Bridge Deformation Monitoring with Fiber Optic Sensors

Daniele INAUDI
Dr
SMARTEC
Grancia, Switzerland

Daniele Inaudi holds a degree in physics and a Ph.D. from the Swiss Federal Institute of Technology in Zurich and Lausanne, respectively. He is co-founder and R&D director of SMARTEC SA, a company active in the domain of civil structural monitoring.

Nicoletta CASANOVA
Civil Eng.
SMARTEC / IMM
Grancia, Switzerland

Nicoletta Casanova received her civil engineering degree from the Swiss Federal Institute of Technology in Zurich. She is co-founder and director of SMARTEC SA. She is also technical director of the Institute of Material Mechanics IMM.

Samuel VURPILLOT
Dr Eng.
IMAC-EPFL
Lausanne, Switzerland

Samuel Vurpillot holds a degree in civil engineering from the Swiss Federal Institute of Technology Lausanne. He is manager of the SOFO project and is working on a Ph.D. dealing with the automatic analysis of monitoring data from bridges.

1. Summary

The security of civil engineering works demands a periodical monitoring of the structures. In many civil structures like bridges, tunnels and dams, the deformations are the most relevant parameter to be monitored. 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.
SOFO is a structural monitoring system using fiber optic deformation sensors. It is able to measure deformations between two points in a structure, which can be from 20 cm up to 10 meters (or more) apart with a resolution of two microns (2/1000 mm) even over years of measurements. The system is composed of optical deformation sensors adapted to direct concrete embedding or surface mounting, the cable network, the reading unit and the data acquisition and analysis software. The system is particularly adapted to precise short and long-term monitoring of deformations. The SOFO system is successfully used in a number of bridges, tunnels, dams and geostructures.
This paper briefly summarizes the measurement principle of the SOFO system and presents two examples of application to the monitoring of existing and refurbished bridges. The Lutrive concrete bridge was instrumented with 40 sensors to monitor its curvature variations under static, dynamic and thermal loading. From the curvature measurements and using a double-integration algorithm it was possible to retrieve the vertical displacements of the bridge. The Versoix bridge was instrumented with more that 100 sensors to monitor the different phases of its enlargement and refurbishment. The sensors were used to characterize the interaction between concrete of very different ages and to follow the horizontal and vertical displacements of the bridge during construction, static loading testing and in the long term.

2. Bridge Monitoring

The security and maintenance of bridges, tunnels, dams requires periodic monitoring, maintenance and restoration. Excessive and non-stabilized deformations are often observed in concrete bridges and although they rarely affect the global structural security, they can lead to serviceability deficiencies.
Furthermore, accurate knowledge of the behavior of the structures is becoming more important as new structures become lighter, new building techniques are introduced and an increasing number of existing bridges are required to remain in service beyond their theoretical service life. Monitoring, both in the short and long term, 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 an accurate and very stable system, able to relate deformation measurements often spaced over years.
Currently available monitoring transducers, such as inductive and mechanical extensometers, GPS, microbending sensors or accelerometers are only suitable for performing measurements in a short range of frequencies. Moreover, some of these techniques are still in the development stage and are only used in laboratory experiments (for example, GPS). Other systems do not offer enough information about the desired parameter (for example, an accelerometer gives the frequency of vibration, but displacement calculations are not always accurate).
Thus, there is a real need of a unique system capable of covering structural deformation requirements in wide range of frequencies.

2.1 Short- vs. long-gage sensors

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 (e.g., concrete, steel, timber, composite materials,…) and observe their behavior under load, temperature variations 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, it is possible to extrapolate information about the behavior of the whole structure from these local measurements.
In the structural approach, the structure is observed from a geometrical point of view. By using long gage length deformation sensors with measurement bases much larger than the characteristic dimensions of the materials (for example a few meters for a concrete bridge), it is possible to gain information about the deformations of the whole structure 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 an impact on the shape of the structure. This approach usually requires a reduced number of sensors when compared to the material monitoring approach.
The availability of reliable strain sensors like resistance strain gages or, more recently, fiber Bragg gratings [1, 2] have historically concentrated most research efforts in the direction of material monitoring rather than structural monitoring. This latter has usually been realized using external measuring methods like triangulation, dial gages and invar wires. Interferometric fiber optic sensors like the SOFO system now offer an interesting means of implementing structural monitoring with internal or embedded sensors.

