Next on the thought agenda is the fact that the boomers possess a great deal of institutional knowledge, knowledge that is critical to organizational continuity and success. We have already established that folks are living longer, more productive lives. Industry is realizing that these graying workers still have plenty to offer. Here’s an interesting statistic - the average age of a construction worker in our part of the industry is 55. The same holds true for the civil engineering profession. Employers are now discovering that contrary to the assumption that older workers may cost you more because of health expenses, health related absenteeism, loss of focus, etc., in fact older healthy workers may cost you less. Those over 65.6 are not only collecting social security payments, but they are on Medicare as well. If an employer is able to offer flex time and fewer hours, older workers are able to supplement the employer’s pay check with their own draws on social security and/or retirement plans. Employers are also discovering that these folks by and large have a work ethic that is not found in younger folks. For people of this ilk, ‘work is life’, not something you have to do as little of as possible and get paid as much as possible. These workers are not running home to take young children to soccer practice, ballet, piano lessons, or the orthodontist. They are not committed to attending parent teacher association meetings, or linking their vacations to school holiday breaks. The ones that want to work, or have to work, appreciate having the opportunity. They don’t think they are owed anything. They relish the chance to continue to contribute to a company’s objectives. While there may be initial problems with older workers having to report to youngsters they quickly get over it. These seasoned citizens want the work, they need the work. They will do the work.

None of the above precludes the need to aggressively recruit young folks into our industry on the design and the construction sides of the coin. I have already written about the need to begin the recruitment process early and often. We are competing for fewer young people with lots and lots of choices. We must make our profession attractive. But that’s another topic.

Here’s the point – don’t discount the value of keeping your older employees. Don’t be afraid to bring ambitious seniors back to help mentor the younger folks. The blend of experience and hopefully wisdom, with exuberant youthful energy and excitement is a terrific combination for any company.

It’s shift the paradigm time.

Please don’t misunderstand my motive in reprinting this – it has nothing to do with hopes for my own future. Just a good sermon for others!

**Closure**

Please send contributions to this column, or an article for GIN, to me as an e-mail attachment in MSWord, to john@dunnicliff.eclipse.co.uk, or by fax or mail: Little Leat, Whisselwell, Bovey Tracey, Devon TQ13 9LA, England. Tel. and fax +44-1626-832919.

Happy Landings!

---

**Overview of Fiber Optic Sensing Technologies for Geotechnical Instrumentation and Monitoring**

**Daniele Inaudi**

**Branko Glisic**

**Introduction**

From many points of view, fiber optic sensors are the ideal transducers for structural health monitoring. Being durable, stable and insensitive to external perturbations, they are especially useful for long-term health assessment of civil structures and geostuctures. Many different fiber optic sensor technologies exist and offer a wide range of performances and suitability for different applications. In the last few years, fiber optic sensors have made a slow but significant entrance in the sensor panorama. After an initial euphoric phase when fiber optic sensors seemed on the verge of becoming prevalent in the whole world of sensing, it now appears that this technology is mainly attractive in the cases where it offers superior performance compared with the more proven conventional sensors. The additional value can include an improved quality of the measurements, a better reliability, the possibility of replacing manual readings and operator judgment with automatic measurements, an easier installation and maintenance or a lower lifetime cost. Finally, distributed fiber sensors offer new exciting possibilities that have no parallel in conventional sensors.

This article reviews the four main fiber optic sensor technologies:
- Fabry-Pérot Interferometric Sensors
- Fiber Bragg Grating Sensors
SOFO Interferometric Sensors

Distributed Brillouin Scattering and Distributed Raman Scattering Sensors and their practical implementation in the form of packaged sensors and readout instruments.

Selected application examples illustrate the practical use of these sensing systems.

Fiber Optic Sensors

There exists a great variety of fiber optic sensors (FOS) for structural and geotechnical monitoring. 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.

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.

**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-co-

---

**Figure 1. Fiber optic sensor types.**

- **Point Sensor:** Fabry-Pérot
- **Quasi distributed (multiplexed):** Fibre Bragg Gratings
- **Long base:** SOFO
- **Distributed Sensor:** Brillouin and Raman Scattering

**Figure 2. Operating principle or a Fabry-Pérot cavity sensor.**

**Figure 3. Examples of geotechnical sensors based on the Fabry-Pérot Cavity principle. Depicted are a piezometer and a displacement transducer.**
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 με 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 as shown in Figure 4. 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.

SOFO Interferometric Sensors

The SOFO Interferometric sensors are

Figure 4. Chain for Fiber Bragg Grating sensors containing strain and temperature sensors. Each sensor reflects a specific wavelength.

Figure 5. SOFO sensor installed on a rebar. The plastic pipe contains the coupled measurement fiber and a free un-coupled reference fiber. The metallic anchors at both ends of the white plastic pipe define the gage length.
long-base sensors, integrating the measurement over a long measurement base that can reach 10m or more.

