Pacific Nordwestern Conference on fiber optic, 1998

Long-Gage Structural Monitoring for Civil Structures

Daniele Inaudi [1,2], Samuel Vurpillot [2], Eric Udd [3]

[1] **SMARTEC SA**
via al Molino 6
CH-6916 Grancia, Switzerland

[2] **IMAC - Stress Analysis Laboratory**
Swiss Federal Institute of Technology, Department of Civil Engineering
CH-1015 Lausanne, Switzerland

[3] **Blue Road Research**
P.O. Box 667, 2555 N.E. 205th Av.
Fairview, Oregon 97024, USA

1. ABSTRACT

The security of civil engineering works demands a periodical monitoring of the structures. The current methods (such as triangulation, water levels, vibrating strings or mechanical extensometers) are often of tedious application and require the intervention of specialized operators. The resulting complexity and costs limit the frequency of these measurements. The obtained spatial resolution is in general low and only the presence of anomalies in the global behavior urges a deeper and more precise evaluation. There is therefore a real need for a tool allowing an automatic and permanent monitoring from within the structure itself and with high precision and good spatial resolution.

In many civil structures like bridges, tunnels and dams, 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 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.

In the case of beams and bridges, long-gage sensors can be used to evaluate the curvature variations and calculate the horizontal and vertical displacements by double integration of the curvatures.

Keywords: Deformation sensor, Structural monitoring, Fiber optic sensors.

2. SOFO SYSTEM SETUP

SOFO is the French acronym of Surveillance d'Ouvrages par Fibres Optiques (or structural monitoring by optical fibers). The measurement setup is based on a double, all-fiber, Michelson interferometer in tandem configuration (see Figure 1) [1]. The 1300 nm radiation of a SLED with a rated power of 0.2 mW and a coherence length of 30 microns 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 pre-tensioned and mechanically coupled to the structure in order to follow its deformations, while the reference fiber is free and acts as temperature reference. Both fibers are installed inside the same sensor pipe. 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, this allows the sensors to be multiplexed in-line [2,3]. 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 (Figure 2). 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 microns by computing the center of gravity of the peaks themselves.

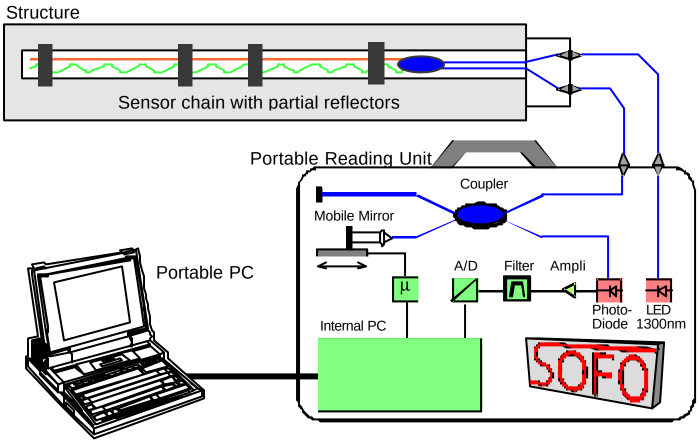

Figure 1: Setup of the SOFO system.

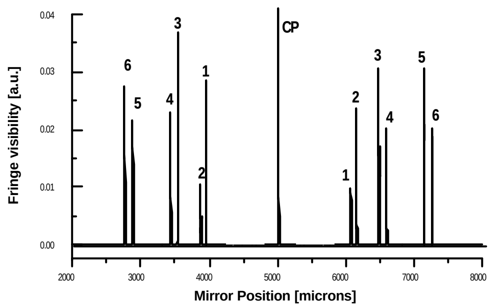

Figure 2: Typical measurement

Figure 3 shows the SOFO reading unit, Figure 4 a SOFO sensor [4] installed along a rebar:

Figure 3: SOFO reading unit with external control PC.

Figure 4 SOFO sensor installed along a rebar before concreting.

The main characteristics of the SOFO system are resumed in the following table:

Sensor Gage length	25 cm to 10 m. Up to 50 m with special sensors.
Cable length	Up to 3 km between the sensor and the reading unit.
Resolution	2 microns, independently from the gage length.
Dynamic range	1% of the gage length in elongation and 0.5% in shortening.
Precision	Better than 0.2% of the measured deformation.
Measurement speed	Less than 10 seconds for each sensor chain.

Stability	Drift not observable over at least three years.

