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 form 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

Glisic, B., Inaudi, D., Nan, C. (2002) "Piles monitoring during the axial compression, pullout and flexure test using fiber optic sensors", 81st Annual Meeting of the Transportation Research Board (TRB), Washington, DC, January 13-17, 2002

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

Introduction

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

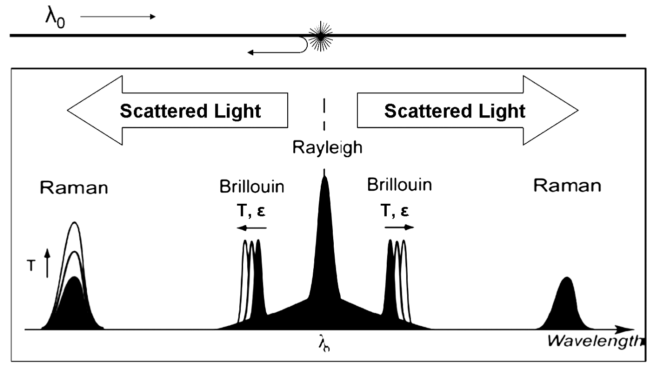

Figure 1. Light scattering in optical fibers and its use for strain and temperature sensing. At every section of fiber, the incoming wavelength λ_0 is scattered backwards. The backscattered light contains new wavelengths that carry information about the strain and temperature conditions at the location where the scattering occurred.

between the two will be explained later) are used to detect and localize seepage in dams and dikes, allowing the monitoring of hundreds of kilometers along a structure with a single instrument and the localization of the water path with an accuracy of 1 or 2 meters. Distributed strain sensors are also used to detect landslide movements and to detect the onset of cracks in concrete dams.

Early applications of this technology have demonstrated that the design and production of sensing cables, incorporating and protecting the optical fibers used for the measurement, as well as their optimal locating and installation in the structure under scrutiny, are critical elements for the success of any distributed sensing instrumentation project.

This article presents advances in distributed sensing systems and in sensing cables design for distributed temperature and strain measurements. The article also reports on a number of significant field application examples of this technology.

Distributed Fiber Optic Sensors

Unlike electrical sensors and localized fiber optic sensors, distributed sensors offer the unique characteristic of being able to measure physical parameters, in particular strain and temperature, along their whole length, allowing the measurements of thousands of points from a single readout unit. The most developed technologies of distributed fiber optic sensors are based on Raman and Brillouin scattering. Both systems make use of a nonlinear interaction between the light and the glass material of which the fiber is made. If an intense light at a known wavelength is shone into a fiber, a very small amount of it is scattered back from every location along the fiber itself. Besides the original wavelength (called the Rayleigh component), the scattered light contains components at wavelengths that are higher and lower than the original signal (called the Raman and Brillouin components). These shifted components contain information on the local properties of the fiber, in particular its strain and temperature. Figure 1 shows the main scattered wavelengths components for a standard optical fiber. If λ_0 is the wavelength of the original signal generated by the readout unit, the scattered components appear both at higher and lower wavelengths.

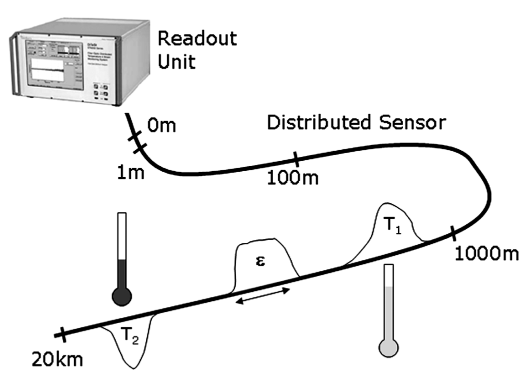

Figure 2. Schematic example of a distributed strain and temperature measurement.

The two Raman peaks are located symmetrically to the original wavelength. Their position is fixed, but the intensity of the peak at lower wavelength is temperature dependant, while the intensity of the one at higher wavelength is unaffected by temperature changes. Measuring the intensity ratio between the two Raman peaks therefore yields the local temperature in the fiber section where the scattering occurred.