The SOFO system is a fiber optic displacement sensor with a resolution in the micrometer range and excellent long-term stability. It was developed at the Swiss Federal Institute of Technology in Lausanne (EPFL) and is now commercialized by the authors’ company, SMARTEC in Switzerland.

The measurement set-up uses low-coherence interferometry to measure the length difference between two optical fibers installed on the structure to be monitored (Figure 5), by embedding in concrete or surface mounting. 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 plastic pipe and the gage length can be chosen between 200mm and 10m. The SOFO readout unit, shown in Figure 6, measures the length difference between the measurement fiber and the reference fiber, by compensating it with a matching length difference in its internal interferometer. The precision of the system is of ±2 μm independently from the measurement basis and its accuracy of 0.2% of the measured deformation even over years of operation.

The SOFO system has been used to monitor more than 300 structures, including bridges, tunnels, piles, anchored walls, dams, historical monuments, nuclear power plants as well as laboratory models. An example of such an application was the monitoring of cast-in-place piles during a load test. A new semi-conductor production facility in the Tainan Scientific Park, Taiwan, is going to be founded on a soil consisting mainly of clay and sand with poor mechanical properties. To assess the foundation performance, it was decided to perform an axial compression, pullout and flexure test in full-scale on-site condition. Four meter long SOFO sensors were selected in order to cover the whole length of the pile with sensors, and obtain averaged strains over long pile sections. The pile was divided into eight sections. In the case of axial compression and pullout tests, a simple sensor arrangement was used: the eight sensors were installed in a single chain, placed along one of the main rebars, one sensor in each section (A1 to A8), as shown in Figure 7. To detect and compensate for a possible load eccentricity, the top cell was equipped with one more sensor (B1) installed on the opposite rebar with respect to the pile axis.

As a result of monitoring, valuable information concerning the structural behavior of the piles was collected. Important parameters were determined such as distributions of strain, normal forces, displacement in the pile, distribution of frictional forces between the pile and the soil, determination of Young’s Modulus, ultimate load capacity and failure mode of the piles as well as qualitative determination of mechanical properties of the soil (three zones are indicated in Figure 7).

For the flexure test, a parallel arrangement was used: each section contained two parallel sensors (as in section 1 of Figure 7) installed on two opposite main rebars, constituting two chains of sensors. This sensor arrangement allowed determination of the average curvature in each cell, calculation of deformed shape and identification of the plastic hinge depth (failure location). A diagram of horizontal displacement for different steps of load as well as the failure location on the pile is shown in Figure 8. More details can be found in Glisic et al (2002).

This example shows an interesting application of long-gauge fiber optic
sensors. The use of long-base SOFO sensors allows the gapless monitoring of the whole length of the pile, and provides average data that is not affected by local features or defects of the pile.

**Distributed Brillouin Scattering and Distributed Raman Scattering Sensors**

Distributed sensors are able to sense at any point along a single fiber line (as shown in Figure 1), typically every meter over many kilometers of length.

In fully distributed FOS, the optical fiber itself acts as sensing medium, allowing the discrimination of different positions of the measured parameter along the fiber. These sensors use an intrinsic property of standard telecommunication fibers that scatter a tiny amount of the light propagating through it at every point along their length. Part of the scattered light returns backwards to the measurement instrument and contains information about the strain and temperature that were present at the location where the scattering occurred. When light pulses are used to interrogate the fiber, it becomes possible, using a technique similar to RADAR, to discriminate different points along the sensing fiber by the different time-of-flight of the scattered light. Combining the radar technique and the spectral analysis of the returned light it becomes possible to obtain the complete profile of strain or temperature along the fiber. Typically it is possible to use a fiber with a length of up to 30 km and obtain strain and temperature readings every meter. In this case we would talk of a distributed sensing system with a range of 30 km and a spatial resolution of 1 m.

Although the fiber used for the measurement is of standard telecommunication type, it must be protected inside a cable designed for transferring strain and temperature from the structure to the fiber while protecting the fiber itself from damage due to handling and to the environment where it operates. To take full advantage of these techniques it is therefore important to select the appropriate sensing cable, adapted to the specific installation conditions.

The article immediately following this one is dedicated to distributed fiber optic sensors. It presents the different scattering sensing techniques, known as Brillouin and Raman Scattering, and their applications in geotechnical monitoring.

**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.

**Reference**


Daniele Inaudi and Branko Glisic, SMARTEC SA, Roctest Group, Via Pobiette 11, 6928 Manno, Switzerland, Tel. +41 91 610 18 00, email: inaudi@smartec.ch, email: glisic@smartec.ch

**Distributed Fiber Optic Sensors: Novel Tools for the Monitoring of Large Structures**

**Daniele Inaudi**

**Branko Glisic**

Distributed fiber optic sensing offers the ability to measure temperatures and strains at thousands of points along a single fiber. This is particularly interesting for the monitoring of large structures such as dams, dikes, levees, tunnels, pipelines and landslides, where it allows the detection and localization of movements and seepage zones with sensitivity and localization accuracy unattainable using conventional measurement techniques.

Sensing systems based on Brillouin and Raman scattering (the difference