Bridge Monitoring by Interferometric Deformation Sensors

(Invited Paper)

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1. ABSTRACT

In many concrete bridges, the deformations are the most relevant parameter to be monitored in both short and long-terms. 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 bridge behavior. We have found that fiber optic deformation sensors, with measurement bases of the order of one to a few metres, can give useful information both during the first days after concrete pouring and in the long term. In a first phase it is possible to monitor the thermal expansion due to the exothermic setting reaction and successively the thermal and drying shrinkages. Thanks to the long sensor basis, the detection of a crack traverse to the measurement region becomes probable and the evolution of cracks can therefore be followed with a reduced number of sensors. In the long-term it is possible to measure the geometric deformations and therefore the creeping of the bridge under static loads, especially under its own weight. In the past two years, our laboratory has installed hundreds of fiber optic deformation sensors in more than five concrete, composite steel-concrete, refurbished and enlarged bridges (road, highway and railway bridges). The measuring technique relies on low-coherence interferometry and offers a resolution down to a few microns even for long-term measurements. This contribution briefly discusses the measurement technique and then focuses on the development of a reliable sensor for direct concrete embedding and on the experimental results obtained on these bridges.

Keywords: fiber optic sensors, structure monitoring, low-coherence interferometry.

2. INTRODUCTION: BRIDGE DEFORMATION MONITORING NEEDS

The monitoring of a new or existing bridge can be approached either from the material or from the structural point of view. In the first case, monitoring will concentrate on the local properties of the materials used in the bridge construction (e.g. concrete, steel, timber,…) and observe their behavior under load or aging. Short base length strain sensors are the ideal transducers for this type of monitoring approach. If a very large number of these sensors are installed at different points in the structure, it is possible to extrapolate information about the behavior of the whole bridge from these local measurements.

In the structural approach, the bridge is observed from a geometrical point of view. By using long gage length deformation sensors with measurement bases of the order of one to a few metres, it is possible to gain information about the deformations of the bridge as a whole and extrapolate on the global behavior of the construction materials. The structural monitoring approach will detect material degradation like cracking or flow only if they have a direct

impact on form of the bridge. This approach usually requires a reduced number of sensors when compared to the material monitoring approach.
The availability or reliable strain sensors like resistance strain gages or, more recently, fiber Bragg gratings [1] have historically concentrated most research efforts in the direction of material monitoring rather than structural monitoring. This latter has usually been applied using external means like triangulation, dial gages and invar wires. Interferometric fiber optic sensors offer an interesting means of implementing structural monitoring with internal or embedded sensors. In the next paragraphs we will give an overview of the different parameters that can be monitored during the whole life-span of a bridge using long gage sensors.

2.1 Bridge construction

For new structures, the construction phase presents a unique opportunity to install sensors and gather data that will be useful for the whole life-span of the bridge. For concrete structures it is even possible to embed the deformation sensors right inside the different structural parts of the bridge like the pillars, the beams and the deck. It is possible to follow the setting reaction of concrete in its expansion and shortening phases and asses the conformity of the material to the prescribed standards. In the case of bridges constructed in successive phases, the sensors can help to optimize the time between successive concrete pours, by evaluating the curing stage of the precedent sections. If the bridge includes pre-stressed elements, the cable tensioning and the associated deformations can also be monitored and the forces can be adjusted to achieve the desired bridge shape. For pre-fabricated elements, the sensors can be installed right at the factory and serve both as an additional quality test of each element separately and as a deformation sensor for the assembled structure.
Problems in bridge construction often come from the foundations. Long deformation sensor can also be used to monitor these critical parts.
Many bridges are particularly vulnerable to external agents like wind, small earthquakes and thermal loading before they are completed. A deformation sensor network can quantify any damage undergone by the structure before it reaches its final static configuration.

2.2 Bridge testing

Many bridges of some importance are load-tested before being put in service. Typically the bridge is loaded with pre-defined patterns of sand-loaded trucks and the induced vertical displacements are compared with the ones calculated by the engineers. The measurements are normally performed with conventional techniques like triangulation and dial gages that are installed for this test only. Embedded and/or surface mounted deformation sensors can replace or supplement these measurements and help compare these extreme loading patterns to the ones that will be encountered by the bridge once in service. The appearance of cracks or other degenerative phenomena during these tests can also be observed.

