Fiber Optic Sensors for Dynamic and Long Term Structural Monitoring

Daniele Inaudi
SMARTEC SA
Manno, Switzerland
www.smartec.ch

Abstract

From many points of view, fiber optic sensors are the ideal transducers for civil structural monitoring. 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. Europe has been on the forefront of fiber optic sensor development and a number of systems have matured to full commercial exploitation and routine application in structural health monitoring. This contribution reviews some of these systems and technologies and briefly presents some significant application examples.

Introduction

The construction and maintenance of the civil infrastructure represents between 10% and 20% of the public investment in most European countries. In the last decade we have however witnessed an increasing shift from investments in the construction of new structures to the maintenance and the lifetime extension of the existing ones. With the exception of the high-speed train lines, most of the transportation network, including highways and railway, is completed and in service. However, the steady increase of the passengers and goods circulating in the continent, amplified by the free circulation policy introduced by the European Community, is putting the civil infrastructure under a rude test. Many bridges and tunnels built a few tens of years ago need repair and in many case an extension of their bearing capacity and lifetime that exceed the original plans. Besides the direct costs associated with these interventions, the disruption to the normal use of the structures causes additional inconvenience including traffic jams and accidents that carry additional hidden costs.

The authorities managing the civil infrastructures face the challenge of maintaining the transportation network in a satisfactory state using a limited budget and with little perturbation to its normal use. This task is far more complex than that of building new structures and requires new management instruments.

Structural health monitoring is certainly one of the most powerful management tools and is therefore gaining in importance in the civil engineering community. Monitoring is often and mistakenly presented as a security tool. This is however only the case for the few structures that present a high potential danger such as nuclear power plants and dams. For most other structures the security risks are very limited and fortunately we rarely witness casualties due to a structural collapse. For all other structures, monitoring should be seen as management tool delivering information on the state of a single structure or on a network of structures. In what we call the information age, structural health monitoring closes the gap between the seemingly inert world of structures and the frenetic one of information technology.

A typical health monitoring system is composed of a network of sensors that measure the parameters relevant to the state of the structure and its environment. For civil structures such as bridges, tunnels, dams, geostructures, power plants, high-rise buildings and historical monuments, the most relevant parameters are:

- ?? Physical quantities: position, deformations, inclinations, strains, forces, pressures, accelerations, and vibrations.
- ?? Temperatures.
- ?? Chemical quantities: humidity, pH, and chlorine concentration.
- ?? Environmental parameters: air temperature, wind speed and direction, irradiation, precipitation, snow accumulation, water levels and flow, pollutant concentration.

Conventional sensors based on mechanical and/or electrical transducers are able to measure most of these parameters. 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 optical fiber sensors seemed on the verge of invading the whole world of sensing, it now appears that this technology is only attractive in the cases where it offers superior performance compared to 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. The first successful industrial applications of fiber optic sensors to civil structural monitoring demonstrate that this technology is now sufficiently mature for a routine use and that it can compete as a peer with conventional instrumentation.

Table 1 Fiber optic sensors for civil structural monitoring in Europe.

	Measured Parameters	**Maturity**	**Active companies and research groups in Europe** (see text for details)
SOFO	Displacement	Commercial	SMARTEC, IMAC-EPFL
Microbending	Displacement	Commercial	OSMOS
Bragg gratings	Strain, temperature, (displacement)	Commercial	ID-FOS, AOS, LETI, EMPA
Fabry-Perot	Strain	Field trials	BAM
Raman	Distributed temperature	Commercial	Sensa, GESO
Brillouin	Distributed temperature and strain	Commercial	SMARTEC, Omnisens, MET-EPFL

Fiber Optic Sensor Types

Europe offers a great variety of fiber optic sensors (Udd 1991, Udd 1995, Inaudi 1997a) for structural monitoring in both the academic and the industrial areas. Unlike the USA, where most efforts seem concentrated to strain sensing, Europe is developing and producing a great variety of sensors for the most disparate types of measurement and application. In this overview we will concentrate on sensors for civil health monitoring that have reached an industrial level or are at least at the stage of advanced field trials.