3. APPLICATION DOMAINS

The SOFO monitoring system has been applied successfully to a number of structures including bridges [5], tunnels, dams and laboratory structures. This includes (the number of installed sensors is indicated in parenthesis):

Bridges:	Highway Bridges: Venoge (40) [6], Lutrive (6+30) [7], Versoix (104) see Figure 6 [8].
	Highway Viaducts: Lully (12) see Figure 5, OA402 (10).
	Road Bridge: Bissone (2).
	Railroad Bridge: Moesa (30) [9].
Tunnels:	Highway Tunnels: Vignes (16), A5 (11).
	Dams Tunnel: Luzzone (8).
Geostructures:	Piles (static loading test): Horw (24)
Dams:	Emosson Dam (2) [10].
	Luzzone Dam (13) see Figure 7.
Monuments	Church: Gandria vault (10)
Other Structures:	EDF Nuclear Power Plant (20).
	Beams and Slabs (laboratory tests): ICOM/EPFL (50), MCS/EPFL (56), IMM (24) see Figure 8.

Figure 5: The Lully highway viaduct.

Figure 6: The Versoix highway bridge.

Figure 7: The Luzzone Dam

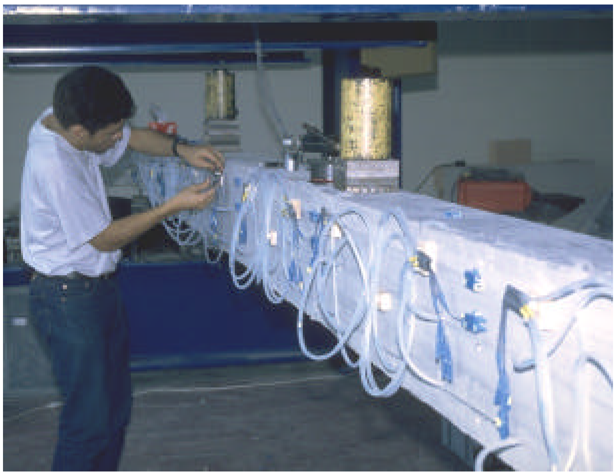

Figure 8: The IMM BPR Beam

Since 1993, almost 600 sensors have been installed. The sensors can be installed easily (by a trained worker) and quickly without disturbing the construction schedule.

By carrying out the presented applications, it has been found that long-gage deformation sensors are useful for measuring and monitoring many different phenomena like:

- Concrete deformation monitoring during setting.
- Prestressing monitoring.
- Neutral axis evolution.
- Concrete-steel interaction.
- Post-seismic damage evaluation.
- Spatial displacement measurement (curvature analysis).
- Crack opening monitoring.
- Creep-flow monitoring.
- Long-term deformation monitoring.
- Restoration monitoring.

Among the well known advantages of fiber optic sensors, the ones that are most interesting for civil engineering applications include their insensitivity to EM fields (thunderstorms, trains, power lines), their good chemical compatibility (no corrosion problems) and the possibility of remote interrogations over long distances without degradation of the measurement precision.

4. APPLICATION EXAMPLE: THE LUTRIVE BRIDGE

The Lutrive (Switzerland) North and South bridges are two parallel twin bridges (see Figure 9). Each one supports two lanes of the Swiss national highway RN9 between Lausanne and Vevey. Built in 1972 by the corbelling method with central articulations, the two bridges are gently curved (r = 1000 m) and each bridge is approximately 395 m long on four spans. The two bridges have the same cross-section. It consists of a box girder of variable height (from 2.5m to 8.5m) and two slightly asymmetric cantilevers meant to reduce the effect of torsion in the curved bridges.

The fourth span of the South bridge, fitted with an hydrostatic leveling system measuring vertical displacements since 1988, was instrumented with 30 6m long SOFO sensors. To measure the curvature variations, the sensors are installed in pairs at the interior of the box girder (see Figure 10). Curvatures are measured with sensors placed near the top and the bottom of bridge web and the vertical displacements can be retrieved by double integration of the curvatures [11]. The sensors were used both for quasi-static testing under thermal loading and under a static load-charging test as well as for statistical characterization of the dynamic behavior of the bridge.

Figure 9: The Lutrive bridge.

