Long-term deformation monitoring of historical constructions with fiber optic sensors

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ABSTRACT: From many points of view, fiber optic sensors are the ideal transducers for civil structural monitoring. Being durable, stable and insensitive to external influences, they are particularly interesting for the long-term health assessment of civil structures.

The SOFO system uses long-gauge optical fiber sensors to monitor deformations with high resolution (0.002 mm), precision (0.2%) and long-term stability (no drift over at least 5 years). The sensors are easy to install, have a dynamic range between -0.5 % and +1.5 % of the sensor active length, are insensitive to electromagnetic perturbations (e.g. thunderstorms), temperature variations, corrosion and moisture. The measurement length can vary between 25 cm and several tens of meters. The sensors can be mounted on the surface of concrete, mortars, bricks, stone, timber, steel and other construction materials or can be embedded in concrete and mortars. To date, we have installed about 1'500 sensors in almost 70 different applications including bridges, tunnels, piles, anchors, nuclear power plants and harbor structures.

In this contribution we will present the application of the SOFO system to the monitoring of historic buildings. In this domain, these sensors are particularly useful for the monitoring of the building's deformations, crack openings, foundation settlements as well as for the evaluation of the effectiveness of restoration and reinforcement interventions. A considerable experience has been gathered, for example, in the evaluation of the adherence between existing materials and newly added ones.

As case study, we will discuss the application of the SOFO system to the monitoring of a cracked church vault and to the long-term monitoring of a harbor quay wall. In the first case, relatively short sensors with a measurement base of 30-50 cm were mounted at different locations along a longitudinal crack that appeared in a small church in Gandria (Switzerland). The crack openings were recorded and their daily and seasonal variations analyzed with respect to ambient temperature variations. It was found that, although the crack opening varied considerably, there was an excellent correlation with the ambient temperature variations and therefore, no long-term evolution of the damage severity. It was therefore concluded that the crack reflected a change in the loading patterns on top of the vault, but that the structure had found a new equilibrium and responded only to temperature variations. In the second case, the east quay wall of the San Giorgio pier in the Genoa Harbor (Italy) has been equipped with an array of more than 60 SOFO fiber optic sensors for continuous monitoring. These sensors allow the measurement of the pier displacements during the dredging works, ship docking and in the long term. The sensors measure the curvature changes in the horizontal and vertical planes and allow a localization of settlements with a spatial resolution of 10 m over a total length of 400 m. The system is in operation since fall 1999, and data has been collected automatically and continuously since then. This case study presents the first analyses and interpretations performed on the monitoring data. Correlation of raw data and curvature analysis to environmental conditions is also presented. Although not properly an historical construction, this old quarry is interesting because, as for many monuments, it is difficult to create a numerical model describing its behavior and a learning process is therefore required to analyze the monitoring data.

1 INTRODUCTION

The management and the security of civil structures and historical constructions in particular requires periodic monitoring, maintenance and restoration. Furthermore, an accurate knowledge of the behavior of a structure is becoming more important as new building and restoration techniques are introduced and the existing constructions are often required to survive undamaged to nearby constructions. Long-term monitoring 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 accurate and very stable systems, able to relate measurements often spaced over long periods of time. Furthermore the sensors should be installed with minimal invasion to the aesthetics and functionality of the structure under test.

2 SHORT AND 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.
Our group has developed a non-incremental long-term monitoring system based on low-coherence interferometry in optical fibers, which has already been successfully applied in a large number of bridges, tunnels, dams and other civil engineering structures, including historical constructions.
This system is named SOFO. SOFO is the French acronym of "Surveillance d'Ouvrages par Fibres Optiques" (or structural monitoring by optical fibers).