The two Brillouin peaks are also located symmetrically at the same distance form the original wavelength. Their position relative to λ_0 is however proportional to the local temperature and strain changes in the fiber section. Brillouin scattering is the result of the interaction between optical and ultrasound waves in optical fibers. The Brillouin wavelength shift is proportional to the acoustic velocity in the fiber that is related to its density. Since the density depends on the strain and the temperature of the optical fiber, we can use the Brillouin shift to measure those parameters. For temperature measurements, Brillouin scattering is a strong competitor against systems based on Raman scattering, while for strain measurements it has practically no rivals.

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 through the different time-of-flight of the scattered light. Combining the radar technique and the spectral analysis of the returned light one can 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 (note that "spatial resolution" is a standard concept of distributed sensing, even though this is not 100% correct in metrological terms) of 1 m. Figure 2 schematically shows an example of distributed strain and temperature sensing. Systems based on Raman scattering typically exhibit temperature accuracy

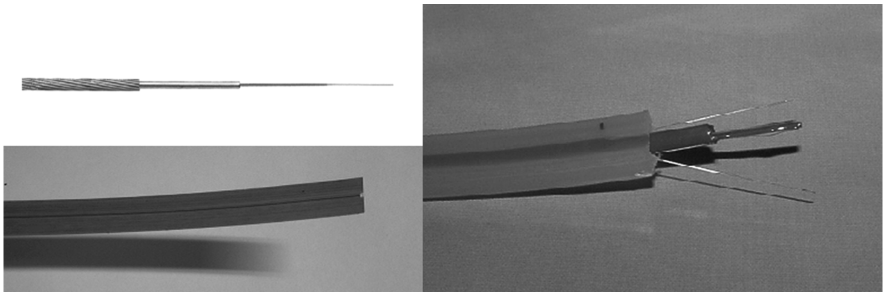

Figure 3. Distributed sensor cables examples. Left-top: temperature sensor; Left-bottom: strain sensor; right: combined strain and temperature sensor.

of the order of ± 0.1°C and a spatial resolution of 1m over a measurement range up to 8 km. The best Brillouin scattering systems offer a temperature accuracy of ± 0.1°C, a strain accuracy of ±20 microstrain and a measurement range of 30 km, with a spatial resolution of 1 m. The readout units are portable and can be used for field applications.

The optical fibers themselves are only 1/8 of a millimeter in diameter and are therefore difficult to handle and relatively fragile. For practical uses, it is therefore necessary to package them in a larger cable, much like copper conductors are incorporated in an electrical cable.

Since the Brillouin frequency shift depends on both the local strain and temperature of the fiber, the sensor set-up will determine the actual response of the sensor. For measuring temperatures it is necessary to use a cable 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. Measuring distributed strains also 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. Special cables, containing both free and coupled fibers allow a simultaneous reading of strain and temperature. Figure 3 shows examples of temperature, strain and combined cables.

Application Examples

This section presents brief application examples of distributed sensing for the monitoring of civil and industrial structures.

Temperature Monitoring in a Concrete Dam

In this application, a Brillouin scattering sensor system was used to monitor the temperature development in the concrete used to build a dam. The

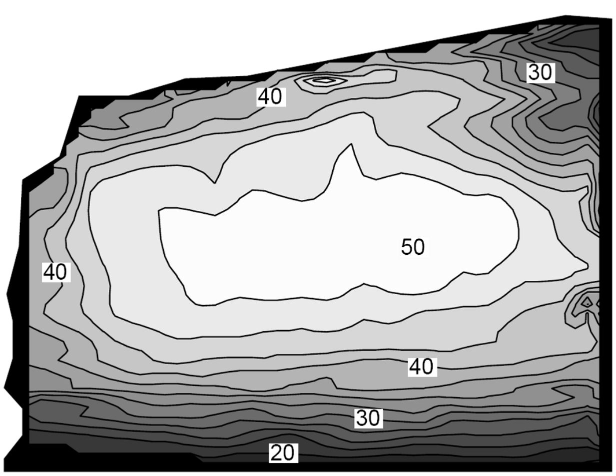

Figure 4. Contour plot (isothermal lines) of the temperature measurements in °C at the Luzzone Dam 30 days after concrete pouring (courtesy of L. Thévenaz).

