# Fiber Optic Sensors for Bridge Monitoring

Joan R. Casas[1] and Paulo J. S. Cruz, M.ASCE[2]

**Abstract:** Advances in the production of optical fibers made possible the recent development of innovative sensing systems for the health monitoring of civil structures. The main reasons for this development are the reduced weight and dimensions of fiber optic sensors, the strong immunity to electromagnetic interference, the improved environmental resistance and the scale flexibility for small-gauge and long-gauge measurements. These systems can provide high-resolution and measurement capabilities that are not feasible with conventional technologies. In addition, they can be manufactured at a low cost and they offer a number of key advantages, including the ability to multiplex an appreciable number of sensors along a single fiber and interrogate such systems over large distances. For these reasons, it is evident that fiber optic sensors will change the instrumentation industry in the same way fiber optics has revolutionized communications. This paper provides an overview of the intensity modulated and spectrometric fiber optic sensors and techniques to assess the condition of existing structures in order to enhance the durability of the new bridges, increasing lifetime and reliability and decreasing maintenance activities. Application of these sensors to monitoring strain, temperature, inclination, acceleration, load measurements, ice detection, vehicles speeds and weights, and corrosion and cracking of reinforced and prestressed concrete structures will be described.

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## Introduction

Existent bridges, particularly those made of reinforced concrete, are deteriorating at a rapid rate, faster than they are being repaired, strengthened, or replaced. Many structures built in the 1960's and 1970's are now considered deficient by today's design standards. The appearance of widespread failures in bridges has highlighted the importance of effective monitoring systems, which are able to identify structural problems at an early stage, guaranteeing in this way the public safety.

Apart from the safety concern, a financial problem also arises. The potential of monitoring systems to reduce operational maintenance costs, by identifying problems at an early stage and verifying the effectiveness of repair procedures, is clearly significant.

An almost complete instrumentation system to evaluate all imaginable physical phenomena would exceed the reasonable amount of financial funds. Additionally, an excess of collected data might not necessarily improve the quality of the drawn conclusions. Therefore, the first step to monitoring a structure is to identify the decisive parameters needed to develop and calibrate consistent engineering models describing the degradation mechanisms threatening safety, serviceability, and durability. In the specific case of a prestressed concrete bridge, the critical parameters to be monitored are the following: Strain, temperature, cracking of the concrete, and corrosion of the reinforcement (rebars and prestressing tendons)

The emerging fiber optic sensing technology satisfies the following exigencies: It is free from corrosion, having long-term stability, and allowing continuous monitoring; it is free from electromagnetic interferences, avoiding undesirable noise; it has a very low signal transmission loss, allowing a remote monitoring; and the cabling and sensors are very small and light, making it possible to permanently incorporate them into the structures. In this way, technology overcomes most of the limitations encountered in other kinds of sensors.

Most of the civil engineering related research in this field has been focused on applications to concrete due to the adaptability of optical fibers and ease by which they can be embedded within concrete (Ansari 1997).

Having no intention of being exhaustive, this paper provides an overview of the physical fundamentals of intensity modulated and spectrometric fiber optic sensors (FOSs). A broad range of applications and techniques to assess the condition of existing and new bridges is presented. The possibility to embed these small and unobtrusive sensors in composite materials, used in the rehabilitation of old bridges, is also highlighted.

## Foundations of Fiber Optic Technology

An optical fiber is a thin flexible strand of dielectric material that can trap optical radiation at one end and guide it to the other. Normally, the fiber consists of at least two optically dissimilar materials. These materials are arranged so that one material with a lower refractive index, called the cladding, completely surrounds the other.

The central material, called the core, carries the light waves. These light waves are trapped in the core by reflection at the interface between core and cladding. Often, the cladding is itself surrounded by further layers which are added mainly for mechanical strength protection, but which are not intended to di-

[1]Full Professor, School of Civil Engineering, Edificio C2, Campus Norte UPC, Gran Capitán s/n, 08034 Barcelona, Spain. E-mail: joan.ramon.casas@upc.es

[2]Associate Professor, Civil Engineering Department, Univ. of Minho, 4800-058 Guimarães, Portugal.

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**Table 1.** Unitary Cost (Estimate) of Current Components and Equipment

| Concept | Price (US$) | Commentary |
|---|---|---|
| Single mode fiber (1,000 m) | 575 | Optical fiber: 125 μm cladding; 900 mm tight buffer |
| Single mode FC/PC patch cables (10 m) | 52.7 | Connectorized on both ends, ϕ3 mm protective outer jacket |
| Cleaver | 1,280 | Standard 125/250 mm and 125/900 mm fibers |
| Strippers | 62 | Double stripping tool: Cladding/coating: 125 μm/250 μm; cladding/buffer: 125 μm/900 μm |
| Splice | 17.7 | Index matching gel within the alignment sleeve to produce low loss (0.5 dB) |
| FC/PC fiber connector | 9.0 | Single mode 125 mm; Ferrule: ceramic (0.2 dB loss) |
| Core-aligning fusion splicer | 20,466 | Splicing in three dimensions 250/400/900 μm fibers |
| Optical time-domain reflectometry | 10,478 | High dynamic range: 37/34 dB (1.31/1.55 μm); sampling resolution: 5 cm (minimum step) |
| Fiber Bragg grating interrogation system | 24,971 | Measures 31 Fiber Bragg gratings along a single fiber; 50 Hz scan frequency |
| FO signal conditioner (Fabry–Pérot sensors) | 15,844 | Four-channel system; precision (0.05%); resolution (0.01%); up to 1,000 Hz sampling rate |

rectly influence the guiding properties of the fibers. These layers consist of a coating and several jackets, which can be made of different materials and with different thicknesses, depending on each application of the fiber. The core and the cladding are usually made primarily of silica with very small amounts of dopants, such as germanium or boron, added to change the refractive index of the core. Commonly, the coating is made of plastic to give flexibility to the fiber.

Every fiber optic sensing system requires several different components, but there are some basic components that are common in all of the systems. These basic components are the following: Light source, splitters and couplers, sensors, demodulation system, and processing system. Table 1 gives an orientation of the cost of current components and equipments.

The FOSs are based on measuring the change of some property of the guided light. But this change can be produced inside the optical fiber or outside, in another medium. According to this, two types of sensors can be distinguished: Intrinsic and extrinsic.

In the intrinsic type of sensors, the measurand directly acts over the fiber and changes some physical properties of the optical fiber. These changes on the fiber produce a change on the properties of the light traveling inside the fiber. Thus, in this type of sensor, the light never exits the optical fiber. The fiber is used as the input/output medium, and also as the sensor.

In the intrinsic sensor, a cavity is formed between two partial mirrors placed inside the fiber [Fig. 1(b)]. This cavity is the sensing region. Internal mirrors are reflectors formed as an integral part of a continuous length of fiber. They are produced by fusion splicing an uncoated fiber to a fiber with a thin dielectric coating on the end.

