

“SOFO: STRUCTURAL MONITORING WITH FIBER OPTIC SENSORS”

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Abstract

In many civil structures like bridges, tunnels and dams, the deformations are the most relevant parameter to be monitored in both short and long term. Strain monitoring gives only local information about the material behavior and too many such sensors would therefore be necessary to gain a complete understanding of the structure's behavior.

We have found that fiber optic deformation sensors, with measurement bases of the order of one to a few meters, can give useful information both during the construction phases and in the long term.

This paper presents the measurement principle of such a system as well as examples of application to the monitoring of concrete bridges, tunnels and dams.

Keywords: structural monitoring using fiber optic sensors

1. Introduction

The security of bridges, tunnels, dams requires periodic monitoring, maintenance and restoration. Excessive and non-stabilized deformations are often observed and although they rarely affect the global structural security, they can lead to serviceability deficiencies.

Furthermore, accurate knowledge of the behavior of the structures is becoming more important as new structures become lighter, as new building techniques are introduced and an increasing number of existing bridges are required to remain in service beyond their theoretical service life. Monitoring, both in the long and short term, helps to increase the knowledge of the real behavior of the structure and in the planning of maintenance intervention.

In the long term, static monitoring requires an accurate and very stable system, able to relate deformation measurements often spaced over years.

On the other side, dynamic analysis of bridges, or short term monitoring, require of a system capable of measuring deformations occurring over relatively short periods of time.

Currently available monitoring transducers, such as inductive and mechanical extensometers, GPS, microbending sensors or accelerometers are only suitable for performing measurements in a short range of frequencies. Moreover, some of these techniques are still in the development stage and are only used in laboratory experiments (for example, GPS). Other systems do not offer enough information about the desired parameter (for example, an accelerometer gives the frequency of vibration, but displacements calculations are not always accurate).

Thus, there is a real need of a unique system capable of covering structural deformation requirements in wide range of frequencies.

1.1 Long term fiber optic monitoring system

In recent past years, fiber optic sensors have gained in importance in the field of structural monitoring. They are the ideal choice for many applications, being easy to handle, dielectric, immune to EM disturbances and able to accommodate deformations up to a few percents.

The IMAC laboratory at EPFL has developed a non-incremental, long term monitoring system based on low-coherence interferometry, which has successfully been used in several bridges, tunnels, dams and other civil engineering structures.

This system is named SOFO[®] (the French acronym of "Surveillance d'Ouvrages par Fibres Optiques" or structural monitoring by optical fibers).

1.2 The SOFO system

The functional principle of the SOFO system is schematized in **Figure 1**.

The sensor consists of a pair of single-mode fibers installed in the structure to be monitored. One of the fibers, called the measurement fiber, is in mechanical contact with the host structure, while the other, the reference fiber, is placed loose near the measurement fiber. All deformations of the structure will then result in a change of the length difference between these two fibers, while a temperature change will affect both fibers identically.

To make an absolute measurement of this path unbalance, a low-coherence double Michelson interferometer in tandem configuration is used. The first interferometer is made of the measurement and reference fibers, while the second is contained in the portable reading unit. This second interferometer can introduce, by means of a scanning mirror, a well-known path unbalance between its two arms.

Because of the reduced coherence of the source (the 1.3 micron radiation of a LED), interference fringes are detectable only when the reading interferometer compensates the length difference between the fibers in the structure to better than a few microns.