Table 1 resumes the sensor technologies that will be discussed in the next paragraphs.

SOFO Displacement Sensors

The SOFO system (Figure 1) 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 (Inaudi et al. 1994, Inaudi 1997b, Inaudi et al. 1997).

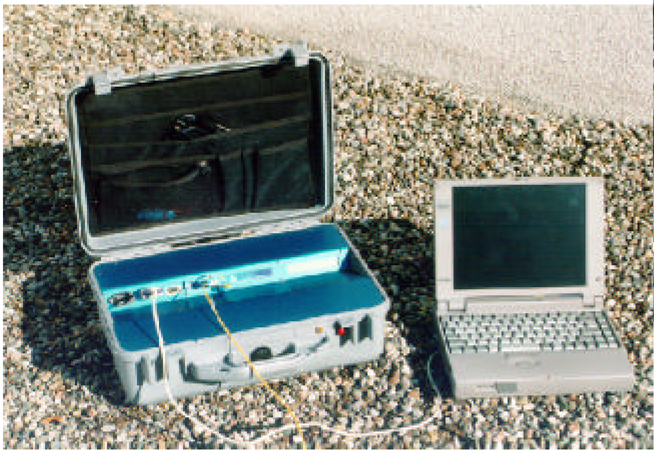

Figure 1: SOFO system reading unit

The measurement setup uses low-coherence interferometry to measure the length difference between two optical fibers installed on the structure to be monitored (Figure 2). The measurement fiber is pretensioned 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.

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.

Figure 2: SOFO Sensor installed on a rebar

Microbending Displacement Sensors

An alternative fiber optic sensor useful for the measurement of length variations is based on the principle of microbending. In that setup, an optical fiber is twisted with one ore more other fibers or with metallic wires (Falco & Parriaux 1992) along its sensing length. When this fiber optic twisted pair is elongated, the fibers will induce bending in one-another and cause part of the light to escape the fiber. By measuring the intensity of the transmitted light it is therefore possible to reconstruct the deformation undergone by the structure on which the sensor is mounted.

A system based on this principle has been marketed for some years through Sicom and more recently by OSMOS. This system was one of the earliest commercial applications of fiber optic sensors for the monitoring of civil structures and was installed in different bridges, tunnels and high-rise structures. Typically obtainable accuracy is of 2 ?m for short periods (below one day) and 2% for the long-term. Arrangements measuring the reflected light intensity with an optical time reflectometer (OTDR) have also been proposed. These setups potentially allow for distributed deformation measurements.

Microbending sensors are conceptually simple, however temperature compensation, intensity drifts, system calibration and the inherently non-linear relationship between intensity and elongation present some challenges. This type of sensor is particularly appropriate for short-term and dynamic monitoring as well as for issuing alarms.

Bragg Grating Strain Sensors

Bragg gratings are periodic alterations in the index of refraction of the fiber core that can be produced by adequately exposing the fiber to intense UV light. The produced gratings typically have length of the order of 10 mm. If white light is injected in the fiber containing the grating, the wavelength corresponding to the grating pitch will be reflected while all other wavelengths will pass through the grating undisturbed. 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 (Kersey 1997). This is typically done using a tunable filter (such as a Fabry-Perot cavity) or a spectrometer. Resolutions of the order of 1 ?? 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 alone and use its reading to correct the strain values. Setups allowing the simultaneous measurement of strain and temperature have been proposed, but have yet to prove their reliability in field conditions. The main interest in using Bragg gratings resides in their multiplexing potential. Many gratings can be written 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 has to be noticed that since the gratings have to share the spectrum of the source used to illuminate them, there is a tradeoff between the number of grating and the dynamic range of the measurements on each of them.