2.3 In-service monitoring

Once the bridge is in-service, its monitoring becomes even more important, since the security of the user is involved. Ideally, all deformations produced by traffic, wind and thermal loading (sunshine, seasonal temperature variations,…) should be reversible. However, all construction materials tend to degrade with age. Concrete cracks and flows, steel is subject to fatigue and rust. A degradation of the building materials usually has an influence on the static behavior of the bridge and can be detected by the deformation sensors. These measurements can lead to early warnings and prediction of potential problems and help in the planing of the necessary maintenance interventions.
The sensor network can monitor the load patterns associated with traffic and record any abnormal (but unfortunately not unusual) overflow of the prescribed carrying capacity. In the case of excessive deformations resulting from partial structural deficiency or an excessive wind or traffic load, the monitoring system can automatically stop or slow the traffic on the bridge.
In seismic areas, one of the most challenging tasks in bridge monitoring is the damage assessment after earthquakes, even of modest amplitude. Bridges can remain inaccessible for a long time before their safety is recertified and they can be re-opened to traffic. An internal sensor network can obviously accelerate this process and discover damage in the bridge and its foundations undetectable by visual inspection.

2.4 Refurbishment

Many concrete bridges constructed even only 10 or 20 years ago already need refurbishment due to degenerative processes like carbonation, chemical aggressions (e.g. deicing salts), steel corrosion and use of poor materials. Typically, the damaged surface of concrete is removed and a new concrete or mortar shell is applied to the bridge. To ensure a durable repair it is necessary to guarantee an excellent cohesion between the old and the new concrete, otherwise the new layers will fall-off after a short time destroying all repairing efforts. Material testing is therefore fundamental and has to be performed both on concrete samples analyzed in the laboratory but also with in-situ measurements. In this case the shrinkage, cracking and plasticity of the new layer have to be measured by embedding sensors at different positions between the old concrete and the surface of the new one.

These sensors, one in place, can serve as a long-term monitoring system for the bridge, without the need to mount sensors on their surface. Embedded sensors are indeed better protected and less subject to external disturbances like direct sunshine, wind and rain.

2.5 Recycling or dismantling

Temporary and re-usable bridges need efficient monitoring systems to asses damages before recycling.

Deformation sensors can also be used to determine the residual carrying capacity of a bridge and when dismantling becomes necessary, help to follow this phase that can be as delicate as the bridge construction.

2.6 Knowledge improvements

Besides the knowledge that can be gathered on a particular bridge instrumented with a sensor network, more general information can be collected and used to refine the knowledge of the real behavior of structures and eventually improve design, construction and maintenance techniques. If similar bridges are constructed in succession, the so-called design-by-testing approach can be used to continuously improve on the design and verify the consequences on the new structures. The measured deformations can be inserted into a feed-back loop to the finite elements programs used to calculate the structure.

Deformation sensors can also be used in the laboratory to experiment with new construction materials and techniques before application to real structures. Testing on reduced-scale models allows the testing of new solutions with reduced costs and risks.

2.7 Smart Structures

Fiber optic sensors are often cited as the first building block of smart structures [2], i.e. structures able to respond to internal and external stimuli with appropriate actions using a series of actuators. The smart structure concept has usually been applied to relatively small structures, but could also find interesting application to bridges. Possible examples include actively damped and adaptive structures. In the first case the bridge would be capable of actively damping vibrations produced by traffic, wind or seismic loads, increasing the comfort of the user and slowing the fatigue damages. This application, however, requires huge forces and energies that are not easy to generate. Adaptive structures would react much slower and only compensate to quasi-static loads or creep and flow effects. This could be achieved for example by changing the force in the post-tensioning cables according to the measured deformations [3].

2.8 Summary

The following table reviews the different applications of deformation sensors to bridge monitoring discussed in the previous paragraphs.

Phase:	Deformation monitoring needs:
Bridge construction	Material testing. Process control (construction in phases). Pre- and post-tensioning monitoring. Quality control in pre-fabrication. Damage assessment during delicate construction phases or due to external

	agents. Foundations monitoring.
Bridge load testing	Deformation monitoring under known loads. Damage assessment. Complement to external measuring systems (triangulation, dial gages,…).
In-service monitoring	Deformation monitoring under traffic, wind, and thermal loading. Cracking, creep and flow and other construction material degradation. Load patterns and excessive load monitoring. Post-seismic damage assessment. Foundations monitoring.
Refurbishment	Quality control of added concrete and mortars. Differential shrinkage monitoring. Instrumentation of existing bridges for long-term monitoring.
Recycling and dismantling	Damage assessment before re-using of structural parts. Safe dismantling.
Knowledge improvements	Design by testing. Feedback to finite elements programs. Testing of new materials and construction techniques. Reduced scale models.
Smart structures	Active damping. Adaptive structures.

Table 1. Deformation monitoring needs during different phases of a bridge's life-span.

