FIBER OPTIC SENSORS FOR STRUCTURAL CONTROL

Daniele Inaudi[1] and Andrea del Grosso[2]

[1] *CTO, SMARTEC SA, Manno, Switzerland*

[2] *Professor, Dep. of Civil, Environmental and Architectural Eng, University of Genoa, Italy*
Email: inaudi@smartec.ch

ABSTRACT:
From many points of view, fiber optic sensors are the ideal transducers for structural control. Being durable, stable and insensitive to external perturbations, they are particularly interesting for the long-term health assessment of civil structures. Many different fiber optic sensor technologies exist and offer a wide range of performances and suitability for different applications. The most widely used sensing techniques include point sensors (Fiber Bragg Gratings and Fabry-Perot interferometers), long-gauge sensors (SOFO) and distributed sensors (Raman and Brillouin scattering sensors). These sensing technologies are now widely used in routine application for static and dynamic monitoring of structures such as bridges, buildings, monuments, tunnels, dams, dykes, pipelines, landslides and many others. This paper reviews these systems and technologies and presents a few significant application examples.

KEYWORDS:
Sensors, Fiber Optic Sensors, Structural Control, Instrumentation

1. FIBER OPTIC SENSORS

There exist a great variety of fiber optic sensors (Udd 1991, Udd 1995, Inaudi 1997) for structural monitoring in both the academic and the industrial areas. In this overview we will concentrate on those that have reached a level of maturity, allowing a routine use for a large number of applications. Figure 1 illustrates the four main types of fiber optic sensors:

- *Point sensors* have a single measurement point at the end of the fiber optic connection cable, similarly to most electrical sensors.
- *Multiplexed sensors* allow the measurement at multiple points along a single fiber line
- *Long-base sensors* integrate the measurement over a long measurement base. They are also known as long-gage sensors.
- *Distributed sensors* are able to sense at any point along a single fiber line, typically every meter over many kilometers of length

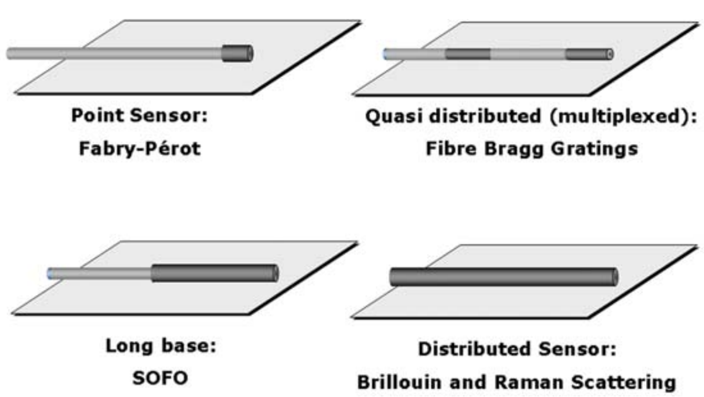

Figure 1: Fiber Optic Sensor Types

The greatest advantages of the FOS are intrinsically linked to the optical fiber itself that is either used as a link between the sensor and the signal conditioner, or becomes the sensor itself in the case of long-gauge and distributed sensors. In almost all FOS applications, the optical fiber is a thin glass fiber that is protected mechanically by a polymer coating (or a metal coating in extreme cases) and further protected by a multi-layer cable structure designed to protect the fiber from the environment where it will be installed. Since glass is an inert material very resistant to almost all chemicals, even at extreme temperatures, it is an ideal material for use in harsh environments such as encountered in geotechnical applications. Chemical resistance is a great advantage for long term reliable health monitoring of civil engineering structures, making fiber optic sensors particularly durable. Since the light confined into the core of the optical fibers used for sensing purposes does not interact with any surrounding electromagnetic field, FOS are intrinsically immune to any electromagnetic (EM) interferences. With such unique advantage over sensors using electrical cables, FOS are obviously the ideal sensing solution when the presence of EM, Radio Frequency or Microwaves cannot be avoided. For instance, FOS will not be affected by any electromagnetic field generated by lightning hitting a monitored bridge or dam, nor from the interference produced by a subway train running near a monitored zone. FOS are intrinsically safe and naturally explosion-proof, making them particularly suitable for monitoring applications of risky structures such as gas pipelines or chemical plants. But the greatest and most exclusive advantage of such sensors is their ability to offer long range distributed sensing capabilities.