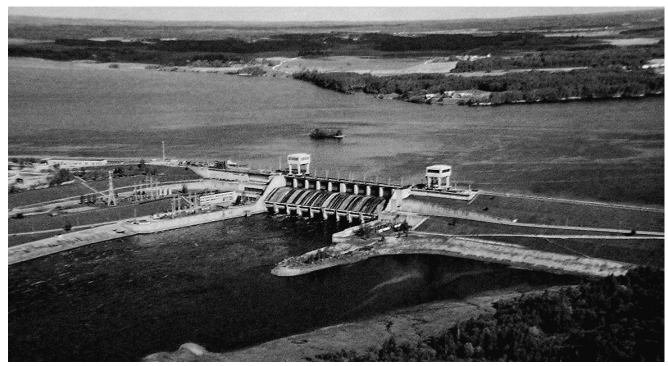

Figure 5. Plavinu Dam in Latvia.

Figure 6. Strain sensor installation in the Plavinu Dam inspection gallery.

Figure 7. Strain and temperature sensing cables installed on a gas pipeline. The picture shows a sensor line attached to the top of the pipeline and one on the side. The sensors are protected with an black neoprene pad. Another sensor line is attached symmetrically on the opposite side. The temperature sensing cable is also installed on top of the pipe. The vertical tube at the center of the picture, brings the optical cables form the pipeline to the junction box.

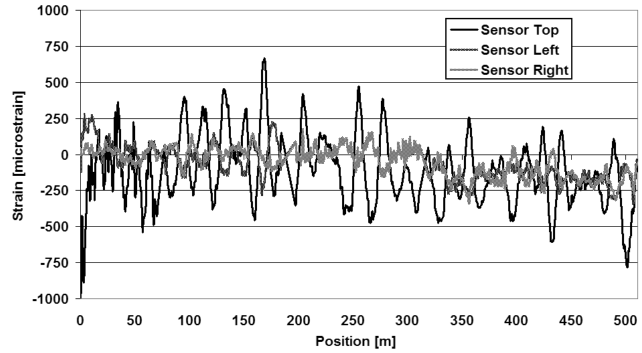

Figure 8. Strain distribution over the monitored part of the pipeline measured by the three distributed strain sensors. Each curve is composed of 500 individual strain points.

Luzzone concrete arch dam was raised by 17 meters to increase the capacity of the reservoir. The raising was achieved by successively concreting 3m thick blocks. The measurements concentrated on the largest block to be poured, the one that rests against the rock foundation at one end of the dam. An armored cable installed in a zigzag pattern during concrete pouring constituted the Brillouin sensor and was placed in the middle of the concrete block thickness. The cable therefore became embedded in the concrete.

The temperature measurements started immediately after pouring and continued over six months. The measurement system was proved reliable even in the demanding environment present at the dam (dust, snow, and temperature excursions). The temperature distributions after 30 days from concrete pouring are shown in Figure 4. 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 distributed sensing make it particularly adapted to the monitoring of large structures where the use of more conventional sensors would require extensive cabling.

Monitoring Bitumen Joints in a Dam

Plavinu dam belongs to the complex of the three most important hydropower stations on the Daugava River in Latvia (see Figure 5). 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 loose bitumen, and a redistribution of loads in the concrete arms appears. Since the structure is nearly 40 years old, the structural condition of the concrete can be compromised because of its ageing. Thus, the redistribution of loads can crack the concrete 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 next to the joints. A Brillouin scattering system, combined with a strain and temperature sensing cable is used for this purpose (see Figure 6). The strain sensors are coupled to the concrete with bolted metallic plates every two meters. The readout unit automatically performs measurements every 15 minutes and a threshold detection software sets off warnings and alarms to the Control Office. Fortunately, so far this has never been the case.