2.1 The SOFO system

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

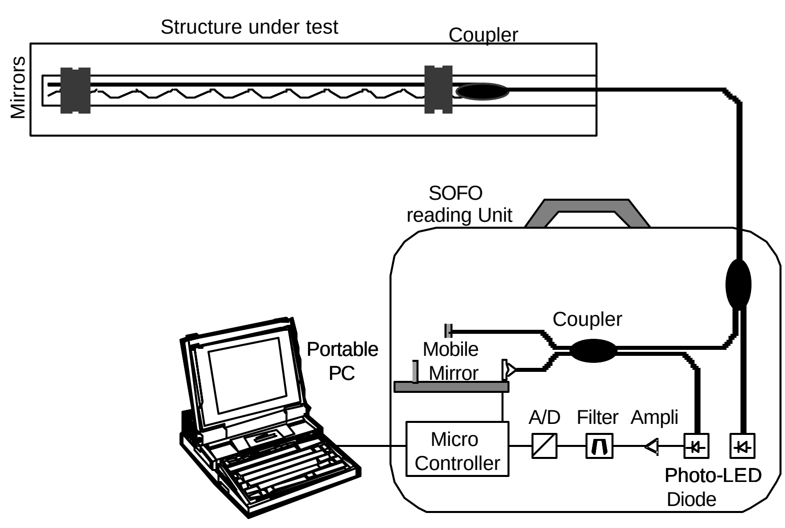

Figure 1: Setup of the SOFO system

The sensor consists of a pair of optical fibers installed in the structure to be monitored. One of the fibers, called measurement fiber, is in mechanical contact with the host structure itself, being attached to it at the two anchorage points, pre-tensioned in between and protected with a plastic pipe. The other, the reference fiber, is placed loose in the same pipe. All deformations of the structure will then result in a change of the length difference between these two fibers.

To make an absolute measurement of this path unbalance, a double Michelson interferometer in 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 used (the 1.3 micron radiation of a LED), interference fringes are detectable only when the reading interferometer exactly compensates the length difference between the fibers in the structure.
If this measurement is repeated at successive times, the evolution of the deformations in the structure can be followed in time.
The precision and stability obtained by this setup have been quantified in laboratory and field tests to 2 micron (2/1000 mm), independently from the sensor length over more than five years. 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.

Figure 2: SOFO fiber optic deformation sensor

Figure 2 shows a typical sensor for length up to 10 m. This sensor is adapted to direct concrete / grout 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 7 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.

2.2 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:
Deformation evolution analysis: This general-purpose package extracts the results concerning a single sensor and displays them as a function of tim e or load. The data can than be exported to other software packages, like spreadsheets or other graphical tools for adequate representation.
Curvature and displacement: 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 fibers are installed horizontally, but vertical displacement ar e 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.
Statistics: Another software package allows the analysis of deformation data from structures undergoing statistically reproducible loads (such as traffic).

3 APPLICATION EXAMPLES

This section will present two significant application examples of this technique: the long-term monitoring of a masonry church vault and the analysis of the deformations of a harbor pier during dredging works.

3.1 Gandria Church monitoring

Situated on a steep hillside surrounding the Lugano Lake, the small Gandria church presents an impressive crack running along the center of the (once) cylindrical vault. Other smaller cracks are partially present on the upper convex side of the vault (see Figure 3).

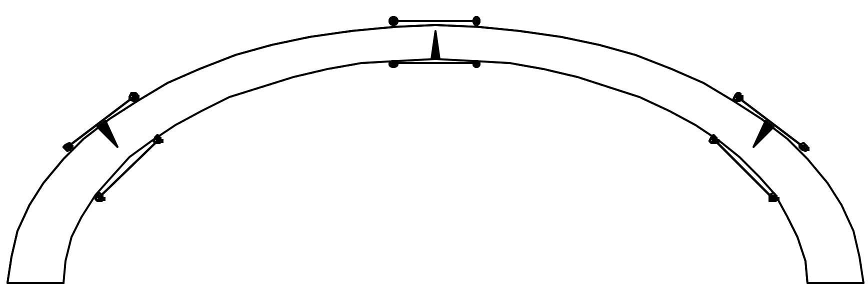

Figure 3: Location of the main cracks and SOFO sensor layout

Since the static system of the church and the evolution of the crack openings are not very well known, it was decided to install ten SOFO sensors to monitor the cracks and the curvature variations of the vault. The sensors are 30-50 cm long and are attached to both sides of the vault using L-brackets (see Figure 4). All optical connections are joined in the church annex and the sensors are measured regularly without the need to install scaffoldings in the church, which is still in use. The sensor installation was carried out in just one day and the sensors are barely visible to the uninformed observer.