Because of their length, fiber Bragg gratings can be used as replacement of conventional strain gages and installed by gluing them on metals and other smooth surfaces (Vohra et al. 1998). With adequate packaging they can also be used to measure strains in concrete over basis length of typically 100 mm.

A large number of research and development projects for this type of sensors are underway worldwide and Europe is by no mean an exception to this trend (Ferdinand et al. 1997). Two European projects STABILOS (Ferdinand et al. 1995) and COSMUS focused on the application of this technology to the measurement of movements in tunnels, mines and other geostructures. In particular, an array of Bragg grating has been installed in the Mont Terri tunnel in Switzerland. The LETI group in France has also used this technology to monitored lock gates (Bugaud et al. 1998) and is introducing the system in the nuclear power industry (Ferdinand 2002), while EMPA (Swiss Federal Laboratories for Materials Testing and Research) has installed them in the Luzzone Dam (Brönnimann et al. 1998) and in a cable stayed bridge.

Fabry-Perot strain sensors

Extrinsic Fabry-Perot Interferometers (EFPIs) are constituted by a capillary silica tube containing two cleaved optical fibers facing each other's, but leaving an air gap of a few microns or tens of microns between them. When light is launched into one of the fibers, a back reflected interference signal is obtained. This is due to the reflection of the incoming light on the glass-to-air and on air-to-glass interfaces. 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.
Contrary to the rest of the world, Europe seems to pay relatively little attention to this interesting sensor technique. A notable exception is the group at BAM in Berlin (Germany), which is using these sensors to monitor the early-age deformations of mortars (Habel et al 1998) and has applied them to the monitoring of a concrete bridge in Charlottenbourg (Habel et al. 1994).

Raman Distributed Temperature Sensors

Raman scattering is the result of a non-linear interaction between the light traveling in a fiber and silica. When an intense light signal is shined into the fiber, two frequency-shifted components called respectively Raman Stokes and Raman anti-Stokes will appear in the back-scattered spectrum. The relative intensity of these two components depends on the local temperature of the fiber. If the light signal is pulsed and the back-scattered intensity is recorded as a function of the round-trip time, it becomes possible to obtain a temperature profile along the fiber (Dakin et al. 1986). A system based on Raman scattering is commercialized by Sensa in the UK and GESO in Germany. Typically a temperature resolution of the order of 1°C and a spatial resolution of less than 1m over a measurement range up to 10 km are obtained for multi-mode fibers. A new system based on the use of singlemode fibers should extend the range to about 30km with a spatial resolution of 8 m and a temperature resolution of 2°C.

Brillouin Distributed Temperature sensors

Brillouin scattering sensors show an interesting potential for distributed strain and temperature monitoring (Karashima et al. 1990). 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. 1997). 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. A commercial system based on spontaneous Brillouin scattering is available from ANDO (Japan).

Figure 3: DiTeSt Reading Unit

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 (Niklès et al. 1994). 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 (Figure 3). 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 ?? 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.

Selected projects

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.

Expo.02 Piazza Pinocchio

Once every generation, Switzerland treats itself to a National Exhibition commissioned by the Swiss Confederation. Expo 02 was spread out in five "Arteplage" over a whole region: the land of the three lakes, on the shores of the lakes of Biel, Murten and Neuchâtel, which are located in the northwest of Switzerland. Each "Arteplage" relates to a theme, which is reflected in its architectures and exhibitions. The "Arteplage" of Neuchâtel was related to "Nature and Artificiality"; a big steel-wood whale eating a village represents the fairy tale named "Pinocchio" from the Italian writer Collodi. The "Piazza Pinocchio" was built together with other exposition buildings on one large artificial peninsula.

Figure 4: Piazza Pinocchio and the big wooden whale

The belly of the whale (Figure 4) holds the exposition dedicated to robotic and artificial intelligence, while the rest of the village was developed on two floors with steel piles / beams and wood walls and floors.

