OVERVIEW OF FIBER OPTIC SENSING TECHNOLOGIES FOR STRUCTURAL HEALTH MONITORING

Daniele Inaudi

SMARTEC / Roctest

Key words: optical sensors, health monitoring, point sensors, long-gauge sensors, distributed sensors

Abstract: From many points of view, fibre optic sensors are the ideal transducers for 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 fibre 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 (Fibre 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 health monitoring of structures such as bridges, buildings, monuments, tunnels, dams, dykes, pipelines, landslides and many others.

This contribution reviews these systems and technologies and briefly presents some significant application examples.

Pregled tehnologij optičnega zaznavanja za uporabo v zdravstvenem monitoringu

Kjučne besede: optični senzorji, spremljanje stanja, koničasti senzorji, porazdeljeni senzorji

Izvleček: Senzorji z optičnimi vlakni so idealni pretvorniki za spremljanje stanja gradbenih konstrukcij. Zaradi svoje trajnosti, stabilnosti in neobčutljivosti do zunanjih motenj, so primerni za dolgoročno zasledovanje stanja gradbenih struktur. Obstaja veliko razliÄnih tehnologij, ki ponujajo širok spekter senzorjev za različne aplikacije. Najbolj pogosto uporabljene so tehnike točkovnega zaznavanja in tehnike porazdeljenih senzorjev. Te tehnike zaznavanja so splošno uporabljene v rutinskih aplikacijah za spremljanje stanja mostov, zgradb, spomenikov, tunelov, jezov, nasipov, vodovodov, zemeljskih plazov. V članku so predstavljeni sistemi, tehnologije in pomembne aplikacije.

1 Fiber optic sensors

There exist a great variety of fiber optic sensors /1/ for structural monitoring in both the academic and the industrial areas. In this overview we will concentrate on SOFO and DiTeSt sensors. These systems for civil health monitoring that have reached an industrial level and have been used in a number of field 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 sen-

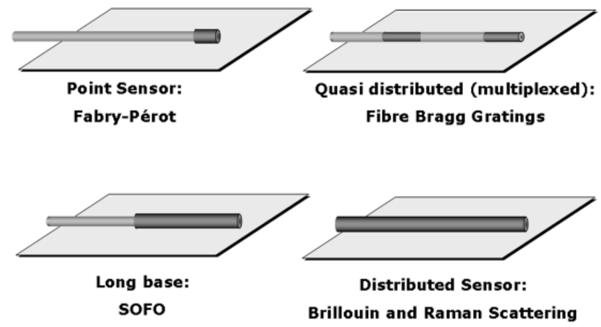


Fig. 1: Fiber Optic Sensor Types

sors 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.

1.2 SOFO Displacement Sensors

The SOFO system (Figure 2) 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 /2/.

Fig. 2: 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 3). 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.

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.

1.3 Bragg Grating Strain Sensors

Bragg gratings are periodic alterations in the index of refraction of the fiber core that can be produced by ade-

Fig. 3: SOFO Sensor installed on a rebar

quately 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 /3/. This is typically done using a tunable filter (such as a Fabry-Perot cavity) or a spectrometer. Resolutions 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 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 trade-off 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. With adequate packaging they can also be used to measure strains in concrete over basis length of typically 100 mm.

1.4 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 (see Figure 4) /4/. 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.

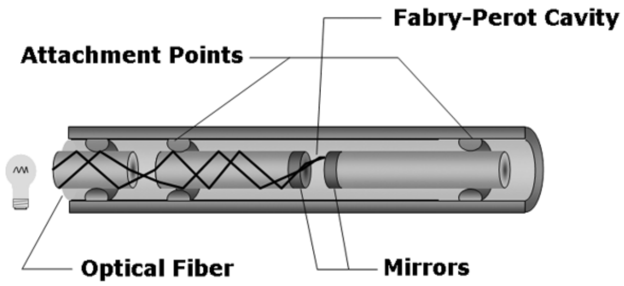


Fig. 4: Fabry-Perot Sensor

1.5 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 /5/. 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.

1.6 Brillouin Distributed Temperature sensors

Brillouin scattering sensors show an interesting potential 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 /6/. 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

Fig. 5: DiTeSt Reading Unit

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 /6/. 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 5). 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 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.

2.1 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 be seen in Figure 6 /7/.

