Reliability and field testing of distributed strain and temperature sensors

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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 pipelines, flow lines, oil wells, dams and dikes. Sensing systems based on Brillouin and Raman scattering have been used for example to detect pipeline leakages, verify pipeline operational parameters, 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 three cable designs for high-temperature sensing, strain sensing and combined strain and temperature monitoring as well as the respective testing procedures during production and in the field.

Keywords: distributed sensing, Raman scattering, Brillouin scattering, strain monitoring, temperature monitoring, cable design

1. INTRODUCTION

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 [1] 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 structural 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.

These very practical requirements have lead to the development of cables specifically designed for sensing applications that will be presented next, together with a few application examples.

2. GENERAL RELIABILITY REQUIREMENTS

All cable designs share common reliability goals independently from the used sensing technique (Brillouin or Raman scattering) and application domain:

- The optical fibers must be compatible with the selected sensing system: singlemode fibers for Brillouin scattering and (usually) multimode fibers for Raman scattering systems.
- The fibers must be protected form external mechanical actions during installation and while in use. In particular the cable design must allow easy manipulation without the risk of fiber damage.
- The cable design must allow sufficient shielding of the optical fibers form chemical aggression by water and other harmful substances.
- All optical losses must be kept as low as possible in order not to introduce degradations to the native instrument's distance range.
- Installation of connectors and repair of damaged sensors should be compatible with field operations.

The next paragraph will describe cable designs for high and low temperatures, distributed strain and combined strain and temperature sensing

3. 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 (see figure 1). 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.

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.

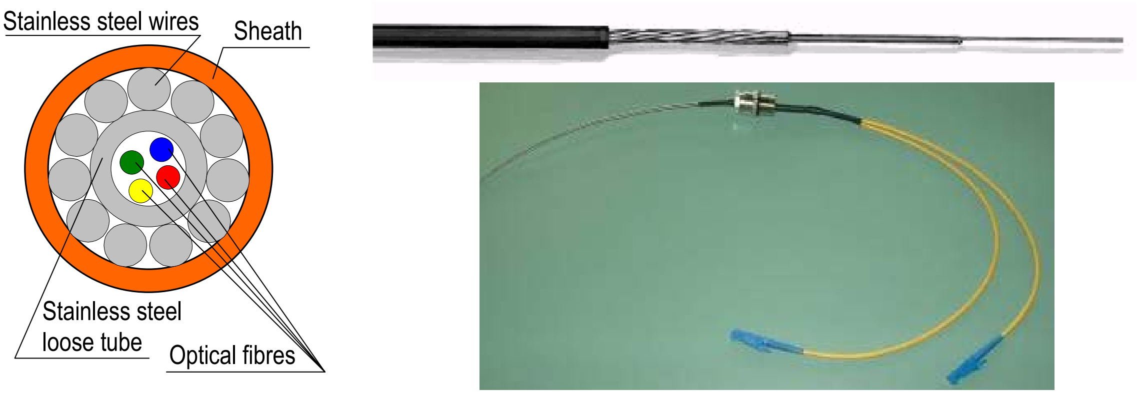

Figure 1: Extreme temperature sensing cable design and termination.

4. 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 [2]. 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 2.

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.