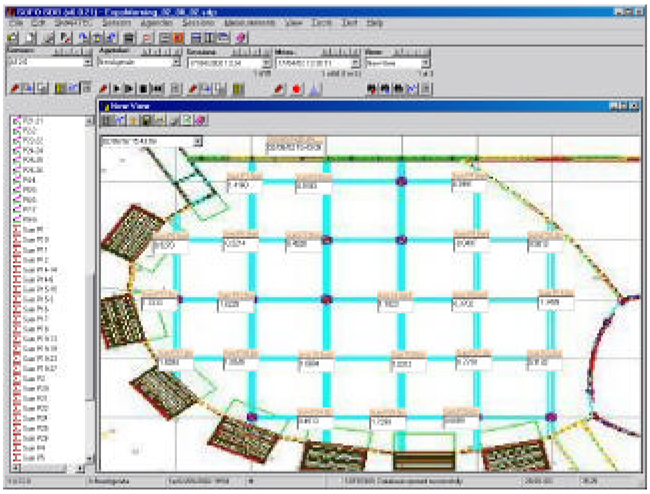

Figure 5: Piazza Pinocchio control center with load indicators

To guarantee that the life loads generated by the visitors accessing the platform would never exceed the design loads, it was decided to install a real-time monitoring system that would guide the exhibition personnel in granting or not the access to additional visitors. The SOFO system based on low coherence fiber optic deformation sensors was selected for this project. 31 SOFO sensors and 31 thermocouples were installed on steel piles to monitor real time visitor's live loads. The main requirements were: real-time computer results display of the live loads during 18 hours a day (Figure 5), automatic thermal-induced strain compensation, real-time warnings and pre-warnings for each single pile, automatic phone calls produced when reaching warning thresholds and remote monitoring for complete management of the monitoring system. The system operated flawlessly during 6 months and generated a few pre-warning, no warning and no false alerts. This project is a nice example of real-time monitoring with integration in a facility management system. If the selective access of the visitors can be considered a form of actuation, we can even describe the Piazza Pinocchio as a true "Smart Structure".

Colle Isarco Bridge

The development of a life extension and/or replacement strategy for highway structures is a crucial point in an effective bridge management system. An example of a global monitoring approach in establishing a bridge management system is represented by the project of the Colle d'Isarco viaduct on the Italian Brenner-Highway A22. The section of the highway that is subject to monitoring activities includes four columns, each of them supporting asymmetrical cantilevers in the north and south direction as can bee seen in Figure 6.

Figure 6: View of the Colle Isarco Bridge on the Brennero Highway in Italy

The overall length of this section is 378 m. The height of the girders near the supports number 8 and 9 is 11 m, at the supports 7 and 10 the height is 4.50 m. The girders have a uniform width of 6 m, the arrangement for each road bed is approximately 11 m wide. A wide set of sensors have been installed, including both traditional and SOFO fiber optic sensors and, due to the large dimensions of the section, a data acquisition system able to collect widely distributed sensing units was also installed (Figure 7). Wireless serial communication is used to transfer the measured data from the almost inaccessible locations on the bridge to the location of the personal computer used to evaluate the measured data.