In the extrinsic kind of sensor, the optical fiber is used purely as the input/output path. The fiber only carries the light from the source to the sensing part, and from the sensing part to the demodulation system. In this case, the Fabry–Pérot cavity is formed between the air–glass interfaces of two fiber end faces aligned inside a hollow-core tube [Fig. 1(a)]. The light does not suffer

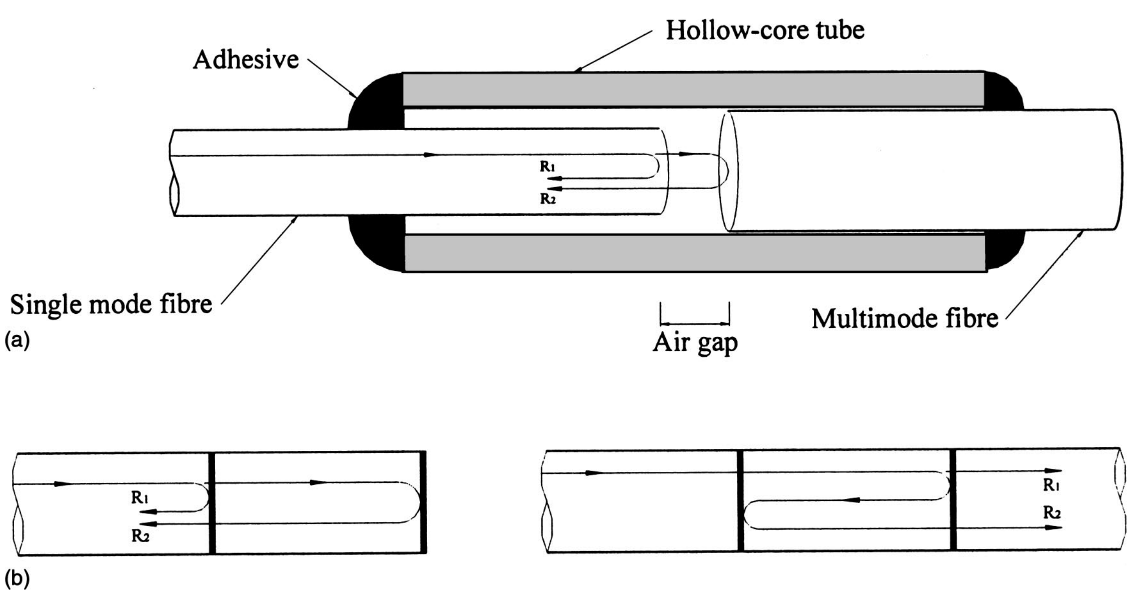


**Fig. 1.** Extrinsic and intrinsic Fabry–Pérot interferometric sensors: (a) Extrinsic sensor and (b) reflective and transmissive configurations of a intrinsic sensor



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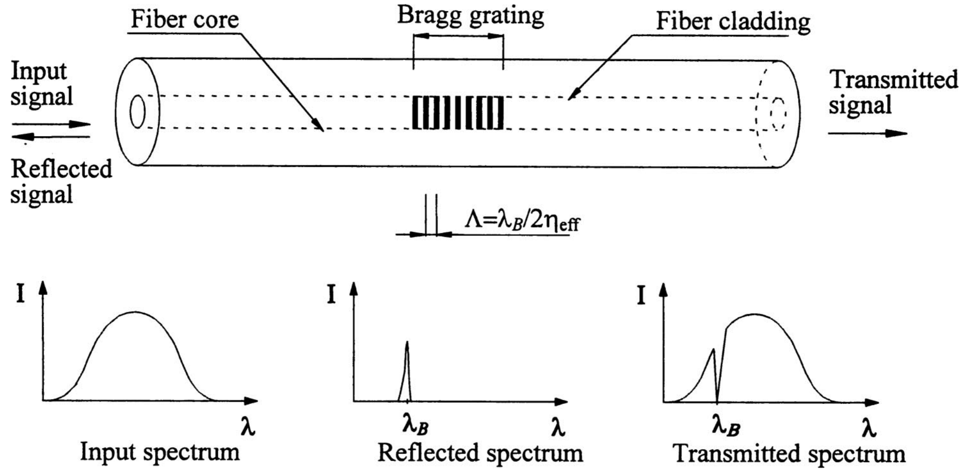


**Fig. 2.** Principle of operation of a fiber Bragg grating sensor

any change while traveling along the optical fiber. In the sensing zone, the light exits the optical fiber and enters another medium, usually air. Then, in this medium, the light is modulated and finally it again enters the optical fiber to be guided to the demodulation system.

The FOSs are based on measuring changes in the physical properties of the guided light. There are mainly four properties of the light that can be modulated: Phase, polarization state, intensity, and wavelength. Thus it is possible to classify the sensors in four different categories depending on which of these properties they modulate: (1) Interferometric sensors, (2) polarimetric sensors, (3) intensity modulated sensors, and (4) spectrometric sensors.

## Intensity-Modulated Sensors

The intensity-modulated sensors are based on monitoring the changes in the intensity of the input light. This kind of sensor is able to measure any parameter that can cause intensity losses in the guided light. The advantages of these sensors are: Simplicity of implementation, low cost, possibility of being multiplexed, and ability to perform as real distributed sensors. The drawbacks are: Relative measurements only and variations in the intensity of the light source lead to false readings, unless a referencing system is used.

The optical time-domain reflectometry (OTDR) is used in almost all the intensity-modulated sensors. Its main application is for fault finding and attenuation monitoring in optical networks. In the field of optical fibers, sensors are used to monitor changes in light intensity in the fibers, and also to develop different schemes of multiplexing.

The OTDR relies on the reflection of light that has been launched into a fiber from an amplitude-modulated and pulsed source. Using the OTDR technique, from the backscattering of the light, it is possible to obtain the value of the light intensity along the whole fiber, by measuring the time of flight of the returned pulses. In this way, it is possible to detect losses in the fiber and to locate these losses with quite good spatial resolution.

## Spectrometric Sensors

The spectrometric sensors monitor changes in the wavelength of the light. These sensors, better known as fiber Bragg grating (FBG) sensors, are not as sensitive as the interferometric sensors, but their configuration, installation, and data processing are extremely easy.

An advantage of these sensors is that the sensed information (shift in wavelength) is an absolute parameter, and thus absolute measurements are obtained, instead of relative ones. The wavelength-encoded nature of the output also permits ease in multiplexing. Several gratings can be placed along a single optical fiber, obtaining, in this way, a quasi-distributed point sensing the measurand.

FBG may be bought from several commercial sources, tuned at the selected wavelength. The only ability required of the user would be to make the optical connections, normally by fusion splicers, which require minor investments and training. This is the common approach for mechanical engineers, mainly interested into the usage of this technology for strain measurements. Procedures for manufacturing FBG require high investments and well trained people, and it is useful only for those people interested in the development of the sensor (Güemes 2002).

### *Principle of Operation*

A FBG is generated by engraving, at the core of the optical fiber and for a short length (about 1 cm), a periodic modulation of its refractive index. It will behave as a series of weak partial reflecting mirrors which, by an accumulative phenomenon called diffraction, will reflect back the optical wavelength. Therefore, if a broadband light is traveling in the core of the optical fiber, the incident energy at such a resonant frequency will be reflected back, with the remaining optical spectra unaffected, as illustrated in Fig. 2. The diffraction law, first established by Bragg and widely used for crystal structure analysis, simplifies, under normal incidence, to the simple equation

$$\lambda_B = 2 \cdot n_{\text{eff}} \cdot \Lambda \tag{1}$$

where $\lambda_B$=center wavelength; $n_{\text{eff}}$=effective refractive index of the fiber core; and $\Lambda$=pitch length of the grating, i.e., the distance between two consecutive points with the same refractive index.

Any change in the pitch length or refractive index will cause a shift in the Bragg peak wavelength. Consequently, any mechanical or thermal strain variation on the FBG can be determined by the corresponding shift in the central Bragg wavelength. Assuming isothermal conditions, the change in $\lambda_B$ is given by



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$$\frac{\Delta\lambda_B}{\lambda_B}=(1-p_e)\varepsilon \quad (2)$$

where $\varepsilon=\Delta L/L=$axial strain over the length of the sensor and $p_e=$effective photoelastic constant for the fiber ($\sim 0.22$).

