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Applications of fiber optic sensors in civil engineering

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Abstract. Recent development of fiber optic sensor technology has provided an excellent choice for civil engineers for performance monitoring of civil infrastructures. Fiber optic sensors have the advantages of small dimensions, good resolution and accuracy, as well as excellent ability to transmit signal at long distances. They are also immune to electromagnetic and radio frequency interference and may incorporate a series of interrogated sensors multiplexed along a single fiber. These advantages make fiber optic sensors a better method than traditional damage detection methods and devices to some extent. This paper provides a review of recent developments in fiber optic sensor technology as well as some applications of fiber optic sensors to the performance monitoring of civil infrastructures such as buildings, bridges, pavements, dams, pipelines, tunnels, piles, etc. Existing problems of fiber optic sensors with their applications to civil structural performance monitoring are also discussed.

Keywords: fiber optic sensors; performance monitoring; civil infrastructure; damage detection.

1. Introduction

In recent years we have seen increasing attention to the substantial deterioration of civil engineering infrastructures due to the aging and usage beyond the design limits of components. Various non-destructive evaluation (NDE) methods, such as ultrasonics, radiography, acoustic emission, eddy current, etc., have been developed to detect damages in civil infrastructures. However, many of these methods suffer from distinct disadvantages such as the lack of portability, susceptibility to electromagnetic interference, and lack of capability for continuous performance monitoring. Electrical strain gauges, on the other hand, are not suitable for monitoring the propagation of internal cracks in concrete since the formation of a crack which intersects across these foil sensors would render them unusable. In addition, electrical strain gauges require smooth bonding surfaces and therefore cannot be readily embedded in the volume of the concrete mix for the detection of cracks and delamination. Furthermore, traditional strain gauges are susceptible to long-term signal drift; therefore, the signal can only be transmitted over short distances (Maalej *et al.* 2004).

The use of composite materials, such as fiber reinforced polymers (FRP), in structural engineering applications, such as bridges and overpasses, is growing. In order to promote their applications, a

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new technology to monitor the performance of these composite materials and to detect their damages effectively is in high demand.

Recent developments in fiber optic sensors (FOSs) have provided an excellent choice to civil engineers because of their small dimensions, good resolution and accuracy, wide temperature operating range, and excellent ability to transmit signal over long distances (Tennyson *et al*. 2000). They are immune to electromagnetic and radio frequency interference and may incorporate a series of interrogated sensors multiplexed along a single fiber. They are also suitable for internal strain measurements because they do not significantly affect the stress and strain states of the material in which they are embedded due to their small dimensions (Bonfiglioli and Pascale 2003).

The past two decades have witnessed an intensive international research in the field of fiber optical sensing. FOSs have been successfully applied to civil structures such as buildings, bridges, dams, etc. (Habel 1995, Merzbacher *et al*. 1996, Tennyson *et al*. 2000). This study will focus on the review of recent developments in FOSs and their applications in the field of civil engineering.

2. Fundamentals for FOSs

An optical fiber is a cylindrical dielectric waveguide made from silica glass or a polymer material. A schematic of a common form of commercial telecom fiber optic cable is shown in Fig. 1. Both the core and the cladding are made from glass or plastic, and the surrounding coatings used to protect the optical fiber are made from acrylate or polyimide materials. Optical fibers come in two configurations, multi-mode (core size 50~100 μm) and single mode (core size <10 μm).

FOSs embedded in or attached to structures expand or contract by small amounts according to strains on the structure and temperature variations. When a portion of the light is sent down the fiber to the sensor, it is modulated according to the amount of the expansion or contraction (change in the length of the sensor). Then, the sensor reflects back an optical signal to an analytical device which translates the reflected light into numerical measurements of the change in the sensor length. These measurements indicate the amounts of strains within the structure.

FOSs may be categorized according to various classification schemes. Based on one scheme, if the effect of the measurand on the light being transmitted takes place in the fiber, they are classified as intrinsic; if the fiber carries the light from the source and to the detector, but the modulation occurs outside the fiber, they are considered to be extrinsic. FOSs can also be divided according to