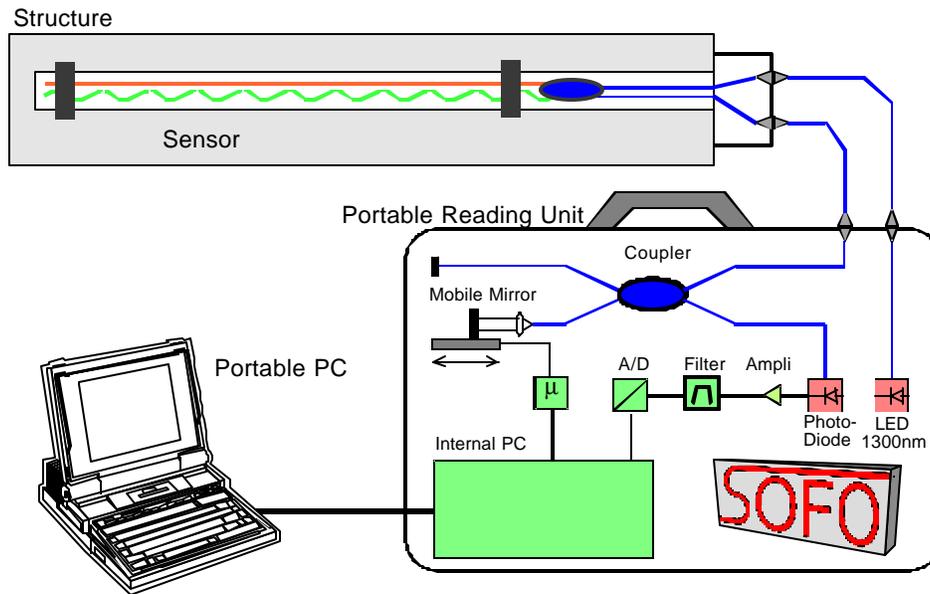


Figure 1: Setup of the SOFO system

If this measurement is repeated at successive times, the evolution of the deformations in the structure can be followed without the need for a continuous monitoring. This means that a single reading unit can be used to monitor several fiber pairs in multiple structures.

The signal detected by the photodiode is pre-amplified and demodulated by a band-pass filter and a digital envelope filter.

The precision and stability obtained by this setup have been quantified in laboratory and field tests to 2 micron, independently from the sensor length over more than four year. Even a change in the fiber transmission properties does not affect the precision, since the displacement information is encoded in the coherence of the light and not in its intensity.

Fig. 2

Figure 2 shows a typical sensor for length up to 10 m. This sensor is adapted to direct concrete embedding or surface mounting on existing structures. The passive region of the sensor is used to connect the sensor to the reading unit and can be up to a few kilometers long.

The reading unit is portable, waterproof and battery powered, making it ideal for dusty and humid environments as the ones found in most building sites. Each measurement takes about 10 seconds and all the results are automatically analyzed and stored for further interpretation by the external laptop computer.

The measurements can either be performed manually, by connecting the different sensors one after the other, or automatically by means of an optical switch. Since the measurement

of the length difference between the fibers is absolute, there is no need to maintain a permanent connection between the reading unit and the sensors. A single unit can therefore be used to monitor multiple sensors and structures with the desired frequency.

1.3 Data Analysis Algorithms

The data analysis packages interpret the data stored by the acquisition software in the database. Some of these packages are general and can be used with each type of structure, while others are aimed to a precise structure or structure type. Examples of such tools are:

- *Displacement evolution analysis:* This general-purpose package extracts the results concerning a single sensor and displays them as a function of time or load. The data can then be exported to other software packages, like spreadsheets or other graphical tools for adequate representation.
- *Curvature:* In beams, slabs, vaults and domes, it is possible to measure the local curvature and the position of the neutral axis by measuring the deformations on the tensile and compressive sides of a given element. In many cases, the evolution of the curvature can give interesting indication on the state of the structure. For example, a beam, which is locally cracked, will tend to concentrate its curvature at the location of the cracks. Furthermore, by double integration of the curvature function, it is possible to retrieve the displacements perpendicular to the fiber direction. This is particularly interesting since in many cases the engineers are interested in deformation that are at a right angle to the natural direction in which the fiber sensors are installed. For example: in a bridge the fibers are installed horizontally, but vertical displacement are more interesting. In a tunnel the fibers are placed tangentially to the vault, but measurement of radial deformation is required. In a dam the fibers are installed in the plane of the wall but displacements perpendicular to it have to be measured. Application examples of these data analysis techniques will be given in the application section.
- *Statistics:* Another software package allows the analysis of deformation data from structures undergoing statistically reproducible loads (such as traffic).