Commercially available white light sources have an spectral width around 40 to 60 nm. As the maximum excursion in wavelength is 10 nm for 10,000 $\mu\varepsilon$, several Bragg gratings, centered at different wavelengths, can be written at the same optical fiber, and interrogated at the same time. Multiplexing is easily implemented. The fact that the information is wavelength encoded makes the sensor very stable to aging, allowing absolute measurements of strain after long terms without recalibrating, a common nightmare with standard strain gauges (Güemes 2002).

Several applications of fiber optics to build sensors for structural monitoring of the most important parameters in bridge structures (cracking, temperature, etc.) have been developed. They are described in the following sections.

## Fiber Optic Sensors for Structural Monitoring

### Crack Sensors

The existing condition of many important concrete structures can be assessed through the detection and monitoring of cracking. For example, in concrete bridge decks, crack openings beyond 0.15 to 0.2 mm will allow excessive penetration of water and chloride ions, leading to the corrosion of steel reinforcements. The crack opening of the order of millimeters, which may occur after a major earthquake, is a sign of severe structural damage (Leung and Elvin 1997).

Conventionally, crack detection and monitoring for bridges have been carried out by visual inspection. The procedure is time consuming, expensive, and yet unreliable. Recently, various researchers have developed fiber optics-based crack sensors for concrete structures. Existing optical crack sensors are, however, very limited in their applications. For example, sensing based on fiber breakage (Rossi and LaMaou 1989) can distinguish between the presence or absence of cracking but cannot provide information on gradual structural degradation. ‘‘Point’’ sensors, developed by Ansari and Navalukar (1993), can detect and monitor the opening of a crack only if the cracking occurs in a small region that is known a priori. The sensor employed in this study was based on the measurement of the intensity loss due to deformation. These sensors were calibrated and were embedded in a fiber-reinforced concrete specimen.

Zako et al. (1995) used an OTDR to measure the cracking point by Fresnel reflection of four optical fibers, which have been bonded to the surface of the mortar beam with epoxy resin. In addition, the crack propagation in the mortar beam can be also measured by the breaking sequence of four optical fibers.

Gu et al. (2000) developed a distributed fiber optic sensor consisting of individual segments spliced on one line. By measuring the Fresnel reflection at each splice between two pieces of fiber, the average strain within each piece can be obtained. Based on the strain reading, the severity of cracking within a certain region can be assessed. An optical time-domain reflectometer was employed for the interrogation of the sensor signal. The structural monitoring capability of the sensor was evaluated through experiments with reinforced concrete beams.

If the splices are placed very close to one another, the cost will be high and also the forward signal may drop rapidly with distance (due to the presence of many reflection points), making the sensor inapplicable to real structures where a long sensing length is required (Olson 2002).

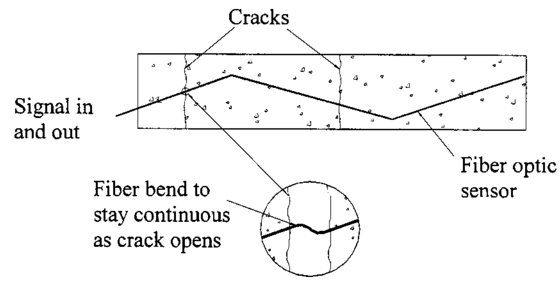


**Fig. 3.** Principle of operation of the zigzag sensor

Cai et al. (2001) applied the distributed optical fiber sensing technology to detect the cracks in a small-scale plaster model test of an arch dam. By using OTDR, the real time monitoring of cracks can be realized. The practice of this technology shows that the sensor network bonded to the downstream surface of the dam will not affect the stiffness of the model, but it must be correctly distributed.

Researchers at the Massachusetts Institute of Technology and Brown University developed a sensor for the reliable detection and monitoring of cracks in concrete structure (Leung and Elvin 1997). The sensor is based on a distributed optical fiber microbending sensor. An optical fiber is embedded in the concrete element in a ‘‘zigzag’’ shape (Fig. 3). Using OTDR equipment, the light intensity distribution along the fiber is measured.

Before the formation of cracks, the backscattered signal along the fiber should follow a relatively smooth curve (the upper line in Fig. 4). In the straight portions of the fiber, the small loss is due to absorption and scattering. In the curved portion (where the fiber turns in direction), macrobending loss may occur depending on the radius of curvature.

When a crack opens in the structure, a fiber intersecting the crack at an angle other than 90° has to bend to stay continuous (Fig. 3). This perturbation in the fiber is very abrupt, and thus can be considered as microbending. This microbending results in a sharp drop in the optical signal (the lower line in Fig. 4). This intensity loss is detected and located by means of the OTDR equipment. Also, from the magnitude of the drop, the crack opening can be obtained if a calibration relation is available.

The proposed technique does not require prior knowledge of the crack locations, which is a significant advancement over existing crack monitoring techniques. Moreover, several cracks can be detected, located, and monitored with a single fiber. For the sensor to work, however, crack directions need to be known. An

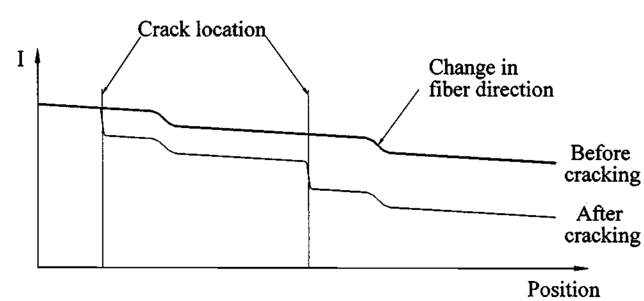


**Fig. 4.** Intensity along the fiber, measured by means of the optical time-domain reflectometry equipment

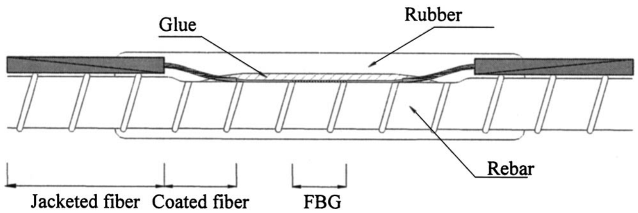


**Fig. 5.** Scheme of the fiber Bragg grating strain sensor

ideal application of the sensor is in the monitoring of flexural cracks in bridges, which may appear at arbitrary locations along the deck, but essentially perpendicular to the spanning direction.

A method for applying the sensor to existing structures was recently proposed and is called the *sensor plate* (Olson 2002). To achieve the requirements in the monitoring of cracks on bridges, the sensor plate is being now improved by researchers of the University of Minho, in Portugal, and of the Hong Kong University of Science and Technology.

### Strain Monitoring

Two different types of fiber optic sensors are commonly used for strain sensing: FBG, and Fabry–Pérot. The Fabry–Pérot technology can be very precise, with a maximum resolution of $\pm 0.01\ \mu\varepsilon$. The FBG technology is less precise, obtaining a resolution around $\pm 10\ \mu\varepsilon$ with standard equipment. The FBG technology also has the advantage of reading absolute values and thus they are unaffected by interrupted measurements. In the case of a Fabry–Pérot, a new calibration is needed every time the readings are stopped.

Many small instruments using FBG sensors have been developed to be embedded into concrete and monitor the strain. However the strain of the concrete is not as useful as the strain of the reinforcing bars. In the tensioned part of the section, if there are no cracks, the strain is the same in concrete as in the rebars, due to continuity. If some cracks appear, the concrete releases some stress and the rebars are more strained. The objective is to measure the parameter that affects the serviceability and also the safety of the bridge, and the ultimate limit state is based on the reinforcement strain. In the compressed part, the strain is the same for concrete as for the rebars. Therefore, the sensor will measure the strain on the reinforcement bars.