1.1 Fabry-Pérot Interferometric Sensors

Fabry-Pérot Interferometric sensors are typical example of point sensors and have a single measurement point at the end of the fiber optic connection cable.

An extrinsic Fabry-Pérot Interferometer (EFPI) consist of a capillary glass tube containing two partially mirrored optical fibers facing each other, but leaving an air cavity of a few microns between them, as shown in Figure 2. When light is coupled into one of the fibers, a back-reflected interference signal is obtained. This is due to the reflection of the incoming light on the two mirrors. This interference can be demodulated using coherent or low-coherence techniques to reconstruct the changes in the fiber spacing. Since the two fibers are attached to the capillary tube near its two extremities (with a typical spacing of 10 mm), the gap change will correspond to the average strain variation between the two attachment points shown in Figure 2.

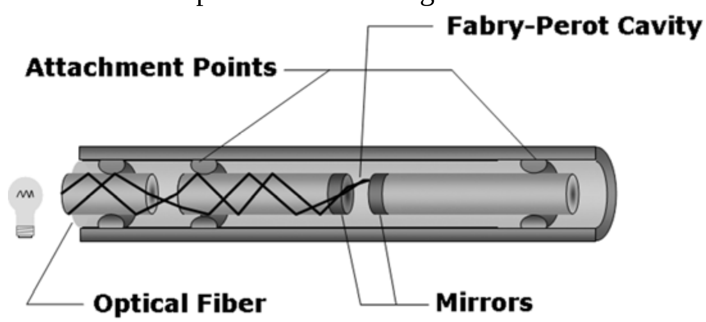

Figure 2: Fabry-Perot Sensor

Many sensors based on this principle are currently available for geotechnical monitoring, including piezometers, weldable and embedded strain gauges, temperature sensors, pressure sensors and displacement sensors.

1.2 Fiber Bragg Grating Sensors

Fiber Bragg Grating Sensors are the most prominent example of multiplexed sensors, allowing measurements at multiple points along a single fiber line.
Bragg gratings are periodic alterations of the density of glass in the core of the optical fiber produced by exposing the fiber to intense ultraviolet light. The produced gratings typically have a length of about 10 mm. If light is coupled in the fiber containing the grating, the wavelength corresponding to the grating period will be reflected while all other wavelengths will pass through the grating undisturbed, as shown in Figure 4. Since the grating period is strain and temperature dependent, it becomes possible to measure these two parameters by analyzing the spectrum of the reflected light. This is typically done using a tunable filter (such as a Fabry-Pérot cavity) or a spectrometer. Precision of the order of 1 $\mu\varepsilon$ and 0.1 °C can be achieved with the best demodulators. If strain and temperature variations are expected simultaneously, it is necessary to use a free reference grating that measures the temperature only and employ its reading to correct the strain values. Set-ups allowing the simultaneous measurement of strain and temperature have been proposed, but their reliability in field conditions has yet to be proved. The main interest in using Bragg gratings resides in their multiplexing potential. Many gratings can be produced in the same fiber at different locations and tuned to reflect at different wavelengths. This allows the measurement of strain at different places along a fiber using a single cable. Typically, 4 to 16 gratings can be measured on a single fiber line. It should be pointed out that since the gratings have to share the spectrum of the source used to illuminate them, there is a trade-off between the number of grating and the dynamic range of the measurements on each of them.
Because of their short length, Fiber Bragg Gratings can be used as replacements for conventional strain gages, and installed by gluing them on metals and other smooth surfaces. With adequate packaging they can also be used to measure strains in concrete over gage length of typically 100 mm.