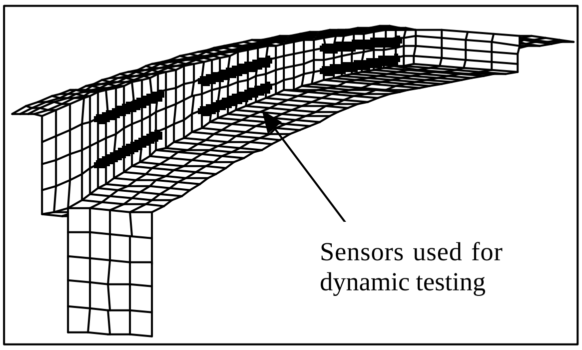

Figure 10: SOFO sensors placement

Static testing:

Measures extended during 24 hours between the 6th of July 1996 at 14h00 to the 7th of July 1996 at 14h00. The temperature gradient measured between the upper and the lower slab oscillated between 2.4°C and 5°C. Measurements were performed each 2 hours during 20 minutes without stopping the traffic, sometimes necessitating a few trials before the bridge regained its calm after the passing of heavy vehicles.

The curvature evolution during 24 hours presents a cycle correlated to the temperature gradient in the bridge. The temperature of the bridge is slightly higher after 24 hours. This non-periodicity is retrieved on the curvature measurements. Taking into account the measurements obtained by an inclinometer placed at 10 m from the articulation and a null displacement on the pile as the border conditions for the double integration, the shape deformation V(x) is calculated for each temporal measurement. This function V(x,t) presents the vertical displacement of a point of co-ordinate x for each dis crete measure at a time t. Figure 11 shows the temporal comparison between the verticals displacements calculated with the fiber optic sensors and the hydrostatic leveling system for a point placed at quarter span. The hydrostatic leveling precision can be estimated to about 5 mm. The precision on the vertical displacement determined by the mathematical model can be obtained by a sensibility study of the model. Considering a precision of 10 μm for the reading unit, 2 cm for the vertical placement of the sensor, 2 cm for the sensors length and 10-5 radians for the inclinometer precision, a standard deviation of 20 μm is obtained. This example shows the possibility of obtaining precise information about the vertical displacement of a single bridge span using only a reduced number of displacement sensors. A precision much higher than the one obtained by external measuring systems like optical or hydrostatic levering can be achieved.

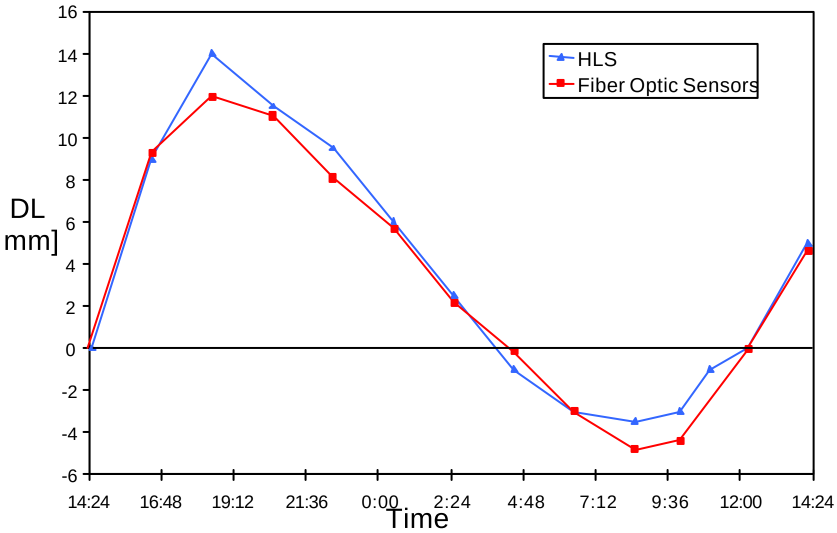

Figure 11: Vertical displacement of the Lutrive Bridge calculated by double-integration of the curvature measurements.

Dynamic testing:

In order to test the statistical analysis algorithm, two sensors placed at quarter-span (see Figure 10) where measured during 24 hours under traffic loading. Both sensors were measured with a single scan of the SOFO system by coherence multiplexing them with an external coupler. The data from the two sensors is therefore correlated since the two readings are obtained in less than 0.1 s.