In Fig. 5, a very simple sensor is presented. It consists of a FBG bonded to a piece of a rebar. The jacket of the fiber is only removed in the sensing zone, which is bonded to the polished surface of the rebar by means of cyanoacrylate. The sensing part is protected by several layers of rubber, and the input/output lead is protected enough by the fiber jackets.

The manufacturing and handling of the sensor is very easy. The 2 m rebar with the sensor can be preassembled in the laboratory before being brought out to the site. At the site, the instrumented rebar is easily tied into the structural rebars already in place. Then, only the fiber lead must be properly tied along the reinforcement cage to the ingress/egress point. The sensor is protected enough to resist the concrete casting.

To demonstrate the feasibility of the sensor to be easily embedded into a concrete structure without suffering any damage, and to prove the good behavior of the sensor, two tests have been conducted (Perez 2001). In these tests, the characteristics of the sensor were obtained. The sensor was tested up to structural failure (2,590 $\mu\varepsilon$) showing a good response. The obtained resolution

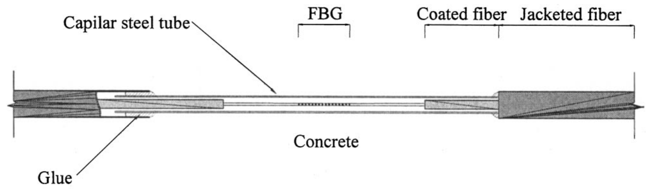


**Fig. 6.** Scheme of the new temperature sensor

was about $\pm 40\ \mu\varepsilon$, due to high noise in the system. But the commercial systems have a maximum noise of about $\pm 0.01$ nm in wavelength, which means an acceptable resolution of $\pm 10\ \mu\varepsilon$.

An alternative procedure could be to embed the sensor fiber in a groove along a rib-free side of the reinforcing bars, in a way that should minimally distort the bond properties (Nellen et al. 2002). These authors used 123 FBG spaced by 10.4 mm to monitor concrete plate strips. With this arrangement, a strain resolution of 20 μm/m was obtained and high strain values up to 27 mm/m and high strain gradients up to 2,000 mm/m could be measured.

For reinforced concrete structures made with fiber composite rebars, optical fiber sensor technology should be an ideal candidate for load monitoring because optical fibers can be embedded in the rebars in the longitudinal direction during fabrication. For such uniaxial structures, optical fibers easily fit into the composite material without any voids and can be entirely integrated with the structure (Uttamchandani et al. 1999).

### Temperature Monitoring

One of the most significant limitations of FBG sensors is their dual sensitivity to temperature and strain. This creates a problem for sensor systems designed to monitor strain, as temperature variations along the fiber path can lead to anomalous strain readings.

The problem with the temperature is not to separate the measured strain in two components: One due to the load and the other to the temperature variation. The problem is that part of the shift in the wavelength is caused by the strain of the host material (load and thermal component together) and part is caused by the change of the optical properties of the fiber due to the temperature variation. The only shift that gives information about the measurand is the former one (due to strain). The other shift causes an error in the value of this measurand.

One approach to addressing this issue is to use reference gratings that are in thermal contact with the structure, but do not respond to local strain changes. Compensation can be achieved by subtracting the shift of the reference gratings from the shift of the sensing gratings. Another approach is to obtain a curve temperature versus shift to subtract. In this way, by measuring the temperature at the same point where the sensor is located, it is possible to correct the measured wavelength shift.

Many different fiber optic sensors for temperature are available. Usually, they rely on the coefficient of thermal expansion of some metal where a Bragg grating sensor is bonded. In this way, the strain sensed with the grating is used to obtain the temperature of the reference metal. But this kind of sensor has an important drawback: The reference material cannot be attached to the structure, in order to avoid load-induced strains. Therefore, these sensors cannot be embedded, unless a box is used to isolate the sensor from any structural strain.

Fig. 6 illustrates a very simple temperature sensor based on the Bragg grating technology. Thus, since it uses the same technology

**Table 2.** Parameters in the Tests to Demonstrate the Feasibility of the Thermal Sensor (Perez 2001)

| Parameter | Test 1 | Test 2 |
|---|---|---|
| Sensor range | [−20, 150]°C | [−20, 150]°C |
| Temperature | 120°C | 120°C |
| Resolution | $\pm 10\ \mu\varepsilon$ (±1°C) | $\pm 10\ \mu\varepsilon$ (±1°C) |
| Frequency | 0.1 Hz | 10 Hz |
| Accuracy | ±0.5°C | ±0.9°C |

as the strain sensors, they can be read by the same optic system. It also means that the temperature sensor can be located in the same fiber lead as the strain sensors, reducing the number of input/output fibers.

To demonstrate the feasibility of easily embedding the sensor into a concrete structure without suffering any damage, two calibration tests have been conducted (Perez 2001). The results are summarized in Table 2. As seen in Table 2, by reducing the frequency to 0.1 Hz, which is acceptable for thermal changes in concrete bridges and many other structures, an accuracy of ±0.5°C can be achieved.

### *Fiber Bragg Grating-Based Inclinometer*

For a long time, many kinds of inclinometers have been available on the market. Nevertheless, few are very accurate and able to be multiplexed. Moreover, most are sensitive to temperature effects in real operating conditions, leading to difficulties in interpreting very small changes in sensor response.

A new family of inclinometers, based on FBG sensors, able to solve all of these problems, has been developed by the *Centre d'Etudes de Saclay* (Ferdinand and Rougeault 2000). The principle of operation of such an inclinometer consists of turning an angle into a proportional strain applied to the FBG transducers. The sensor illustrated in Fig. 7 is made of two mechanical parts linked by a high-quality axis of rotation, whose main function is to sustain a hanging mass and two prestrained FBGs. The upper part is fixed to the body of the inclinometer and moves with respect to the structure. The lower part is submitted to gravitational forces. Both fibers are slightly prestrained, to remain in tension during any rotation. With such a simple mechanical model, it is easy to get a linear relationship linking the tilt angle and the induced strain on the FBGs.

The use of two FBGs makes it possible to self-compensate for the temperature effects. Under rotation, the shifts in wavelength of each grating are in opposite directions (one FBG increases its strain and the other decreases it), but under a variation in temperature, both wavelengths shift in the same direction.

### *Fiber Bragg Grating Acceleration Sensor*

A novel acceleration sensor using FBG technology has been recently developed (Krämmer et al. 2000). The principle of operation is a spring-mass system with an inertial mass connected to a frame through an optical fiber which contains two spectral partial overlapping Bragg gratings.