1.3 SOFO Displacement Sensors

The SOFO system (Figure 3) is a fiber optic displacement sensor with a resolution in the micrometer range and an excellent long-term stability. It was developed at the Swiss Federal Institute of Technology in Lausanne (EPFL) and is now commercialized by SMARTEC in Switzerland.
The measurement setup uses low-coherence interferometry to measure the length difference between two optical fibers installed on the structure to be monitored (Figure 4). The measurement fiber is pre-tensioned and mechanically coupled to the structure at two anchorage points in order to follow its deformations, while the reference fiber is free and acts as temperature reference. Both fibers are installed inside the same pipe and the measurement basis can be chosen between 200mm and 10m. The resolution of the system is of 2 μm independently from the measurement basis and its precision of 0.2% of the measured deformation even over years of operation.

Figure 3: SOFO system reading unit

Figure 4: SOFO Sensor installed on a rebar

The SOFO system has been successfully used to monitor more than 150 structures, including bridges, tunnels, piles, anchored walls, dams, historical monuments, nuclear power plants as well as laboratory models.

1.4 Brillouin Distributed Temperature sensors

Brillouin scattering sensors are ideal for distributed strain and temperature monitoring. Systems able to measure strain or temperature variations of fibers with length up to 50 km with spatial resolution down in the meter range are now demonstrating their potential in field applications. For temperature measurements, the Brillouin sensor is a strong competitor to systems based on Raman scattering, while for strain measurements it has practically no rivals.

Brillouin scattering is the result of the interaction between optical and sound waves in optical fibers. Thermally excited acoustic waves (phonons) produce a periodic modulation of the refractive index. Brillouin scattering occurs when light propagating in the fiber is diffracted backward by this moving grating, giving rise to a frequency-shifted component by a phenomenon similar to the Doppler shift. This process is called spontaneous Brillouin scattering.

Acoustic waves can also be generated by injecting in the fiber two counter-propagating waves with a frequency difference equal to the Brillouin shift. Through electrostriction, these two waves will give rise to a traveling acoustic wave that reinforces the phonon population. This process is called stimulated Brillouin amplification. If the probe signal consists in a short light pulse and its reflected intensity is plotted against its time of flight and frequency shift, it will be possible to obtain a profile of the Brillouin shift along the fiber length.

The most interesting aspect of Brillouin scattering for sensing applications resides in the temperature and strain dependence of the Brillouin shift (Niklès et al. 1994). This is the result of the change the acoustic velocity according to variation in the silica density. The measurement of the Brillouin shift can be approached using spontaneous or stimulated scattering. The main challenge in using spontaneous Brillouin scattering for sensing applications resides in the extremely low level of the detected signal. This requires sophisticated signal processing and relatively long integration times.

Systems based on the stimulated Brillouin amplification have the advantage of working with a relatively stronger signal but face another challenge. To produce a meaningful signal the two counter-propagating waves must maintain an extremely stable frequency difference. This usually requires the synchronization of two laser sources that must inject the two signals at the opposite ends of the fiber under test. The MET (Metrology laboratory) group at Swiss Federal Institute of Technology in Lausanne (EPFL) proposed a more elegant approach. It consists in generating both waves from a single laser source using an integrated optics modulator. This arrangement offers the advantage of eliminating the need for two lasers and intrinsically insures that the frequency difference remains stable independently from the laser drift. SMARTEC and Omnisens (Switzerland) commercialize a system based on this setup and named DiTeSt. It features a measurement range of 10 km with a spatial resolution of 1 m or a range of 25 km with a resolution of 2 m. The strain resolution is 2 $\mu\varepsilon$ and the temperature resolution 0.1°C. The system is portable and can be used for field applications.

