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MONITORING A SUBTERRANEAN STRUCTURE WITH THE SOFO SYSTEM

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ABSTRACT

The SOFO system is a deformation measurement system based on low-coherent interferometry in single-mode optical fibres. It has been successfully tested and applied to different types of civil structures such as bridges, tunnels, dams and piles. Due to its high resolution and precision, long term stability, easy application, and its capability to measure the deformation of very early age concrete, this system has been applied on subterranean structures.

A cut-and-cover tunnel "Champ Baly" on the A1 road, near Yverdon, Switzerland, is cast in high performance concrete and the SOFO system is used to monitor its behaviour. In this paper we present the installation of the SOFO system in the tunnel and the results of the monitoring campaigns during the first months after the concrete pouring. The very early age deformation, cracking localisation and its quantification are presented as well as the evolution of the global spatial behaviour. The SOFO system reveals to be the appropriate monitoring technique for subterranean structures.

1 INTRODUCTION

The importance of many subterranean structures requires not only quality design and construction, but also adequate monitoring. In addition to material losses, failure of civil structures may involve human victims. In order to preventively recognise failures and to increase safety, different structural monitoring systems have been developed. They are mainly based on the measurement of the deformations, the displacements or the strains of a structure. These traditional systems (e.g. surveying networks, hydrostatic levelling systems, etc.) have, however, some inconveniences.

In general, they can only be applied when the structural construction work is finished. Therefore, using them, only the behaviour of the finished structure can be monitored. Researches show however that, in the case of concrete structures, early age damage can significantly affect the durability of a structure [1].

Furthermore traditional system can often only be used to monitor one parameter: extensometer for local deformations, geodesic surveying network for global behaviour, etc.

As a result, the structure needs to be equipped with several different systems to monitor different parameters. The reading and treatment of measurement data can be difficult and toilsome if the read-out is not centralised, remote or automatic or if, for each measurement, the installation of reading set-ups or sensors is required.

The inconveniences mentioned above, and new fibre optic sensing technology have led to the development of a new structural monitoring system. The SOFO (French acronym for Surveillance d'Ouvrage par Fibres Optiques - Structural Monitoring Using Optical Fibres) system has been developed at the Laboratory of Strain Measurement and Analysis of the Swiss Federal Institute of Technology (IMAC-EPFL) during the last six years. The system is easy to install and operate, insensitive to variations of temperature and humidity or to electromagnetic fields. It makes possible continuous, automatic and reliable monitoring. It has been successfully tested in various types of structures such as bridges, dams and geostructures throughout Switzerland, Europe and North America. In this paper an application of the SOFO measurement system to a cut-and-cover tunnel is presented.

2 SOFO MEASUREMENT SYSTEM

The SOFO measurement system is based on low coherence interferometry [2] in single-mode optical fibres. The three main components of the system are a reading unit, the fibre optic sensors and the appropriate software. Its functional principle is represented in Figure 1.

