Full-Length Tunnel Structural Monitoring

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ABSTRACT

New and existing tunnels can present structural risks related to surrounding geotechnical and hydrological conditions as well as unknowns related to design assumptions and construction materials. Such risks can materialize through the apparition of abnormal deformations, cracks, water ingress or, in the worse cases, collapse. The localization of such events or their precursor signs is a-priori unknown, so traditional instrumentation in chosen cross-sections is ineffective for damage detection and localization. Regular visual inspection is more effective in terms of detection probability, but is typically limited in terms of temporal intervals between visits. Additionally, tunnels are often difficult to inspect since the access is restricted due to operational reasons.

If such structural risks have been recognized in the design phase or have been identified by inspection, installing a distributed fiber optic sensing system allows a permanent monitoring of the tunnel over its whole length. Sensing cables are typically installed longitudinally along the tunnel length at different positions around the section and provide detection and localization or abnormal deformations and settlements, formation or development of cracks and unusual temperatures.

This contribution presents the application of distributed optical fiber sensing to the permanent monitoring of a highway, a railway and a penstock tunnel. For each project we provide information about the system design, installation and monitoring results.

TUNNEL MONITORING NEEDS

The growing demand of tunnel safety during construction and in operation, has stimulated, in the last years, the development of several monitoring techniques capable of detecting and localizing early-stage events, thus preventing structures from major failures and leading to a better knowledge of the structure itself. In the field of geotechnical applications such as tunnels, where both the large structure dimensions and damage location forecast represent a challenge, distributed techniques offer the capability of monitoring the whole length of the tunnel using a single fiber optic sensor.

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Thus, using a limited number of very long sensors, it is possible to monitor structural and functional behavior of tunnels with a high measurement and spatial resolution at a reasonable cost [1]. Typical needs in tunnel monitoring include: detection and localization of cracks in concrete lining, monitoring horizontal and vertical deformations, convergence monitoring, joint movements and localization of water ingress points. All those events are unpredictable in their location. It is therefore unpractical to address those using traditional point sensor installed at some predefined locations, since events can occur in-between those instrumented sections [2]. The common practice is therefore to rely on regular visual inspection. This, however, often requires to stop traffic in the tunnel and this strongly limits the frequency of such inspections. A permanent and autonomous monitoring system able to cover the whole length of the tunnel, therefore present real operational and safety advantages.

DISTRIBUTED STRAIN SENSING

Unlike electrical and localized fiber optic sensors, distributed sensors offer the unique characteristic of being able to measure physical 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 [3]. Both systems make use of a non-linear interaction between the light and the silica material of which a standard optical fiber is made. If light at a known wavelength is launched into a fiber, a very small amount of it is scattered back at every point along the fiber. The scattered light contains components at wavelengths that are different from the original signal. These shifted components contain information on the local properties of the fiber, in particular its strain and temperature. For strain and deformation monitoring, Brillouin scattering is the only option, since Raman is only sensitive to temperature.

Brillouin Distributed Strain Technology

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 exceeding 50 km with spatial resolution down to 1m, are now demonstrating their usefulness in field applications. 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.

Sensing Cables

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 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 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. The next section will introduce different cable designs to measure strain and temperature in different applications.

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 from external humidity, side pressures, crushing and longitudinal strain applied to the cable. These designs have proven very effective in guaranteeing the longevity of optical fibers used for communication and they can be used as sensing elements for monitoring temperatures in the –40°C to +80°C range, in conjunction with Brillouin or Raman monitoring systems. For Brillouin scattering systems, 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, a goal contradicting all experience from telecommunication cable design, where the exact opposite is required. 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. Some cable design combines the two functions into a single packaging, or make use of distributed Raman sensing for temperature monitoring. Figure 1 illustrates several distributed strain sensing cables.