2. Application examples: long term monitoring

In the next paragraphs, we will present a choice of applications of the current SOFO system for different monitoring purposes in bridge, tunnel and dam maintenance.

2.1 Versoix bridge: interaction between new and old concrete

The North and South Versoix bridges are two parallel twin bridges. Each one supported two lanes of the Swiss national highway A9 between Geneva and Lausanne. The bridges are classical ones consisting in two parallel pre-stressed concrete beams supporting a 30 cm concrete deck and two overhangs.

In order to support a third traffic lane and a new emergency lane, the exterior beams were widened and the overhangs extended. The construction progressed in two phases: the interior and the exterior overhang extension. The first one began by the demolition of the existing internal overhang followed by the reconstruction of a larger one. The second phase consisted to demolish the old external overhang, to widen the exterior web and to rebuild a larger overhang supported by metallic beams. Both phases were built by 14 m stages.



Figure 3: The Versoix bridge during works

Because of the added weight and pre-stressing, as well as the differential shrinkage between new and old concrete, the bridge bends (both horizontally and vertically) and twists during the construction phases. In order to increase the knowledge on the bridge behavior, the engineer choose low-coherence SOFO sensors to measure the displacements of the fresh concrete during the setting phase and to monitor the long term deformations of the bridge. The bridge was instrumented with more than hundred SOFO sensors.

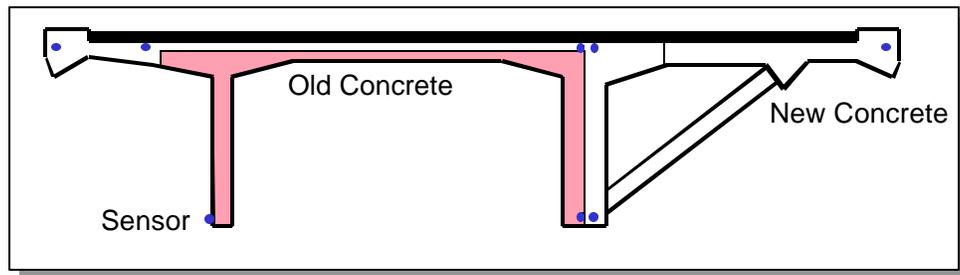


Figure 4: The Versoix bridge, Section

Figure 5 shows the concrete deformations measured in one sensor during the first year.

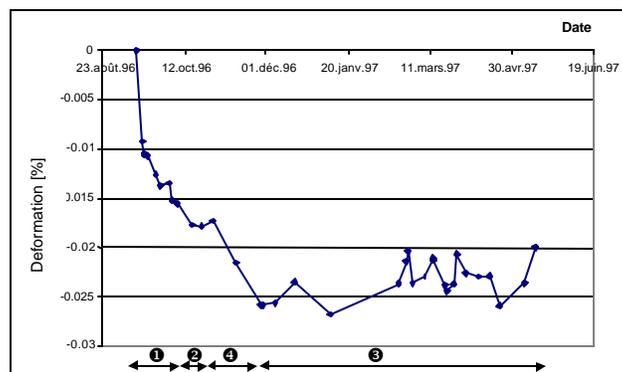


Figure 5 Deformation measurement of the bridge

All the optical fiber sensors of a same concrete pouring stage indicate a same behavior. On the graph, four phases are distinguishable: the first is the drying shrinkage (phase 1), followed by a stabilization phase (phase 2) and finally there is a zone of variation (phase 5) corresponding to the thermal elongation of the bridge. Phase 4 is due to the decrease of the bridge temperature during the month of November 1996. These variations are consistent with a temperature variation of about 10°C that was actually observed.

