength at grating fabrication and does not reflect shifts which may have occurred during sensor installation. However, tests simulating the sensor installation process suggest that this source of error is minimal.

The measurements presented in Fig. 8 have been corrected for thermal apparent strain arising from both the sensor itself as well as the thermal expansion mismatch between sensor and host, and hence represent the stress-induced component of the strain. It must be recognized, however, that these corrected strains reflect the prevailing temperature via the overall thermal behavior of the structure. Since the three prestressing materials possess widely different thermal expansivities, an attempt was made to normalize the data with respect to temperature so that a more meaningful comparison can be made regarding permanent tendon relaxation. The steel reinforcement is thermally well-matched with the concrete, and hence the girders are assumed to possess an overall expansivity equal to that of the concrete. The measurements were normalized to a temperature of 20°C by using the relative thermal expansions of the concrete and the prestressing tendon. The resulting initial relaxation, and the amount that has occurred over the subsequent 18 months that the bridge has been in service, are given in Fig. 10 and Fig. 11 provides the strain history.

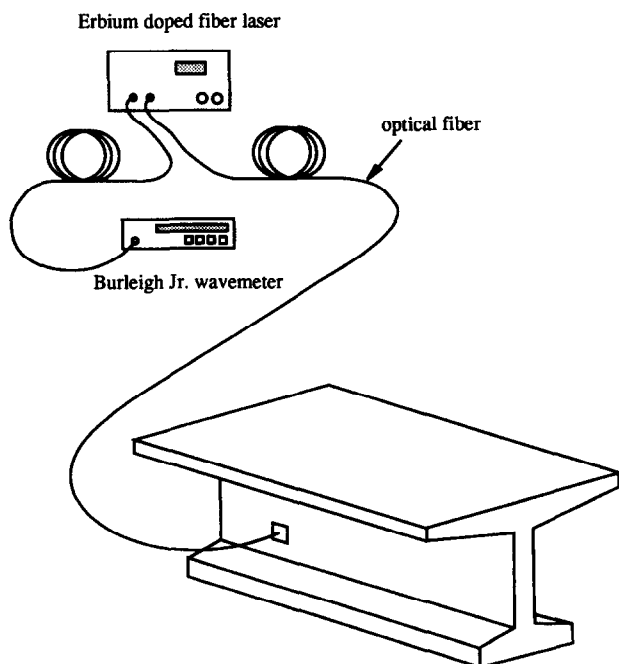


Fig. 9. Instrumentation set-up for static measurements.



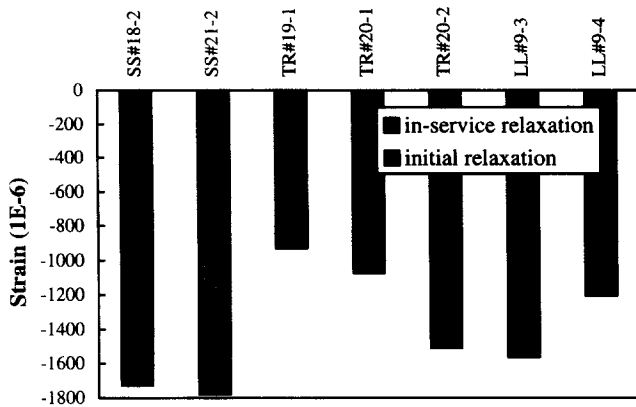


Fig. 10. Equivalent strain relaxation measurements at 20°C.

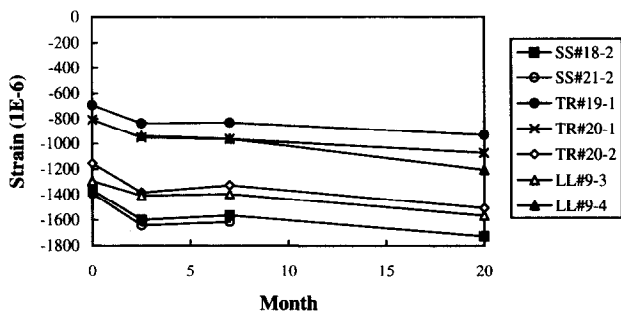


Fig. 11. Strain-relaxation history.