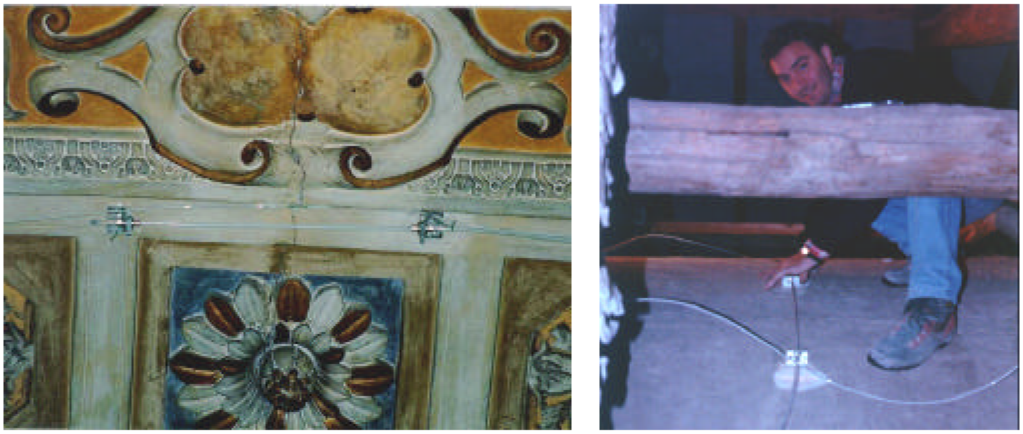

Figure 4: SOFO sensor installed underneath and above the Gandria Church vault

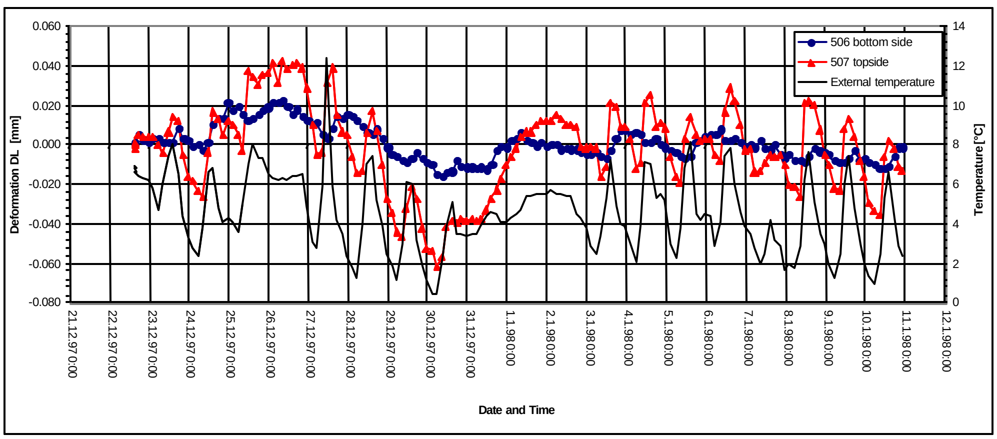

Figure 5: Measurement of two sensors above and below the vault and to the air temperature during three weeks.

Figure 5 shows measurements performed automatically using an optical switch at the end of 1997. The daily deformations are clearly identifiable, while relatively large variations are observable on December 24-25, when the church was heated for (and by) the Christmas celebrations.

Because of budget restriction and since the deformations were expected to evolve smoothly, it was decided against installing a reading unit permanently in the church. Instead, measurement campaigns of at least one week were carried out at intervals of about 3 months. This monitoring program allows the observation of the deformations due to the daily and seasonal temperature variations. The results from two of the sensors are shown in Figure 6 along with the recorded internal and external temperatures.

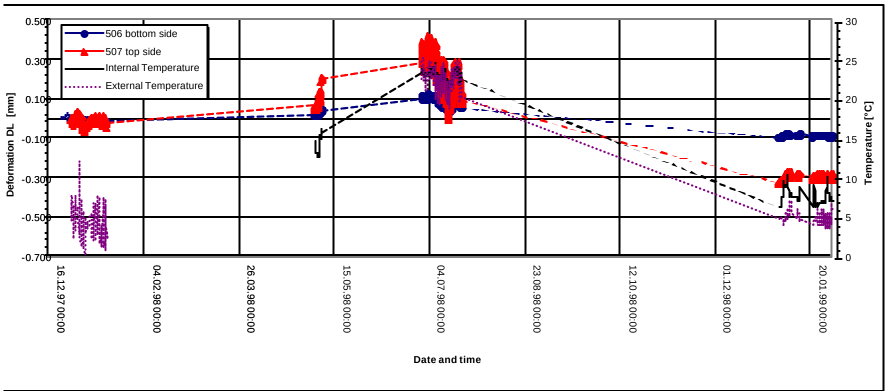

Figure 6: Long-term monitoring of the Vaults deformations, internal and external temperatures

It can be observed that the deformations are not completely reversible, since after one year and with very similar temperature readings, the sensors measure a small compression of 0.1 and 0.3 mm respectively. These values are not considered as significative and do not represent a threat to the vault stability.