Data Management and Visualization Software

The main functions of data management software are aimed to measure distributed sensors automatically and process the large amount of data automatically to detect and localize the undesired events. The operator can view in real time the sensors' measurement history in graphical form (as in the example of Figure 2). Software is also able to trigger alerts (message, mail and phone call) and show warnings on the display. Warnings can be generated for different types of events, including: strain, temperature,

SMARTProfile:
Embedding and survace mounting on concrete

SMARTape:
installation on smoth surfaces, such as steel

Hydro&Geo Cable:
embedding in soil or shotcrete

Figure 1. Examples of distributed strain sensing cables.

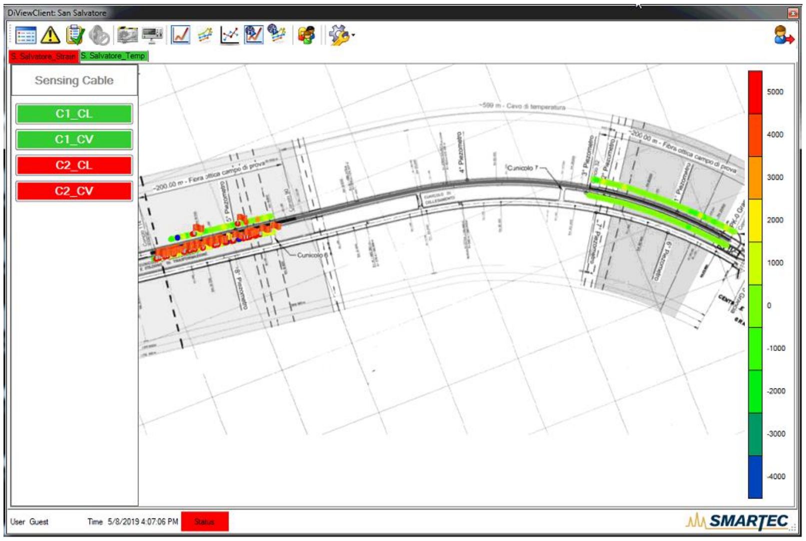

Figure 2. Examples User Interface for distributed monitoring of a tunnel (San Salvatore Tunnel, see below for details), colors indicate level of strain recorded as a function of position. Two sections are instrumented in this case.

leakage and cracks. The software is able to combine measurements from different sensing cables, to obtain complex results, such as temperature compensated strains. Another data analysis module is dedicated to the detection of cracks from distributed strain data [4]. The software stores all information related to a sensor in a single database structure. All data can be easily accessed from third-party software for further analysis or integration in SCADA systems.

APPLICATION EXAMPLES

San Salvatore Tunnel

A portion of the concrete lining of the San Salvatore tunnel collapsed in June 2017 due to water accumulation (see Figure 3). To enable prevention of similar events, it was decided to install distributed fiber optic sensors on the tunnel liner for a continuous, remote and automatic monitoring.

Figure 3. Local collapse of the San Salvatore Tunnel vault.

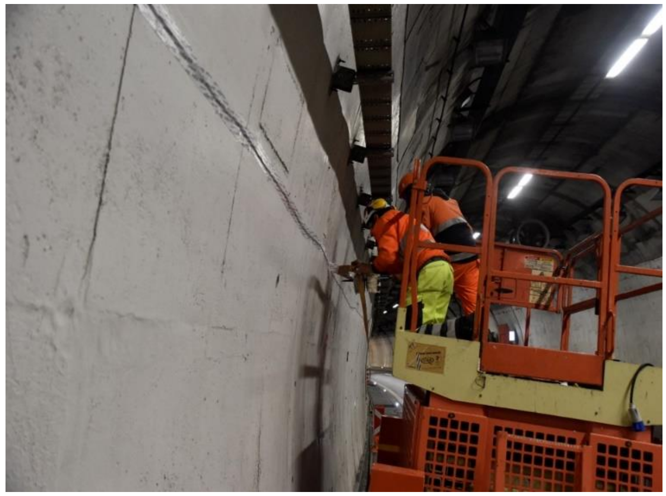
Figure 4. SMARTProfile sensor installation on the tunnel lining.

The A2 motorway, so-called Gotthard route, is one of the most important north-south transport arteries in Europe and one of Switzerland's busiest motorways. Thousands of car and lorry drivers use the route on a daily basis, which runs from Basle via Lucerne, then through the Gotthard tunnel to Lugano and continues on the Italian side in the direction of Milan. This heavily traffic stressed route passes through the San Salvatore Tunnel in Ticino.