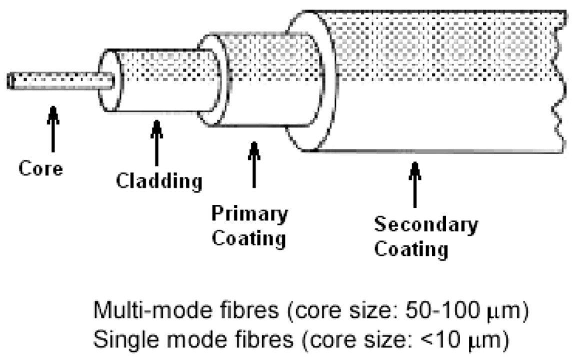

Fig. 1 Structure of an optical fiber

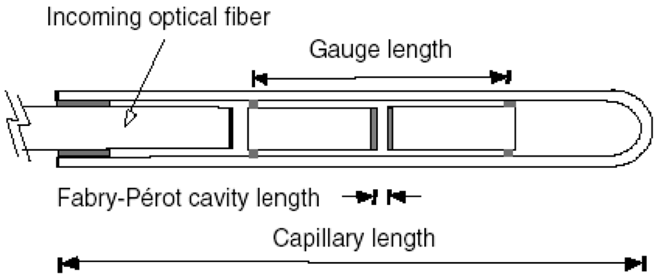

Fig. 2 Schemetic diagram of a FP Sensor

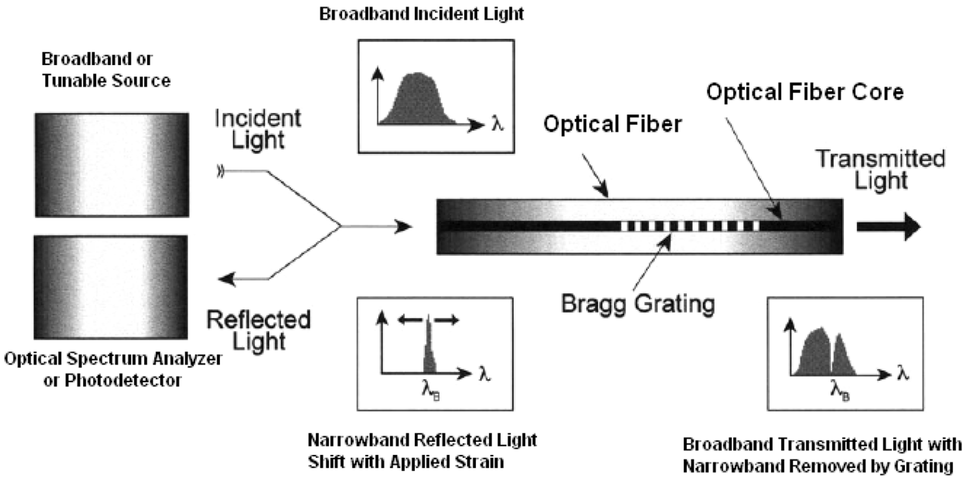

Fig. 3 Fiber Bragg Grating concept

whether sensing is localized (point), distributed, or multiplexed. Localized or point sensor, as the name implies, detects measurand variation only in the vicinity of the sensor. If sensing is distributed along the length of the fiber, an optical time domain reflectometry (OTDR) is needed to determine the location of any variation in the measurand. Wavelength multiplexing can be achieved by fabricating gratings at slightly different frequencies within a broad-band source spectrum (Merzbacher *et al*. 1996). Two different types of FOSs are commonly used in civil applications, the Fabry-Pérot (FP) sensor (Fig. 2) and the Fiber Bragg Grating (FBG) sensor (Fig. 3).

A FP sensor consists of two semi-reflective mirrors facing each other, as indicated in Fig. 2. The mirrors are placed on the tips of multimode optical fibers, which are spot-fused into a capillary. The air gap between the mirrors defines the FP cavity; the distance separating the fuse spots is the gauge length. Any strain variation will change the length of the FP cavity, therefore inducing optical signals. To measure strains, a white-light is sent into one end of the fiber optic cable and its reflected signal is received by a readout unit; then the strain in a FP sensor is measured using the following equation:

$$\varepsilon = \Delta L_{cavity}/L_{gauge} \tag{1}$$

where ΔL_{cavity} is the change in the cavity length and L_{gauge} is the gauge length.

Taking the temperature effect into consideration, the real strain can be obtained using the following equation:

$$\varepsilon_r = \varepsilon - \beta\Delta T \tag{2}$$

where ε is the total strain in a FP sensor obtained using Eq. (1), ε_r is the real strain of the structure, β is the thermal coefficient of structure, and ΔT is the temperature change relative to the temperature at installation.

A FBG sensor consists of a region of germanium-doped glass fiber core that has been exposed to ultraviolet radiation using a phase mask to fabricate a periodic 'grating' of material with a modulated index of refraction. The precise spacing of the grating, called the 'pitch', reflects the incident light with a narrow band centered about the 'Bragg' wavelength, defined by

$$\lambda_0 = 2n\Lambda \tag{3}$$

where λ_0 is the Bragg wavelength, n is the average effective index of refraction of the grating, and Λ is the pitch spacing, as shown in Fig. 3. The FBG also provides a linear response based on the measurement of wavelength shift ($\Delta\lambda$) due to the straining of the gauge. After taking into account temperature effects which will also cause a wavelength shift, measuring $\Delta\lambda$ provides a means of determining the strain according to the equation:

$$\Delta\lambda/\lambda_0 = (GF)\varepsilon + \beta\Delta T \tag{4}$$

where $\Delta\lambda = \lambda - \lambda_0$, GF is the FBG gauge factor, typically about 0.75 – 0.82, ε is the strain, β is the thermal coefficient, and ΔT is the temperature change relative to the temperature at installation.

The sensed information of FP sensors is the FP cavity length, which is different from the sensed information of FBG sensors, the optic wavelength. However, both of them are absolute parameters. Therefore, the outputs of both sensors do not depend directly on the total light intensity levels and losses in the connecting fibers and couplers. While the FP 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. However, a new calibration is needed every time when the readings are stopped for a FP sensor, while a FBG sensor requires no calibration (Casas and Cruz 2003).

A few kinds of FOSs specifically designed for monitoring parameters such as crack, strain, and corrosion have been developed. They are described in the following sections.

3. Typical FOSs

3.1 Crack sensors

The failure of concrete structures usually starts with cracks. The damage condition of a concrete structure can be assessed through the monitoring of cracks. Many non-destructive evaluation techniques, such as visual inspection, radiography, ultrasonics, and acoustic emission have been developed for damage detection; however, all of them have a common limitation that continuous assessment of cracks cannot be made in situ during the service of structures. Fiber optic crack sensors developed recently have provided a good solution to this problem.

FOSs have been used for crack detection by a number of researchers. Wanser and Voss (1994) used multimode OTDR to measure both longitudinal and transverse crack growth and crack displacement such as longitudinal crack separation and transverse shear crack displacement, respectively. Habel (1995) performed a real-time crack detection and crack growth rate measurement by measuring the attenuation of light transmitted in the fiber optic crack sensors due to the surface crack growth. Liu and Yang (1998) used distributed FOSs to monitor concrete cracks based on the light loss due to the microbending of optical fiber bridging cracks with the use of OTDR. Lee *et al.* (2000) demonstrated the capability of Intensity-Based Optical Fiber Sensors (IOFSs) to monitor the fatigue crack growth of steel structures by detecting the stiffness changes near the crack.

Although fiber optic crack sensors have been successfully applied in many cases, they suffer from some limitations. For example, conventional "point" sensors, which measure the strain at a local point, can detect and monitor the opening of a crack only if the cracking occurs in a small region that is known a priori, and thus, can easily miss cracks (Ansari and Navalukar 1993). Integrated sensors, which measure the displacement between two points separated by a relatively large distance, cannot distinguish the case of many fine cracks and the case of one widely open crack (Wolff and Miesseler 1992).

To overcome these problems, Leung *et al.* (2000) developed a novel fiber optic "distributed" sensor that can (i) detect the formation of cracks without requiring a priori knowledge of the exact crack locations, (ii) carry out continuous monitoring once the crack is formed, and (iii) detect and monitor a large number of cracks with a very small number of fibers.