3. The SOFO 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.

The IMAC laboratory at EPFL has developed a non-incremental, long-term monitoring system based on low-coherence interferometry, which has successfully been used in several bridges [3], tunnels [4], dams [5] and other civil engineering structures. This system is named SOFO® (the French acronym of "Surveillance d'Ouvrages par Fibres Optiques" or structural monitoring by optical fibers). A detailed description of the functional principle of this system can be found in the cited literature [6, 7]. In this contribution we will concentrate on static measurements, however the SOFO system is being extended to dynamic measurements. In the near future it will therefore be possible to perform on the same network of sensors both dynamic and long-term measurements. The following table resumes the performance of the SOFO system:

Parameter	
Gage length	20cm to 10m for standard sensors Up to 50m with special (long) sensors
Cable length	Up to 5 km
Resolution	2µm, independently from gage length
Dynamic range of the sensors	1% elongation, 0.5% shortening for standard sensors Can be modified for special sensors (elongation ε, shortening 3-ε%)
Precision	Better than 0.2% of the measured deformation
Measurement speed	Less than 10 seconds per measurement
Stability	Drift not observable over at least four years

4. Data Analysis

The data analysis software packages interpret the data stored by the acquisition software in a 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:

- *Displacement evolution analysis:* This general-purpose package extracts the results concerning a single sensor and displays them as a function of time or load. The data can than be exported to other software packages, like spreadsheets or other graphical tools for adequate representation.
- *Curvature:* In bridges, 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 sensor direction. This is particularly interesting since in many cases the engineers are interested in deformations that are at a right angle to the natural direction in which the fiber sensors are installed. For example: in a bridge the fibers are installed horizontally, but vertical displacement are more interesting. In a dam the fibers are installed in the plane of the wall, but displacements perpendicular to it have to be measured. Application examples of these data analysis techniques will be given in the application section.
- *Statistics*: Another software package allows the analysis of deformation data from structures undergoing statistically reproducible loads (such as traffic).

5. Application examples

5.1 The Versoix Bridge

The North and South Versoix bridges are two parallel twin bridges. Each one supported two lanes of the Swiss national highway A9 between Geneva and Lausanne. The bridges are classical ones

consisting in two parallel pre-stressed concrete beams supporting a 30 cm concrete deck and two overhangs.
In order to support a third traffic lane and a new emergency lane, the exterior beams were widened and the overhangs extended. The construction progressed in two phases: the interior and the exterior overhang extension. The first one began by the demolition of the existing internal overhang followed by the reconstruction of a larger one. The second phase consisted to demolish the old external overhang, to widen the exterior web and to rebuild a larger overhang supported by metallic beams. Both phases were built by 14 m stages. Because of the added weight and pre-stressing, as well as the differential shrinkage between new and old concrete, the bridge bends (both horizontally and vertically) and twists during the construction phases. In order to increase the knowledge on the bridge behavior and performance and to optimize the concrete mix, the engineer choose low-coherence SOFO sensors to measure the displacements of the fresh concrete during the setting phase and to monitor the long term deformations of the bridge. The bridge was instrumented with more than hundred of these sensors.

Figure 1: The Versoix Bridge during the rehabilitation works

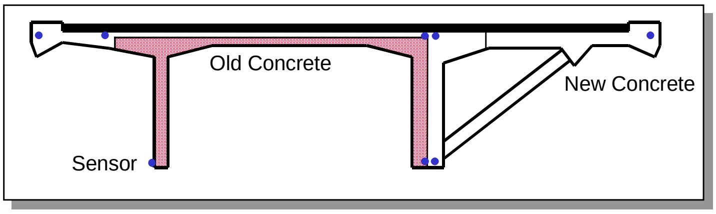


Figure 1: The Versoix Bridge cross-section and placement of the sensors

5.1.1 Fiber optic instrumentation

To obtain a good representation of the bridge deformations, it was necessary to find a mean to measure the horizontal, vertical and torsion displacements of the bridge during the different construction phases and in the long term. To measure them, we decided to use an algorithm retrieving the displacements from curvature measurements. In order to guarantee a sufficient redundancy and to follow the concrete pouring stages of 14 m, 1 section of sensors was placed each 7 m. Because of budget limitations, only 2 of the 6 spans were instrumented. A preliminary study by finite element