The tunnel built in 1968 is currently under restoration and this represents a challenge for the two 1,730 m long twin-lane bores, particularly regarding the construction materials used at that time. Due to water penetration accumulated behind the concrete lining, a portion of the lining along the fast lane collapsed on June 2017. Immediately following that event the Swiss Federal Roads Office defined urgent measures deemed to mitigate the risk that a similar event could be repeated elsewhere in the tunnel. Among all the urgent safety measures to be taken it was decided to install distributed fiber optic sensors onto the tunnel liner for a continuous and automatic monitoring of the tunnel structural condition.

Two lines of distributed fiber optic sensors are now tightly affixed onto the tunnel lining and allow detection and localisation every 1 meter of concrete lining deformation and cracks formation due to any hydrostatic pressure behind the lining (Figure 4). The sensing cable is glued to the concrete suface along the whole length, allowig continuous transfer of strain from concrete to the sensing fiber. In case of cracks, the sensor partially debonds and provides evidence of the crack formation through the apparition of a localized strain peak. The monitoring system allows a fully automatic and continuous monitoring of the tunnel integrity and provides a rapid and effective response to potential defects and failure/collapse, thus increasing the safety of the structure and its users. The monitoring unit, installed in the control room at the entrance of the tunnel, performs a measurement automatically every 15 minutes approximatelly. The recorded strains are compared to a baseline and significant variations are immediatelly reported via email to the responsible engineers. The effects of temperature variations, both seasonal and daily, are compensated using a temperature sensing cable installed in an existing cable tray. An example of result is illustrated in figure 5. For most of the sections under exam, approximately 250m long, the strain variations are in the order of 100-200 microstrains and well correlated with temperature variations.

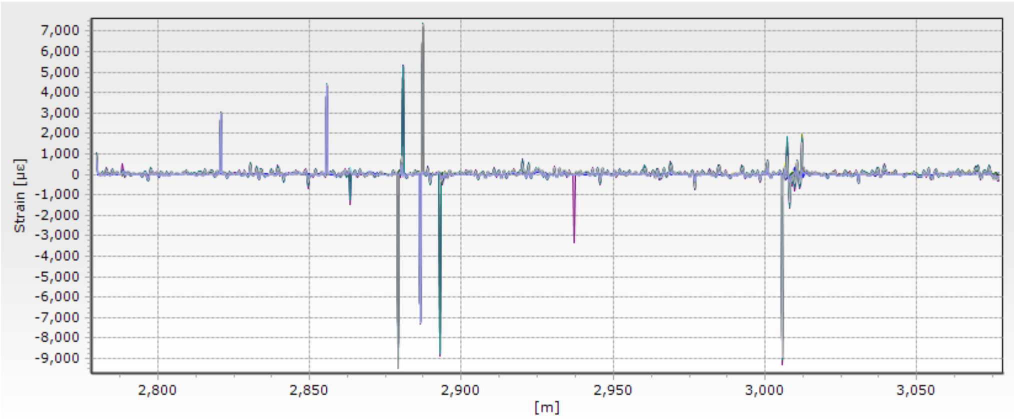

Figure 5. Strain variations in a localized section of the San Salvatore Tunnel. Strain peaks are correlated with small crack mouvements.

At some locations strain peak are clearly visible and indicative of small crack mouvements. Since craks produce a very concentrated strain, the recorded values are very high, even if the cracks only open by a fraction of mm. The data analysis software is able to identify and localize the onset of new cracks that were not previously identified.

Barcelona High-Speed Rail Tunnel

The main aim of the monitoring in this project is to provide a distributed system able to increase knowledge on the structural behaviors. The main monitoring parameter is average strains distribution in five longitudinal lines, two on the side walls and one on the floor, between the two rail lines. This system was installed in 2010. In order to perform automatic and centralized monitoring of about 12km of SMARTprofile sensor divided in several sections, the client decided to install the DiTeSt reading unit with a 16 channels optical switch. Measurements are carried out automatically and continuously.

