OVERVIEW OF FIBRE OPTIC SENSING APPLICATIONS TO STRUCTURAL HEALTH MONITORING

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Abstract: Fibre optic sensors have proven to be 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 and geotechnical 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 presents some significant application examples, in particular to Bridges, Buildings, Geostructures and Pipelines.

1. FIBER OPTIC SENSORS

There exist a great variety of fiber optic sensors (UDD 1991, UDD 1995, INAUDI 1997) 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.

1.1. SOFO Displacement Sensors

The SOFO system (Figure 1) 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.

The measurement setup uses low-coherence interferometry to measure the length difference between two optical fibers installed on the structure to be monitored (Figure 2). 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.

Figure 1: SOFO system reading unit

Figure 2: SOFO Sensor installed on a rebar

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.

1.2. Brillouin Distributed Temperature sensors

Brillouin scattering sensors are ideal 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. 1994). 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.

Figure 3: DiTeSt Reading Unit

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. 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 3). 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 APPLICATIONS

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. Alptransit Tunnel

Switzerland is currently building a new railway line across the Alps. The Alptransit project is intended to make goods transport more economical and passenger transport faster (up to 250 km/h). The most impressive works of this new line will be the Gotthard base tunnel with its two tubes of 57 km each. The construction of these tunnels presents unparallel challenges due to their exceptional length and the difficult geological conditions found in some areas along the route. The Gotthard base tunnel must pass through a vast range of layers, from the very hard Gotthard granite, through the high-stress pennine gneiss of the Leventina, to the butter-soft rock of the Tavetsch Intermediate Massif. One of the difficult areas is the south portal in Bodio. Due to constraints in the layout of the tunnel and the necessity to cope with the existing railway line, highway and roads, it is necessary to build the portal and the first 300m of tunnel in a loose stone formation. In order to optimize the support and confining structures in this area, SMARTEC SA was asked to install SOFO sensors to monitor the buttresses at the tunnel entrance and the concrete lining inside the tunnel (Figure 4). The sensors give quantitative information on the real loads that are carried by these structures in the short and long term. An automatic monitoring system records deformations and temperatures continuously and enables a correlation with the different construction phases.

Figure 4: Support Buttresses at the south portal of the new Alptransit Gotthard tunnel

In this case, monitoring concentrated mainly during construction, as it is often the case for geotechnical projects. Once the measurement systems are removed, the installed sensors remain however available for future manual measurements or to restore permanent monitoring if new unforeseen events occur.

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 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 5. 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).

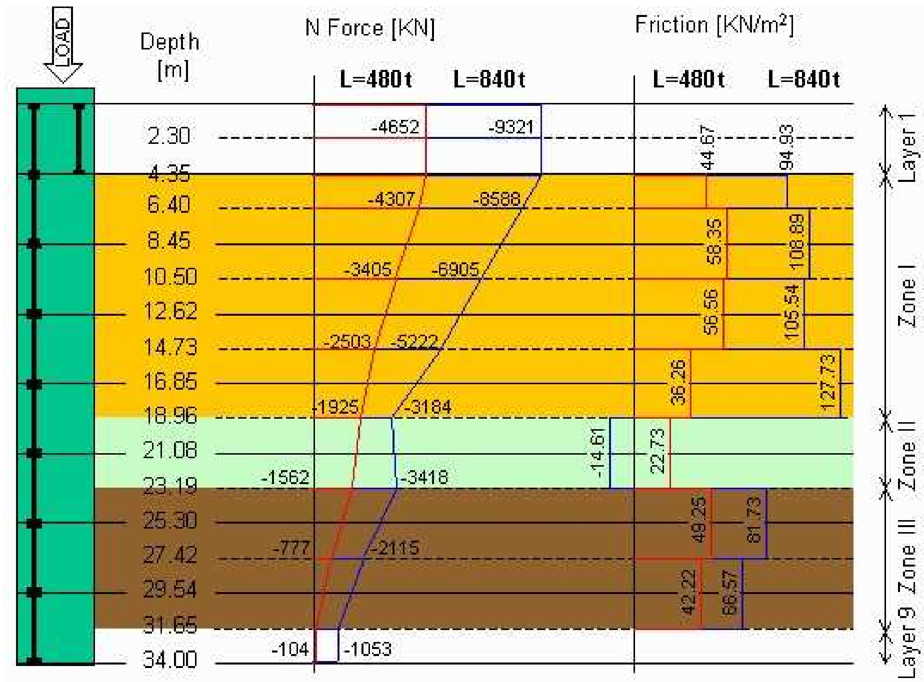

Figure 5: Sensor topology and results obtained by monitoring during the axial compression test

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 5), 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 5) 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 (GLISIC ET AL. 2002).