In the case of the inertial mass moving to the left-hand side, the reflections of the grating on the left-hand side move to shorter wavelengths due to compression, while the reflections of the grating on the right-hand side move to longer wavelengths due to elongation. Thus, the spectral overlap decreases and the total amount of reflected light increases. On the other hand, when the

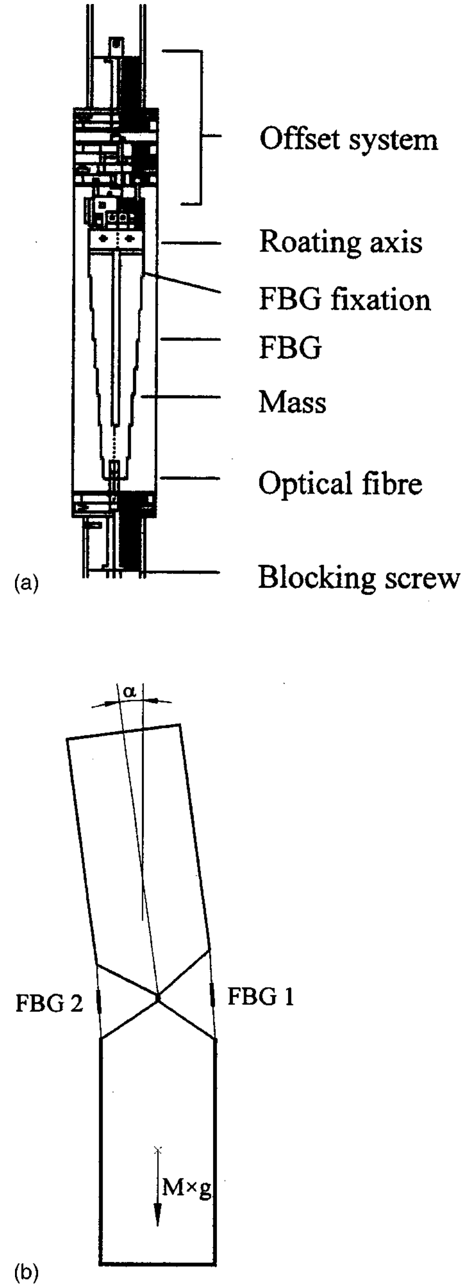


**Fig. 7.** Fiber Bragg grating-based inclinometer (Ferdinand and Rougeault 2000): (a) Inclinometer design and (b) Principle of operation

inertial mass moves to the right-hand side, the amount of reflected light decreases due to the increasing spectral overlap. Taking continuous measurement of the displacement of the inertial mass, it is possible to get the acceleration of this mass.

A first setup of the acceleration sensor is shown in Fig. 8. A small inertial mass is attached to the end of a long lever arm. An optical fiber is fixed to the frame at two points and to the end of a short lever arm that is perpendicular to the long arm. Thus, the sensor is sensitive to accelerations in the vertical direction according to the indicated motion of the seismic mass. This motion is transformed by the pivot point into a stretching or a compression of the FBG sensors in horizontal direction.

The sensor is insensitive to temperature changes since variations induce the same spectral shift in both gratings and in the



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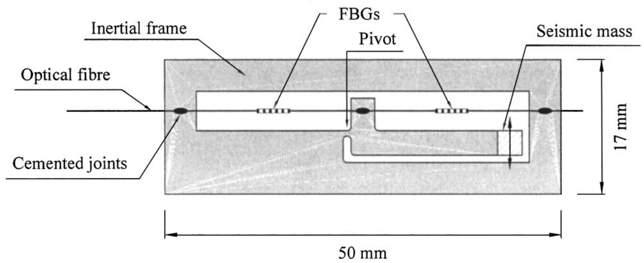


**Fig. 8.** Design of a fiber Bragg grating acceleration sensor (Krämmer et al. 2000)

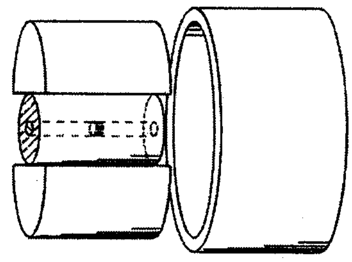

**Fig. 10.** View of sensors type 1 and 2 placed on a longitudinal rebar

same direction. Thus, the reflected overall amount of light is not influenced by temperature variations.

### Corrosion Monitoring

Until now only few FOSs have been developed to directly monitor the corrosion of the reinforcement in a concrete structure. Some of these sensors are based on the Bragg grating technology. As these sensors use the same technology of the strain and temperature sensors, they can be read by the same optic system, and furthermore, several sensors of any of these three types can be located in the same fiber lead. Moreover, the thermal compensation for these sensors will be the same as the one used in the strain sensors.

When the corrosion affects a steel bar, this expands increasing its diameter. Based on this phenomenon, some new sensors have been recently proposed (Casas and Frangopol 2001). Sensor type 1 consists of a FBG disposed around a noncorrugated steel bar in a circle perpendicular to its axis, by means of super glue (Fig. 9). With this disposition, the sensor measures the angular strain produced around the bar. When the bar expands due to corrosion, the perimeter of its section increases and the FBG is strained, which is detected as a shift in the Bragg wavelength of the sensor. The manufacturing of this sensor is very easy and it can be done also in a laboratory before being brought to the site. Sensor type 2 is a FBG in contact with the rebar. In this case, the sensor measures the strain in the concrete around the bar in the radial direction due to the expansion of the bar diameter caused by corrosion.

A three-axis strain and temperature fiber grating sensor formed by writing two overlaid fiber gratings onto a birefringent fiber has been patented (U.S. Patent No. 6144026). The birefringent axes are well defined so that transverse strain can be measured along with longitudinal strain and temperature. The same author proposed further improvements in the measurement of transverse strain and a corrosion sensor that is compatible with a fiber grating strain sensor system usable for structural health monitoring.

The transverse loading may be created by encapsulating a fiber grating into a heat-expanded sleeve (Fig. 10). When the sleeve cools and contracts, it forces the half cylinders together so they transverse load the fiber grating there between. When a fiber is transverse loaded by these mechanisms, a peak-to-peak separation of the reflected and transmitted spectral profiles of the fiber grating results (Fig. 11). As corrosion or other chemical reaction of the sleeve occurs, the transverse strain is relieved and the peak-to-peak spectral separation changes allowing a measurement of corrosion.

### Other Uses

Being small and unobtrusive FBG sensors are ideal for: Load cells as illustrated in Fig. 12 (Schulz et al. 1998; Matsumura et al. 2002); ice detection on pavements and traffic monitoring and control systems (Schulz et al. 1998; Lee et al. 2000; Udd et al. 2000).

A FOS to acquire traffic loads is installed in the immediate neighborhood of the monitored Colle d'Isarco viaduct. The optic fiber is double refractive, uncovered, and embedded between two metal strips which are welded together (Fig. 13). This system has shown to be reliable for several years (Bergmeister and Santa 2001).

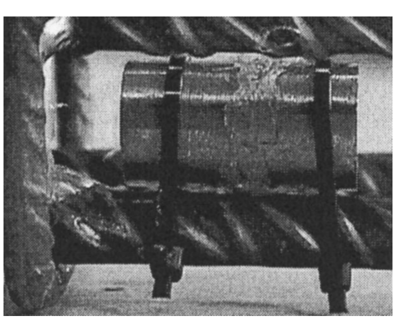

**Fig. 9.** Sensor 1 attached to the longitudinal rebar

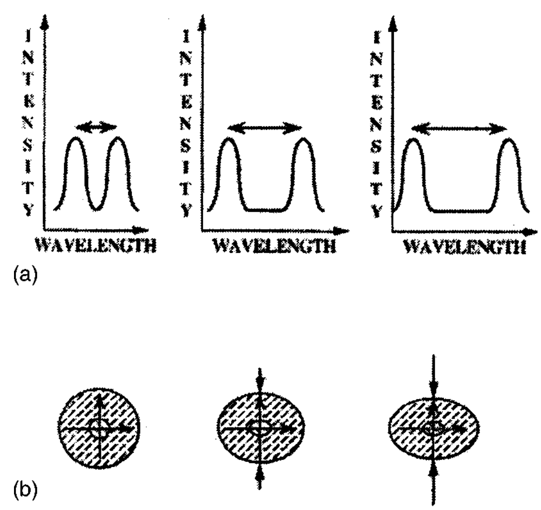


**Fig. 11.** Behavior of the transverse sensitive corrosion sensor: (a) Intensity versus wavelength diagrams of the spectral reflective output and (b) cross-sectional views with different amounts of transverse stresses