As shown in Figure 6, the sensors are installed in a broken line pattern connecting to both the tunnel lining and the vertical support columns. In this way, the relative movements between the two can be detected and localized.

Figure 6. Sensor installation in the high-speed rail tunnel in Spain.

Penstock in Switzerland

During a normal inspection, one expert detected a crack in a penstock located in the Swiss Alps. This crack was located in a horizontal armored section of an underground penstock. This started a complete non-destructive test of the 200m long section, which revealed that no welds were 100% free of micro-cracks. This can be explained by a landslide that occurred in the surrounding land at a speed of about 0.5 mm/year. It was therefore decided to seal all welds with an elastic strip made of rubber and capable of up to 300% elongation. These rubber strips have been glued on each weld, including those with no cracks.

To allow continuous monitoring of this section and of the welds it was decided to implement a monitoring system based on conventional sensors (measuring pressure and flow around the penstock), but also a distributed strain sensing system installed along the whole disturbed length [5]. Four lines of sensing cables were installed inside the penstock as visible in Figure 11. An additional sensor line was installed in a nearby inspection gallery that is also experiencing cracking.

The system has been in operation for three years and the resulting data is continuously assessed according to a pre-defined protocol to identify any new behavior that could be indicative of crack movements [6]. An example of data visualization is presented in Figure 12. The vertical lines represent areas of higher strain. It can be noticed that those lines are continuous over the whole time period, indicating that no new high strain area has appeared.

Figure 7. Penstock equipped with four lines of longitudinal strain sensing cables. The white circumferential strips are the sealing rubber bands.

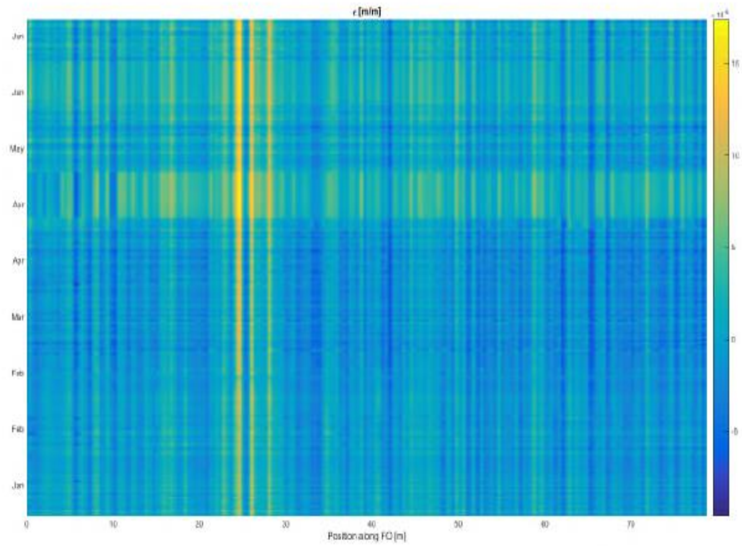

Figure 8. Pseudo color plot of strain versus time (vertical) and position (horizontal).
Courtesy of HYDRO Exploitation SA [6].

CONCLUSIONS

The use of a distributed fiber optic monitoring system, allows continuous monitoring and management of tunnels, increasing their safety and allowing the owner to take informed decisions on the operations and maintenance. The presented monitoring system and the application examples shown in this paper demonstrate how it is possible to obtain information on the tunnel state and conditions. In particular, a distributed fiber optic system allows continuous monitoring of strain along the whole length of the tunnel. Distributed strain monitoring allows the early detection of deformations and cracks, enabling an intervention. This is a useful tool for on-demand inspection and maintenance. In general, distributed strain/deformation and temperature sensing is a useful technology that ideally complements the current monitoring and inspection activities, allowing a denser acquisition of operational and safety parameters. To achieve the above-mentioned goals and take full advantage of the described sensing technology, it is a fundamental requirement, however, to select and appropriately install adequate sensing cables, adapted to the specific sensing need.

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