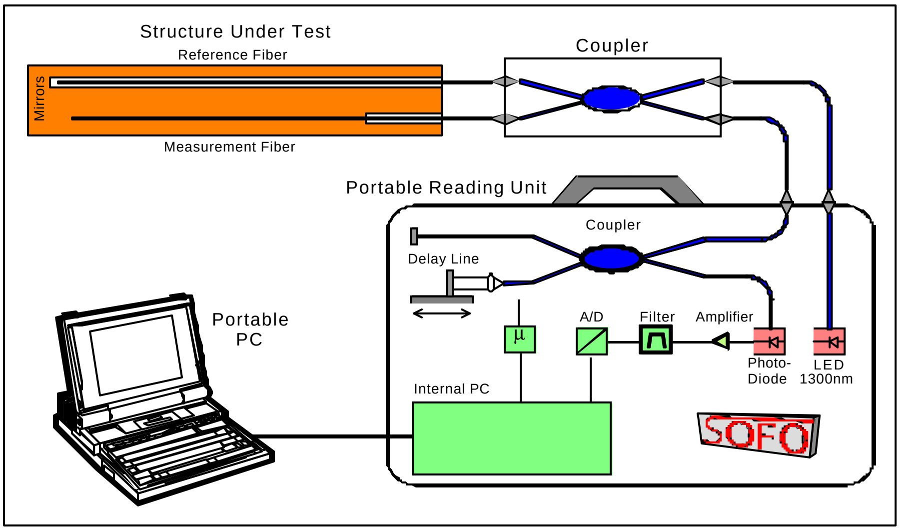

Figure 1: Set-up of the SOFO System

The reading unit is composed of a light emitter (light emitting diode - LED), a low-coherence Michelson interferometer with a mobile scanning mirror, optical set up and an internal PC. The sensor consists of two mono-mode optical fibres named the "measurement" and the "reference" fibre. The measurement fibre is in mechanical contact with the host structure and follows its deformation, while the reference fibre, placed close to the measurement fibre, is loose and independent of the behaviour of the structure. Any deformation of the structure will result in a change of the length difference between the two fibres.

Infrared light is emitted by the LED, sent through the mono-mode optical fibre to the sensor, split by the coupler and introduced into the two arms of the sensor. Then, the light reflects off the chemical mirrors deposed on the ends of each of the fibres and returns through the coupler to the reading unit, i.e. to the mobile Michelson interferometer. The interfered light contains the information of the length difference between the measurement and the reference fibre. This difference is retrieved using the mobile mirror and transmitted to the external PC. By successively repeating the measurements, it is possible to determinate the evolution of the deformation of the auscultated structure.

The main characteristics of the SOFO system are given in Table 1.

Parameter	SOFO characteristics
Gage length	20cm to 10m for standard sensors Up to 50m with special (long) sensors
Resolution	2µm, independently from gage length
Dynamic range of the sensors	1% elongation, 0.5% shortening for standard sensors
Dynamic range of the reading unit	Up to 70mm in elongation and shortening
Precision	Better than 1% of the measured deformation
Measurement speed	Less than 10 seconds
Stability	Drift not observable over at least four years

Table 1:Specifications of SOFO Measurement System

The SOFO system is well adapted to construction site conditions. The portable, battery powered and waterproof reading unit can be operated in dusty and humid environments.

The standard SOFO sensor [3] is composed of two zones, the active zone that is used for the measurement of deformation, and the passive zone that serves as guide of information. The sensor is schematically represented in Figure 2.

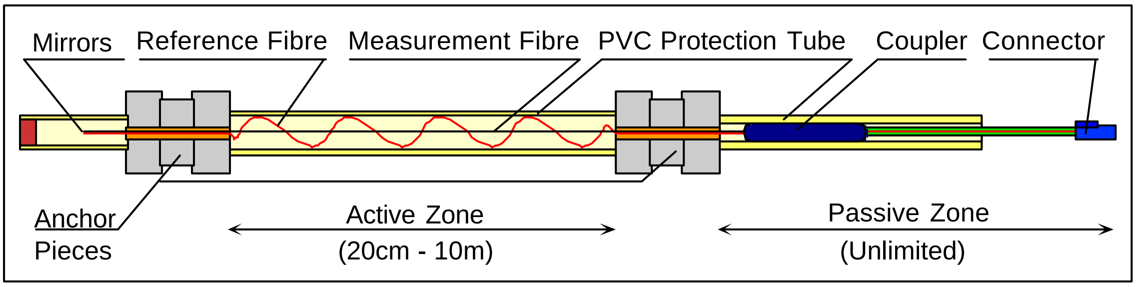

Figure 2: Schema of a SOFO Standard Sensor

The active zone is delimited by two anchor pieces and consists of two optical fibres placed in a protection tube. The anchor pieces have a double role: first to attach the sensor to the structure and second to transmit the deformation from the structure to the active zone. The deformation of the structure induces a change of the distance between the anchor pieces, and this change is registered by the measurement fibre. The measurement fibre is pre-tensioned between the anchor pieces in order to be able to measure a shortening of the structure as well as an elongation. The reference fibre is independent of both the measurement fibre and the deformation of the structure, and its purpose is to cancel the temperature influence on the sensor. The length of the active zone of the standard sensors ranges from 20 cm to 10 m. Exceeding the upper limit, the independence of the reference fibre can not be guaranteed.