3. FIBER OPTIC MONITORING SYSTEM

3.1 Requirements

In the previous paragraphs we have presented a large palette of measurements that can be performed on bridges using long-gage length deformation sensors. Interestingly, most of these applications have similar requirements for the performances of the sensors that are used. Table 2 resumes the typical requirements for such sensors.

Parameter:	Requirements:
Gage length	20 cm to 6 m for most bridges up to 100 m for particular applications like suspension bridges
Resolution	1 to 100 microns, depending on application and gage length (corresponds to a strain resolution of a few microstrains)
Dynamic range (Maximum measurable deformation)	Up to 1% of the gage length in elongation and shortening. Deformations of a few mm are typical.
Precision	Better than 1% of the measured deformation
Measurement speed	A few tens of Hz for traffic monitoring. All other quasi-static measurements require the measurement of a whole bridge span in less than a few minutes.
Stability	For long term measurements the resolution should be guaranteed for at least a few years.
Other requirements	The system should be rugged enough to survive the demanding conditions found at a building yard and in general outdoors environments. The sensors should be immune to EM disturbances and corrosion and be non-conducting. Low cost.

Table 2. Typical requirements for deformation sensors for bridge monitoring .

Many of above requirements can be satisfied with fiber optic sensors that are indeed easy to handle, dielectric, immune to EM disturbances and can accommodate deformations up to a few percents. The precision requirements, the long gage lengths and the stability required by these applications point to the use of interferometric schemes. However, due to their incremental nature, most interferometric setups require continuous and uninterrupted monitoring, which is a major drawback for long-term applications. Low-coherence interferometry offers most of the advantages of interferometric sensors but features non-incremental operation allowing absolute measurements to be performed at any given time. Our laboratory has developed a monitoring system based on low-coherence interferometry that meets most of the requirements resumed in Table 2.

3.2 The SOFO system

SOFO is the French acronym of Surveillance d'Ouvrages par Fibres Optiques (or structural monitoring by optical fibers). The proposed measurement setup is based on a double, all-fiber, Michelson interferometer in tandem configuration (see Figure 1) [4]. The 1.3 micron radiation of a Light Emitting Diode (LED) with a rated power of 0.2 mW and a coherence length of 30 mm is launched into a monomode fiber and split, by means of a monomode coupler, into a pair of fibers called respectively the reference and the measurement fibers. The reference fiber is mechanically coupled to the structure and follows its deformations, while the reference fiber is installed freely inside a pipe and acts as temperature reference. The light is reflected by mirrors at the end of the fibers or by a series of partial reflector pairs installed at different fiber locations which allows the sensors to be multiplexed in-line [5]. The analyzer is a Michelson interferometer with one of the arms terminated with a mobile mirror. It allows the introduction of an accurately-known path difference between its two arms. The signal detected by the photodiode is pre-amplified and demodulated by a