It is also possible to notice that the daily deformation excursions are much larger during the summer months and this is compatible to the larger temperature changes experienced in that period. It can also be noticed that the deformations are well correlated to temperature variations. The total amplitude of the deformation during one year is rather large (up to 0.6 mm). This explains the reason for the rapid cracking of the glass plates that were installed on the crack. However, the good correlation with temperature and the reversible behaviour during this year points to a general stability of the vault. Furthermore, the negative residual values seem to indicate a kind of "healing" of the cracks rather than a progressive opening of the same. This corroborates the engineer supposition that the crack were generated due to a de-compression of the vault produced during refurbishing work, but that the structure has now found a new stable configuration. The monitoring is now continued with longer periodicity.

3.2 Genoa San Giorgio Levante pier monitoring

The San Giorgio pier is used for coal import and it has been recently subjected to a retrofitting programme, partly under way. The facility has been realised in the 20's and the vertical walls delimiting the quays are made of heavy concrete blocks; more recently, a further section has been added to the pier in order to increase berthing space and actually the pier measures 400 metres in length. Planned developments consist in dredging of the east basin from the actual 11 m to a water depth of 14 m, to allow berthing of bigger ships: this work has been planned for 2001, and has required the strengthening of the east wall (Figure 7).

Figure 7: The San Giorgio Levante Pier

Retrofitting of the wall has been performed in 1998; to avoid disruption of the wall during dredging, the structure has been underpinned with jet-grouting columns up to the depth of 18 m, and the blocks have been connected by means of vertical steel rods. Stability has been improved with permanent active tendons installed along the entire length of the pier. After execution of the consolidation works, the east wall has been equipped with a system of sensors in order to study the structural movements over a long period of time. Monitoring has the objective of detecting deviations from normal structural behaviour that may indicate a state of damage in the structure. Therefore, monitoring is organised in distinct phases: the first phase, before dredging operations, has the aim of determining what a *normal* structural behaviour can be; a second phase, during dredging, will be intended to detect potential damaging of the wall caused by the works and, finally, a third phase will involve health monitoring in the long term.

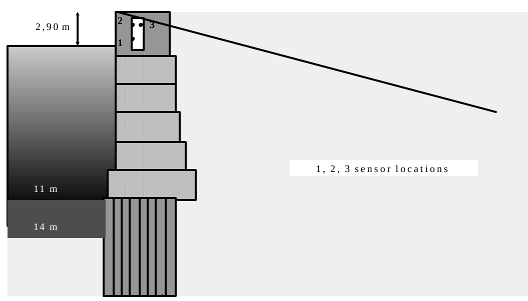

Figure 8: Quay wall cross-section, strengthening works and sensor locations.

The quay wall has been equipped with 72 SOFO sensors (67 of them continuously functioning), installed in such a way to have 3 sensors for each measuring section (Figure 8). All sensors have an active length of 10 metres; sensors have been positioned at the 3 vertices of the service gallery located in the crown blocks, except in the last extension part, where no gallery was built: therefore in the last 5 sections only a pair of sensors have been installed in the upper surface of the crown block, underneath the pavement. Cabling of sensors has been organised in three groups (A, B, C, starting from the sea side), each one controlled by a junction box collecting 24 optical cables. The junction boxes are in turn connected to the reading unit by means of cables located in an underground duct. The reading unit is connected to the sensors through a programmable optical switch. Data are collected and stored in a computer database (SOFODB). The reading unit is connected to the Port of Genoa Information Network and the database is made available on-line.
After a few months, needed for the tuning of the system, the data have been permanently stored in the database starting from 30 November 1999; acquisition campaigns have been programmed

four times a day, each campaign elapsing 15 minutes to completion. Monitoring has been therefore addressed to characterise a long-term structural response.