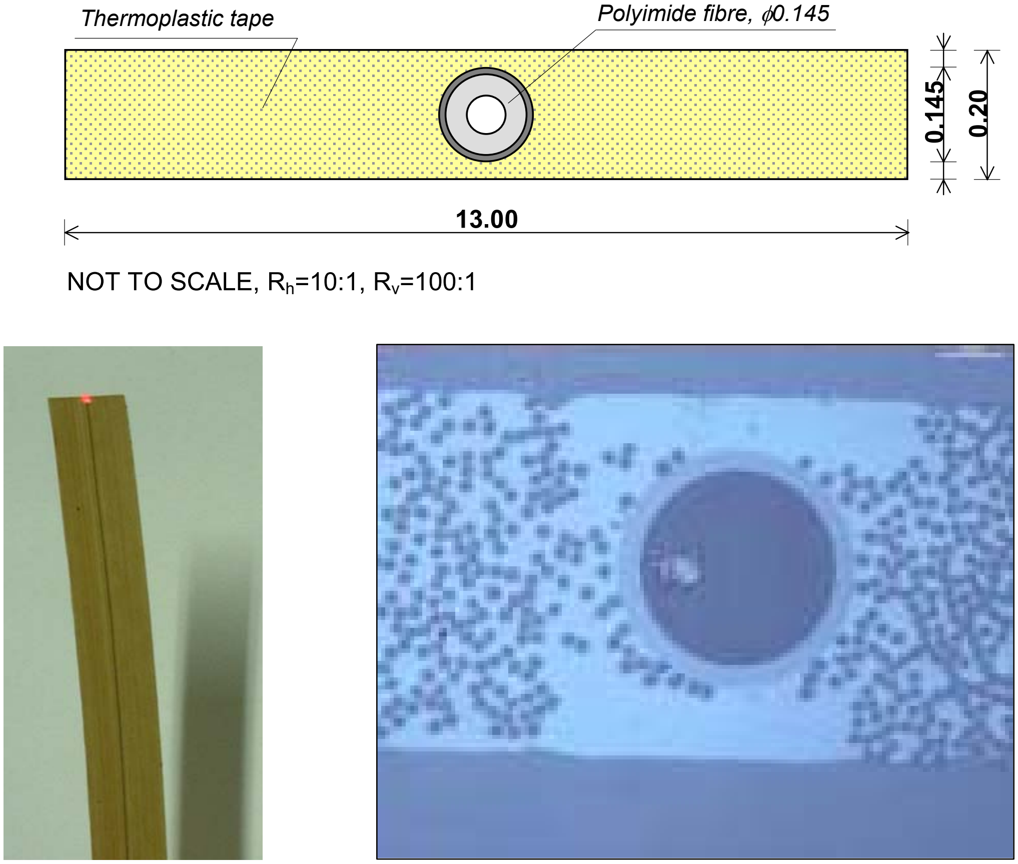

Figure 2: Cross-section, picture and micrograph of the sensing tape: SMARTape

5. 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 [3]. 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 3) 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).

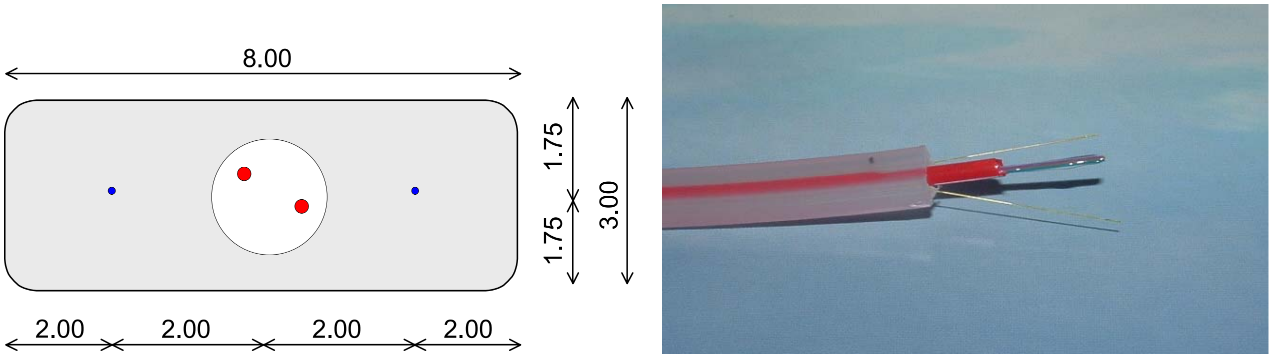

Figure 3: SMARTprofile cross-section and sample. The red tube contains the free fibers.

6. APPLICATION EXAMPLES

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

6.1 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 [4].
The Luzzone dam was recently raised by 17 meters to increase the capacity of the reservoir (Figure 4). 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 4: Luzzone Dam raising works