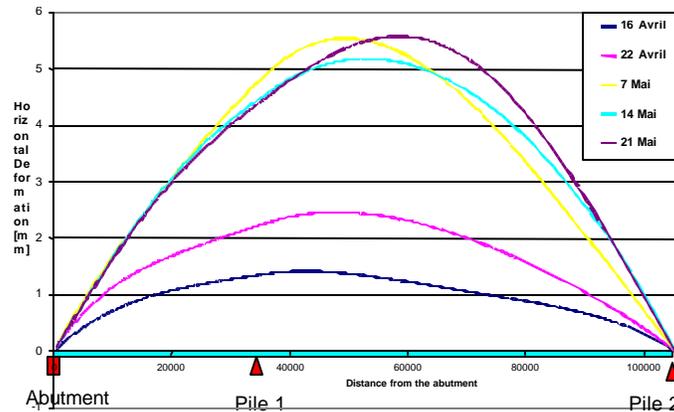


Figure 6: Horizontal displacement of the bridge

Figure 6 shows the horizontal displacement of the two spans of the bridge as calculated by the double integration algorithm and for different times relatively to the line Abutment-Pile 2. The observed 'banana' effect is due to the shrinkage of the concrete of the new exterior overhang. This effect stabilizes to a value of 5 mm of horizontal lateral displacement after one month.

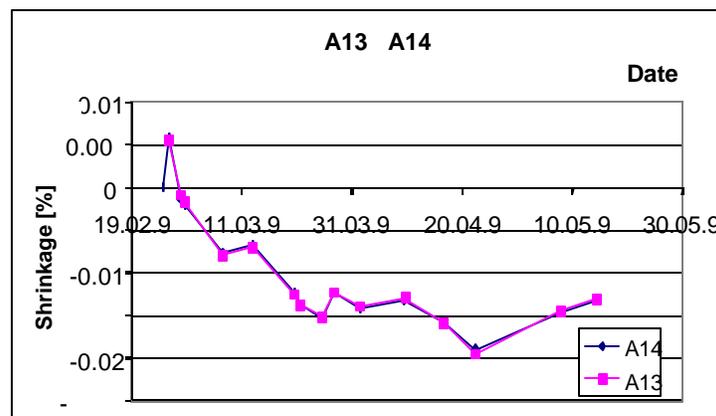


Figure 7: Differential shrinkage between the old and new concrete

Figure 7 shows an example of the measurement of shrinkage for two sensors, A14 (new concrete) and A13 (old concrete). All the compared sensors indicated the same behavior: overall the differential shrinkage is zero, indicating a good cohesion between the two concretes.

During a load test, performed in May 1998 after the end of construction works, were also monitored the vertical displacement of the bridge.