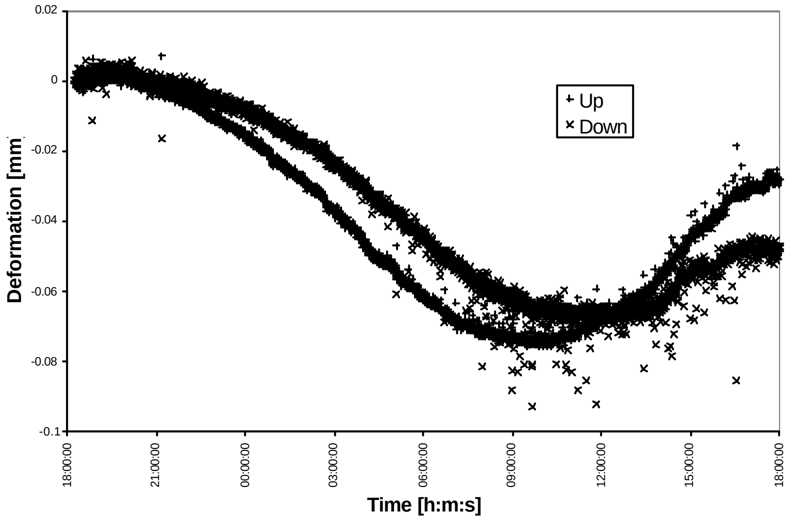

Figure 12: Deformation data obtained on two parallel sensors placed at quarter-span in the Lutrive bridge.

Figure 12 shows the results obtained by the two sensors. The drift in the measurements on both sensors is due to the bridge's temperature variations that were however very small in this cold winter day. The total drift is of only about 80 microns over a sensor length of 6 m. This corresponds to a temperature variation of the order of 1°C. By subtracting the two deformation values and dividing by their length and distance it is possible to obtain the curvature variations of the bridge.

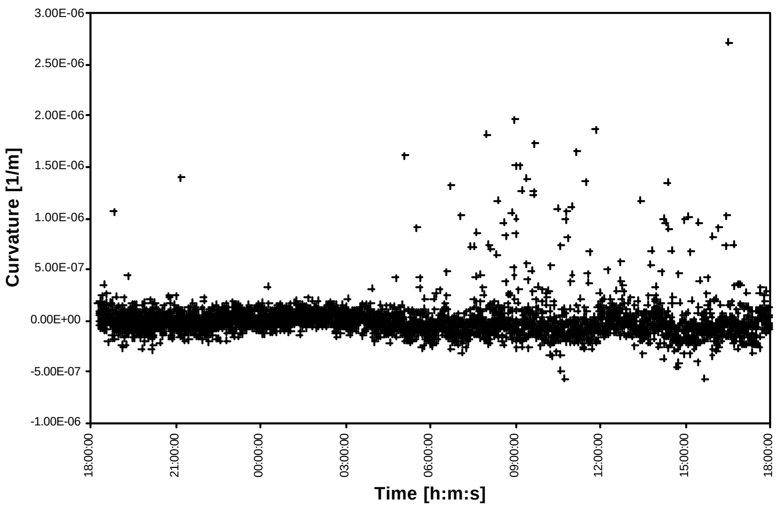

Figure 13: Curvature data after removing the bridge's temperature drift.

Figure 13 shows the curvature readings after removal of the bridge's temperature drift with a polynomial fit on the initial data. Has expected most data points lie around a zero curvature corresponding to the mean static state of the bridge. High curvature values indicate a deformation induced by the passage of a truck. It can be noticed that these points are concentrated during the day when truck circulation is allowed. Except for one reading around 21:00 no trucks were registered during the night. Most curvatures are positive and indicate a downward bending of the bridge under the quasi-static loading of the truck. A few points lie outside the noise floor curve for negative curvatures. These ere either rebounds of the bridge after a truck leaves the instrumented span or deformations induced by trucks on neighboring spans.

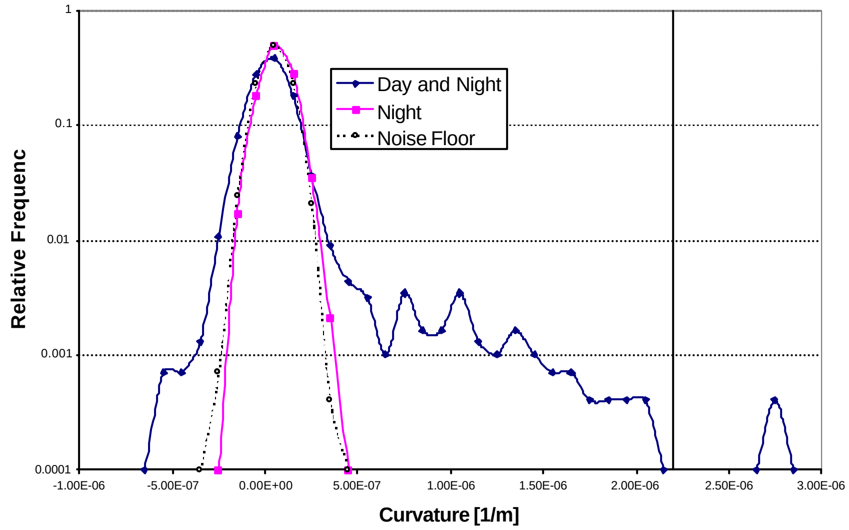

Figure 14: Relative curvature frequency of the data in Figure 13.