The passive zone transmits the information from the active zone to the reading unit. It is composed of one mono-mode optical fibre, a connector and a coupler, all protected by a plastic tube. The coupler is placed in the passive zone of the sensor, close to the anchor piece in order to increase the precision and to facilitate the manipulation during the measurement. The length of the passive zone is nearly unlimited and depends only on the distance between the sensor emplacement position and the reading unit. If this distance is long (above 40 metres) the passive zone can be extended by a simple fibre optic cable. The sensor is connected to the reading unit using a Diamond E2000 connector.

The sensors are protected with a PVC tube for easy manipulation, fast installation and high resistance during the pouring and the vibrating of concrete. Due to the low rigidity of the sensor, it is possible to measure the deformation of concrete starting with the pouring phase, including the very early age deformation of concrete.

3 CUT-AND-COVER TUNNEL "CHAMP BALY"

The cut-and-cover tunnel of Champ Baly is situated on the motorway A1, connecting Lausanne with Bern, in Switzerland. Construction work began in July 1998 and the end of the concrete pouring phase was in August 1999. The cross-section of the tunnel consists of two reinforced concrete vaults (Figure 3).

Figure 3: Champ Baly Cut-and-cover Tunnel under Construction

The length of the tunnel is 230 m and the volume of concrete used is approximately 6000 m^3. The concrete has been poured in twenty-one stages, i.e. nineteen 11.60 m long vaults and two 6 m long portals. The first 9 stages are built in ordinary concrete and the last 12 stages in high performance concrete (Figure 4) [4].

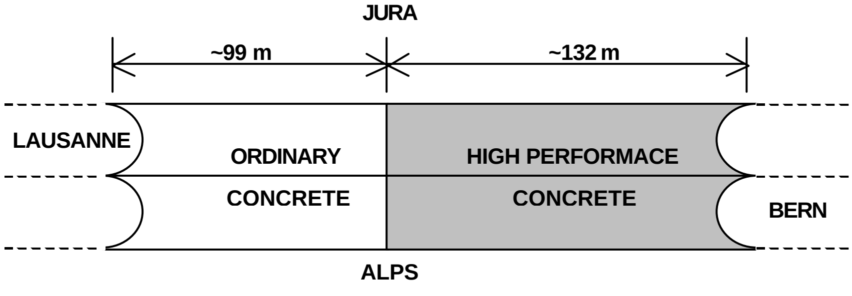

Figure 4: Simplified Plan View of the Cut-and-cover Tunnel of Champ Baly

4 SOFO SENSORS AT CHAMP BALY

The construction of the Champ Baly cut-and-cover tunnel served as a pilot project for the application of High Performance Concrete in Switzerland. The Structural Concrete Laboratory of the Swiss Federal Institute of Technology (IBAP-EPFL) is conducting a research project to assess potential durability gains from the use of concrete with silica fume [4, 5, 6, 7]. It conducted the measurement presented below. The SOFO measurement system was selected for the early age and long term monitoring of longitudinal deformations in two reference sections of the tunnel. One section is built of ordinary concrete, and the other one of high performance concrete. Only the ordinary concrete section is presented in this paper. The section has been equipped with nine 4 metres long SOFO sensors and nine thermocouples prior to the pouring of concrete, as shown in Figure 5. Each thermocouple is placed close to one sensor, which allows measuring the concrete temperature at each sensor location. In Figure 5 the thermocouples are represented by numbers (1, 2, … 9) and the sensors by "S" followed by their respective serial number (S-740, S-741, etc.).