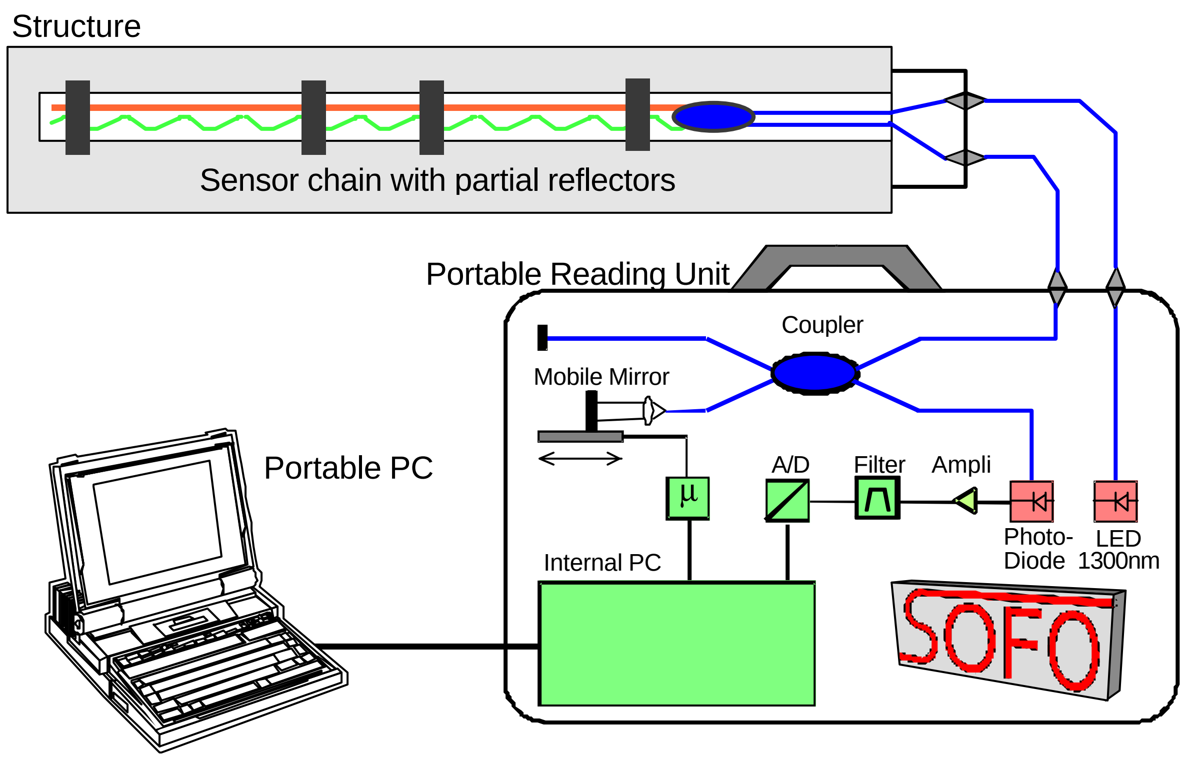

Figure 1 Setup of the SOFO system

band-pass filter and a digital envelope filter. For each pair of partial reflectors a triple coherence peak is observed. The central peak is obtained when the Michelson analyzer is balanced, whereas the side peaks correspond to the mirror positions where the path unbalance between the analyzer arms corresponds to the length difference between two twin partial reflectors or the end mirrors. The central peaks from all partial reflectors will thus overlap to a peak of higher intensity, while the lateral peaks will in general appear at different locations. By following the position of the side peaks it is possible to determine the total deformation undergone by the measurement fiber between the corresponding partial reflectors and the coupler. The position of the peaks can be determined with a precision of about 2 mm by computing the center of gravity of the peaks themselves.
The analyzer is assembled into a portable, battery powered and rugged unit adapted to in-field applications.
The main characteristics of the SOFO system are resumed in Table 3.

Parameter:	Requirements:
Gage length	20 cm to 8 m for each sensor section. Up to 6-8 section per chain. Up to 50 m with special sensors
Resolution	2 microns, independently from the gage length.
Dynamic range (Maximum measurable deformation)	1% in elongation and shortening (sensors). Up to 150 mm in elongation and shortening (reading unit)
Precision	Better than 1% of the measured deformation.
Measurement speed	Less than 10 seconds for each sensor chain
Stability	Drift not observable over at least three years.
Other requirements	Rugged, portable and battery powered reading unit. Sensors adapted to direct concrete embedding or surface mounting on existing structures.

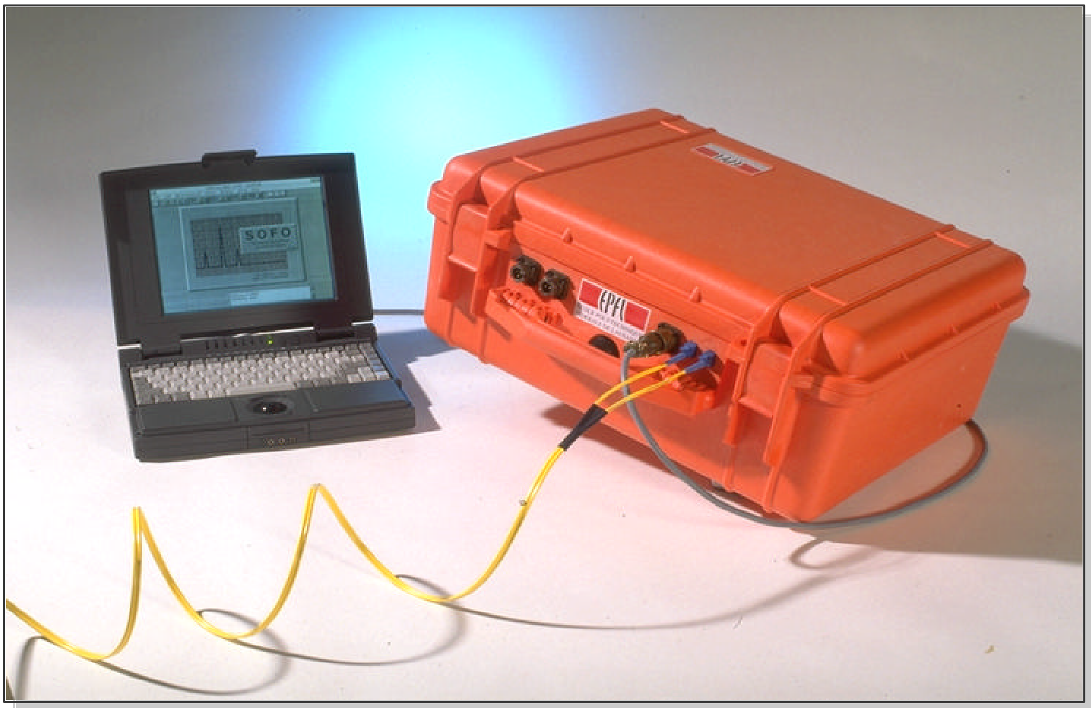

Figure 2 SOFO Portable reading unit.