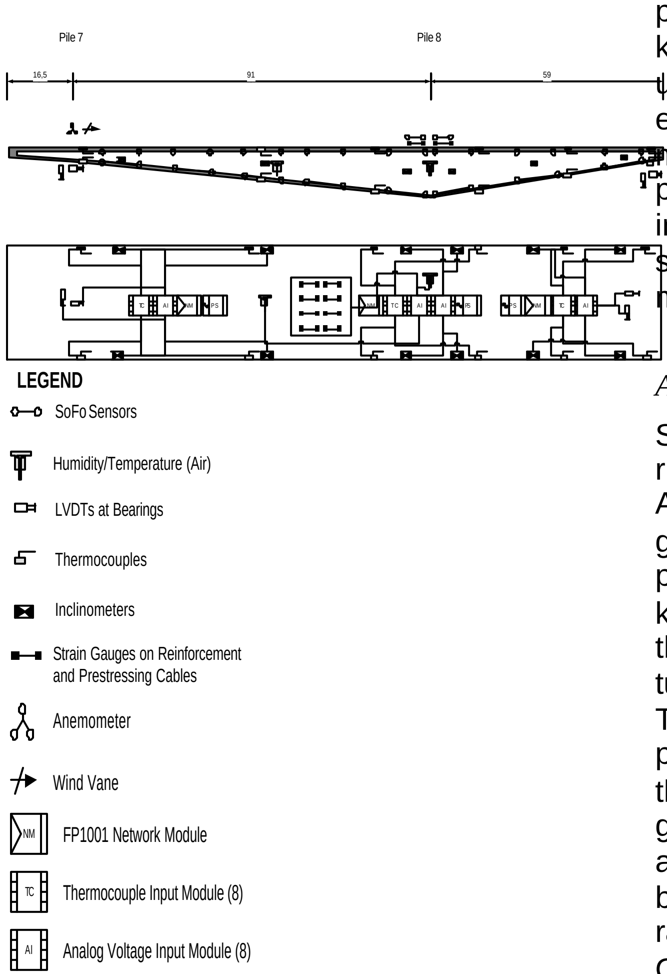

Figure 7: Layout of the Colle Isarco Bridge Instrumentation (courtesy of K. Bergmeister)

Data evaluation is performed by a combination of analytical modeling and fine-tuning of the system parameters. The system aims to the creation of the appropriate match between the non-linear simulation and the measured data. Since the measurement processes usually introduce a certain amount of variability and uncertainty into the results due to the limited number of measurement points and the partial knowledge on the actions, this randomness can affect the conclusions drawn from measurements. Randomness in measured variables can however be accounted for by their probability density functions. Once a model and its calibration has gained a certain level of completeness, analytical prediction provides a quantitative knowledge and hence it becomes a useful tool to support structural evaluation, decision making, and maintenance strategies. This ambitious project aims to a full integration of instrumentation into the decision-support system for structural maintenance.

Alptransit Tunnel

Switzerland is currently building a new railway line across the Alps. The Alptransit project is intended to make goods transport more economical and passenger transport faster (up to 250 km/h). The most impressive works of this new line will be the Gotthard base tunnel with its two tubes of 57 km each. The construction of these tunnels presents unparallel challenges due to their exceptional length and the difficult geological conditions found in some areas along the route. The Gotthard base tunnel must pass through a vast range of layers, from the very hard Gotthard granite, through the high-stress pennine gneiss of the Leventina, to the butter-soft rock of the Tavetsch Intermediate Massif. One of the difficult areas is the south portal in Bodio. Due to constraints in the layout of the tunnel and the necessity to cope with the existing railway line, highway and roads, it is necessary to build the portal and the first 300m of tunnel in a loose stone formation. In order to optimize the support and confining structures in this area, SMARTEC SA was asked to install SOFO sensors to monitor the buttresses at the tunnel entrance and the concrete lining inside the tunnel (Figure 8). The sensors give quantitative information on the real loads that are carried by these structures in the short and long term. An automatic monitoring system records deformations and temperatures continuously and enables a correlation with the different construction phases.

Figure 8: Support Buttresses at the south portal of the new Alptransit Gotthard tunnel

In this case, monitoring concentrated mainly during construction, as it is often the case for geotechnical projects. Once the measurement systems are removed, the installed sensors remain however available for future manual measurements or to restore permanent monitoring if new unforeseen events occur.

Luzzone Dam

Distributed temperature measurements are highly interesting for the monitoring of large structures. In the presented application, SMARTEC and the MET-EPFL group used the DiTeSt system to monitor the temperature development of the concrete used to build a dam (Thévenaz et al. 1998).