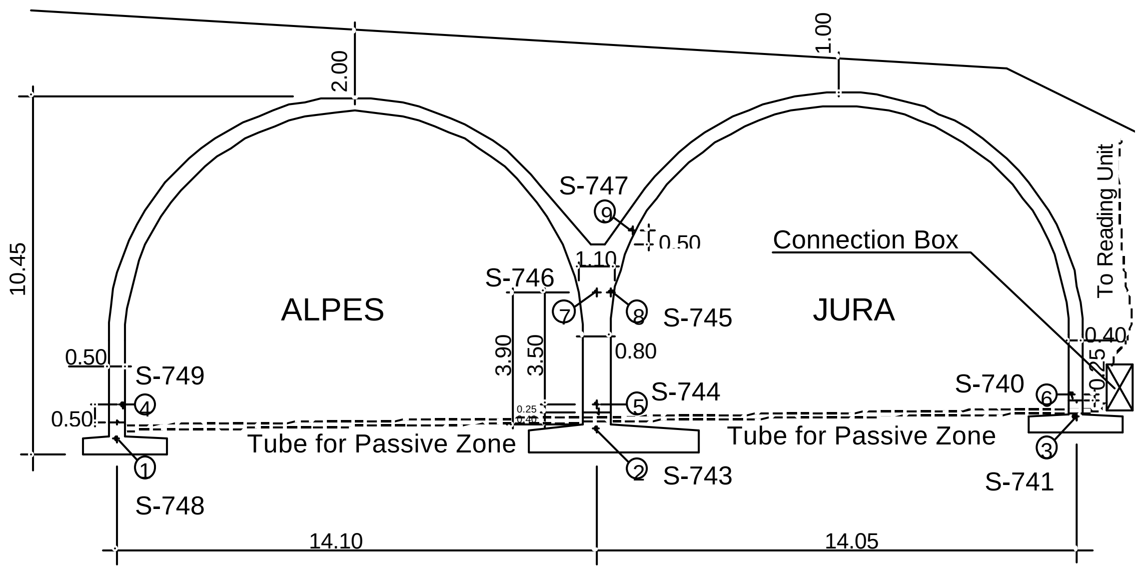

Figure 5: Cross-section of the Tunnel and Sensor Placement

Sensors S-748, S-743 and S-741 are located in the foundations, which have been cast approximately three months prior to the vaults. The other sensors were mounted on the vault rebars a few days before the casting took place. The passive zones of the sensors are guided through plastic tubes to the connection box (see Figure 5). The reading unit is placed in a small portable chamber some twenty metres away from the tunnel. It is linked to the connection box by means of an optical cable.

Since the tunnel was under construction, the connection box installation was temporary in order to allow the early age measurements. Once construction is finished, the connection box will be permanently installed in the tunnel. The complete installation of sensors, box and cable took approximately 6 hours, mainly due to the difficult access to the sensor location zones.

5 RESULTS OF MEASUREMENT

The measurements start with the casting of the foundations. Since the early age deformation of the foundation was not of interest, only periodical measurements are done. Unfortunately one of the sensors (S-741) was damaged during the pouring. The total (long-term) deformation of the foundations measured by SOFO sensors are presented in figure 6.

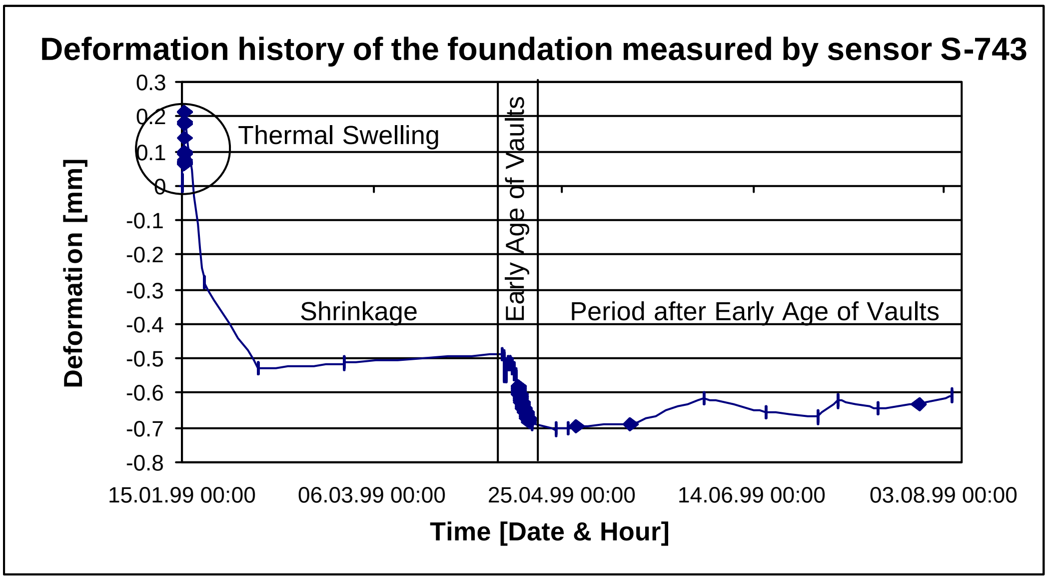

Figure 6: Long-term Deformation Measurements of the Foundations

The vaults early age deformation was monitored during seven days following concrete pouring. Measurements were recorded automatically every 30 minutes. The early age deformation and the temperature measurements are shown in Figures 7 and 8. Periodical deformation measurements of the tunnel sections are continued on at a 10-day interval. The results of one of these measurements are presented in Figure 6.