Fig. 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.

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.

2.2 Pile loading test

A new semi-conductor production facility in the Tainan Scientific Park, Taiwan, is 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 meters SOFO sensors were used. The pile was divided into eight zones (called

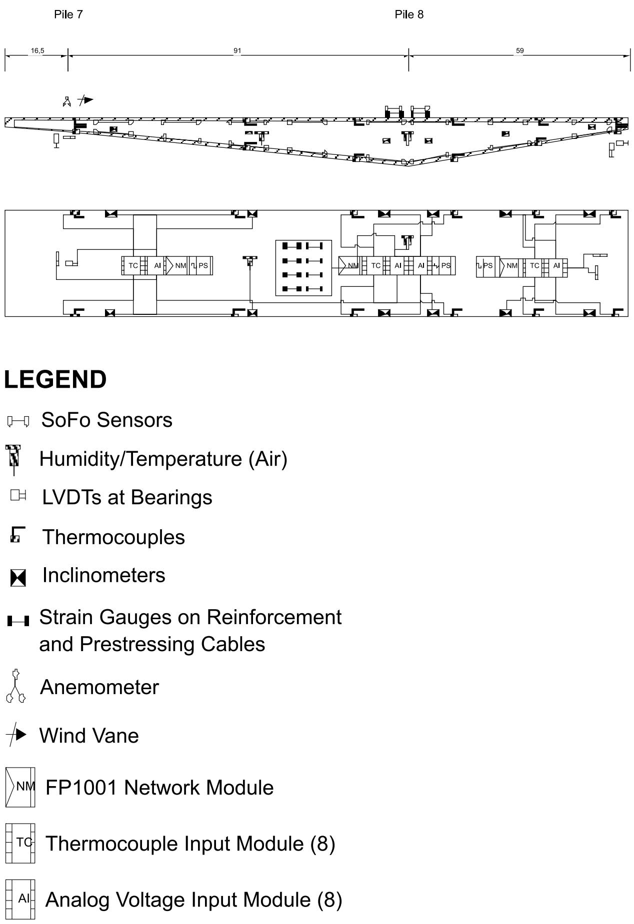


Fig. 7: Layout of the Colle Isarco Bridge Instrumentation (courtesy of K. Bergmeister)

cells). In the case of axial compression and pullout tests, a simple topology was used: the eight sensors were installed in a single chain, placed along one the main rebar, one sensor in each cell, as shown in Figure 8. To detect and compensate for a possible load eccentricity, the top cell was equipped with one more sensor installed on the opposite rebar with respect to the pile axis (see Figure 5).

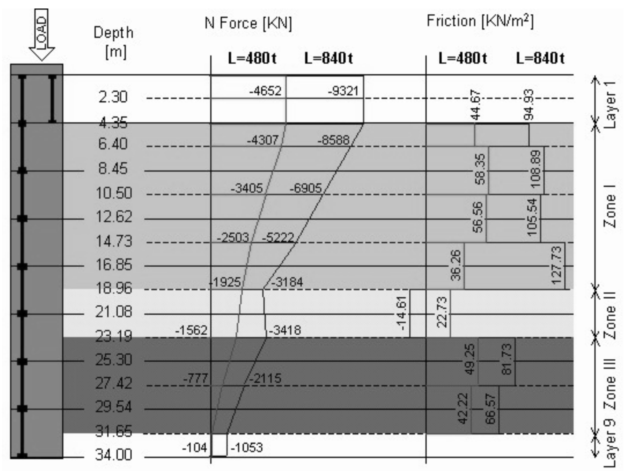


Fig. 8: Sensor topology and results obtained by monitoring during the axial compression test

As a result of monitoring rich information concerning the structural behavior of the piles is collected. Important parameters were determined such as distributions of strain, normal forces (see Figure 9), displacement in the pile, distribution of frictional forces between the pile and the soil, determination of Young modulus, ultimate load capacity and failure mode of the piles as well as qualitative determination of mechanical properties of the soil (three zones are distinguished in Figure 5).

In case of flexure test, a parallel topology was used: each cell contained two parallel sensors (as in cell 1 in Figure 8) installed on two opposite main rebars, constituting two chains of sensors. This topology allowed de-termination of average curvature in each cell, calculation of deformed shape and identification of failure point. Diagram of horizontal displacement for different steps of load as well as failure location on the pile are presented in Figure 6. In Figures 5 and 6 loads are presented in tons /8/.