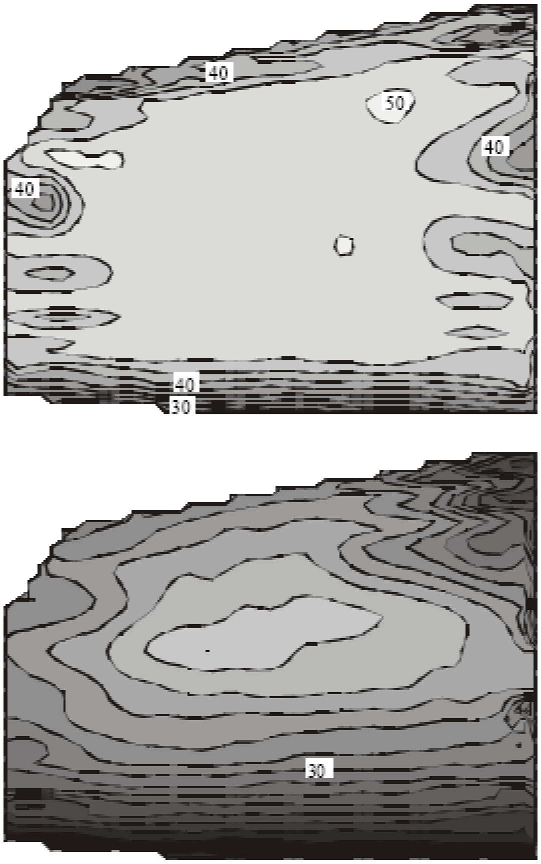

Figure 5: temperature measurements in the Luzzone Dam 15 and 55 days after concrete pouring (courtesy of L. Thévenaz, EPFL)

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 5. 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.

6.2 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 6). 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.

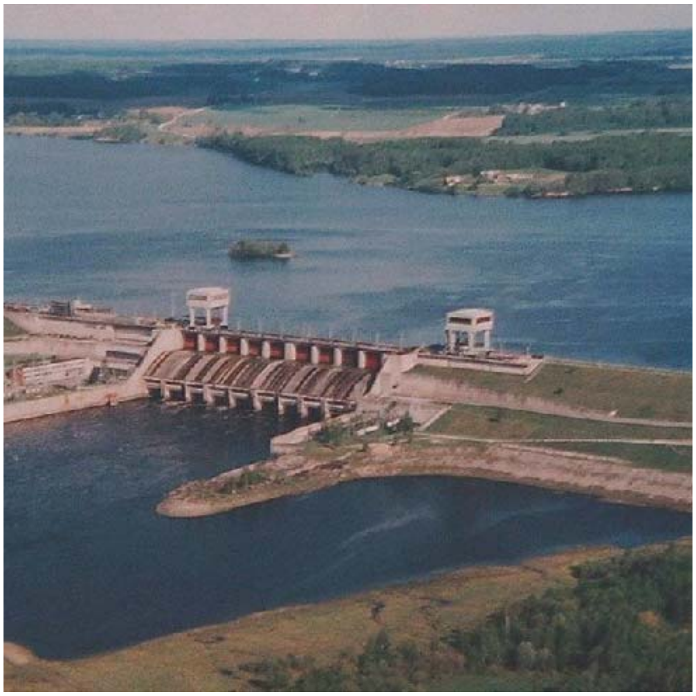

Figure 6: Plavinu dam in Latvia

Figure 7: 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 7). 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.

6.3 Gas Pipeline Monitoring

About 500 meters of a buried, 35 years old gas pipeline, located in 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 8). 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. 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. At present stage, 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 8: SMARTape on the gas pipeline.

6. CONCLUSIONS

The following table compares the performances of the presented cable designs and specifies their application domains and limitations.

	Extreme temperature sensor	**SMARTape**	**SMARTprofile**
Measurement parameters	Temperature	Strain	Strain and temperature
Number of fibers	1 to 4	1	2 for strain and 2 for temperature
Typical losses @1550nm	0.3 dB / km	5 dB / km	2.0 dB/km for strain 0.3 dB/km for temperature
Temperature range	-180 to +300 °C	-180 to +140 °C	-40 to + 60 °C
Chemical aggression resistance	Good to Excellent (with polymer sheath)	Excellent	Good
Application examples	Fire detection, cryogenic tanks, high-temperature pipeline monitoring, remote heating system monitoring, steam generator monitoring	Pipeline strain, composite pipes monitoring, surface installation on concrete, steel and timber, embedding in composites	Strain, temperature, leakage and 3rd party intrusion detection for pipelines

Table 1: Comparison of the sensor performances and characteristics.

The presented sensor designs were developed explicitly for use with distributed sensing systems, in particular with Brillouin scattering systems (BOTDR, BOTDA and BOFDA). Their characteristics are optimized for sensing fidelity and longevity in structural health monitoring applications. This required new approaches departing from the conventional telecommunications cable design, but using similar processes to achieve mass-production and low cost per meter. The first application examples show how these new designs can be effectively used in field conditions.

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