Among the various environmental sources causing long-period displacement of the wall, it has been found that temperature is playing the most important role. No apparent influence of the amount of coal stored in piles on the quay has been found. Correlation to environmental temperature has been therefore studied to a greater extent.

In all the cells, it has been apparent that response to environmental temperature variations is delayed by a few days, due to the thermal inertia of such a massive structure.

Sensor readings can be put in strict correlation with temperature variations, but different sections may respond to temperature in a different way. In particular, cells containing joints in the crown blocks give responses out-of-phase with respect to temperature variation, while monolithic cells give responses in-phase.

The plots in Figure 9 show the different behaviour of the two types of cells. The difference is visible considering biweekly thermal variations (shown in tenth of degree Celsius) as well as in the complete observation period (winter cycle and beginning of summer cycle).

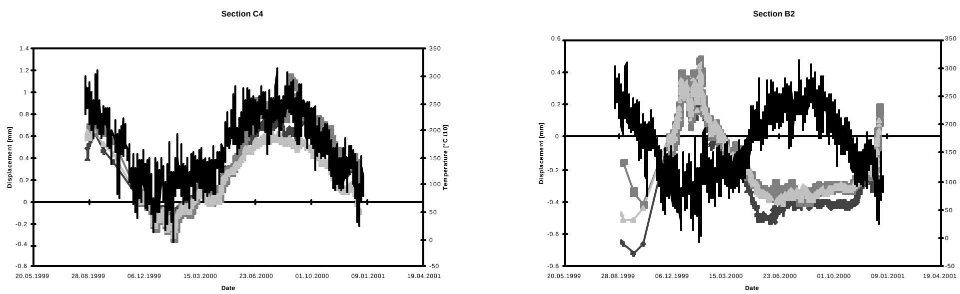

Figure 9: Time-strain-temperature plot for a section in-phase and out-of-phase with thermal variations.

Figure 10 shows the curvature of a cell for a complete 1-year period. It can be observed that the most significant deformations appear during the summer months and that the behavior is reversible, since the curve returns to its initial value after one year of measurements.

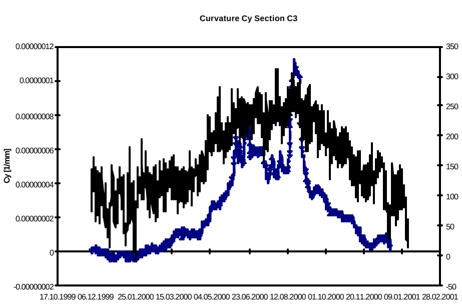

Figure 10: Time-curvature-temperature plot for one complete year.

4 CONCLUSIONS

The monitoring of historic buildings and of existing structures in general is one of the essential tools for a modern and efficient management of the heritage infrastructures. 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 focused to more accurate measurements, but also to 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 quite a few have evolved into commercial products.
It is difficult to find a common reason for the success of so diverse types of sensors. Each one seems to have found a niche where it can offer performance that surpass or complement the ones of the more traditional sensors. If three characteristics of fiber optic sensors should be highlighted as the probable reason of their present and future success, we would cite the stability of the measurements, the potential long-term reliability of the fibers and the possibility of performing distributed and remote measurements.
The success of fiber optic sensors depends not only on the underlying optical technology, but even more on the ability of practically and reliably installing the sensors in real structures, with minimum disturbance to the construction progress or the normal operation of the structure. To achieve these goals it is important to develop ad-hoc packaging and accessories (cables, junction boxes, etc.) that makes possible for non-specialists to use fiber optic sensors in the field.
The SOFO system has emerged as one of the leading fiber optic sensor systems for the monitoring of civil structures. The presented examples show how this system can be used to obtain precise and reliable deformation measurements over years of operation. This long-term stability is particularly important for the detection of slowly developing pathologies, were the time-scale of the events can easily spread over year. Conventional sensors that can suffer from measurement drift would be unable to distinguish between real deformations and reading errors. The examples of the monitoring of the Gandria Church vault and of the San Giorgio Levante pier also show how the monitoring strategy and measurement frequency can be adapted to the observed phenomena and to the available budget.
In both cases, obtaining precise, reliable and dense data contributed to found engineering judgment on objective data and significantly narrow the uncertainty often associated with subjective judgment.

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