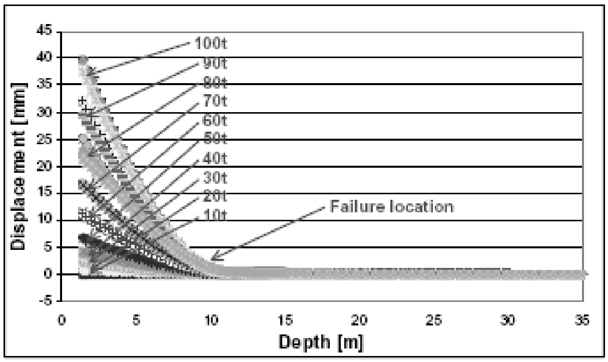


Fig. 9: Deformed shapes of the pile and identification of failure location

2.3 I35W Bridge, Minneapolis

This application example is a good example of a truly integrated structural health monitoring system, combining different sensing technologies to achieve the desired level of monitoring.

The collapse of the old I35W Bridge in Minneapolis in 2007 shook the confidence of the public in the safety of the infrastructure that we use every day. As a result, the construction of the replacement bridge (see Figure 10) must rebuild this confidence, by demonstrating that a high level of safety can not only be attained during construction, but also maintained throughout the projected 100-year lifespan of the bridge.

One of the central factors contributing to this is the design and installation of a comprehensive structural health monitoring system, which incorporates many different types of sensors measuring parameters related to the bridge performance and ageing behavior. This system continuously gathers data and allows, through appropriate analysis, to obtain actionable data on the bridge performance and health evolution /9/. The data provided is be used for op-

Fig. 10: New I35W Bridge in Minneapolis

erational functions, as well as for the management of ongoing bridge mainteonance, cmplementing and targeting the information gathered with routine inspections.

The monitoring system was designed and implemented through a close cooperation between the designer, the owner, the instrumentation supplier and University of Minnesota.

The main objectives of the system are to support the construction process, record the structural behavior of the bridge, and contribute to the intelligent transportation system as well as to the bridge security.

The design of the system was an integral part of the overall bridge design process allowing the SHM system to both receive and provide useful information about the bridge performance, behavior and expected lifetime evolution.

Monitoring instruments on the new St Anthony Falls Bridge measure dynamic and static parameter points to enable close behavioral monitoring during the bridge's life span. Hence, this bridge can be considered to be one of the first 'smart' bridges of this scale to be built in the United States.

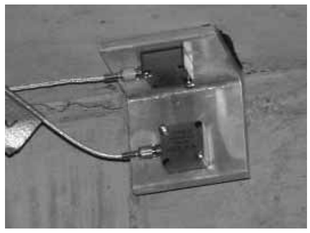
The system includes a range of sensors which are capable of measuring various parameters to enable the behavior of the bridge to be monitored. Strain gauges measure local static strain, local curvature and concrete creep and shrinkage; thermistors measure temperature, temperature gradient and thermal strain, while linear potentiometers measure joint movements. At the mid-spans, accelerometers are incorporated to measure traffic-induced vibrations and modal frequencies (Eigen frequencies). SensCore corrosion sensors are installed to measure the concrete resistivity and corrosion current.

Meanwhile there are long-gauge SOFO fiber optic sensors which measure a wide range of parameters, such as average strains, strain distribution along the main span, average curvature, deformed shape, dynamic strains, dynamic deformed shape, vertical mode shapes and dynamic damping – they also detect crack formation. Some of the installed sensors are shown in Figure 11.

Long-gauge SOFO fiber optic sensor

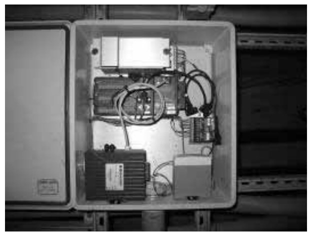
Vibrating Wire Strain Gauge

Concrete humidity and corrosion



Accelerometer

SOFO Fiber Optic Sensor Datalogger



Vibrating wire and temperature sensors datalogger

Fig. 11: Sensing components

The sensors are located throughout the two bridges, the northbound and southbound lanes, and are in all spans. However, a denser instrumentation is installed in the southbound main span over the Mississippi river, as depicted in Figure 12. This span will therefore serve as sample to observe behaviors that are considered as similar in the other girders and spans.