Since it is not possible to predict where a crack might appear along the length of the dam, instrumenting it with conventional discrete sensors, even long-gage ones, would have required the installation of hundreds of sensors, along with their cables and data acquisition systems. Thanks to distributed sensing the same goal can be achieved with just two cables and a single readout unit.

Monitoring a Gas Pipeline

About 500 meters of a buried 35-year old gas pipeline, located in Italy, lie in a landslide-prone area. Distributed strain monitoring was selected in order to improve an existing vibrating wire strain gage monitoring system. The landslide progresses with time and could damage

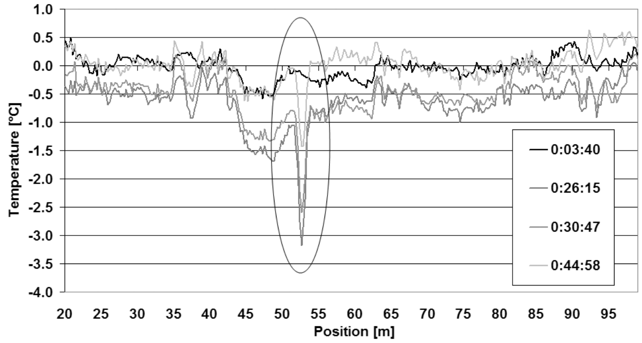

Figure 9. Results of leakage test; leakage is detected as temperature drop at the leakage location.

the pipeline until it would be put out of service. In the past, three symmetrically located vibrating wires strain gages were installed in several sections at a distance typically of 50 to 100m, chosen as the most stressed locations according a preliminary engineering evaluation. These sensors were very helpful, but could not fully cover the length of the pipeline as they provide only local measurements.

Distributed strain and temperature sensing cables were installed at the project. Three parallel lines consisting of five segments of strain sensing cable were installed over whole length of the pipeline for which there were concerns, at approximately 0°, 120° and –120° around the pipeline circumference (see Figure 7). The sensing cables were epoxy-glued to the surface of the pipeline along their whole length and protected with a neoprene mat. This instrumentation allows the monitoring of strain, curvatures and deformed shape of the pipeline every meter (corresponding to the spatial resolution of the Brillouin system in use). The temperature sensing cable was installed onto the upper line (0°) of the pipeline in order to compensate the strain measurements for temperature and for leakage detection purposes. All the sensors are connected to a central measurement point by means of optical extension cables and connection boxes. They are interrogated from this point using one single readout unit. Since the landslide process is slow, the measurement sessions were performed manually once a month.

In case of need, a dedicated readout unit can be installed onsite and the data transmitted wirelessly to the pipeline owners. All the measurements obtained with the system are correlated with the measurements obtained with vibrating wire strain gages placed at a few selected locations.

Figure 8 shows the strain changes recorded after burying the pipeline. This figure contains more than 1,500 strain measurement points, a coverage that could never be achieved with any conventional strain sensing technology.

During the installation of the sensors and the burying of the pipeline, a gas leakage simulation test was performed by installing an empty plastic tube over a distance of 50m at the beginning of the first monitored segment, connecting the surface of the pipe at that point with the open air. Carbon dioxide was injected into the tube, cooling down the pipe end to mimic conditions expected in the case of a gas leakage. A reference temperature measurement was performed before injecting the carbon dioxide. Afterwards temperature measurements were performed every two to ten minutes and compared with the reference measurement. The results of the test are presented in Figure 9. The test was successful, and the point of the simulated leakage was clearly observed and localized (encircled area in Figure 9).

Conclusions

The use of distributed fiber optic sensors for the monitoring of civil and geotechnical structures opens new possibilities that have no equivalent in conventional sensors systems. Thanks to the use of a single optical fiber with a length of tens of kilometers it becomes possible to obtain dense information on the strain and temperature distribution in the structure. This technology is therefore particularly suitable for applications at large or elongated structures, such as dams, dikes, levees, large bridges and pipelines.

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