Distributed Fiber optic Strain and Temperature Sensing for Structural Health Monitoring

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ABSTRACT: Distributed fiber optic sensing presents unique features that have no match in conventional sensing techniques. The ability to measure temperatures and strain at thousands of points along a single fiber is particularly interesting for the monitoring of large structures such as bridges, pipelines, flow lines, oil wells, dams and dikes. Sensing systems based on Brillouin and Raman scattering have been used for example to measure cables and pavement temperatures in bridges, detect pipeline leakages, prevent failure of pipelines installed in landslide areas, optimize oil production from wells and detect hot-spots in high-power cables.
The measurement instruments have been vastly improved in terms of spatial, temperature and strain resolution, distance range, measurement time, data processing and system cost. Analyzers for Brillouin and Raman scattering are now commercially available and offer reliable operation in field conditions.
New application opportunities have however demonstrated that the design and production of sensing cables is a critical element for the success of any distributed sensing instrumentation project. Although standard telecommunication cables can be effectively used for sensing ordinary temperatures, monitoring high and low temperatures or distributed strain present unique challenges that require specific cable designs.
This contribution presents different cable designs for high-temperature sensing, strain sensing and combined strain and temperature monitoring, as well as relevant application examples to the monitoring of civil and oil & gas structures.

1 INTRODUCTION

Structural health monitoring is certainly one of the most powerful management tools and is therefore gaining in importance in the civil engineering community. 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.
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.
From many points of view, fiber optic sensors are indeed the ideal transducers for civil structural monitoring. Being durable, stable and insensitive to external perturbations, they are par-

ticularly interesting for the long-term health assessment of civil structures. This contribution will concentrate on distributed fiber optic sensors that offer unique characteristics that are unparalleled by the conventional sensors.

2 DISTRIBUTED FIBER OPTIC SENSORS

Unlike electrical and localized fiber optic sensors, distributed sensor offer the unique characteristic of being able to measure physical and chemical parameters along their whole length, allowing the measurements of thousands of points using a single transducer. The most developed technologies of distributed fiber optic sensors are based on Raman and Brillouin scattering. Both systems make use of a non-linear interaction between the light and the silica material of which the fiber is made. If light at a known wavelength is launched into a fiber, a very small amount of it is scattered back every point along the fiber. The scattered light contains components at wavelengths that are different form the original signal. These shifted components contain information on the local properties of the fiber, in particular their strain and temperature.

2.1 *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). Systems based on Raman scattering is commercialized by SMARTEC in Switzerland, Sensornet in the UK and Sensa in the UK. Typically a temperature resolution of the order of 0.1°C and a spatial resolution of 1m over a measurement range up to 8 km are obtained for multi-mode fibers.

Figure 1:Raman Scattering system (DiTemp)

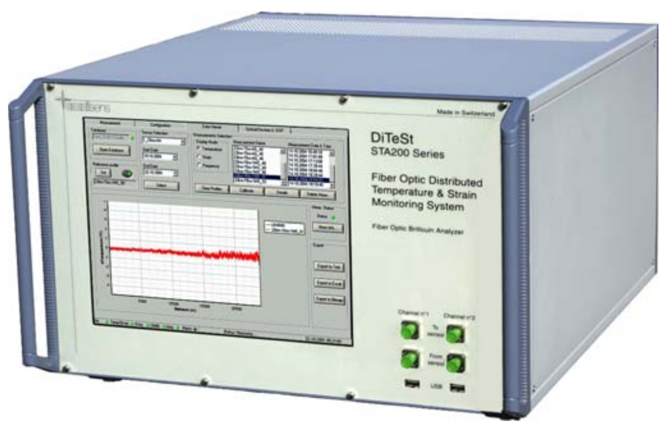

Figure 2: Brillouin Scattering system (DiTeSt)

2.2 *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).

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 2). 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.

2.3 *Sensing Cable Design*

Traditional fiber optic cable design aims to the best possible protection of the fiber itself from any external influence. In particular it is necessary to shield the optical fiber form external humidity, side pressures, crushing and longitudinal strain applied to the cable. These design have proven very effective in guaranteeing the longevity of optical fibers used for communication and can be used as sensing elements for monitoring temperatures in the –20°C to +60°C range, in conjunction with Brillouin or Raman monitoring systems.

Sensing distributed temperature below 20°C or above 60°C requires a specific cable design, especially for Brillouin scattering systems, where it is important to guarantee that the optical fiber does not experience any strain that could be misinterpreted as a temperature change due to the cross-sensitivity between strain and temperature.

On the other hand, the strain sensitivity of Brillouin scattering prompts to the use of such systems for distributed strain sensing, in particular to monitor local deformations of large structures such as pipelines, landslides or dams. In these cases, the cable must faithfully transfer the struc-

tural strain to the optical fiber, a goal contradicting all experience form telecommunication cable design where the exact opposite is required.
Finally when sensing distributed strain it is necessary to simultaneously measure temperature to separate the two components. This is usually obtained by installing a strain and a temperature sensing cables in parallel. It would be therefore desirable to combine the two functions into a single packaging.