The total expected loss of prestress in the steel tendons has been estimated as 380 MPa or 1900  $\mu\epsilon$ . The lower Young's modulus of CFRP tendons leads to 25% less stress loss than for steel tendons. Indeed the measurements show lower losses for the CFRP tendons. At measurement location 3, high losses arise due to the combined effects of post-tensioning and dead-load effects. The post-tensioning of the girders, which was estimated to be responsible for a loss of approximately 650  $\mu\epsilon$  in the steel, will have somewhat less effect at the ends of the girders where it rises to the top of the cross-section as shown in Fig. 7(a). The dead load contributes compressive stresses at location 3 and tensile stresses at locations 2 and 4, with those at location 4 being larger due to the relative lengths of the girders.

Figure 12 provides examples of dynamic strain monitoring of traffic loads. These measurements were made with a commercially available Fiber Optic Grating Strain Indicator (ElectroPhotonics Corp., Toronto, Canada) which possesses a strain resolution of 1  $\mu\epsilon$  over the range from 8000 to 10000  $\mu\epsilon$ . A 25 ton single-axle truck was passed over the bridge on

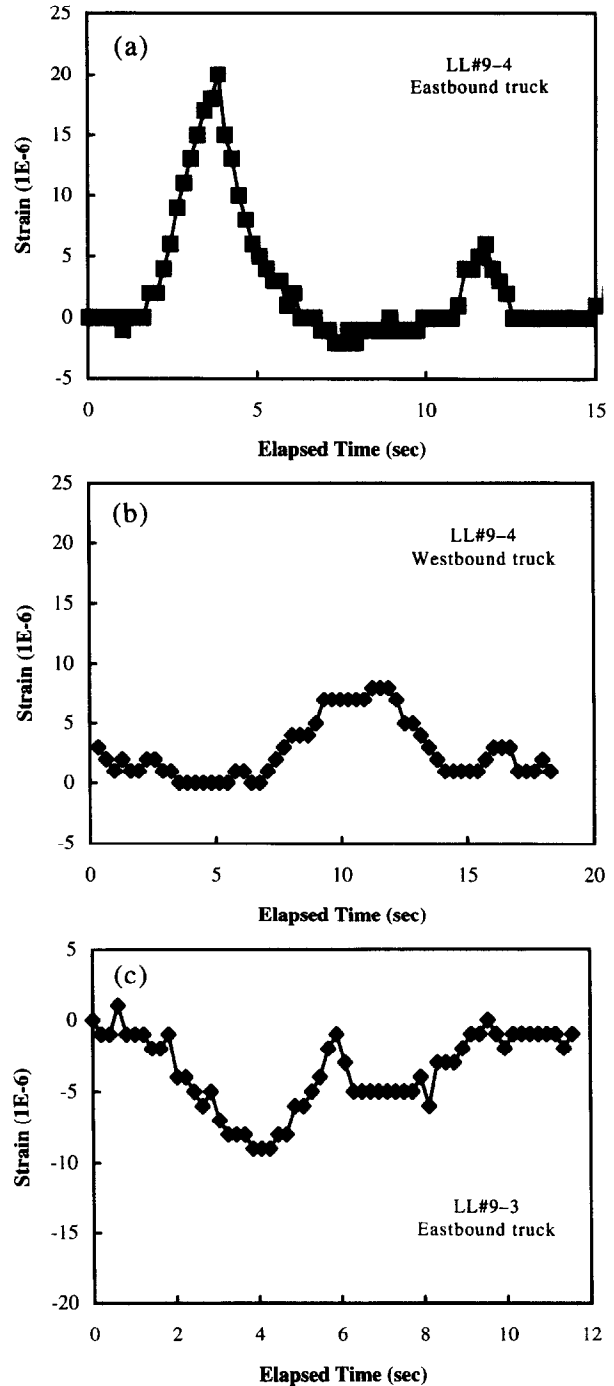


Fig. 12. Traffic-induced strains in CFRP Leadline tendon.

the eastbound and westbound lanes at a slow speed (10 to 30 kph) for these measurements. At locations 2 and 4 this resulted in consistent peak strains of 20 to 25  $\mu\epsilon$  for truck passes directly over the sensor location. In one case, shown in Fig. 12(a), the response to a second smaller truck following the 25 ton truck can be identified. Truck passes on the opposite lane [see Fig. 12(b)] produced observable but significantly lower responses. In location 1 there was