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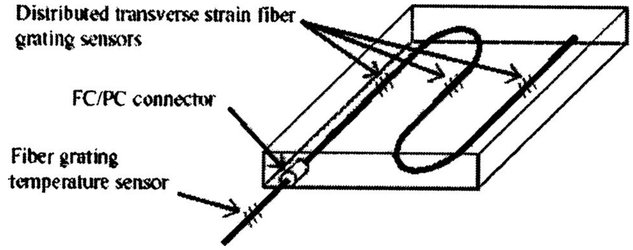


**Fig. 12.** Load cell with embedded distributed transverse fiber Bragg grating sensors (Schulz et al. 1998)

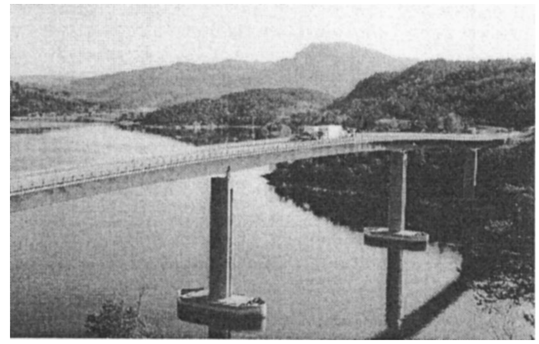

**Fig. 14.** Mjosundet bridge (McKinley and Boswell 2002)

## Applications to Bridge Monitoring

This section summarizes some recent applications of fiber optic systems to the short- and long-term monitoring of a wide range of bridge types. Three applications are focused in depth, giving special attention to the objectives of the measurement program and to the tradeoffs between FOSs and conventional sensors. A brief summary of the advantages of the fiber optic systems to be used in the monitoring of bridges and structures built or repaired with advanced composite materials is also presented.

### *Mjosundet Bridge*

In the aim of an EU Brite-EuRam funded project entitled MILLENNIUM—"Monitoring of Large Civil Engineering Structures for Improved Maintenance" two fiber optic-based monitoring systems have been designed, developed, and tested with laboratory and field trial environments (McKinley 2000). The field trial was undertaken on the Mjosundet Bridge (Fig. 14). This bridge is located in Aure, about 50 km north of Kristiansund on the west coast of Norway. It is a five-span continuous composite bridge. It is practically symmetrical with two end spans of 41 m, two intermediate spans of 82 m, and a center span of 100 m giving a total length of 346 m. The optical fiber sensors were mounted inside the bridge in conjunction with conventional strain gauges (ERSG). The high bandwidth system is capable of measuring up to 100 sensors at rates up to 200 Hz with very low noise levels (McKinley and Boswell 2002).

A total of six locations within the structure were monitored in order to assess the bending strains at the center of the bridge and the shear strains close to one of the supports of the middle span of the bridge. The results show that there has been no degradation of the bonding mechanisms that have been employed for attaching the FBG sensors to the structure for the duration of the field trials (11 months).

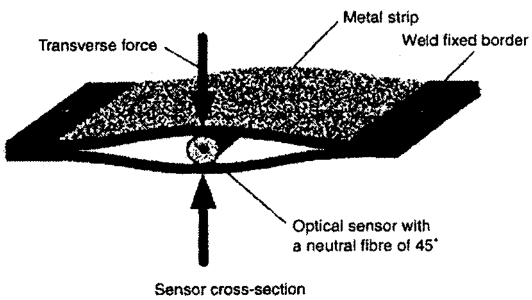


**Fig. 13.** Fiber optic weight in motion sensor (Bergmeister and Santa 2001)

The construction of a model of Mjosundet with a section scale of one-fifth and length scale of one-twentieth has been completed to assess the optimum sensor positioning (Fig. 15). In the laboratory model, only the central and one adjacent side spans have been modeled. Also, as part of the laboratory testing, a number of tests were conducted on smaller scale steel beams and a steel concrete composite panel in order to assess various bonding techniques for the attachment of the optical fibers to the surface of the materials (McKinley and Boswell 2002).

Instrumentation of the bridge model involves the use of FOSs, electrical resistance strain gauges, displacement transducers, and load cells. These are located at four sections along the bridge, two of which represent those used in field trial (Fig. 16). Linear variable differential transducers (LVDTs) and load cells are placed at the load points.

A comparison between the two types of sensor system (ERSG and FOS) was used to assess the performance of the optical fiber-based monitoring techniques (McKinley and Boswell 2002). For sensed locations on the field trial structure with ERSG and FOS sensors at the same location (a total of ten sensor points), a comparison between the two types of sensor was possible with the following results: 1.2 $\mu\varepsilon$ average difference between ERSG and FOS for ten sensors over four tests; 11.9 $\mu\varepsilon$ standard deviation of difference for same sampling batch.

Similarly, a comparison of all of the sensors from two field trial tests conducted 13 months apart is possible after factoring the data to account for differences in the load levels, which shows: 7.2 $\mu\varepsilon$ average change for 28 FOS sensors over the 2 tests conducted 13 months apart; 18.8 $\mu\varepsilon$ standard deviation of the change for same sampling batch; $-4.3$ $\mu\varepsilon$ average change for 8 ERSG sensors over the 2 tests conducted 13 months apart; 7.6 $\mu\varepsilon$ standard deviation of the change for same sampling batch.

The significance of this research program lies in the fact that, besides showing that the accuracy of FOSs mounted in real structures is as good as for traditional sensors, the long-term performance of such sensors and the possibility of sensor trees to be easily manufactured up to thousands of meters in length, makes them ideal for large-scale continuous monitoring in civil engineering structures. Similar objectives are not affordable for traditional electrical-based techniques.

### *Colle Isarco Bridge*

In the Colle Isarco Bridge (Fig. 17), on the Brennero highway between Italy and Austria, a wide range of techniques were used to monitor strains, linear and rotational displacements, accelera-



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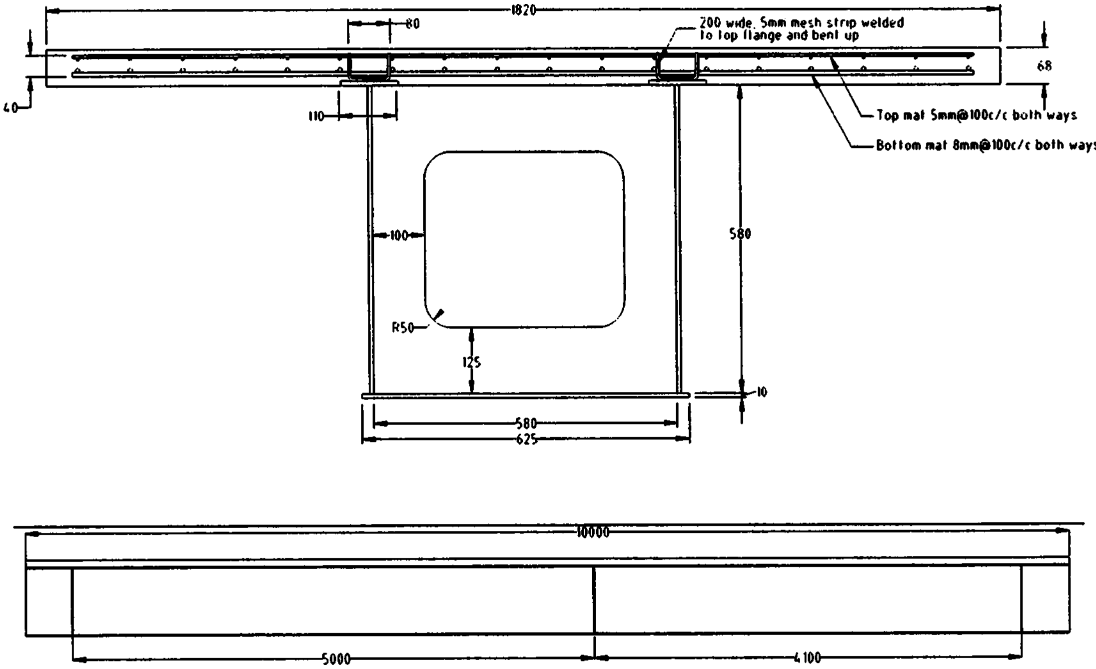


**Fig. 15.** Model bridge dimensions (McKinley 2000)

tions, corrosion, etc. This bridge carries most of the traffic between Italy and Austria, including a large number of heavy trucks and has recently been refurbished.