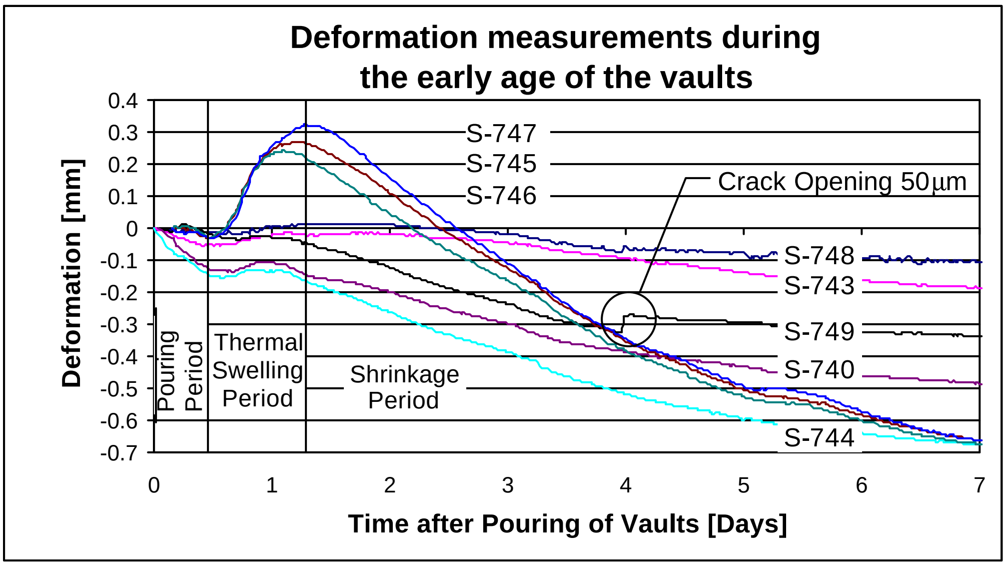

Figure 7: Deformation Measurements at the Early Age of the Vaults

6 DISCUSSION OF RESULTS

Since the subject of this paper is to present an application of the system SOFO on concrete subterranean structures, the results of the measurements are discussed in general terms. Additional results and detailed analysis can be found in [7].

Three different periods during the early age deformation are distinguished and separated by lines in Figure 7. The first period corresponds to the pouring period. During this period the concrete is cast with the sensors measuring the corresponding deformation. A relatively small deformation due to the additional load of the fresh vault concrete is noticed with the sensors that measure the deformation of the foundation (S-748 and S-743). The deformation of the foundation is significantly smaller than the deformation measured with the sensors located in the lower part of the vaults (sensors S-749, S-744 and S-740). This is a consequence of the plasticity and rheology of fresh concrete. Finally the sensors that are higher in the vaults (S-746, S-745 and S-747) measured very small deformation due to the reduced load at theirs locations. Since the setting time is retarded, the new concrete is in a "dormant period" during the pouring period. This fact is also confirmed by the temperature measurements (Figure 8).