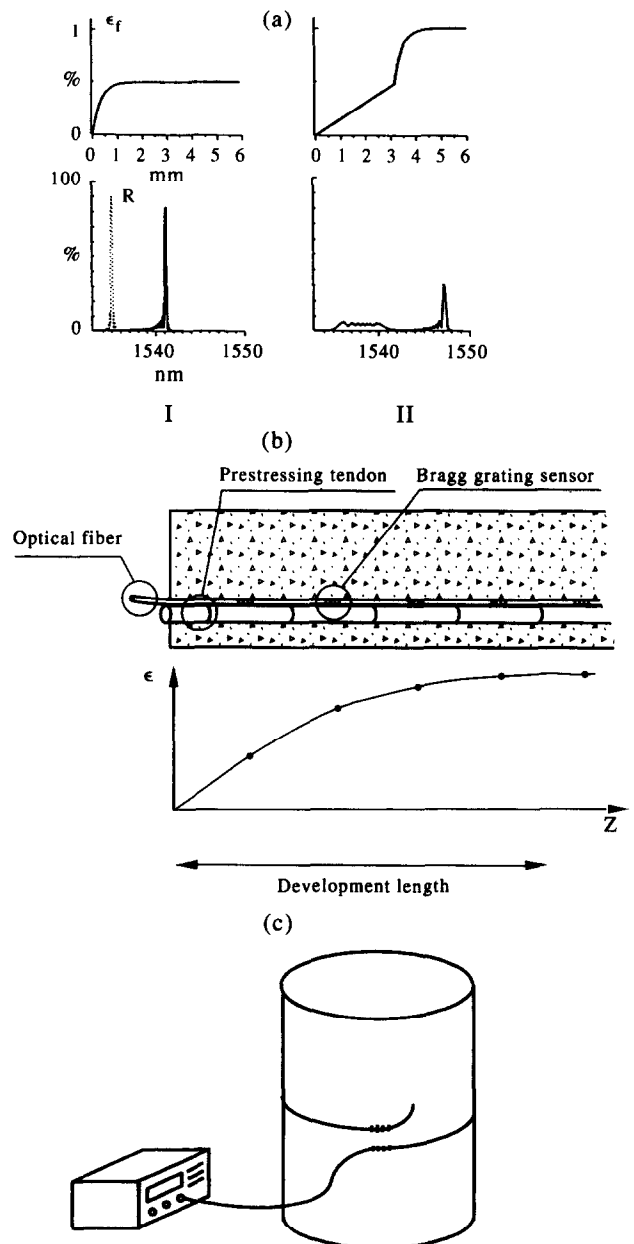
no measurable response, and, as is expected, in location 3 [see Fig. 12(c)] the eastbound truck produced compressive strains of up to  $10 \mu\epsilon$ .

## OTHER APPLICATIONS

Recent work performed by our group has established that a more complete spectral interrogation of the fiber-grating sensor signal can reveal information about the strain distribution along the grating axis. Close examination of the spectral distribution of the grating-reflected spectrum allows the calculation of strain gradients of the order of  $10 \mu\epsilon/\text{mm}$ .<sup>31-33</sup> Another technique based on phase information contained in the reflected signal from the grating also allows strain gradients to be obtained and has the potential to yield higher order information about the strain distribution.<sup>34</sup> This feature, which has been termed *intra-grating sensing*, has potential application in the measurement of stress transfer, a critical feature in reinforcement, prestressing and anchorage design. It also has potential for damage detection and monitoring since damage and failure are often accompanied by large strain gradients or perturbations in the local strain distribution. Self-diagnosis of the sensor during its service life is also possible since, in the absence of an obvious failure resulting in signal loss or anomalous measurements, a less apparent case of sensor debonding will be signaled by a distinct alteration in the strain distribution along the sensor which is measurable by the techniques referred to above. These techniques are currently being used to assess the nature of the interfacial adhesion between fibers and their host, and stress profiles in bonded joints and at the free edge of composite laminates. For example, LeBlanc *et al.*<sup>33</sup> have examined the strain profile at the end of optical fibers embedded in epoxy and have been able to make inferences regarding elastic, plastic and frictional stress transfer during failure progression of the fiber/host bond. Figure 13(a) illustrates the self-diagnostic capability of grating sensors. As a result of the strain redistribution in the sensor resulting from debonding, the spectrum displays a distortion of the single narrow peak characteristic of a well-bonded sensor.