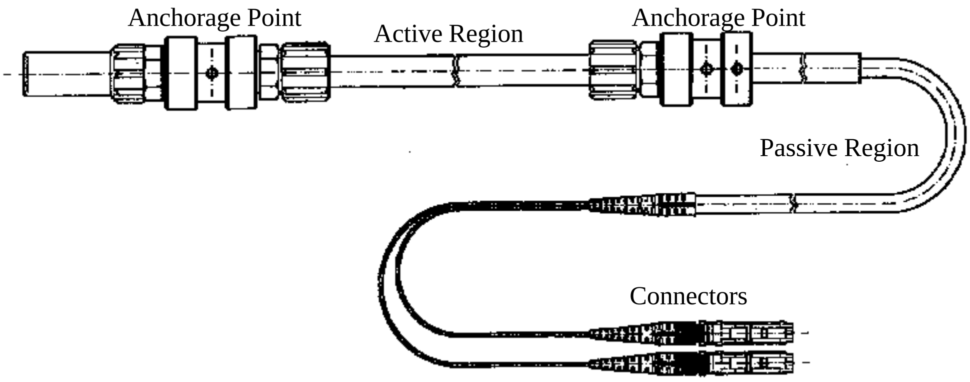

Figure 3 SOFO Deformation sensors for direct concrete embedding. The active region extends between the two anchorage points. The passive region can be up to a few km long and connects the sensor to the reading unit.

Table 3. Typical requirements for bridge monitoring .

Except for the dynamic traffic measurement, the SOFO system can therefore be used for all the applications cited in section 2. 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. Figure 2 shows the portable reading unit with the portable PC.

Figure 3 shows a typical sensor for length up to 8 m. This sensor is adapted to direct concrete embedding or surface mounting on existing structures [6]. 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.

4. APPLICATION EXAMPLES

In the next paragraphs, we will present a choice of applications examples of the SOFO system to achieve different monitoring porpoises in bridge maintenance.

4.1 Venoge bridge: material testing during construction and load tests

The Venoge highway bridge near Lausanne is a four-span bridge consisting of two parallel steel girders of 1.0 ÷ 1.9 m in height supporting a 23 cm thick concrete deck. To widen the bridge, two identical bridges were built in 1995 on each side of the existing bridge creating a third traffic lane and a new emergency lane in each direction. The Venoge bridge widening and the different phases of its construction allowed the observation of many interesting phenomena. Monitoring the real behavior of this steel-concrete bridge under direct and indirect actions was the general aim of this experiment, which can be divided into 2 main objectives:

- Monitoring of the shrinkage effects, especially during the first hours after concreting. It is very interesting to control the thermal expansion phases, to understand the real behavior of the steel-concrete interaction.
- Verification of the bridge behavior under static forces during load testing.

More than 30 fiber optic sensors, a few wire strain gauges and about 24 thermocouples were installed in the deck and on the steel girders. Forty-eight strain gauges where fitted on the steel girders, while four instrumented bearings were installed on the extremities of the first span [7].
The chart presented in Figure 4 shows the results obtained by 4 fiber optic deformation sensors during the first month after concreting.
The thermal expansion phase is perceptible with an elongation value around 0,06 ‰. During the cooling phase, the fiber optic sensor measurements present a discontinuity pointing to the formation of cracks, in particular between the 4th and 9th august, eight days after concreting. Observations in the pile zone have indeed shown the appearance of cracks of 0,1 - 0,15 mm width, separated by 2 m, eight days after the concreting. The good correlation between the