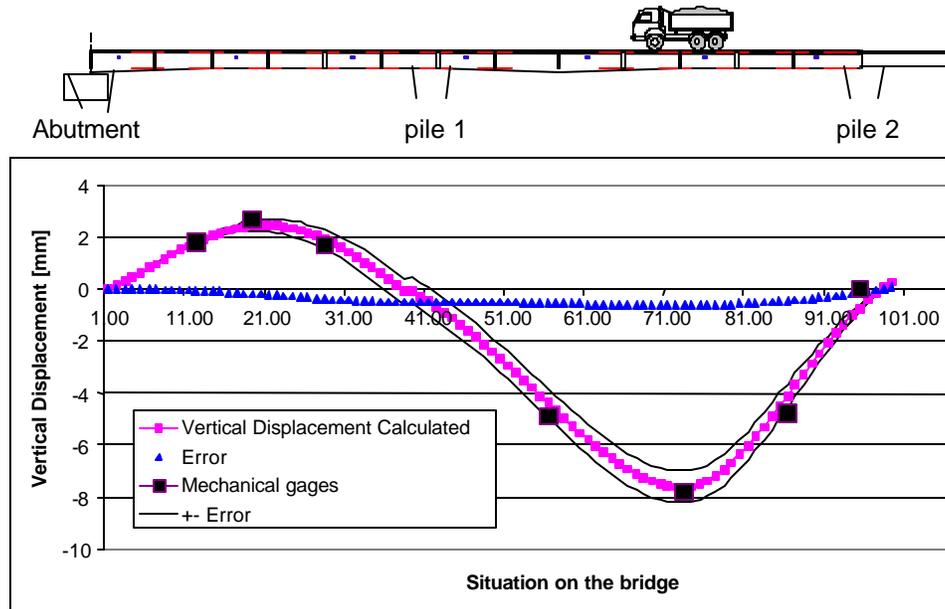


Figure 8: Vertical displacement, case A

Figure 8 shows the measurement with SOFO sensors (Vertical Displacement Calculated) compared to those obtained with the dial gages (invar wires under the bridge) during the load test. This case of load test (Case A) consists in 6 trucks on the second span of the bridge (position 73 in the graph). The error of the algorithm is estimated considering a 5 μm accuracy of the SOFO system.

The algorithm (Vertical Displacement Calculated) retrieves within the error uncertainty, the position of the piles and the vertical displacement measured with the dial gages.

Figure 9 shows the measurements during the load test for the case B. The case B consists in 6 trucks on the third span of the bridge (position right, out of the graph).

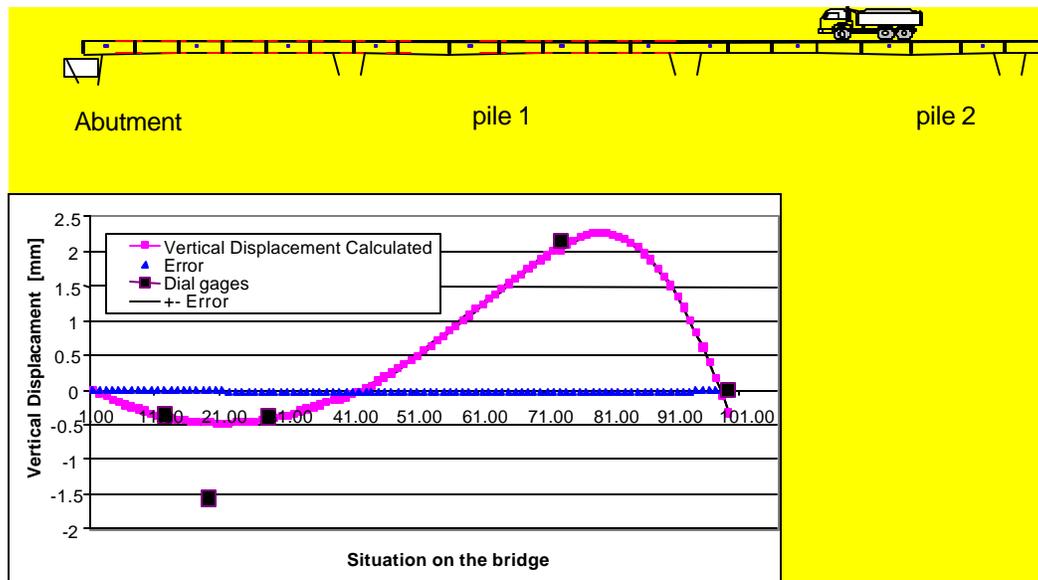


Figure 9: Vertical displacement, case B

In this case the possible error is very small because the torsion is not significant and the condition “the plain sections remain plain” for the algorithm is better respected.

The algorithm with 4th degree polynomial retrieves the position of the piles and the directly measured vertical displacement (series 5). Only position 19 of the mechanical gages doesn't match well: this is because this mechanical gage is placed on the side of the bridge, where torsion is more important.

2.2 Luzzone dam

The Luzzone dam is placed in a dell valley in the south of the Swiss Alps.

This 30 years old arc dam is 208 m high, with a crown length of 530 m and produces 1000 million of kWh per year. In order to increase the energy production, the holder company decided in 1990 to heighten the structure by 17 m. During the heightening, the concrete block number 24 was instrumented with 10 SOFO sensors and about 200 thermocouples.

Figure 10 shows a photo of the raised Luzzone dam, the location of the 3 considered SOFO sensors and of the 6 thermocouples. The monitoring of this block allows the engineer to acquire information on the thermo-mechanical behavior of the dam. The aim of the project is in a first phase to understand the influence of the nonlinear thermal gradients induced during the hydration process on the dam deformations and in a second phase to study the mechanical behavior of the dam under different environmental conditions.