Quasi-distributed sensing is also available on a larger scale by employing the serial multiplexing capability of fiber-grating sensors. When

strain distributions are required over lengths of the order of 1 m, the usefulness of intra-grating sensing is limited. However, several grating sensors distributed appropriately along the fiber will allow strain distributions to be mapped to the spatial resolution required and over arbitrary lengths. As illustrated in Fig. 13(b), this can be accomplished with what can be considered to be a single sensing element



**Fig. 13.** Illustration of different fiber-optic grating-based sensing techniques. (a) Intra-grating sensing, e.g. sensor diagnostics. Sensor strain distribution and corresponding reflection spectrum<sup>33</sup> for: (I) fully adhered sensor; (II) partially debonded sensor. (b) Quasi-distributed sensing using a series of point sensors, e.g. measurement of stress development in prestressing rods. (c) Long-gage sensing, e.g. measurement of circumferential strain in concrete columns.

embedded in or mounted on the surface of the host element.

Fiber-optic sensors are unique in their ability to measure deformation over arbitrary gage lengths. A variety of techniques offers this possibility<sup>35</sup> but a promising field-deployable technique is based on low-coherence white-light interferometry. Such a sensor has been demonstrated in the measurement of circumferential strains in concrete cylinders for testing purposes and has clear advantages over conventional measurement techniques owing to its true path-integrated strain measurement. Here fiber gratings can play a role<sup>36</sup> by forming an isolated inter-grating gage region as illustrated in Fig. 13(c). This important feature was not available with earlier implementations which relied on a simple mirrored fiber-end face. The added benefits of this implementation include the potential for several long-gage sensors along one optical fiber and the use of the fiber gratings for the secondary task of local strain sensing. Thus fiber gratings provide the potential for a multi-task, multi-element fiber-optic sensor.

With increased usage of CFRP materials in the construction industry it will become very desirable to embed sensors in tendons and bars during their manufacture. This would provide excellent protection for the sensor and leads, and yield a very convenient means of instrumenting concrete structures. Fiber-grating sensors are ideal for this application for a number of reasons. Firstly, the sensor is intrinsic to the fiber which results in high strength and simplifies integration of the sensor to the manufacturing processes for CFRP materials, whether this is pultrusion, fiber winding or wet lay-up. Secondly, the continuous manufacture of instrumented bars is made possible by the serial multiplexing capability of fiber-grating based sensors. For routine production and usage of instrumented components, production must be able to proceed without interruption, and installation of the reinforcement must occur without undue complication. The presence of many sensors along one fiber allows the bars to be cut to arbitrary length without regard for sensor location. Provided that the sensor spacing is satisfactory with respect to the required precision for sensor positioning, installation can also be performed without knowledge of sensor location. Hence instrumented bars can be produced and handled in essentially the same

manner as non-instrumented bars. Sensors can be located *a posteriori* by using, for example, OTDR (optical time-domain reflectometry) techniques.

In Canada these applications and others are being pursued within the national research network ISIS (Intelligent Sensing for Innovative Structures). In addition to the development of new sensing technologies and new materials and structural concepts for civil engineering, considerable effort is being made to incorporate fiber-optic sensing technology into structures. Recently, fiber-optic grating sensors were successfully installed into a glass/epoxy reinforcement gridwork which was subsequently embedded in the concrete curb structure of a new road bridge in Nova Scotia, Canada\*.

## CONCLUSIONS

Fiber-optic Bragg grating sensors represent a significant inclusion into the field of structural monitoring. Since these sensors operate in the spectral domain, they can be seen as the optical analog of the popular electrical vibrating-wire technology. In addition to their long-term stability, fiber-grating sensors are small and durable, allowing unobtrusive attachment to and embedment within a wide variety of materials used in concrete structures. Furthermore, it has been demonstrated that fiber gratings have the potential for multi-task, multi-element sensing, allowing (for example) local strain sensing, long-gage sensing and sensor self-diagnostics.

The first field application of fiber-optic grating sensors has resulted in direct measurements of stress relaxation in prestressing strands within the concrete girders of a road bridge. Over a period of 19 months both steel and CFRP prestressing strands have been monitored, revealing significant differences in their behavior and confirming to some extent the expectation of reduced stress loss in the CFRP tendons. In addition, it has been possible to obtain measurements of girder response to heavy traffic loading. This application has provided an illustration of fiber-grating sensor technology under realistic field conditions and points the way to effective use of this tech-

\*This project was carried out in cooperation with Auto-Con Composites, Toronto, Canada and the CAD/CAM Centre, Technical University of Nova Scotia.

nology. Application to the monitoring of concrete structures can also be expected to benefit from exploitation of the many modes of strain measurement available with fiber Bragg grating technology.

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