2.4 *Extreme temperature sensing cable*

The extreme temperature sensing cables are designed for distributed temperature monitoring over long distances. They consist of up to four single mode or multimode optical fibers contained in a stainless steel loose tube, protected with stainless steel armoring wires and optionally a polymer sheath. These components can be differently combined in order to adapt the cable to the required performance and application. The use of appropriate optical fibre coating (polyimide or carbon/polyimide) allows the operation over large temperature ranges, the stainless steel protection provides high mechanical and additional chemical resistance while the polymer sheath guarantees corrosion protection. The carbon coating offers improved resistance to hydrogen darkening. The over-length of the optical fibers is selected in such a way that the fiber is never pulled or compressed, despite the difference in thermal expansion coefficients between glass and steel. The total cable diameter is only 3.8 mm (see figure 3).

These cables can be used in a wide range of applications that require distributed temperature sensing, such as temperature monitoring of concrete in massive structures, waste disposal sites, onshore, off-shore and downhole sites in gas and oil industry, hot spots, cold spots and leakage detection of flow lines and reservoirs, fire detection in tunnels and mapping of cryogenic temperatures, just to name a few.

Figure 3: Extreme temperature sensing cable design and termination

2.5 *Strain sensing tape: SMARTape*

When strain sensing is required, the optical fiber must be bonded to the host material over the whole length. The transfer of strain is to be complete, with no losses due to sliding. Therefore an excellent bonding between strain optical fiber and the host structure is to be guaranteed. To allow such a good bonding it has been recommended to integrate the optical fiber within a tape in the similar manner as the reinforcing fibers are integrated in composite materials. To produce such a tape, we selected a glass fiber reinforced thermoplastic with PPS matrix. This material has excellent mechanical and chemical resistance properties. Since it production involves heating to high temperatures (in order to melt the matrix of the composite material) it is necessary for the fiber to withstand this temperature without damage. In addition, the bonding between the optical fiber coating and the matrix has to be guaranteed. Polyimide-coated optical fibers fit these requirements and were therefore selected for this design.

The typical cross-section width of the thermoplastic composite tape that is used for manufacturing composite structures is in the range of ten to twenty millimeters, and therefore not critical for optical fiber integration. The thickness of the tape can be as low as 0.2 mm, and this dimension is more critical since the external diameter of polyimide-coated optical fiber is of 0.145 mm approximately. Hence, only less than 0.03 mm of tape material remains on top or bottom of the optical fiber, with the risk that the optical fiber will emerge from the tape. The scheme of the sensing tape cross-section, with typical dimensions, is presented in Figure 4.

The use of such sensing tape (called SMARTape) is twofold: it can be used externally, attached to the structure, or embedded between the composite laminates, having also a structural role.

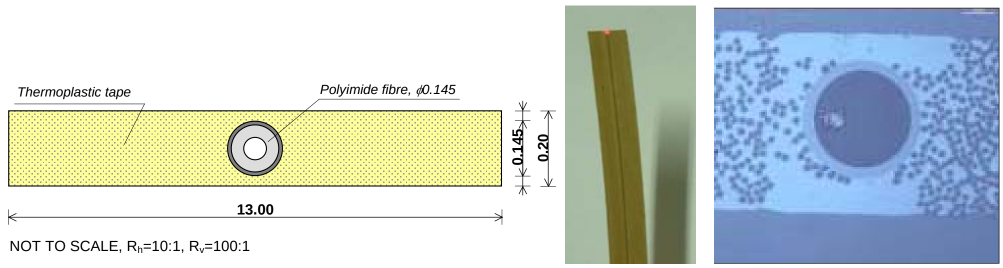

Figure 4: Cross-section picture and micrograph of the sensing tape: SMARTape

2.6 *Combined Strain and temperature sensing: SMARTprofile*

The SMARTprofile sensor design combines strain and temperature sensors in a single package. This sensor consists of two bonded and two free single mode optical fibers embedded in a polyethylene thermoplastic profile. The bonded fibers are used for strain monitoring, while the free fibers are used for temperature measurements and to compensate temperature effects on the bonded fibers. For redundancy, two fibers are included for both strain and temperature monitoring. The profile itself provides good mechanical, chemical and temperature resistance. The size of the profile makes the sensor easy to transport and install by fusing, gluing or clamping. The SMARTprofile (see figure 4) sensor is designed for use in environments often found in civil geotechnical and oil & gas applications. However, this sensor cannot be used in extreme temperature environments nor environments with high chemical pollution. It is not recommended for installation under permanent UV radiation (e.g. sunshine).