The monitoring system includes 96 fiber optic SOFO 10 m length sensors (French acronym of ''*Surveillance d'Ouvrages par Fibre Optique*'' or structural monitoring by FOSs). They were installed parallel to the neutral axis of four box girders, in order to determine the vertical, horizontal, and torsional deformations. Forty additionally sensors of the same type were installed on two piles and sixteen prestressing members. These long base-length FOSs have a sensitivity of 2 μm and were developed by Inaudi et al. (1997) and Vurpillot et al. (1998).

These sensors are based on the principle of low coherence interferometry. The infrared emission of a light-emitting diode is launched into a standard single mode fiber and directed, through a coupler, toward two fibers mounted on, or embedded in, the structure. The measurement fiber is in mechanical contact with the structure itself and will follow its deformations. The second reference fiber is installed free in the same pipe. Mirrors, placed at the end of both fibers, reflect the light back to the coupler, which

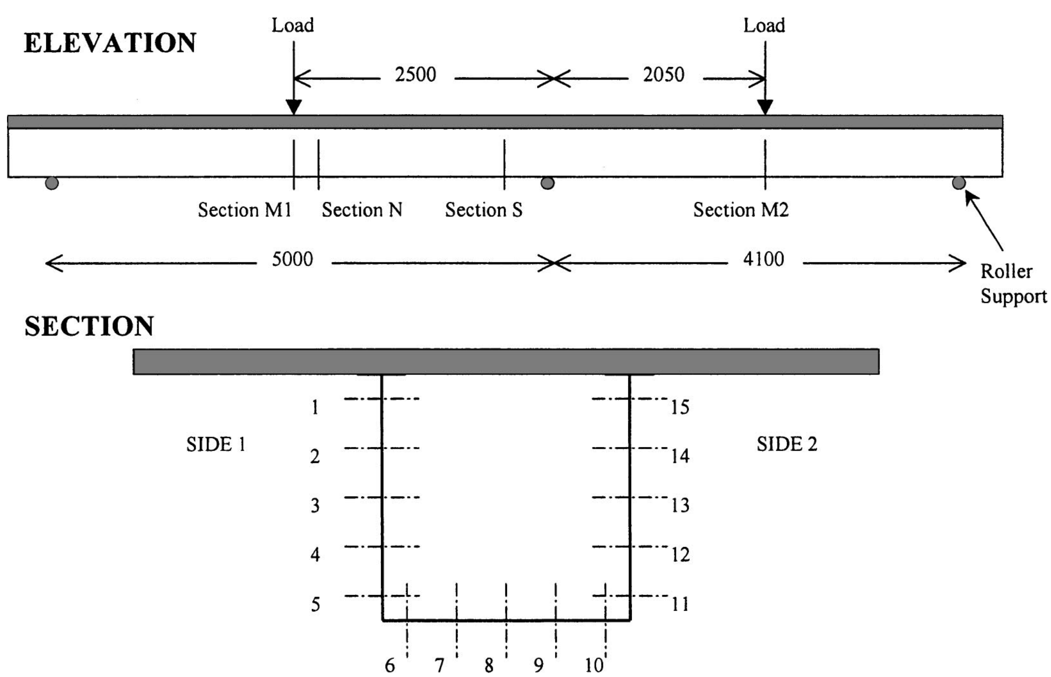


**Fig. 16.** Strain gauge and optical fiber positions on bridge model (McKinley 2000)



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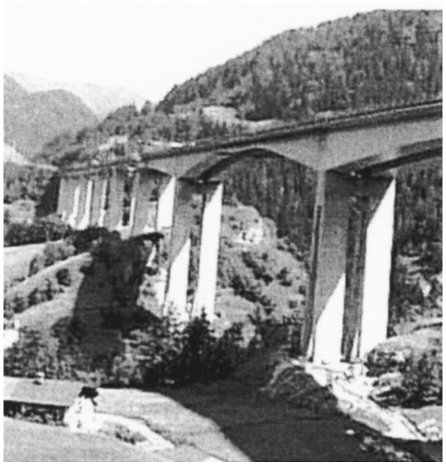


**Fig. 17.** Colle Isarco bridge

recombines the two beams and directs them toward the analyzer (Bergmeister and Santa 2001). A fiber optic system to acquire traffic loads was installed in the neighborhood of this viaduct (Fig. 13).

## Bridge over River Ave

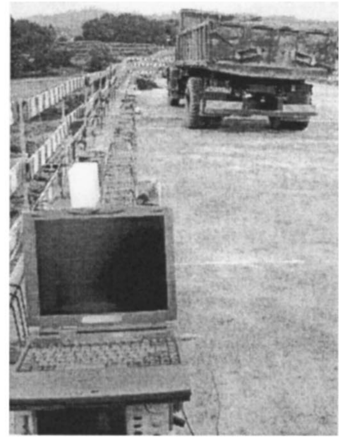
A similar global monitoring concept is presently being used in the construction of the bridge over River Ave, in Guimarães, Portugal. The use of binary binders was tested to enhance the durability of the concrete structure. In different piers, use has been made of the addition of silica fume, fly ashes, metakaolin, latex, and corrosion inhibitors, to allow comparative assessment of the durability.

The monitoring plan, coordinated by the Structural Division of the University of Minho, includes the installation of: Eighty-eight full-bridge strain gauges to measure the strain in the rebars, forty-eight embedment strain gauges to measure the strain in the concrete, and eighty-eight PT100 to measure the temperature in the concrete (Cruz 2002). Fifty-two corrosion sensors, developed by the Portuguese company *ICORR*, have been installed in this bridge to monitor the concrete corrosivity in different depths of the cover layer. In addition, this plan controls the concrete durability and includes the measurement of the concrete permeability, the setup, and execution of several tests to trace the evolution of the concrete behavior (shrinkage, creep, fracture, chloride penetration, carbonation, etc.).

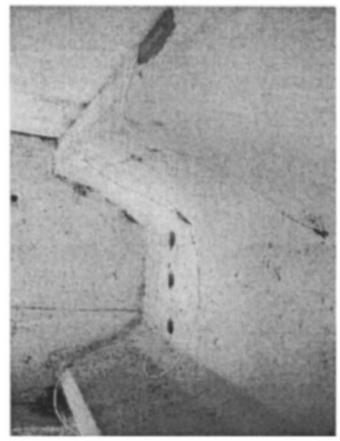
Additionally, some strain and temperature FBG sensors protected by thin cured laminates (carbon fibers and Kevlar fibers) have been recently installed in a precasted *I* beam of an access viaduct and a static loading test has been conducted (Fig. 18). In the next months, further FOS will be installed in the bridge box girders and in the bridge piers.

