FIBER OPTIC DEFORMATION SENSORS FOR BRIDGES MONITORING



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SUMMARY

In many concrete bridges, the deformations are the most relevant parameter to be monitored in both short and long-terms. We have found that fiber optic deformation sensors can give useful information during the first days after concrete pouring and in the long term.
This contribution discusses the measurement technique and then focuses on the development of a sensor for direct concrete embedding and on the results obtained on some bridges.

1. 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.
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.

1.1 Summary

The following table reviews the different applications of deformation sensors (bridges).

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.

2. FIBER OPTIC MONITORING SYSTEM

Our laboratory has developed a monitoring system based on low-coherence interferometry that meets most of the requirements resumed in Figure 1 and Table 2.

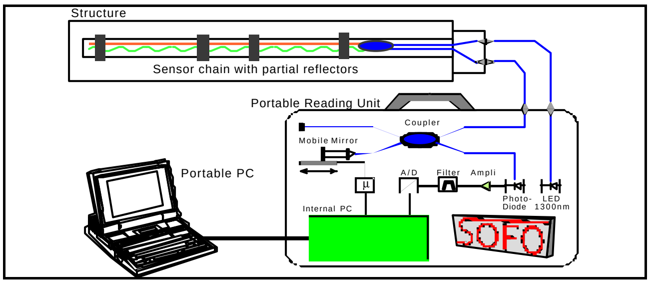

Figure 1 : Setup of the SOFO system

2.1 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) [1].

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 measurement 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 [2].

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 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 μm 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 2.

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.

Table 2 - Typical requirements for bridge monitoring

Except for the dynamic effect measurement, the SOFO system can therefore be used for all the applications cited in section 1.1. 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. á shows the portable reading unit with the portable PC.

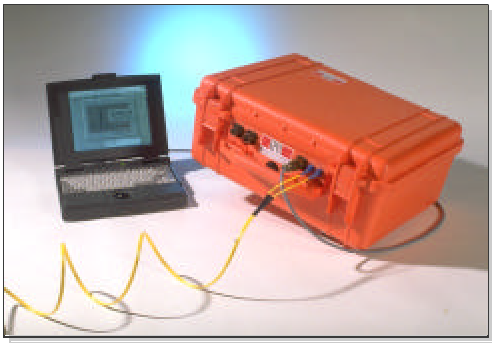

Figure 2 : SOFO Portable reading unit.

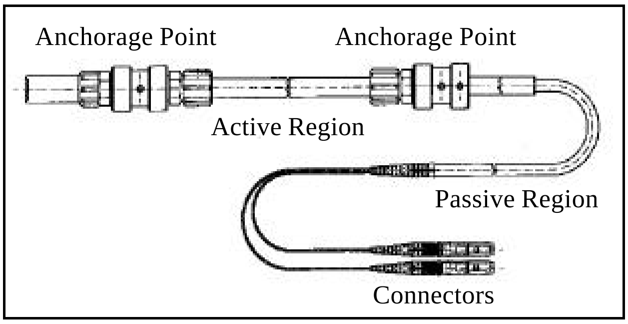

Figure 3 : SOFO Deformation sensors for direct concrete embedding. The active region extends between the two anchorage points. The passive region can be up to a few km long and connects the sensor to the reading unit.

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 [3]. 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.

3. APPLICATION EXAMPLES

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

3.1 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. It is very interesting to control the thermal expansion phases, to understand the real behavior of the steel-concrete interaction.

More than 30 fiber optic sensors were installed in the deck [4]. The chart presented in ã 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.

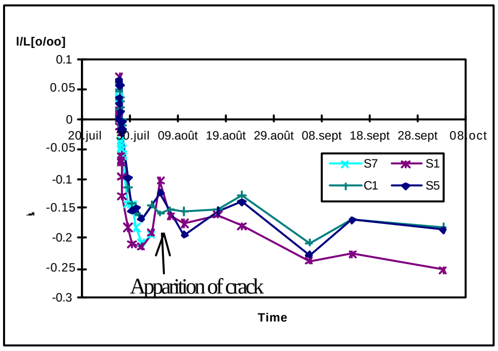

Figure 4 : Shrinkage measurements during one month on the Venoge bridge deck. Four different sensors are shown. The apparition of a crack in one of the sections is clearly visible

3.2 Moesa bridge: damage assessment during delicate construction phases

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 embedded 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 shrinkage.

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 5a 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 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 5b shows the elongation of the bridge (obtained by averaging the left and right sensors) and its qualitative 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 (the lunch brake can also be easily identified!) 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 sunshine on one of the sides of the bridge.

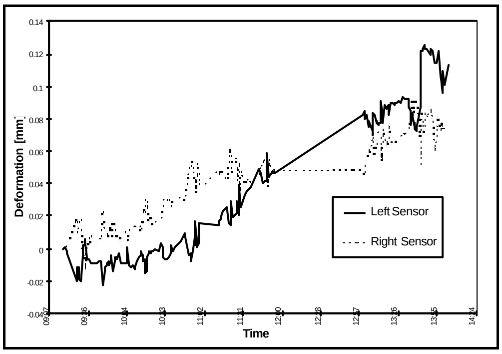

Figure 5a

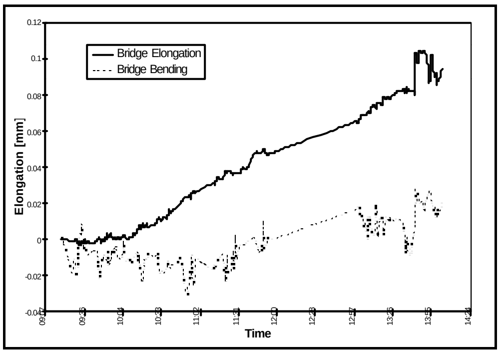

Figure 5b

Figure 5a : Deformations during the load test. The load cases a-f correspond to different load patterns. Figure 5b : Elongation and qualitative bending of the bridge.

3.3 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 [5].
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 6. 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 and therefore measures partially hindered shrinkage .

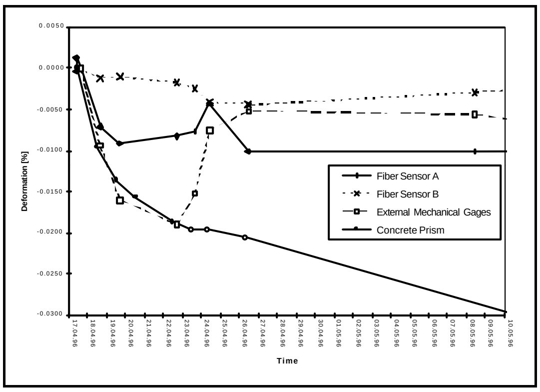

Figure 6 : Refurbishment of the Bissone road bridge. Shrinkage measurement with internal fiber optic sensors (A near the surface, B near the old concrete), with external mechanical gages and on two prisms in the laboratory.

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

4. 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 [6] as well as to other civil structures in order to monitor their behavior and the properties of the construction materials used.

5. ACKNOWLEDGEMENTS

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