Since the Brillouin frequency shift depends on both the local strain and temperature of the fiber, the sensor setup will determine the actual sensitivity of the system. For measuring temperatures it is sufficient to use a standard telecommunication cable. These cables are designed to shield the optical fibers from an elongation of the cable. The fiber will therefore remain in its unstrained state and the frequency shifts can be unambiguously assigned to temperature variations. If the frequency shift of the fiber is known at a reference temperature it will be possible to calculate the absolute temperature at any point along the fiber. Measuring distributed strains requires a specially designed sensor. A mechanical coupling between the sensor and the host structure along the whole length of the fiber has to be guaranteed. To resolve the cross-sensitivity to temperature variations, it is also necessary to install a reference fiber along the strain sensor. Similarly to the temperature case, knowing the frequency shift of the unstrained fiber will allow an absolute strain measurement.

2. SELECTED APPLICATIONS

This section will introduce a few projects showing an effective use of fiber optic technology for the health monitoring of different types of structures, with different aims and during different phases of the structure's lifetime.

2.1 Bridge crack detection

Götaälvbron, the bridge over Göta river (figure 5), was built in thirties and is now more than seventy years old. The steel girders were cracked and two issues are in cause of steel cracking: fatigue and mediocre quality of the steel. The bridge authorities repaired the bridge and decided to keep it in service for the next fifteen years, but in order to increase the safety and reduce uncertainties related to the bridge performance an integrity monitoring system has been mandatory.

Figure 5: View to nearly one kilometer long Götaälvbron Bridge.

The main issue related to selection of the monitoring system has been the total length of the girders which is for all the nine girders more than 9 km. It was therefore decided to monitor the most loaded five girders (total length of 5 km approximately) and logically a fiber optic distributed sensing system have been selected. For the first time a truly distributed fiber optic sensing system, based on Brillouin scattering effect is employed on such large scale to monitor new crack occurrence and unusual strain development.
In order for system to be able to detect the cracks in every point, it was decided to glue the SMARTape to the steel girder. The crack should not damage the sensor, but create its delaminating from the bridge (otherwise the sensor would be damaged and should be repaired). The gluing procedure was therefore established and rigorously tested in laboratory and on-site. Photograph of on-site gluing operation is presented in Figure 6. The full performance was also tested in laboratory and on-site, and photograph of tested SMARTapes installed on the bridge is presented in the same figure.

Figure 6: On-site test of SMARTape gluing procedure (left) and installed SMARTapes.

The installation of SMARTape sensors was challenge itself. Good treatment of surfaces was necessary and number of transversal girders had to be crossed. Limited access and working space in form of lift basket, often combined with cold and windy environment and sometimes with the night work, made the installation particularly difficult. The measurements of SMARTape are compensated for temperature using the temperature sensing cable that has also the function of bringing back the optical signal to the DiTeSt reading unit.

2.2 Stress measurements in the main cable of a suspension bridge under dead and traffic loads

Describing the dynamic behavior of large cable bridges is actually a very frequent and relevant application in the field of experimental vibration analysis for civil engineering structures. This interest is due to the fact that these bridges are usually very strategic structures, and are known to be very sensitive to vibrations. The global 3D dynamic behavior of these bridges and local hanger or stay cable vibrations has been studied extensively in the literature over the past few years. However, few studies have described the specific aspects of the strand dynamic deformation in the main parabolic cables to date.
In the particular case of the Île-d'Orléans bridge near Québec city, Canada, there are similarities with the Lions' Gate Bridge in Vancouver, Canada. The Île-d'Orléans bridge was opened to traffic in 1935, which is more than 72 years ago (Fig 7).