This project is one of the first to combine very diverse technologies, including vibrating wire sensors, fiber optic sensors, corrosion sensors and concrete humidity sensors into a seamless system using a single database and user interface.

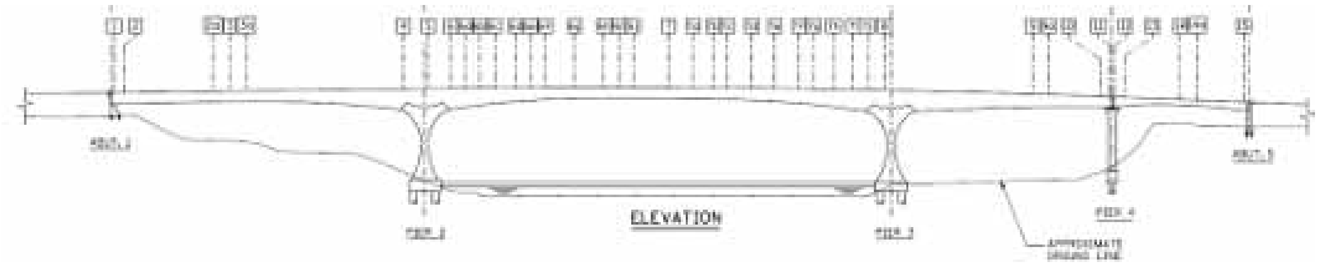


Fig. 12: Sensor locations

2.4 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 /10/.

The Luzzone dam was recently raised by 17 meters to increase the capacity of the reservoir (Figure 13). 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.

Fig. 13: Luzzone Dam raising works

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 14. 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.

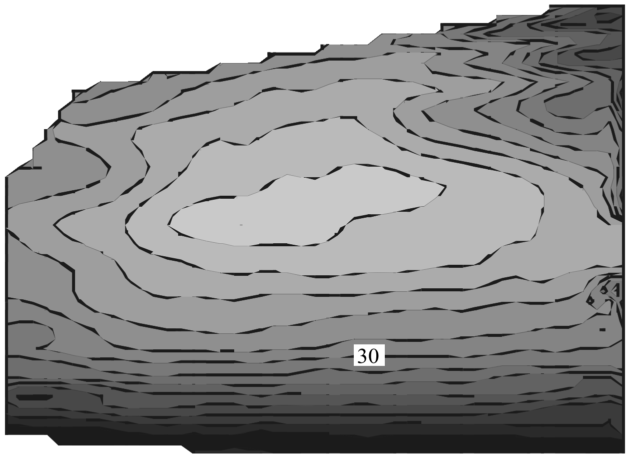


Fig. 14: Temperature measurements in the Luzzone Dam 15 days after concrete pouring

2.5 Bridge crack detection

Götaälvbron, the bridge over Göta River (Figure 15), 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 and integrity monitoring system has been mandatory.

Fig. 15: 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 /11/.

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 16. 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.

Fig. 16: 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.

2.6 Bitumen Joint Monitoring

Plavinu hes is a dam belongs to the complex of three most important hydropower stations on the Daugava River in Latvia (see figure 17). In terms of capacity this is the largest hydropower plant in Latvia and is considered to be the third level of the Daugavas hydroelectric cascade. It was constructed 107 km distant from the firth of Daugava and is unique in terms of its construction - for the first time in the history of hydro-construction practice; a hydropower plant was built on clay-sand and sand-clay foundations with a maximum pressure limit of 40 m. The HPP building is merged with a water spillway. The entire building complex is extremely compact. There are ten hydro-aggregates installed at the hydropower plant and its current capacity is 870,000 kW.

One of the dam inspection galleries coincides with a system of three bitumen joints that connects two separate blocks of the dam. Due to abrasion of water, the joints lose bitumen and the redistribution of loads in concrete arms appears. Since the structure is nearly 40 years old, the structural condition of the concrete can be compromised due to ageing. Thus, the redistribution of loads can provoke damage of concrete arm and as a consequence the inundation of the gallery. In order to increase the safety and enhance the management activities it was decided to monitor the average strain in the concrete arm next to the joints /12/. The DiTeSt system with SMARTape deformation (see Figure 18) sensor and Temperature Sensing Cable is used for this. The sensors were installed by company VND2 with SMARTEC support and configured remotely from the SMARTEC office. Threshold detection software with SPST (open-ground) module was installed in order to send pre-warnings and warnings from the DiTeSt instrument to the Control Office.