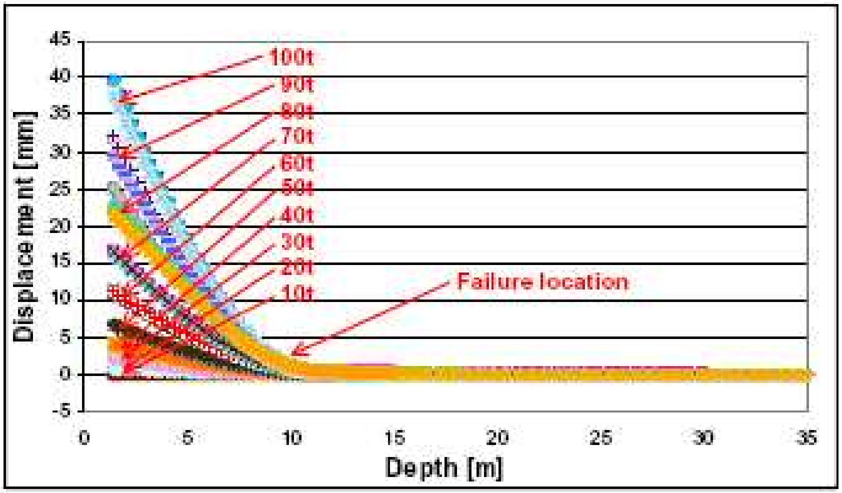

Figure 6: Deformed shapes of the pile and identification of failure location

2.3. Bitumen Joint Monitoring

Plavinu is a dam that 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.

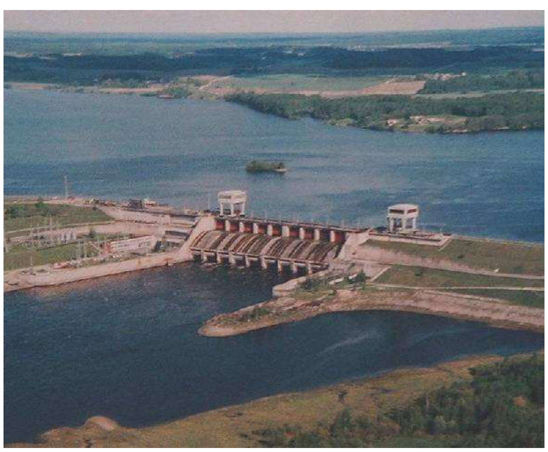

Figure 7: Plavinu dam in Latvia

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 com-promised 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 (see Figure 8) 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.

2.4. Bridge crack detection

Götaälvbron, the bridge over Göta river (figure 9), 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 an integrity monitoring system has been mandatory.

Figure 9: 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.

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 test is presented in Figure 10. 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.

Figure 10: On-site test of SMARTape gluing procedure (left) and installed SMARTapes for full performance tests (right).

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.

2.5. 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, currently 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.

Figure 9: SMARTape on the gas pipeline.

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 ex-tension 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 per-formed with success using the temperature sensing cable.

3. CONCLUSIONS

The monitoring of new and existing structures is one of the essential tools for a 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 the sensing technology can therefore be produced by more accurate measurements, but also from systems that are easier to install, use and maintain. In the recent years, fiber optic sensors have moved the first steps in structural monitoring and in particular in civil engineering. Different sensing technologies have emerged and evolved into commercial products.
If three characteristics of fiber optic sensors should be highlighted as the probable reason of their present and future success, I would cite the stability of the measurements, the potential long-term reliability of the fibers and the possibility of performing distributed and remote measurements.

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