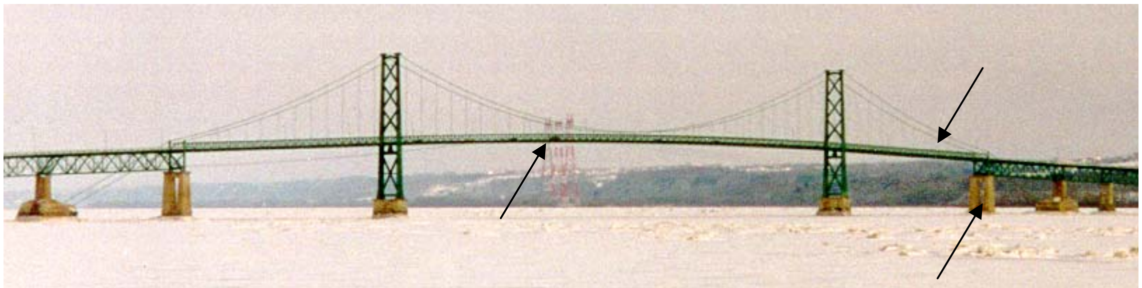

Figure 7: Side view of the Île-d'Orléans bridge (arrows point to locations where the main cable was opened and the anchor block was tested).

It measures 722 m between anchor blocks, and has three spans of 127 m, 323 m (centre span), and 127 m in length respectively. The bridge has been subjected to different measurements campaign in order to evaluate its condition and various aspects of its structural behavior by Talbot (2001, 2002); Talbot & Stoyanoff (2005) and Talbot & Laflamme (2007).
In order to evaluate a suspension bridge, it is necessary to make a series of specific openings in the main cable, which is the most important element of a suspended structure, in order to expose the wires so that the requisite measurements can be made. Unlike stay-cables or hangers, the main cable is usually hidden from view by a protective covering. The recently published guide on the inspection of such cables (NCHRP 534, 2004) was used as a basis for defining the steps to be followed. However, the guide had to be adapted in light of the fact that the cable of the Île-d'Orléans bridge cable is not made up of thousands of parallel wires, but rather of 37 twisted strands.
In order to measure the stresses induced in the strands by traffic loads, the deformations of certain strands of the centre-east section of the main cable and in the south anchorage chamber were measured under controlled traffic conditions, using two 12-wheel trucks, each having a scale weight of slightly more than 30,000 kg. Quasi-static responses (at 7 km/h) and dynamic responses (at 72 km/h – the maximum safe speed for two trucks) were tested (Talbot et al. 2007). The tests reported on here were carried out during the day, at a time when the bridge was completely closed to normal traffic so that the test vehicles could travel side by side from south to north in the two narrow driving lanes.

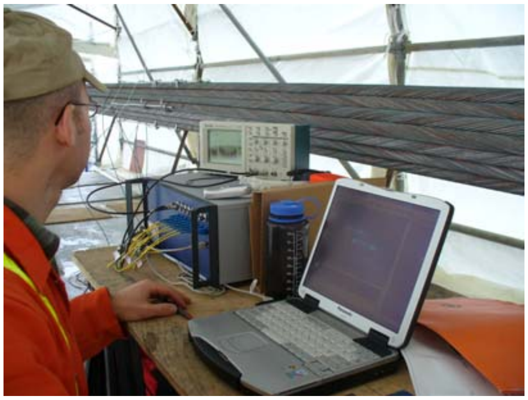
Figure 8: SOFO sensors, open cable section.


Figure 9: SOFO sensors, cable section in the anchorage chamber.