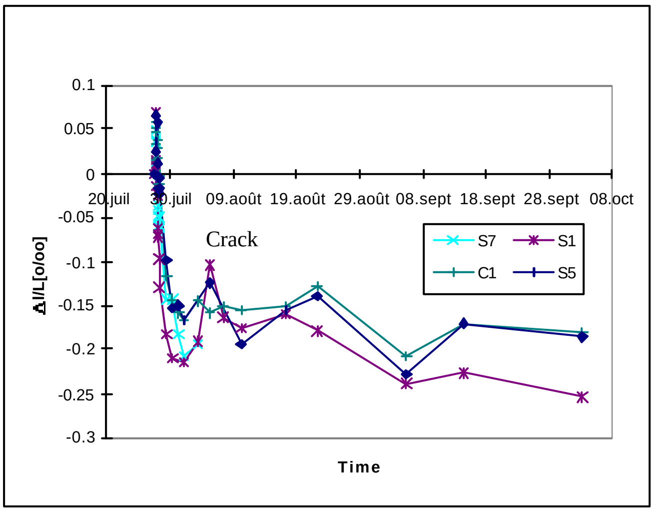

Figure 4 Shrinkage measurements during one month on the Venoge bridge deck. Four different sensors are shown. The apparition of a crack in one of the sections is clearly visible.

crack width measured with a magnifying glass and the readings of the optical fiber sensor shows the value of placing such sensors in a concrete structure.
The load test, performed 4 months after concreting, consisted in placing 25 tons trucks on the bridge. They were placed in accordance with 6 load patterns (a, b, c, d, e, f, o (without trucks)) during 5 minutes each time. The load

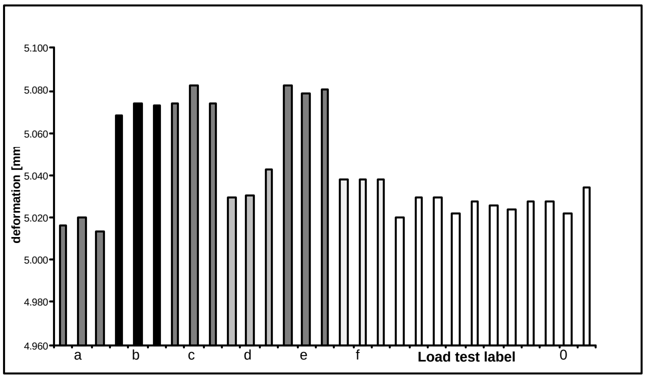

Figure 5 Deformations during the load test. The load cases a -f correspond to different load patterns.

cases were repeated 3 times and separated by a zero load test (load case 0). During the 5 minutes of loading, the vertical displacements of the bridge were measured at 12 different locations by external dial gauges. Figure 5 shows the values measured by a fiber optic sensor in relation to the load case. This figure shows a good repeatability for the SOFO sensor when a load case is repeated. The deformations produced by the different load cases can be easily recognized. The error on the readings can be estimated to about 4 microns.

4.2 <u>Moesa bridge: damage assessment during delicate construction phases</u>

The Moesa railway bridge is a composite steel concrete bridge on three spans of 30 m each. The 50 cm thick concrete deck is supported on the lower flanges of two continuous, 2.6 m high I-beams. The bridge has been constructed alongside an old metallic bridge. After demolishing this one, the new bridge has been moved a distance for 5 m by 4 hydraulic jacks and positioned on the refurbished piles of the old bridge.

About 30 fiber optic, low-coherence deformation sensors were imbedded in the concrete deck to monitor its deformations during concrete setting and shrinkage, as well as during the bridge pushing phases. In the days following concrete pour it was possible to follow its thermal expansion due to the exothermic setting reaction and the following thermal and drying shrinkages. The deformations induced by the additional load produced by the successive concreting phases were also observed.

During the bridge push, which extended over six hours, the embedded and surface mounted sensors monitored the curvature variations in the horizontal plane due to the uneven progression of the jacks. Excessive curvature and the resulting cracking of concrete could be ruled out as a result of these measurements. Figure 6 shows the results obtained by two 2 m long sensors placed along the bridge length, at the position of one of the jacks and placed on the

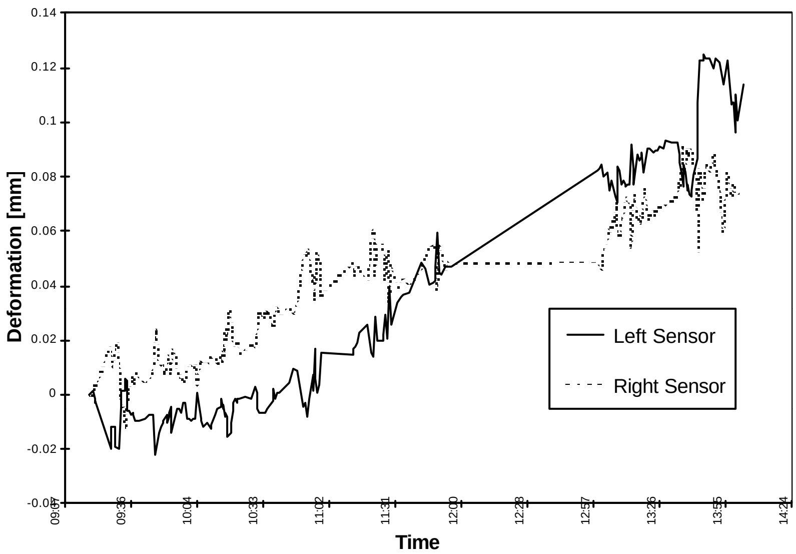

Figure 6 Deformations during the load test. The load cases a-f correspond to different load patterns.