The principle of the sensor is illustrated in Fig. 4, which shows a "zigzag" sensor at the bottom of a bridge deck. Before the formation of cracks, the backscattered signal vs time follows a relatively

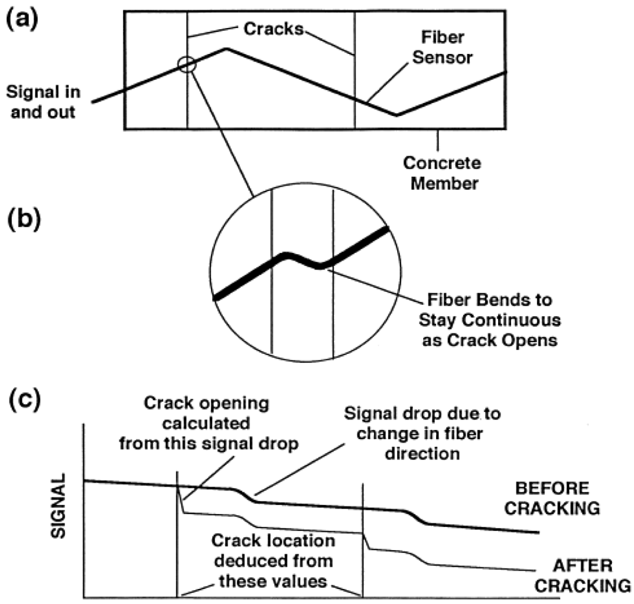

Fig. 4 The novel crack sensing concept (Leung *et al.* 2000)

smooth curve (the upper line in Fig. 4c). The signal loss in the straight portions of the fiber is probably due to the absorption of light by the cladding. In the curved portion, where the fiber changes in direction, some light energy will then move into the cladding and dissipate, causing bending loss, which depends 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. 4b). The sudden bending of an optical fiber at the crack results in a sharp drop in the optical signal (lower line, Fig. 4c). From the time values on the OTDR record corresponding to the sharp signal drops, the location of cracks in the structure can be deduced. Also, from the magnitude of the drop, the crack opening can be obtained if a calibration relation is available.

The proposed technique by Leung *et al.* (2000) does not require prior knowledge of the crack location, which is a significant advancement over existing crack monitoring techniques. However, for the sensor to work, the crack direction needs to be known. Also, to sense cracks effectively, several sensors should be employed, because with a single fiber, results will be difficult to interpret if a crack intersects the “zigzag” fiber at a location where the fiber direction changes (Leung *et al.* 2000).

3.2 Strain sensors

Due to their small size, FOSs can be either embedded into or surface-bonded onto different materials, such as concrete, steel rebars, steel plates, FRP strips, etc. There have been many reports on the application of FBG and FP sensors to structural performance monitoring in recent years (Tennyson *et al.* 2000), and many of them are based on the ability of FOSs to measure the internal strain of structures.

Grossman and Huang (1998) used FP sensors for multidimensional strain measurement. Bonfiglioli and Pascale (2003) carried out experiments using fiber optic strain sensors for internal measurements in concrete specimens. Their research showed the possibility of measuring the internal strain state without influencing the stress state of the specimen, owing to the small dimensions of FOSs. Kenel *et al.* (2005) used multiplexed FBG sensors to measure strains along 10-mm-diamater reinforcing bars embedded in reinforced concrete beams subjected to bending. The authors found that the sensors were capable of measuring large strains and strain gradients with high precision, without significantly affecting the bond properties.

In many cases the health condition of a concrete structure depends on the strain condition of reinforcement bars. A lot of research has been conducted on the measurement of strains on reinforcement bars (Casas and Cruz 2003). Fig. 5 shows a FBG strain sensor bonded to a piece of rebar. The jacket of the fiber is only removed in the sensing zone, which is bonded to the polished

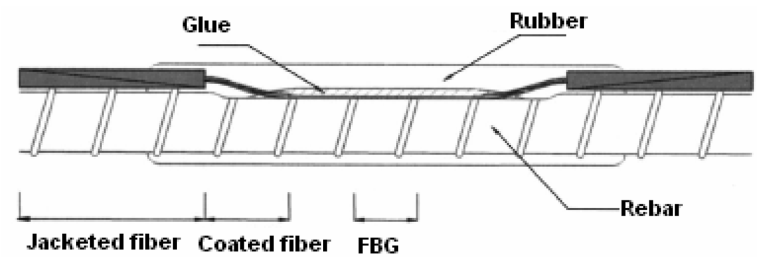

Fig. 5 Scheme of the Fiber Bragg Grating strain sensor (Casas and Cruz 2003)

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 by the fiber jackets.

Recently, FRP sheets, laminates, and plates have been frequently employed in the rehabilitation of civil infrastructures strongly suffered from overload, aging, and chemical attack by deicing salts. The integration of FOSs with these advanced composite materials has been the subject of interest and intensive research in recent years. Gheorghiu *et al.* (2005) studied the performance of fiber optic strain sensors attached to the carbon fiber reinforced polymer (CFRP) plates used to strengthen concrete structures. Strain measurements from these FOSs were compared with those obtained by the collocated electrical strain gauges (ESGs). Their experimental results showed that the FOSs were precisely measuring strains below 4000 $\mu\varepsilon$ (the difference observed between FOSs and ESGs always remained lower than 5%), and that the load amplitude and the number of fatigue cycles had virtually no influence on the FOS readings for strains smaller than 3300 $\mu\varepsilon$. These results confirmed that FOSs were capable of measuring strains precisely for a variety of loading conditions, load range, and number of fatigue cycles.

3.3 Corrosion sensors

The corrosion of steel cables and reinforcing steel in concrete represents one of the leading causes of durability problems affecting civil infrastructures. As a result of the corrosion of reinforcing steel, a large radial pressure is exerted on the surrounding concrete, which may result in local radial cracks. These cracks in turn accelerate the corrosion process of the reinforcement; finally, the reinforced member will experience a loss of strength. Detection of corrosion of reinforcement bars has been one of the most challenging tasks in the health monitoring of civil infrastructures.