Fig. 10

The positions of the six thermocouples (T1 to T6) are shown in Figure 10 b) and c). From the recorded local temperature evolution, temperature profiles along the width of the concrete lift can be obtained. Figure 11 shows temperature profiles at 8 selected times. The highest temperatures in the lift were reached at about 65 hours after pouring. From this time, the temperature in concrete decreases very slowly in the central part of the lift for a quite long period. The large dimensions of the concrete element can explain this behavior. In this case the center of the lift is under quasi-adiabatic conditions. At the same time the outer surfaces

exposed to the surroundings cool down. This situation induces high temperature gradients between the center and the outer surfaces of the lift. At very advanced times the entire element cools down gradually, the heat produced by the ongoing hydration process of the cement is much lower than the heat loss through the exposed surfaces (see figure 11 curves 11.5 d, 46 d, 73 d). It must be outlined that the temperatures at the right outer surface ($x = 0$ cm) are higher than the temperature on the left surface ($x = 700$ cm). This is due to the fact that the right side of the lift is exposed to south and is consequently more influenced by solar radiation.

The prediction of thermal gradients in the concrete dam can be calculated with FE program. A fairly good correlation between experimental measurements and numerical simulations is generally found.

SOFO[®] sensors have been embedded in concrete in order to measure the evolution of the local deformations in the lift induced by temperature variations. The position of the three sensors is shown in Figure 10 b) and c).

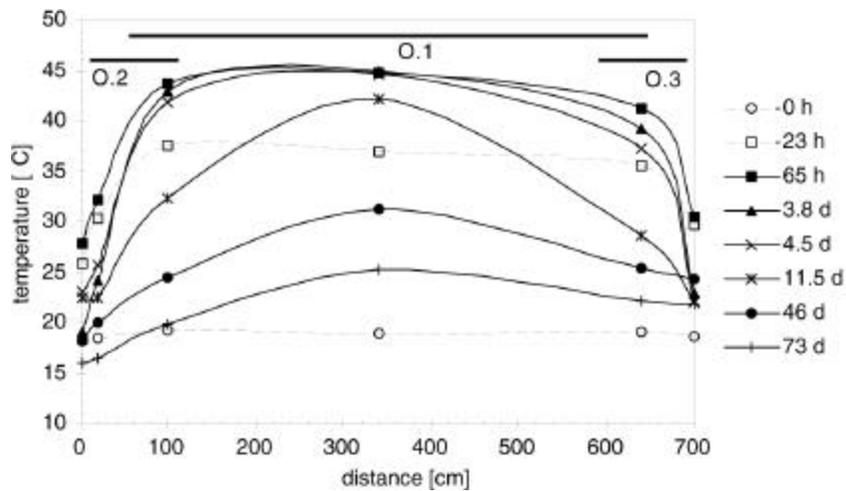


Figure 11: Measured time dependent temperature distribution

Figure 12 shows the recorded relative thermal deformations as function of time. The thermal strain relative to the central part of the lift (line O.1) increases quite quickly during a period of about 64 hours. This duration corresponds roughly to the heating up (induced by the hydration process) of the center of the lift (see Figure 11). From this time onwards, the central region of the lift contracts slowly as the temperature decreases.