## Monitoring of Bridge Incorporating Advanced Composite Materials

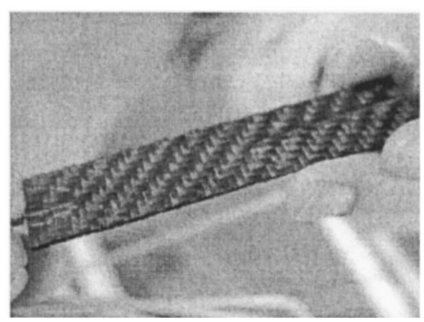
Advanced composites offer some advantages over traditional procedures for repairing concrete structures, due to their optimal corrosion properties, low weight, and decreasing costs. Thin cured laminates may be externally bonded or dry fabrics can be applied wet and in situ cured over the concrete structure, conforming to its surface irregularities. The combination of advanced composites and fiber optic strain sensors is easy and offers important



(a)



(b)



(c)

**Fig. 18.** Bridge over Rio Ave: (a) Static loading test; (b) sensors applied in a precasted *I* beam; and (c) strain and temperature fiber Bragg grating sensor protected by a thin cured laminate

advantages that are not possible to accomplish with the traditional sensors, mainly the embedding of the sensor in the composite material or in the interface between materials in the manufacturing or retrofitting processes.

Tests on a concrete beam repaired with carbon fiber-reinforced plastic (CFRP) and instrumented with Bragg gratings have been conducted in Barcelona, showing the possibility of an intelligent repair (Casas et al. 2002).

An externally prestressed concrete continuous beam with two spans 7.20 m each, representative of current in-service bridge structures, was loaded up to failure and repaired (Fig. 19). Beam surface near the cracks was mechanically prepared to establish



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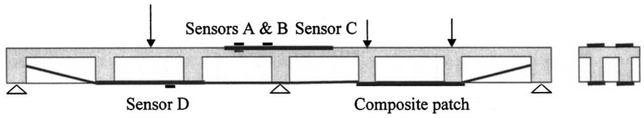


**Fig. 19.** Bragg grating locations and location of the carbon fiber-reinforced plastic sheets (Casas et al. 2002)

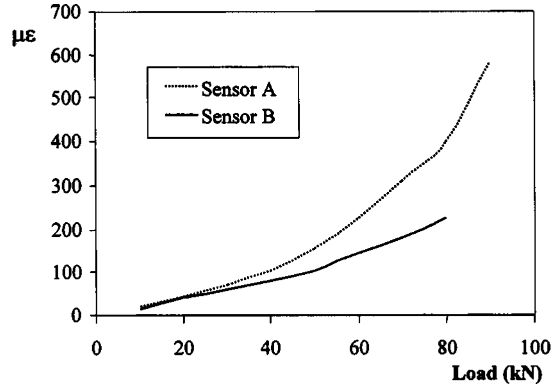


**Fig. 21.** Bragg grating measurements

adequate bonding. Composite patches, made of two layers of carbon fabric, in situ impregnated with room-temperature epoxy resin, were extended over the crack locations to transmit the load from the discontinued steel bars. Fiber optic strain sensors were placed both in the internal and external surfaces (Casas 1999).

Besides the Bragg grating sensors, conventional resistive strain gauges in concrete, reinforcing and prestressing steel, composite patch surface, and LVDTs were added to acquire complete information on strain and deformation all over the structure. Up to 70 channels of instrumentation were continuously monitored during the tests. Additional and redundant strain gauges were located in the external surfaces of the CFRP sheets close to the FOSs in order to compare and check the experimental data provided by the two measurement techniques.

Load versus strain is plotted in Fig. 20, obtained with strain gauges and FBG in the same location over the carbon sheet. Coincidence is very satisfactory, even at the nonlinear region of the concrete beam. Visible nonlinearity starts near 80 kN, still with considerable residual strength. Small differences between strain gauges and Bragg gratings are due to the creep of the concrete. In fact, measurements in the gauges and FBG were made at the same load level but at different times.

Results for Bragg grating sensors A and B are shown in Fig. 21. They were at the same positions, interior and exterior faces, of the composite patch (see Fig. 19). A shear lag due to the finite thickness of the adhesive layer can be seen even in the elastic range (up to 80 kN). The strain measured by sensor A, located in the interface directly over the concrete and embedded in the adhesive, is higher than that measured by sensor B, at the same location but on top of the composite patch. This phenomenon could be monitored thanks to the FBG technology because no other available sensors were able to measure strain in the interface.

The Beddington Trail Highway Bridge in Calgary is one of the first bridges in Canada to be outfitted with fiber-reinforced plastic (FRP) tendons and a system of structurally integrated optical sensors for remote monitoring (Fig. 22). Fiber optic Bragg grating strain and temperature sensors were used to monitor the behavior during the construction and under serviceability conditions [Intelligent Sensing for Innovative Structures (ISIS) 2002].

The Taylor Highway Bridge in Manitoba, a two-lane 165.1 m long structure (Fig. 23), has 4 out of 40 precast girders reinforced with CFRP stirrups. These girders are prestressed with carbon FRP cables and bars. Glass FRP reinforces portions of the barrier walls.

FBGs were used to monitor the strains in the CFRP reinforcement of the girders and the deck slab, as well as the GFRP reinforcement of the barrier walls. Selective girders, reinforced by conventional steel reinforcement, were also instrumented using FBGs. A total of 63 FBG sensors and two serially multiplexed fiber optic cables, each consisting of three FBGs, were glued to the reinforcing CFRP bars. Due to the relatively high initial prestressing strain and the limit full range of the FBGs, most of the sensors were installed after tensioning the prestressing tendons. The sensors measure both temperature and strain. The multiplexed signals are processed on site and then transmitted via a modem to the central station (Tennyson and Mufti 2000).

## Conclusions

A state of the art of the fiber optic monitoring systems has been presented, which proves that it is possible to apply this technology in the field of long-term monitoring of bridges. The reduced weight and dimensions of FOSs, the strong immunity to electro-

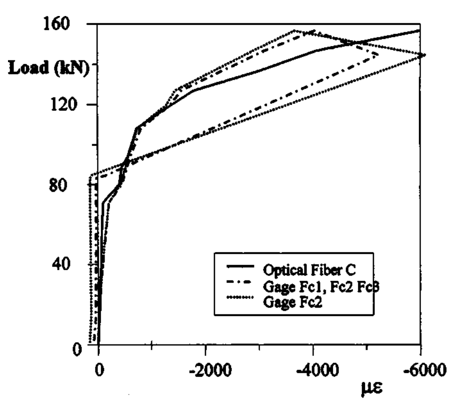


**Fig. 20.** Strain measurements (fiber optic sensor and strain gauges)

**Fig. 22.** Beddington Trail Highway bridge (ISIS 2002)



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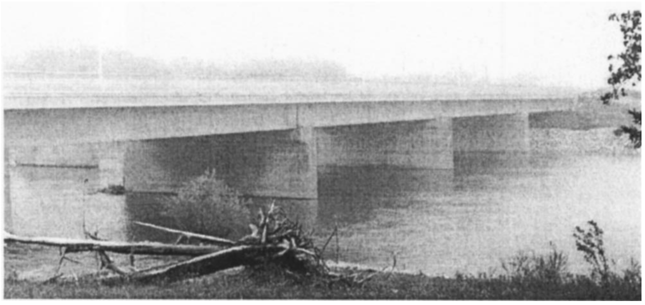

**Fig. 23.** Taylor Highway bridge (ISIS 2002)

magnetic interference, the improved environmental resistance, and the scale flexibility for small- and long-gauge measurements, are the main advantages of these systems and the reasons for being applied worldwide. Furthermore, a broad range of applications is possible using the same basic equipments.

Techniques have been developed that allow optical fibers to be bonded onto steel, concrete, and composite (glass, carbon, etc.) surfaces, or embedded within concrete or composite materials, monitoring internal and external parameters. These are monitoring possibilities that are not affordable for standard electrical sensors. In the future, it is expected that FOSs will play a major role in the real time structural monitoring and in smart bridges.

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