Using FOSs for corrosion detection is just somewhat recent research. Fuhr *et al.* (1995) installed all-fiber corrosion sensors on three bridges in Vermont. Based on the absorption of light propagating in the evanescent wave by the steel reinforcement bar, the degree of corrosion can be measured. Fuhr and Huston (1998) studied the feasibility of using embedded FOSs for corrosion monitoring of reinforced concrete roadways and bridges. They proposed to use a warning alarm in which a predetermined threshold of 'fiber events or faults' can be set when detecting the structure's internal damage.

Casas and Frangopol (2001) proposed that the corrosion of a non-corrugated steel bar could be detected by using a FBG sensor placed around it in a circle perpendicular to its axis, by means of super glue. 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 sensor is strained, which can be detected as a shift in the Bragg wavelength of the sensor.

Similarly, Maalej *et al.* (2004) studied the feasibility of using fiber optic sensing technology for monitoring corrosion-induced damage in reinforced concrete beams through experiments. However, the way in which the corrosion sensors were placed was different from that employed by Casas and Frangopol (2001). Fig. 6 shows a photograph of the embedded FOSs used in their study. A concrete-embeddable fiber optic strain sensor based on the FP configuration was used to monitor the corrosion-induced tensile strain in the concrete perpendicular to the plane of the reinforcement steel bars where splitting cracks/delamination were likely to occur (Fig. 7).

The research results of Maalej *et al.* (2004) clearly demonstrated the feasibility of the proposed technique as an additional approach to monitoring corrosion-induced damage in reinforced concrete structures where visual inspection is not possible.

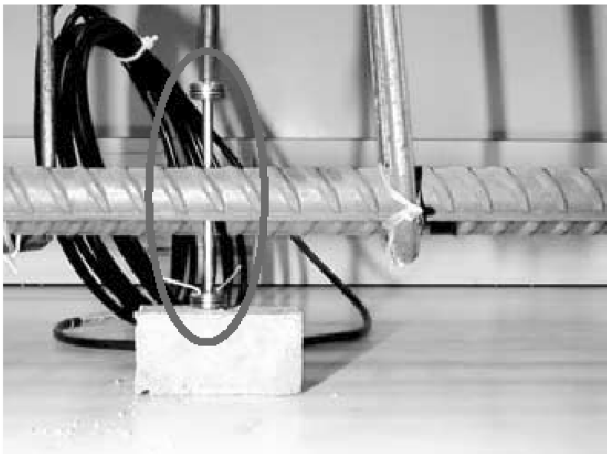

Fig. 6 Location of fiber optic strain sensor (Maalej *et al.* 2004)

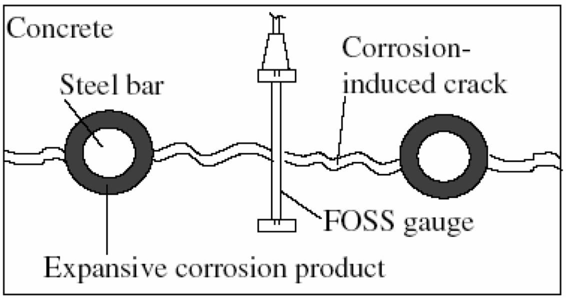

Fig. 7 The concept of using FP sensor to detect corrosion-induced damage (Maalej *et al.* 2004)

4. Applications of FOSs

Applications of FOSs in civil infrastructures have become increased in recent years. Successful applications of FOSs to structural monitoring of civil infrastructure demonstrated their advantages over traditional methods. In this section, recent applications using FOSs in civil infrastructures are described.

4.1 Buildings

FOSs have been successfully used in measurement of parameters such as strain, temperature, displacement, and cracks in buildings. Early in 1992, Fuhr *et al*. (1992) reported an embedded FOS network that was used for the monitoring of the Stafford Medical Building, a five-storey 65,000 square foot concrete structure at University of Vermont, Burlington. Pressure sensors and wind sensors were mounted to the external brick skin on the walls, and other sensors were embedded into the floor, the load bearing support columns, and the ceiling, by attaching to the rebars using tape. This sensor network allowed measurements of vibration, wind pressures, loading, creep, and parameters relating to building performance, such as crack development.

Iwaki *et al.* (2001) developed a series of FBG sensor modules for a 12-floor steel frame building with damage tolerance construction techniques. A total of 64 FBG sensors were installed in this building. Utilizing the multiplexing capability of FBG sensors, an average of six sensors were installed in a single optical fiber. Displacement, strain, and temperature of the building were measured. Their study showed that with the feature of multiplexing capability, FBG sensors are ideal for the performance monitoring of large structures. However, the information of accuracy compared with conventional sensors is not available.

Apart from their applications in new buildings, the application of FOSs in the performance monitoring of historical buildings has also been subject to intensive research interests. In Italy, four long gauge FBG sensors were installed on the primary arch of the Cathedral of Como in Northern Italy, a significant cultural heritage built in 1936, to identify any significant structural deterioration (Whelan *et al.* 2002). These four sensors were installed across, above, and under the primary arch of this building, using surface mounting brackets. Each sensor has two serially connected Bragg gratings, with one measuring strain or displacement, while the other monitoring temperature. A displacement resolution of 0.1 μm and temperature resolution of 0.1^{o}C were achieved with the technique of FP tunable filter demodulation system.

Palazzo Elmi-Pandolfi in Foligno, another historical building dating back to 1600 in Italy, has been repaired and retrofitted by CFRP with embedded Brillouin sensors, one kind of fiber optic sensors that measure strains by using Brillouin frequency shift. The low cost of the sensor made monitoring all the critical areas rather affordable, while the distributed sensing feature allowed detecting anomalies in load transfer between the FRP and substrate, and the location of eventual cracking patterns (Bastianini *et al.* 2005).

4.2 Bridges

Among the applications of FOSs to all civil infrastructures, bridges are probably the most frequently reported ones. A state-of-the-art review of FOSs for bridge monitoring was reported by Casas and Cruz (2003).

In Germany, extrinsic Fabry-Pérot interferometer (EFPI) sensors were installed on a bridge in Berlin which had visible cracks (Habel and Hofmann 1994). The EFPI sensors were directly attached to the exposed steel reinforcement bars near a crack and measured both deformation and vibration due to a test load, as well as normal traffic. Strains on the order of tens of microstrains with an uncertainty of 1 microstrain were detected, which provided an accurate measurement.