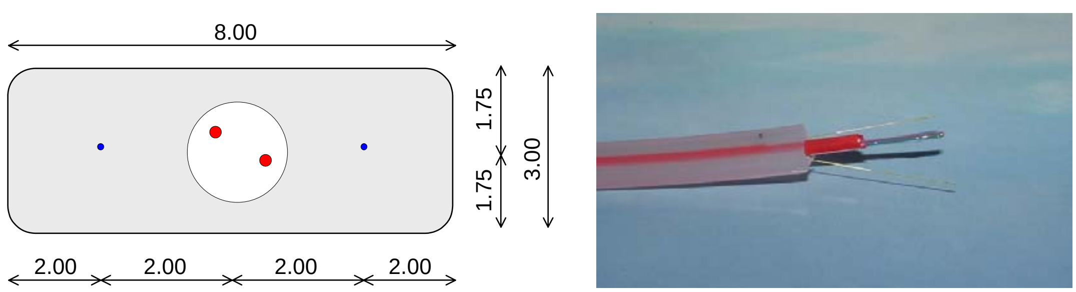

Figure 5: SMARTprofile cross-section and sample. The red tube contains the free fibers

3 APPLICATION EXAMPLES

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

3.1 *Luzzone Dam Temperature monitoring*

Distributed temperature measurements are highly interesting for the monitoring of large structures. In the presented application, SMARTEC and EPFL 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 6). 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.

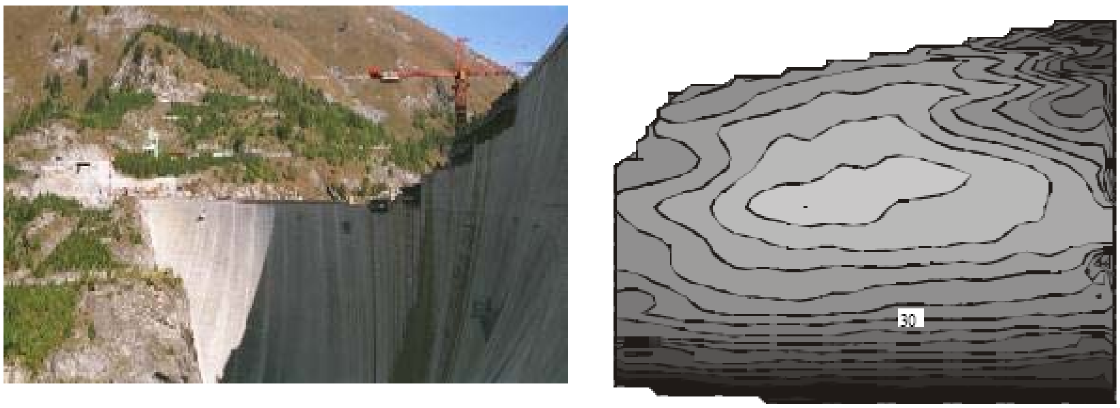

Figure 6: Luzzone Dam raising works and temperature measurements in the Luzzone Dam 55 days after concrete pouring (courtesy of L. Thévenaz)

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 6. 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.

3.2 *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 7). 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.

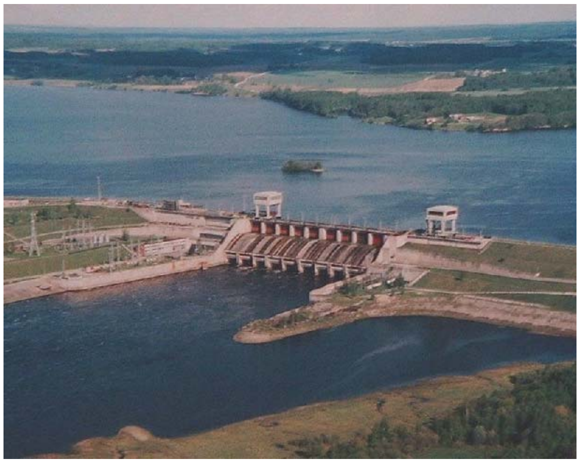

Figure 7: Plavinu dam in Latvia

Figure 8: SMARTape installation in the inspection gallery.

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. The DiTeSt system with SMARTape deformation sensor and Temperature Sensing Cable is used for this purpose (see figure 8). 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.

3.3 *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. Three parallel lines constituted of five segments of SMARTape sensor were installed over whole concerned length of the pipeline (see figure 9). 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 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. 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.

 

Figure 9: SMARTape on the gas pipeline.

4 CONCLUSIONS

The use of distributed fiber optic sensors for the monitoring of civil structures and infrastructures opens new possibilities that have no equivalent in the conventional sensors system. Thanks to the use of a single optical fiber with a length of tens of kilometers has sensing elements; it becomes possible to obtain dense information on the structure's strain and temperature distribution. This technology is therefore particularly suitable for applications to large or elongated structures; such has dams, large bridges and pipelines.
The presented applications examples show that using an appropriate sensor design, it is possible to successfully install distributed sensors on large structures and obtain useful data for the evaluation and management of the monitored structures.

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