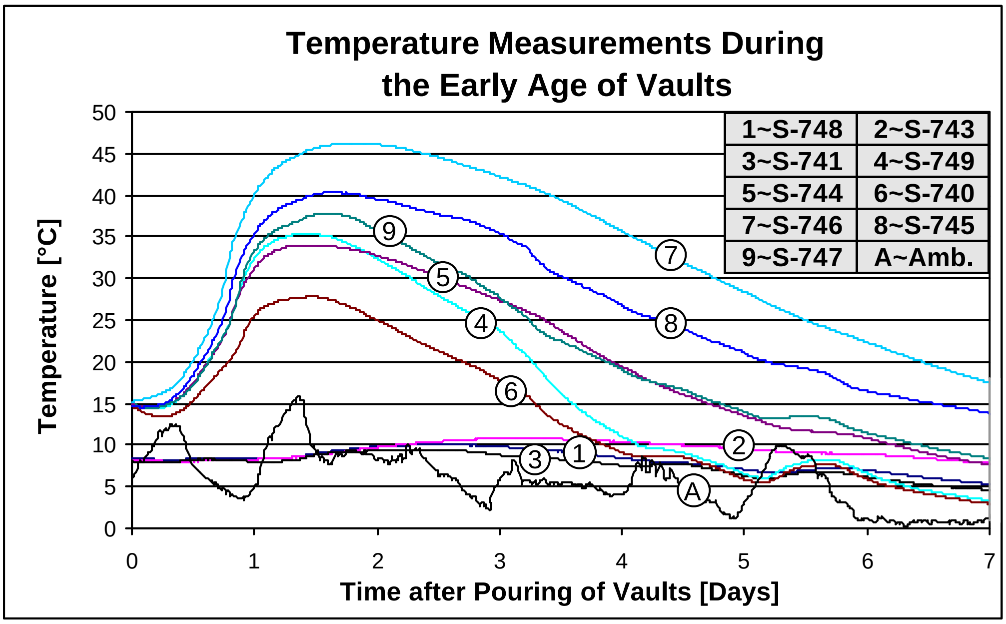

Figure 8: Temperature Measurements at the Early Age of the Vaults

The second period in Figure 7 is the thermal swelling period. During this period the hydration process is activated, the temperature increases and induces the deformations too [6]. While the deformation of the foundation is very small, the deformation of the lower parts of vaults is larger and the deformation of the upper parts of the vaults is very important. The smaller deformation of the lower parts of the vaults can be explained by their restraint of the foundations. The upper parts of the vaults are not confined and the concrete in these zones swells significantly. During this period the concrete is set and stresses are generated in the vaults.

During the shrinkage period (see Figure 7) the deformation is generally decreasing due mostly to the thermal shrinkage of concrete. During this period, a 50 μm wide crack opening was recorded by sensor S-749 and later visually confirmed on the structure. The crack is a consequence of the vault-foundation interaction and the early age deformation provoked by thermal stress.

Different behaviours of the tunnel's different parts can be identified and described by three different types of curves shown in Figure 7. The first type concerns the foundation, the second type the lower parts of the vaults, and the third type the upper parts of the vaults. The deformation curves of the foundation and the lower parts of the vaults after the cooling are parallel and point to monolithic behaviour of the foundations and the vaults. The deformation curve of the upper parts of the vaults is not parallel to the other curves and indicate that the cross-section does not remain plane during early age deformations. Since the bonding between the vaults and the foundation can be assumed to be good, stresses are therefore introduced into the vaults. As a consequence, cracking of concrete may appear.

Regarding long term deformation of foundations, four distinct phases can be identified in the behaviour shown in figure 6. First, the very early deformation due to thermal swelling followed by the shrinkage period subsequently. The casting of the vaults introduces additional deformation into the foundation. Finally, the foundation deformation in the period after the pouring of vaults is relatively stable and follows the thermal variations of the environment.

7 CONCLUSIONS

The implementation of the SOFO system for the monitoring of structural deformations in the concrete of the Champ Baly cut-and-cover tunnel leads to the following remarks:

1) The installation of the SOFO system was relatively rapid and did not affect, nor slow down, the construction process.
2) Only one sensor was broken during the installation, which confirms the resistance and reliability of the system. The construction workers were not requires to give particular care to the sensors.
3) The complete history of behaviour of each part of the monitored sections, the foundations as well as the vaults was registered. The very early age and early age are included too.
4) The very early age and the early age deformation were measured automatically during the first seven days without any human intervention. Measurements were taken every 30 minutes.
5) Using the SOFO system, it is possible to calculate the evolution of the average strain in different parts of the monitored sections as well as the curvature of the sections. If additional sections of the tunnel had been equipped with sensors, it would be possible to retrieve the spatial deformation of the tunnel using the double integration of the curvature [8].
6) The SOFO system was able to record the time of opening of cracks as well as to measure their width.

8 ACKNOWLEDGEMENTS

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