left and on the right of the bridge, respectively. Interestingly, most deformations are symmetrical on the two sensors indicating a simple bending of the bridge.

Figure 7 shows the elongation of the bridge (obtained by averaging the left and right sensors) and its bending (obtained by subtracting the two values). The elongation is due to the heating action of the sun on the bridge. The bending is mainly due to the uneven progression of the four jacks. The eight successive pushing phases are clearly recognizable[1] by the corresponding negative peaks in the bending curve. After each push phase the bridge was re-aligned by operating the jacks separately. The slight increase of bending during the day is probably due to the direct

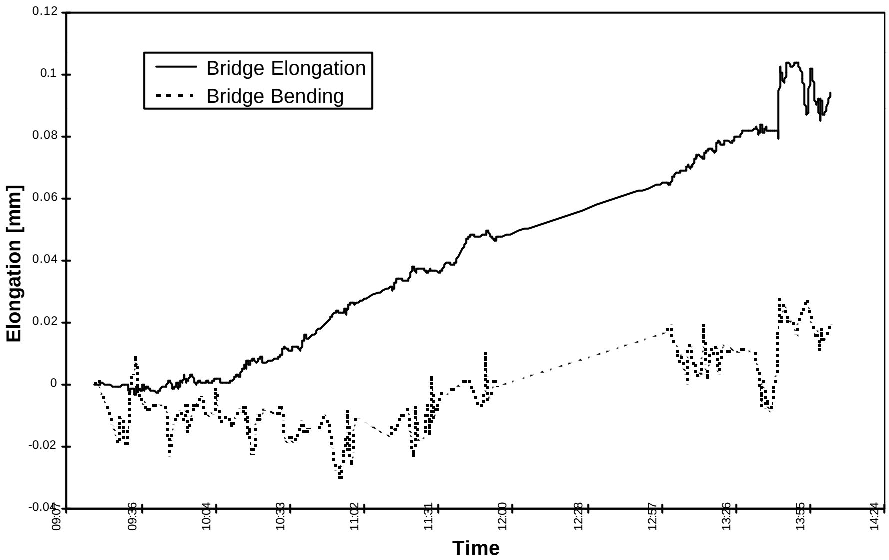

Figure 7 Elongation and bending of the bridge. The elongation is obtained by averaging the left and right measurements. The bending is obtained by subtracting them.

sunshine on one of the sides of the bridge.

4.3 Bissone bridge: shrinkage monitoring during refurbishing

The Bissone-Lugano bridge is a road viaduct of the 60's along the lake Ceresio in southern Switzerland. Due to the critical concrete condition caused by mechanical and chemical ageing, refurbishing measures were necessary. Part of the structure was hydro-demolished and rebuilt with new concrete. The healing concrete has to respect certain mechanical and chemical characteristics. In particular, the shrinkage of the healing coat has to be limited in such a way to prevent tension cracks. On the lake side of the bridge two fiber optic SOFO sensors were installed, with an active length of 1.50 m. Shrinkage deformation was measured regularly during setting (several hours), then with regular intervals of 1 day, 1 week, and so on [8].

For the sake of comparison, external deformation was monitored by conventional mechanical gages over a distance equivalent to the active length of the internal fiber optic sensor (1500 mm). Shrinkage measurements were also made on two concrete prisms held in laboratory at a constant temperature of 20°C and relative humidity of 60%. The results are shown in Figure 8. The shrinkage measurement made with mechanical gages are here considered as point "0".

The results show different behaviors between the two fiber optic sensors that are placed in two different positions. The first one is located entirely inside the new healing concrete, while the second one lies along the interface between old and new concrete.

In the first case (sensor A) the measurement with fiber optic sensors reflects qualitatively the measurement made at the surface with the conventional mechanical gage. The internal shrinkage is at the beginning quantitatively lower as can be explained by the fact that at the surface is in contact with the air and therefore drying more rapidly.

[1] The lunch brake can also be easily identified!