In Switzerland, 58 long-gauge FOSs (between 3 and 5 m) were embedded in pairs near the top and bottom surfaces of the concrete arch slab of the Siggenthal Bridge in order to measure the deformation of arch segments. From this measured deformation, the curvatures in the vertical plane and perpendicular displacements of the whole concrete arch during both the construction and in-service periods were determined. Preliminary monitoring results showed that the daily temperature fluctuation during summer had particularly large influence on the arch and should be taken into consideration during the bridge design phase (Inaudi *et al.* 2002).

Idriss *et al.* (1998) designed a multiplexed Bragg grating optical fiber monitoring system for a 40 ft span non-composite steel girder concrete deck bridge, with a strain resolution of 0.95 microstrain. Sensors were bonded to the tension steel in the slab and attached to the bottom flange of the girders to measure the strains throughout the bridge. Several levels of damage in the form of torch cuts in one of the girders were introduced with the final cut resulting in a half depth fracture of the girder.

The monitoring system recorded a definite change in the structure's response. From the time when the change in condition was recorded, the time when the damage occurred was determined. The location of the crack was also obtained from the change in the response of the slab and a loss in load observed on one girder.

In Canada, the application of FOSs to the health monitoring of bridges is very active. An overview of the development and application of FOSs for monitoring bridges in Canada was given by Tennyson *et al*. (2001).

The Beddington Trail Bridge in Alberta is the first bridge instrumented with FOSs in Canada and the first bridge known to contain pre-stressed carbon fiber composite cables with FBG sensors embedded in the concrete girders supporting the bridge. A total of 20 FBG sensors were installed by Electro-Photonics Corporation (EPC) of Canada in 1993, with pre-testing of the composites and sensors performed at the University of Manitoba. The network of FBG sensors was connected to a junction box which provides onsite monitoring. To check the integrity of the carbon fiber cables and the FBG sensors, measurements were made in November, 1998, and 18 of the sensors were still operative. No structural problems were detected at that time (Tennyson *et al*. 2001).

The Taylor Bridge in Manitoba (Canada) is the world's largest span bridge that uses FRP for shear reinforcement, and a FOS system for remote monitoring. This 165 m long bridge consists of 40 pre-stressed concrete AASHTO-type girders, which are standard girders defined by American Association of State Highway and Transportation Officials (AASHTO).

Monitoring technology for the Taylor Bridge is shown schematically in Fig. 8. FBG sensors were used to monitor the strains in the CFRP reinforcement of the girders, the deck slab of the Taylor Bridge, and in the GFRP reinforcement of the barrier wall. The FBG sensors used in the Taylor

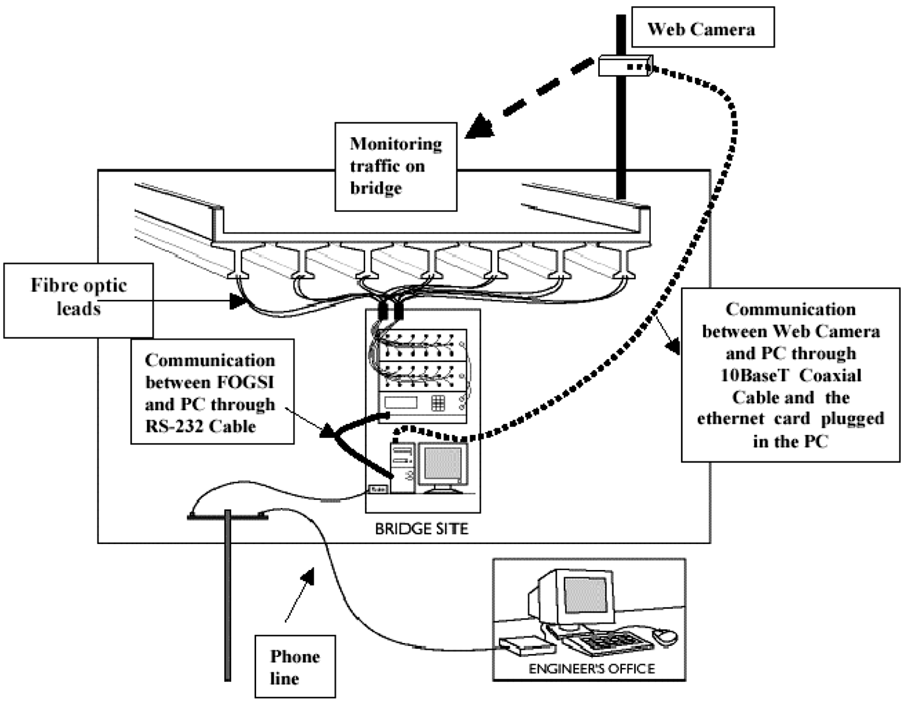

Fig. 8 Monitoring technology for the Taylor Bridge (Tennyson 2001)

Bridge were fabricated by Electro-Photonics Corporation and have a full range of 10,000 microstrains.

A total of 65 FOSs were installed on the reinforcements of the structural members. Out of the 65 sensors, 63 were single FBG sensors and the remaining were multiplexed FBG sensors. As shown in Fig. 8, these 65 sensors were installed on the following bridge components: the girders reinforced with CFRP, selected girders reinforced with steel, the deck slab reinforced with CFRP, and the barrier wall reinforced with GFRP. In addition, 20 thermocouples were used at different locations on the bridge in order to compensate for temperature effects. A 32-channel fiber optic grating indicator, the FLS3500R, was used to take strain measurements. The FBG sensors clearly recorded the strain changes experienced by the CFRP tendons under the truck and the trailer loading, with the peak values below 15 microstrains.

FOS technology has recently been used in China's fast growing infrastructure. Ou *et al*. (2005) reported an application of FBG sensors in the health monitoring of the 300-meter-span Binzhou Yellow River Highway Bridge, the first cable stayed bridge with three towers along the Yellow River, the second longest river in China. In order to monitor the strain and temperature of the steel cable and reinforced concrete beam and to evaluate the health condition of the bridge, one sensing network consisting of about 130 FBG sensors mounted in 31 monitoring sections had been built. One four-channel FBG interrogator was used to read the wavelengths from all the sensors, associated with four computer-controlled optic switches connected to each channel. Both the interrogator and the optic switches were controlled by a written computer program simultaneously. Data obtained since the bridge's opening to traffic during the load test had shown that the strain and temperature status of elements as well as the bridge were in good condition.