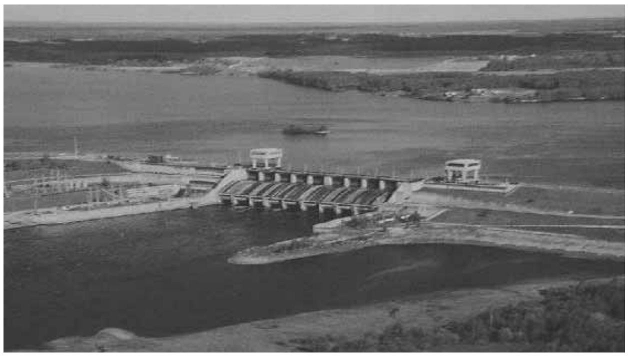


Fig. 17: Plavinu dam in Latvia

2.7 Gas Pipeline Monitoring

About 500 meters of a buried, 35 years old gas pipeline, located near Rimini, Italy, lie in an unstable area. Distributed strain monitoring could be useful in order to improve vibrating wire strain gauges monitoring system, actually used in the site. The landslide progress with time and could damage pipelines up to be put out of service. Three symmetrically disposed vibrating wires were installed in several sections at a distance typically of 50/100 m chosen as the most stressed ones according a preliminary engineering evaluation. These sensors were very helpful, but could not fully cover the length of the pipeline and only provide local measurements.

Different types of distributed sensors were used: SMARTape and Temperature Sensing Cable /13/. Three parallel lines constituted of five segments of SMARTape sensor were installed over whole concerned length of the pipeline (see figure 19). The lengths of segments were ranged from 71 m to 132 m, and the position of the sensors with respect to the pipeline axis were at 0°, 120° and –120° approximately. The strain resolution of the SMARTape is 20 micro-strains, with spatial resolution of 1.5 m (and an acquisition range of 0.25m) and provides the monitoring

Fig. 18: SMARTape installation in the inspection gallery

Fig. 19: SMARTape on the gas pipeline.

of average strains, average curvatures and deformed shape of the pipeline. The Temperature Sensing Cable was installed onto the upper line (0°) of the pipeline in order to compensate the strain measurements for temperature. The temperature resolution of the sensor is 1°C with the same resolution and acquisition of the SMARTape. All the sensors are connected to a Central Measurement Point by means of extension optical cables and connection boxes. They are read from this point using a single DiTeSt® reading unit. Since the landslide process is slow, the measurements sessions are performed manually once a month. In case of earthquake a session of measurements is performed immediately after the event. All the measurements obtained with the DiTeSt® system are correlated with the measurements obtained with vibrating wires. The sensors have been measured for a period of two years, providing interesting information on the deformation induced by burying and by the landslide progression. A gas leakage simulation was also performed with success using the temperature sensing cable.

3 Conclusions

Structural health monitoring is not a new technology or trend. Since ancient times, engineers, architects and artisans have been keen on observing the behavior of built structures to discover any sign of degradation and to extend their knowledge and improve the design of future structures. Ancient builders would observe and record crack patterns in stone and masonry bridges. Longer spans and more slender arches were constructed and sometimes failed during construction or after a short time /14/. Those failures and their analysis have led to new insight and improved design of future structures. This continued struggle for improving our structures is driven by engineering curiosity, but also by economic considerations.

As for any engineering problem, obtaining reliable data is always the first and fundamental step towards finding a solution. Monitoring structures is our way to get quantitative data about our bridges and help us in taking informed decisions about their health and destiny. This paper has presented the ad-vantages and challenges related to the implementation of an integrated structural health monitoring system, guiding the reader in the process of analyzing the risks, uncertainties and opportunities associated with the construction and operation of a specific bridge and the design of a matching monitoring system and data analysis strategy. Acknowledgments

Acknowledgments (if any) should appear as a separate non-numbered section before the list of references.

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Daniele Inaudi
SMARTEC / Roctest

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