The Dynamic SOFO system and the SMARTEC SOFO deformation sensors were used for this project. The sensors are classified as "long base" sensors, because they can be manufactured with base lengths from 20 cm up to several meters. In this project, we used sensors with a base length of 30 cm. The sensors are protected by a plastic casing. The active part of the sensor is located between two steel mechanical clamp points on the strands, and consists of two optical fibers: an "active fiber" that is fixed between the two attach points; and a "reference fiber", which is left free between the clamp points, that measures the effects of temperature. Michelson's interferometry principle is used to measure the difference in length between the two fibers caused by the relative movements of the two extremes of the base. An optomechanical system was used to acquire the high frequency signals (Del Grosso et al., 2005). The sampling frequency was 250 Hz for the quasi-static response measurements and 500 Hz for the dynamic response measurements. Six SOFO sensors (Figs 8-9) were placed at the corners of a hexagon formed by the main cable, as shown in Figures 10 and 11.
The redundancy provided by six sensors was ultimately quite useful, because some of the sensors did not function properly at all times. Having five functioning sensors meant that we were always able to calculate the resulting stresses. In fact, a minimum of four sensors is required in order to measure the four internal forces (axial, two moments, and one bi-moment), as is the case with measurements on steel sections (Talbot et al., 1993). This approach yields an approximation, because it assumes that the section that is made up of 37 strands behaves as a perfectly cohesive whole, which is probably not always the case. Still, it can highlight if the cable does not behave simply like a purely axial element, which conventional suspension bridge theory states that it should.
Figures 10 and 11present selected findings for a complete vehicle run. There is a notable difference in the deformations recorded by the six sensors, which suggests that the main cable does not behave as a purely axial element. These considerable differences are all the more important in light of the fact that the mean stress in the anchorage chambers is greater than at the centre of the bridge, because the angle of the cable is greater, in accordance with suspension bridge theory.
The resulting axial (strand mean) stresses were calculated, and they compare favorably with the theoretical values yielded by the 3D finite element model. The maximal theoretical stress for the centre was 466.6 kN, while the experimentally observed stress was 429.0 kN. The theoretical stress for the anchorage chamber was 495.3 kN, compared to the experimentally observed stress of 438.6 kN (the model was originally calibrated to be slightly conservative). The sensor values and the calculation of a main moment (not shown here) are indicative of the stress gradient. At the centre of the bridge, the base of the cable tends to be overstressed, whereas the opposite is true for the anchorage chamber.

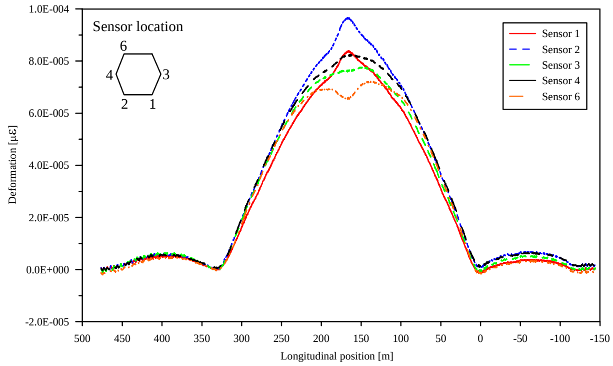

Figure 10: SOFO deformation sensor readings at the centre of the bridge for 2 trucks moving at 7 km/h.

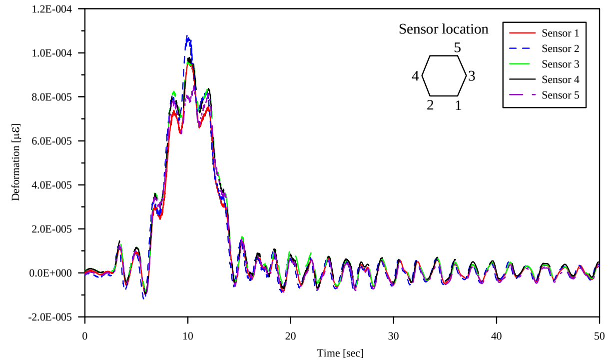

Figure 11: SOFO deformation sensor readings at the centre of the bridge for 2 trucks moving at 72 km/h.

CONCLUSIONS

The monitoring of new and existing structures is one of the essential tools for modern and efficient management of the infrastructure network. Sensors are the first building block in the monitoring chain and are responsible for the accuracy and reliability of the data. Progress in sensing technologies comes from more accurate and reliable measurements, but also from systems that are easier to install, use and maintain. In recent years, fiber optic sensors have taken the first steps in structural monitoring and in particular in civil and geotechnical engineering. Different sensing technologies have emerged and evolved into commercial products that have been successfully used to monitor hundreds of structures. No longer a scientific curiosity, fiber optic sensors are now employed in many applications where conventional sensors cannot be used reliably or where they present application difficulties.

If three characteristics of fiber optic sensors should be highlighted as the reasons of their present and future success, we would cite the precision of the measurements, the long-term stability and durability of the fibers and the possibility of performing distributed and remote measurements over distances of tens of kilometers.

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