The Luzzone dam was recently raised by 17 meters to increase the capacity of the reservoir (Figure 9). The raising was realized by successively concreting 3m thick blocks. The tests concentrated on the largest block to be poured, the one resting against the rock foundation on one end of the dam. An armored telecom cable installed in serpentine during concrete pouring constituted the Brillouin sensor.

Figure 9: Luzzone Dam raising works

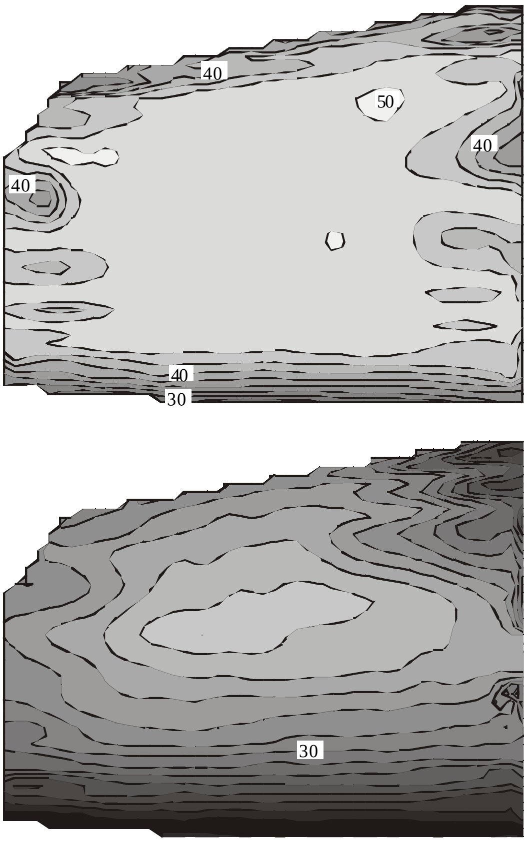

Figure 10: Temperature measurements in the Luzzone Dam 15 and 55 days after concrete pouring (courtesy of L. Thévenaz)

The temperature measurements started immediately after pouring and extended

over 6 months. The measurement system proved reliable even in the demanding environment present at the dam (dust, snow, and temperature excursions). The temperature distributions after 15 and 55 days from concrete pouring are shown in Figure 10. Comparative measurements obtained locally with conventional thermocouples showed agreement within the error of both systems.
This example shows how it is possible to obtain a large number of measurement points with relatively simple sensors. The distributed nature of Brillouin sensing make it particularly adapted to the monitoring of large structures were the use of more conventional sensors would require extensive cabling.

Conclusions

The monitoring of new and existing structures is one of the essential tools for a 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 the sensing technology can therefore be produced by more accurate measurements, but also from systems that are easier to install, use and maintain. In the recent years, fiber optic sensors have moved the first steps in structural monitoring and in particular in civil engineering. Different sensing technologies have emerged and quite a few have evolved into commercial products.
It is difficult to find a common reason for the success of so diverse types of sensors, each one seems to have found a niche where it can offer performance that surpass or complement the ones of the more traditional sensors. If three characteristics of fiber optic sensors should be highlighted as the probable reason of their present and future success, I would cite the stability of the measurements, the potential long-term reliability of the fibers and the possibility of performing distributed and remote measurements. Furthermore, the much larger market of fiber optic telecommunication offers an interesting potential for cost reduction in most components used for sensing applications.
In the near future it is therefore to expect that fiber optic sensors will consolidate their presence in the structural sensing industry.

Acknowledgements

The author is indebted to Prof. K. Bergmeister, U. Santa, Prof. A Del Grosso, B. Glisic, M. Niklès and L. Thévenaz for providing information on the presented application examples.