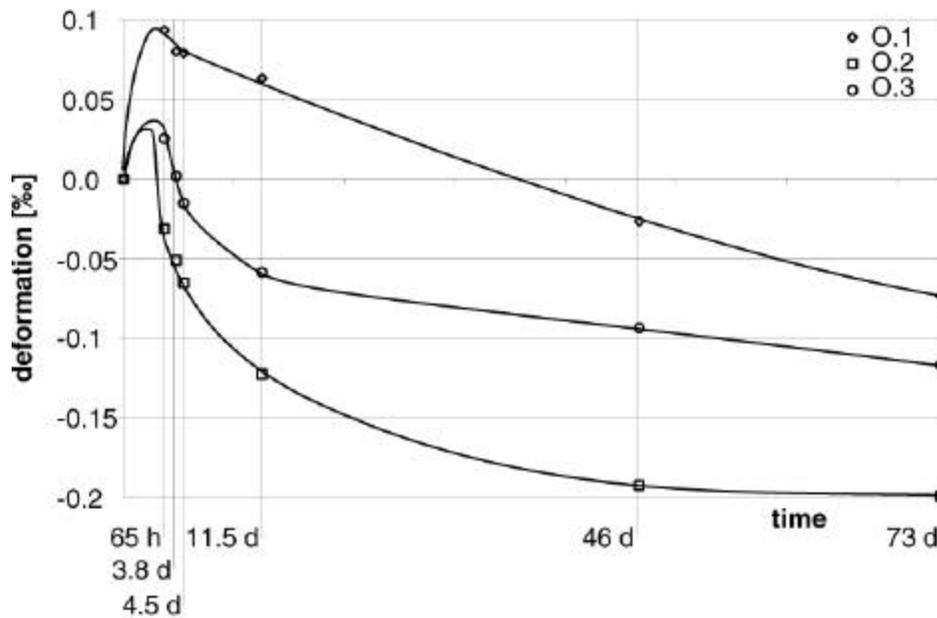


Figure 11: Deformations measured with SOFO sensors O.1, O.2, O.3

The same observations can be made in case of the evolution of the thermal strains in the outer regions as it is shown in Figure 11 by lines O.2 and O.3. In both cases, the contraction occurs suddenly (peaks of the curves) and the decrease is much steeper than in the case of the center. This sudden drop is directly correlated to the sudden drop of the temperature in these regions, which is induced by the demolding of the lift. In this case the low thermally conductive wood framework does not reduce the heat loss through the outer surfaces anymore. Notice that the peak of the curve O.3 in Figure 12 is shifted with respect to the peak of the curve O.2, because the demolding of the right side of the lift took place some hours later than those of the left side. The behavior of the observed deformation is clearly reflected by the measured time-dependent temperature profiles shown in Figure 11.

2.3 The Mt. Terri tunnel

SOFO sensors were installed in the Mt. Terri tunnel to evaluate the rock decompression during excavation with a tunnel-boring-machine. The general aim of the experiment is the study of the rock (opalinus clays) cracking and its loss of impermeability. This data is particularly important to evaluate the suitability of such rock formations for the storage of nuclear waste.

Nine sensors were installed by grouting in a borehole executed from an existing tunnel parallel to the new one. The active length of the sensors was chosen to have a higher data density in the proximity of the new tunnel. The first four sensors are 250 mm long, the next two are 500 mm long and the other are 1m, 2m and 4m long. All the sensors and cabling could be comfortably installed in the same 100 mm borehole (Figure 13).

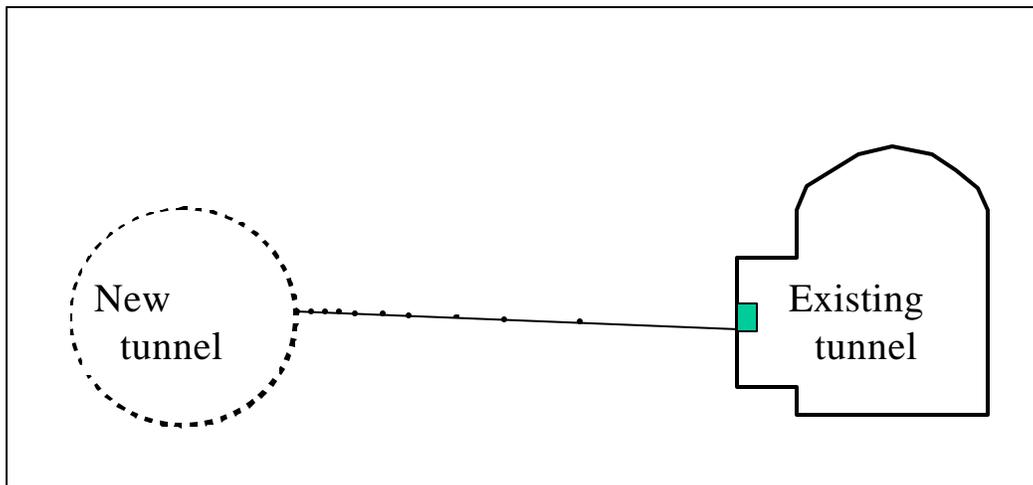


Figure 13: Sensor installation in the Mt. Terri tunnel.