Figure 14 show the statistical analysis on the whole set of data (Day and Night, 3269 data points), the night data only (Night, 996 points) and of a Monte-Carlo simulation based on simulated deformation measurements with a standard deviation of one micron (noise Floor, 3267 points). The good agreement between these two latter curves indicates that the noise floor of the SOFO system limited the measurements during the night. During the day the higher deformations due to the passage of the trucks are clearly visible. The vertical line indicates the curvature that was obtained during the static loading test with a truck of 28 t placed at center span. Since the load limit on the Swiss highway network is 28 t, Figure 14 indicates that the dynamic effects on the bridge are very limited. A rebound of a passing truck could for example induce higher curvatures than this same truck statically placed on the bridge. The isolated event at 2.7 10^{-6} 1/m either indicates an overweight truck (some 40 t trucks are also circulating) or two trucks on the bridge at the same time.

This same figure can be used to quantify the probability of having a truck on the bridge at any give time. This is given by the ratio of the number of points of the Day and Night curve inside, respectively outside the Noise Floor curve. This ratio gives 90% and indicates the probability of obtaining a reliable static deformation value when the measurements are performed under traffic conditions. Therefore it can be considered sufficient to perform three measurements on each sensor and discard any statistically aberrant value to obtain a reliable value. A theoretical analysis considering the truck traffic density, the mean truck speed, the mean transit time gives a slightly lower value of 80%.

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 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 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 large number of new and existing bridges as well as to other civil structures in order to monitor their short and long-term behavior.

6. ACKNOWLEDGEMENTS

The authors are indebted to Prof. L. Pflug, P. Rastogi, S. LLoret, B. Glisic, M. Pedretti, R. Passera, P. Colombo, and the whole EPFL-ISS teams for their help, encouragement and useful discussions. This research program is conducted under the financial support of the Swiss CTI (Commission pour la Technologie et l'Innovation) and of the Board of the Swiss Federal Institutes of Technology.

7. REFERENCES

Further information on the SOFO project at the following WWW home pages: \\www.smartec.ch and \\imacwww.epfl.ch.

[1] "Low-coherence deformation sensors for the monitoring of civil-engineering structures", D. Inaudi, A. Elamari, L. Pflug, N. Gisin, J. Breguet, S. Vurpillot, Sensor and Actuators A, 44 (1994), 125-130.
[2] "Coherence multiplexing of in-line displacement and temperature sensors", D. Inaudi, Optical Engineering, Vol. 34, Nr. 7, July 1995.
[3] "In-line coherence multiplexing of displacement sensors: a fiber optic extensometer", D. Inaudi, S. Vurpillot, S. Lloret, Smart Structures and materials, San Diego February 1996, SPIE Volume 2718-28.
[4] "Embedded and surface mounted sensors for civil structural monitoring", D. Inaudi, N. Casanova, P. Kronenberg, S. Vurpillot, Smart Structures and materials, San Diego February 1997.
[5] "Bridge Monitoring by Interferometric Deformation Sensors", D. Inaudi, S. Vurpillot, N. Casanova, Laser Optoelectronics and Microphotonics: Fiber Optics Sensors, SPIE, Beijing November 1996, invited paper.
[6] "Bridge monitoring by fiber optic deformation sensors: design, emplacement and results", S. Vurpillot, D. Inaudi, J.-M. Ducret, Smart Structures and materials, San Diego February 1996, SPIE Volume 2719-16.
[7] "Structural monitoring by curvature analysis using interferometric fiber optic sensors", D. Inaudi, S. Vurpillot, N. Casanova, P. Kronenberg, to be published in Smart Materials and Structures Journal.
[8] "Bridge spatial deformation monitoring with 100 fiber optic deformation sensors", S. Vurpillot, N. Casanova, D. Inaudi, P. Kronenberg, Smart Structures and materials, San Diego February 1997.
[9] "Railway bridge monitoring during construction and bridge sliding", D. Inaudi, N. Casanova, P. Kronenberg, S. Vurpillot, Smart Structures and materials, San Diego February 1997.
[10] "Dam monitoring with fiber optic sensors", P. Kronenberg, N. Casanova, D. Inaudi, S. Vurpillot, Smart Structures and materials, San Diego February 1997.
[11] "Structural monitoring by curvature analysis using interferometric fiber optic sensors" D. Inaudi, S. Vurpillot, to be published in Smart Materials and Structures.