Wang *et al*. (2005) reported another application of FOSs on the construction control of mass concrete of the Nanjing 3rd Yangtze Bridge in China. A total of 237 FRP-packaged FBG temperature and strain sensors have been used to monitor the temperature and strain condition of mass concrete structures of the bridge. Their research results have shown that the FRP-packaged FBG sensors are proper for construction control of mass concrete structures.

4.3 Pavements

Fiber optic traffic sensors (FOTSs) have been designed to embed into road surface of flexible

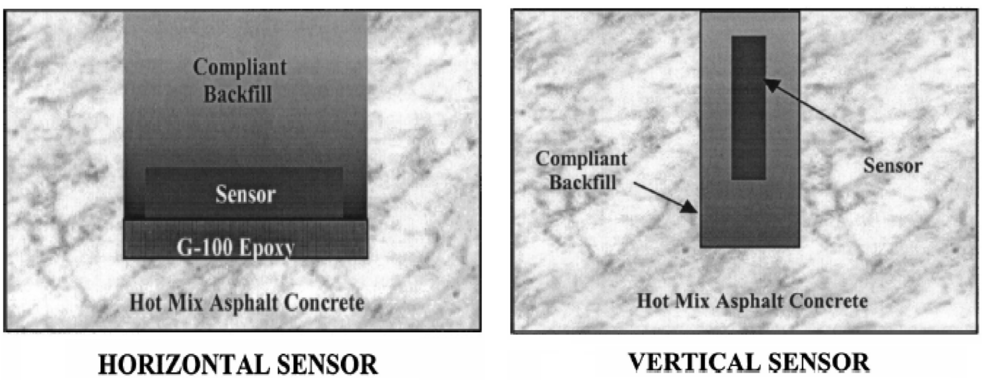

Fig. 9 FOTS placement options (Eckroth 1999)

pavement to detect traffic flow. FOTS technology was developed using the fiber optic microbending theory. When an external force or pressure is applied on an optical fiber, the fiber bends over the small radii mesh strands, and thus, the light focused into the fiber's inner core is refracted out of the core into the fiber's protective buffer layers, causing a decrease in light intensity (Grossman *et al.* 1994). Early in 1993, Body *et al.* (1993) used FOSs embedded in road surface to detect vehicle weight.

Eckroth (1999) suggested two methods in which a FOTS can be embedded into the road surface (Fig. 9). In one method, a FOTS was horizontally embedded into the asphalt concrete, and in the other, a FOTS was vertically embedded.

Cosentino *et al.* (2003) studied how the sensor functioned when placed in narrow vertical grooves, and they concluded that compared with horizontally installed sensors, vertically installed sensors can avoid stress concentrations caused by vehicle tires, and display longer lives. When FOTSs are placed in narrow vertical grooves, the signal or light intensity losses are a result of the groove becoming narrower as tires load the surrounding pavement. The associated groove movements are sufficient to cause a light loss that can be recorded using existing roadside computer and data acquisition systems for either traffic classification or vehicle weighing for traffic moving at slow speeds.

Cosentino *et al.* (2003) also suggested that vertically installed sensors should be placed near the pavement surface in a groove approximately 3.2 mm wide. Although the exact groove depth for optimizing the sensitivity was not determined, the groove theoretically moved more and would cause additional light to be refracted out of the microbending sensors as this depth increases. Based on the lab and field data as well as the results from a series of finite-element models and their correlations, finally they suggested that a depth of approximately 19 mm would be acceptable, and stated that depths in excess of this amount may cause premature structural damage to the pavement. However, the accuracy information is not available.

Bergmeister and Santa (2001) installed a FOS in the neighborhood of the Colle Isarco viaduct to acquire traffic loads. The FOS installed (Fig. 10) was double refractive, uncovered, and embedded between two metal strips which were welded together. The FOS system in their study has shown to be reliable for several years (Bergmeister and Santa 2001).

Udd *et al.* (2001) installed 28 specially designed FBG traffic sensors in surface-cut slots of the Horsetail Falls Bridge in the Colombia River Gorge National Science Area of the United States, and tested the monitoring system by running vehicles of different weights at a speed of 10-18 km per

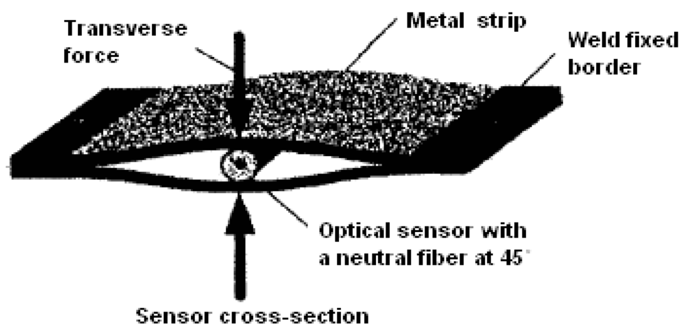

Fig. 10 Fiber optic weight-in-motion sensor (Bergmeister and Santa 2001)

hour. They also installed five long gauge FBG sensors in the I-84 freeway to test the ability of these sensors to classify and counter vehicles. The sensing system they developed could achieve a resolution of less than 0.1 micro-strain with a dynamic range of 400 micro-strain at a 10kHz sampling rate, which can satisfy the traffic monitoring requirement, and was able to discriminate tractor-trailers, buses, and even the traffic in adjacent lanes in some cases, since the amplitude of the signal appears to be closely proportional to the vehicle weight and the speed of the vehicle. The driving direction can also be determined by the separation of peaks and their order of appearance in adjacent FBG sensors. The test results obviously demonstrated the advantages of FBG sensors over traditional vehicle monitoring devices.