Figure 14 shows the observed strains (given by the measured deformations divided by the sensor's active length). It can be seen that no significant deformation was measured before the arrival of the tunnel-boring-machine at the location of the extensometer. After the passing of the machine, large strains are measured on the first 4-5 sensors, while the other show much smaller (but still easily measurable) strains. The large value registered on sensor 453 can be explained with the formation of a crack.

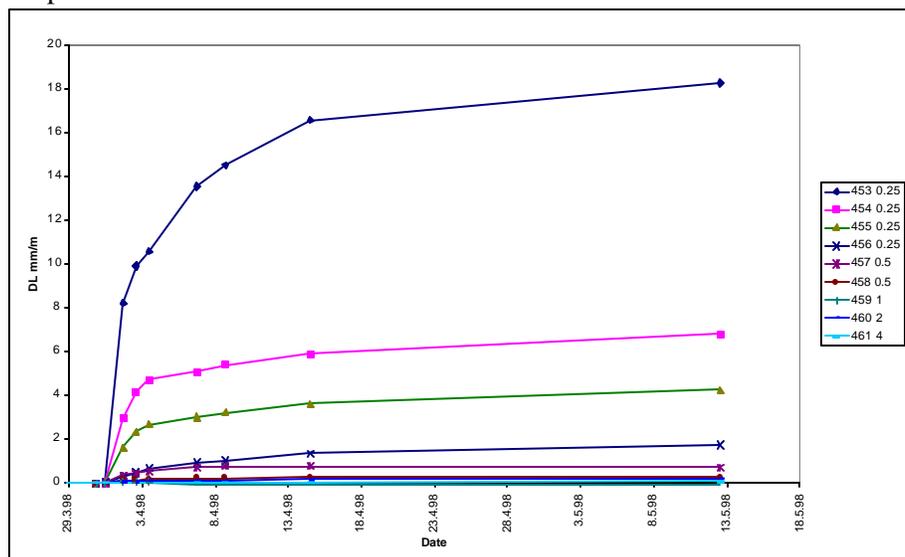


Figure 14: Strain measurement in the Mt. Terri Tunnel

This application takes advantage of the peculiarities of the SOFO sensors. On one hand, it is possible to adapt the active length to the phenomenon to be observed. On the other hand, the high precision and the dynamic range of the system allow the measurement of deformations over a large spectrum of magnitudes and little a-priori knowledge on the expected deformations is required. Finally, the absence of moving parts in the sensors greatly reduces the risk of sensor malfunctioning in the case of large transverse deformations.

3. Conclusion

The benefits of structural monitoring are obvious. A continuous or at least regular monitoring of a structure increases the knowledge on its behavior and help to guarantee its safety and to plan for maintenance interventions.

Besides short-gage strain sensors that measure directly the local properties of the construction materials, long-gage length deformation sensors can give additional and complementary information on the global behavior of the structure.

The SOFO monitoring system is composed of a portable reading unit (adapted to field conditions), of series of sensors (that can be either embedded into concrete or surface mounted on metallic and other existing structures) and of a software package (allowing the treatment of the large data-flow resulting from these measurements). This system has been applied to a large number of new and existing bridges as well as to other civil structures in order to monitor their short and long-term behavior.

The combination of adequate monitoring techniques and numerical simulations is a powerful tool that enables the understanding of complex structural phenomena. In this way the design of more durable structures can be enhanced.

4. Acknowledgment

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