References

Brönnimann R. et al. 1998. Packaging of Fiber Optic Sensors for Civil Engineering Applications", Symposium DD, Reliability of Photonics Materials and Structures, San Francisco, paper DD7.2

Bugaud M. et al. 1998. Health Monitoring of Composite Plastic Waterworks Lock Gates using in-Fiber Bragg Grating Sensors", 4th European Conference on Smart Structures and Materials, Harrogate, UK

Dakin, J. P. et al. 1986. Distributed optical fiber Raman temperature sensor using a semiconductor light source and detector, Proc, IEE Colloq. on Distributed Optical Fiber sensors

Falco & Parriaux 1992. Structural metal coatings for distributed fiber sensors, Opt. Fiber Sens. Conf. Proc., pp. 254

Ferdinand P. et al. 1997. Application of Bragg grating sensors in Europe, 12th International conference on OFS '97- Optical Fiber Sensors, Williamsbourg, OSA Technical Digest Series, Vol. 16, pp. 14-19

Ferdinand P. et al. 1994. Mine Operating Accurate Stability Control with Optical Fiber Sensing and Bragg Grating technology: the Brite-EURAM STABILOS Project, OFS 10 Glasgow, pp. 162-166. Extended paper: Journal of Lightwave Technology, Vol. 13, No. 7, pp. 1303-1313, 1995

Ferdinand P. et al. 2002. "Potential Applications for Optical Fiber Sensors and Networks within the Nuclear Power Industry" in Optical Fiber Sensing Technology, J. M. Lopez-Higuera ed., Universidad de Cantabria

Habel W. & Hofmann D. 1994. Determination of Structural Parameters Concerning Load Capacity Based on Fiber Fabry-Perot-Interferometers, Proc. SPIE, Vol. 2361, pp. 176-179

Habel W. et al. 1998. Non-reactive Measurement of Mortar Deformation at Very Early Ages by Means of Embedded Compliant Fiber-optic Micro Strain Gages, 12th Engineering Mechanics ASCE Conference, La Jolla USA

Inaudi D. 1997a. Fiber optic smart sensing, Optical Measurement techniques and applications, P. K. Rastogi editor, Artech House, pp. 255-275

Inaudi D. 1997b. Field testing and application of fiber op-tic displacement sensors in civil structures, 12th International conference on OFS '97- Optical Fiber Sensors, Williamsburg, OSA Technical Digest Series, Vol. 16, pp. 596-599

Inaudi D. et al. 1994. Low-coherence deformation sensors for the monitoring of civil-engineering structures, Sensor and Actuators A, Vol. 44, pp. 125-130

Inaudi D. et al. 1997. Embedded and surface mounted fiber optic sensors for civil structural monitoring, Smart Structures and Materials Conference, San Diego, SPIE Volume 3044, pp. 236-243

Karashima T. et al. 1990. Distributed Temperature sensing using stimulated Brillouin Scattering in Optical Silica Fibers, Optics Letters, Vol. 15, pp. 1038

Kersey A. 1997. Optical Fiber Sensors, Optical Measurement techniques and applications, P. K. Rastogi editor, Artech House, pp. 217-254

Niklès M. et al. 1994. Simple Distributed temperature sensor based on Brillouin gain spectrum analysis, Tenth International Conference on Optical Fiber Sensors OFS 10, Glasgow, UK, SPIE Vol. 2360, pp. 138-141

Niklès M. et al. 1997. Brillouin Gain Spectrum Characterization in Single-Mode Optical Fibers", Journal of Lightwave Technology, Vol. 15, No. 10, pp. 1842-1851

Thévenaz L. et al. 1998. Truly Distributed Strain and Temperature Sensing Using Embedded Optical Fibers, Smart Structure and Materials Conference, San Diego USA, SPIE Vol. 3330, pp. 301-314

Udd E 1995. Fiber optic smart structures, Wiley, New York, 1995

Udd E. 1991. Fiber Optic Sensors, Wiley

Vohra S. T. et al. 1998. Quasi-Static Strain Monitoring During the Push Phase of a Box-Girder Bridge Using Fiber Bragg Grating Sensors", European Workshop on Optical Fibre Sensors, Peebls Hydro, UK