4.4 Other applications

Fuhr and Huston (1993) reported the application of FOSs to the Winooski One hydroelectric dam in Vermont. Multi-functional fibers capable of simultaneously sensing vibrations and pressures were developed and embedded to measure and monitor the water pressure exerted on the upstream face of the dam's spillway and the vibration frequencies and amplitudes induced into the powerhouse section of the dam as the electrical and water loads vary. Vibration frequencies obtained from the embedded sensors were in good agreement with the induced frequencies, with an average full scale error level of 0.77% and a peak error of 2.03%. The fiber sensors helped resolve a problem during the start-up of the hydroelectric plant when the expected generator efficiency was not achieved (Fuhr *et al.* 1994).

In Switzerland, FOSs were applied for long term surveillance of a tunnel near Sargans. The sensors were made of glass fiber reinforced polymers (GFRP) with embedded FBG sensors and were used to measure distributed strain fields and temperature (Nellen *et al.* 2000).

In Italy the San Giorgio Harbor pier was equipped with an array of more than 60 FOSs for continuous monitoring (Inaudi *et al.* 2001). These sensors allowed continuous measurement of the pier displacements during the dredging works and ship docking. The sensors measured the curvature changes in the horizontal and vertical planes and allowed a localization of settlements with a spatial resolution of 10 m over a total length of 400 m. The system has been in operation since fall 1999, and data has been collected automatically and continuously since then.

In structural integrity monitoring of long pipelines, FOSs have demonstrated their great potential since it is difficult to detect damages to pipelines with conventional methods. In Indonesia, a 110 km pipeline was equipped with one type of vibration sensors to monitor its integrity and to alert ongoing damages caused by excavation equipment, theft, landslide or earth movement (Fernandez *et al.* 1996). Based on the principle of modal-metric interference effect, the vibration monitoring unit can pinpoint the location of an anomaly by detecting the changes of backscattered light characteristics caused by disturbances of fiber compression, elongation or twist. This monitoring system can monitor a fiber of length up to 50 km with a resolution of 0.1 km. In October 1998, the system successfully detected damage to the pipeline at a precise position, caused by a landslide (Li *et al.* 2004).

Tennyson *et al.* (2003) investigated the application of "long gauge" FOSs to monitor the behavior and integrity of pipelines. Tests were conducted on pipe sections under a variety of load conditions including internal pressure, axial compression, bending, and local buckling, and test data was monitored remotely through internet access. Results obtained showed that the FOSs could track changes in loads, detect pre-buckling deformations, and measure post-buckling plastic strains. Using analytical models in combination with real-time measurements of the pipe's response, predictions of the operational lifetime for the pipe were made.

Glisic *et al*. (2002) monitored the average strains of two sets of piles under axial compression, pullout, and flexure tests, using long gauge FOSs. The sensors used in their study gave rich information concerning the piles' behavior and soil properties. The Young's modulus of the piles, the occurrence of cracks, the normal force distributions, and the ultimate load capacity in the case of axial compression and pullout tests, as well as the curvature distribution, horizontal displacement, deformed shape, and damage localization in the case of the flexure tests were determined. Moreover, through the tests the pile-soil friction distributions, the quality of soil, and the pile tip force were estimated.

Lee *et al*. (2004) also performed a series of laboratory and field tests to evaluate the applicability of an FOS system in the instrumentation of piles. The authors found that the distributions of axial load in three model piles and a field test pile evaluated from the strains measured by FBG sensors were comparable, in terms of both magnitude and trend, with those obtained from conventional strain gauges. Based on the successful application in the analysis of the axial load transfer in piles, the authors suggested that the use of these sensors in drilled shafts and other types of cast-in-situ concrete piles is feasible.

5. Existing problems with FOSs

Although FOSs have been successfully applied to many civil engineering structures to monitor displacements, strains, cracks, etc. and have demonstrated their advantages over traditional monitoring devices and technologies, some issues with the application of FOSs still need further investigation. The existing problems with FOSs will be described in the following sections.

5.1 Strain and temperature discrimination

One of the main drawbacks of FBG sensors is their dual sensitivity to temperature and strain. Therefore, in order to obtain accurate strain, the contributions to the wavelength shift caused by strain and temperature have to be separated. There are two approaches to address this problem. The first approach is called reference fiber method, which uses a reference Bragg grating subjected to the same thermal environment but free from mechanical load. Compensation can then be achieved by subtracting the wavelength shift of the reference grating from the wavelength shift of the sensing grating. The second approach is to obtain a temperature-wavelength shift curve to subtract the temperature effect. 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 (Casas and Cruz 2003). Currently, the research on simultaneous measurements of strain and temperature using FBG strain sensors is still very active (Li *et al*. 2004).

5.2 Effects of coating materials on strain measurement

The glass core of optical fibers is usually coated with low modulus softer protective coatings. Ansari and Yuan (1998) argued that the mechanical properties of the protective coatings employed in conjunction with optical fibers altered the strain transduction capabilities of the sensor. They pointed out that a portion of the strain was absorbed by the protective coating of the optical fibers, and hence, only a segment of structural strain was sensed. Based on a few realistic assumptions and their experimental results, they found that the strain-transfer characteristics of optical fibers depended on the mechanical properties of the glass core, the protective coating, and the gauge length of the optical fiber. They finally developed a mathematic expression to represent the linear relationship between the strains measured by the strain gauge, ε_g, and the corresponding strain, ε_{sg}, measured by the optical fiber over the gauge length $2L$:

$$\varepsilon_g = \alpha\,(k, L)\,\varepsilon_{sg} \tag{5}$$

where α is the constant of proportionality between the two measurements, and it is a function of the optical fiber gauge length, L, and its mechanical properties, k. The authors also stated that it was possible to achieve $\alpha = 1.0$ by using bare fibers.

However, Li *et al.* (2002) argued that while the assumption made by Ansari and Yuan was true for glass, it was not valid for some coating materials which undergo plastic deformation when subjected to strains beyond their elastic limits. They argued that while the linear elastic model developed by Ansari and Yuan worked out in applications where the concrete deformations were small and within the linear range, in applications involving large deformations and when concrete cracking occurred, the fiber optic coating deformed in a plastic manner, and the linear elastic model did not adequately portray the concrete strains. They finally introduced an elasto-plastic model through which it was possible to interpret the actual level of structural strains from the values measured by an FOS. Their theoretical findings were verified by embedding interferometric sensors in mortar samples and then comparing the stress-strain response of the samples measured by extensometers and FOSs.