In the second case (sensor B), the movement of the fiber optic sensor is affected by the interaction between old and new concrete. As expected, prisms of new concrete tested in the laboratory under constant temperature and humidity show much larger shrinkage strain than the bridge. These measurements show the influence on the repaired beam of environmental factors like temperature and humidity variations (high gradients during the day) as well as of hydration

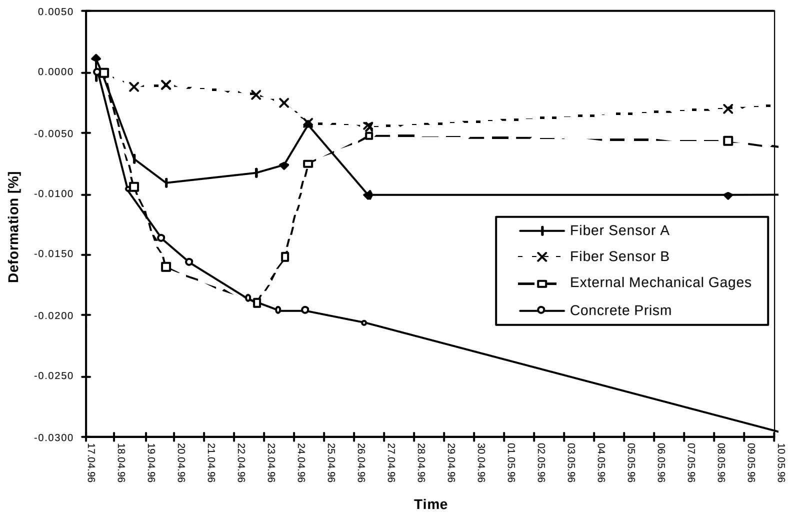

Figure 8 Refurbishment of the Bissone road bridge. Shrinkage measurement with internal fiber optic sensors (A near the surface, B near the old concrete), with external mechanical gages and on two prisms in the laboratory.

process of the fresh concrete. The good adhesion of the new concrete to the old one can therefore be verified.

4.4 Other bridges and structures

Besides the three examples detailed in the precedent paragraphs, other bridges in Switzerland have been instrumented with deformation sensors of the SOFO type. The most interesting examples include:

- **Lutrive bridge**: This aging pre-stressed concrete bridge has been retrofitted with a number of surface mounted sensors installed inside the box girder. By measuring locally the deformation of horizontally placed sensors at different heights, it is possible to calculate the local vertical curvature, much like in the case of the Moesa bridge (where the bending was however in the horizontal plane). If the curvature is measured at different points along the bridge length, it becomes possible to retrieve the vertical displacements by doubly integrating the fitted curvature function. It can be shown that about 4 to 6 sensor pairs are sufficient to calculate with good precision the displacements of each bridge span [9]. In the case of the Lutrive bridge, the measurements extended over 24 hours and allowed visualizing the displacements of the bridge under thermal loading due to air temperature variations and direct sunshine. The results were found to be in good agreement with those obtained by conventional mechanical sensors measuring the displacements directly. This type of instrumentation can simplify these measurements, because no external sensor (e.g. triangulation or dial gauges) is required.
- **Versoix bridge**: This concrete bridge is being enlarged to add a traffic and an emergency lane. More than 100 SOFO sensors will be installed in two of the bridge’s spans in order to retrieve the horizontal and vertical displacements induced by the added concrete and its shrinkage.
- **Lully bridge**: This elegant viaduct is constituted by a thin concrete deck supported by a tubular truss. Several SOFO sensors will be installed in the deck to monitor its shrinkage partially hindered by the truss and point to the formation of cracks (unlikely).

- **Other structures**: Besides bridges, many other civil structures can benefit from the installation of deformation sensors. The presented system has been tested on concrete beams and slabs [10], mixed slabs (steel-concrete and timber-concrete), in foundation piles, rock anchorage, tunnel vaults and as optical extensometer in a dam foundation.

5. CONCLUSIONS

The benefits of structural monitoring are obvious. A continuous, or at least regular monitoring of a structure can increase the knowledge on its behavior and help to increase 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. In this framework, fiber optic sensors offer the unique advantage of measuring the deformations right inside the structure. They are particularly immune to EM disturbances and corrosion that often affect other similar sensors. The SOFO monitoring system is composed of a portable reading unit adapted to field conditions, of a series of sensors that can be either embedded into concrete or surface mounted on metallic and other existing structures and from a software package allowing the treatment of the huge data-flow resulting from these measurements. This system has been applied to a number of new and existing bridges as well as to other civil structures in order to monitor their behavior and the properties of the construction materials used.

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