Bonfiglioli and Pascale (2003) did research on internal strain measurements in concrete elements with FOSs, and they suggested that while the use of bare fibers should be the most suitable choice for the strain measurement, several factors should be taken into consideration. First, the small size of the fibers could affect the reliability of the measurement because the gauge length could be too small compared to the aggregate size. Second, a particular procedure has to be developed and applied to hold in place and protect the fiber during casting so that only the sensitive part of the fiber comes in contact with the concrete, while the remaining part must be free of sliding to avoid damage due to concrete cracking. Moreover, the protruding part of the fiber has to be adequately protected and held in place to prevent it from breaking during the casting, vibrating, handling, and testing of the specimen. Finally, the chemical compatibility between the optical fiber and the fresh concrete has to be evaluated.

5.3 The bonding of FOSs

There are many factors that can affect the performance of FOSs, such as installation procedure, poor choice of adhesive, insufficient anchorage or bond length of sensors, and the geometry and the mechanical properties of the capillary.

To ensure accurate measurements, effective bonding between FOSs and the host materials is particularly important. A sufficient bond surface is always needed to achieve this. Experience with recent applications showed that polyimide coated fibers and epoxy glues were possible to obtain an excellent mechanical coupling between the fiber and the anchorage in concrete structures (Inaudi

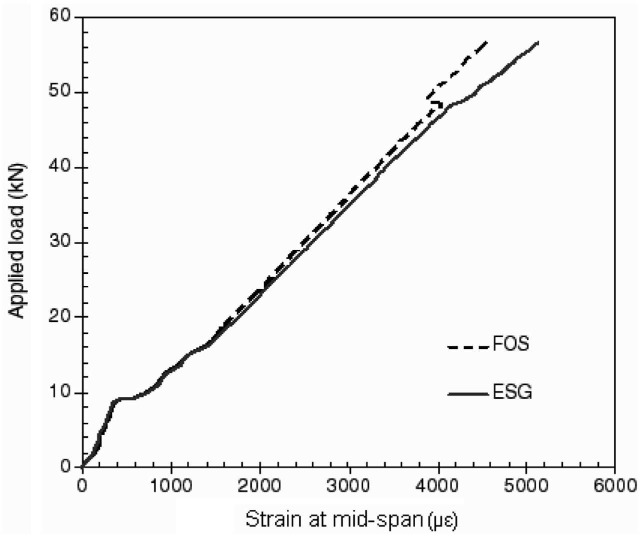

Fig. 11 FRP strain at midspan ($\mu\varepsilon$) (Gheorghiu *et al.* 2005)

2001). In addition, some properties of adhesive, especially the thermal coefficient, should be approximately equal to that of the host material to avoid slippage between the interfaces.

Lee *et al.* (2000) observed some deviation of the IOFSs signal from the strain gauge signal when using IOFSs to monitor the fatigue crack growth in steel structures. The authors argued that the delay of the IOFS signal may be due to the incomplete cure of the epoxy adhesive caused by the unbalanced and improper mixing. The authors also suggested that the sensor construction should be improved by using optimal bonding methods or fusion splicing.

Gheorghiu *et al.* (2005) also observed a drop in the reading of FOS during their experiments. Fig. 11 shows the comparison of the reading obtained from both FOS and ESG. They argued that this drop was probably due to the degradation of the bond between the FOS and the CFRP. The authors also argued that other factors such as the FOS installation procedure and the geometry and the mechanical properties of the capillary could alter the performance of the sensor.

5.4 Effect of embedded optical fibers on properties of the host material

With the increasing applications of FOSs to structural health monitoring, reworded as following: the degradation of properties of host structures and materials due to the embedded sensors has raised considerable concern. A state-of-the-art review on the effect of embedded optical fibers on mechanical properties of the host materials was given by Kuang and Cantwell (2003). They pointed out that since the physical size of conventional optical fiber sensors (typically ranging from 100-300 μm in diameter) is at least an order of magnitude larger than the reinforcing fibers, they could be expected to compromise the mechanical properties of the host structure.

Roberts and Davidson (1991) performed a detailed study to evaluate the influence of different diameters of optical fibers and their coating types on the tensile and compressive strength of laminate in which the optical fibers were embedded. Holl and Boyd (1993) studied the effects of embedded optical fibers on the mechanical properties of a graphite/epoxy composite host material.

Table 1 A comparison of properties between FBG sensors and FP sensors

	Characteristic	Sensed information	Precision	Need for calibration	Temperature sensitivity	Multiplexing ability
FBG	Intrinsic	Optic wavelength	Low	No	High	Yes
FP	Extrinsic	FP cavity length	High	Yes	Low	No

The static performance of the host material, in which optic fibers with diameters of 125 μm and 240 μm were embedded, was evaluated, and the research results showed little influence of the optical fibers on crack initiation or propagation, as well as on failure strength. Mall *et al.* (1996) studied the effect of embedded optical fibers on the compressive strength as well as the stiffness of a graphite-epoxy composite. They found that all specimens where the optical fibers were placed parallel to reinforcing fibers resulted in no degradation of the compressive strength. Also, no change in modulus was observed due to the presence of optical fibers in any group of specimens. Previous research showed that FOSs have little effect on the host material if their size is small enough compared with that of the host material.

6. Conclusions

This paper presents a review of the recent research of FOSs and their applications to the structural monitoring of civil infrastructures. Two commonly used FOSs, namely FBG sensors and FP sensors, have been reviewed. Both sensors can be used to measure strains and detect cracks as well as corrosions. A comparison of their properties is summarized in Table 1. In reality, FBG sensors are preferred in applications of large structures, such as buildings and bridges, in that they can be multiplexed along a single fiber. Another advantage as shown in the table is that the FBG requires no calibration. However, FP has higher precision and lower temperature sensitivity. OTDR has also been used in crack detection. With the great advantages over traditional sensors, FOSs are expected to play a more important role in the real-time structural performance monitoring of structures, as well as in smart structures and intelligent systems in the future.

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