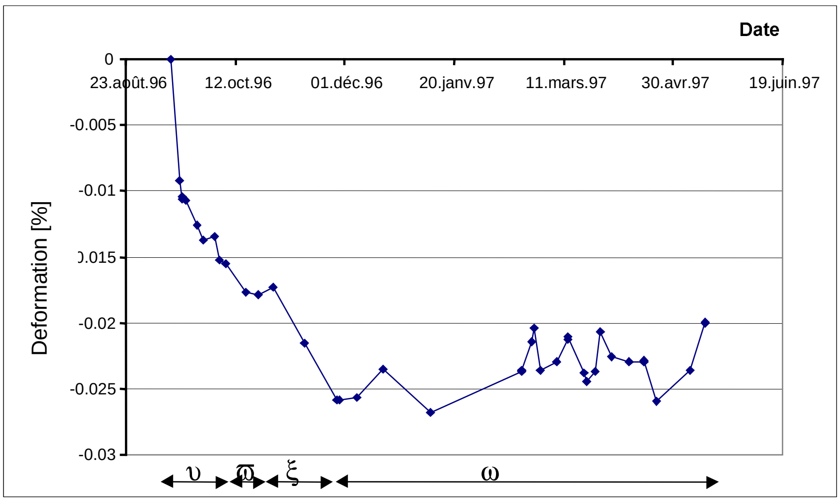


Figure 2: Typical deformation measurement over 8 months

simulation showed that the deformations of the two spans could be approximated by two 5th degree polynomial functions. At least 4 curvatures measurements for each span are therefore necessary to obtain the bridge spatial displacements. In each section, five sensors have been embedded in the new concrete and one sensor has been installed on the surface of the old concrete (see ***Figure 1***). To obtain a good representation of the mean curvature, sensors with four-meter active length were chosen. Two additional sensors were installed to give information about the differential shrinkage between the old and the new concrete. These sensors are rigidly connected to the existing concrete and their measurements can be compared with parallel sensors placed in the newly added concrete. This installation scheme is repeated 12 times, 5 times in the first span and 8 in the second one.
The horizontal and vertical curvature is calculated separately for each of the 12 sections using all the 8 sensors. The spatial displacements are then calculated by integrating the mean curvature of the 12 sections.

5.1.2 Measurements on single sensors

Figure 2 shows the typical concrete deformations measured in one sensor during the first 8 months. All the optical fiber sensors of a same concrete pouring stage indicate about the same behavior. On the graph, four phases are distinguishable: the first is the drying shrinkage (phase 1), followed by a stabilization phase (phase 2) and finally there is a zone of variation (phase 3) corresponding to the thermal elongation of the bridge. Phase 4 is due to the decrease of the bridge temperature during the month of November 1996. These variations are consistent with a temperature variation of about 10°C that was actually observed.

5.1.3 Global displacement measurements

The horizontal and vertical displacements of the first two spans of the bridge were calculated using the double-integration algorithm previously described.
Figure 3 shows the horizontal displacement of the two spans of the bridge as calculated by the algorithm, for different times and relatively to the line Abutment-Pile 2. The observed 'banana' effect is due to the shrinkage of the concrete of the new exterior overhang. This effect stabilizes to a value of 5 mm of horizontal lateral displacement after one month.
During a load test, performed in May 1998 after the end of construction works, the vertical displacement of the bridge was also monitored using the fiber optic sensors.
Figure 4 shows the measurement with SOFO sensors (Vertical Displacement Calculated) compared to those obtained with dial gages (invar wires under the bridge). This load pattern (Case A) consists in 6 trucks placed on the second span of the bridge (position 73 in the graph). The error of the algorithm is estimated from the deviation from a flat surface of the section deformations (the algorithm is based on the assumption that plan sections remain plain under load). The algorithm (Vertical Displacement Calculated) retrieves within in the error interval the position of the first pile (not entered as a boundary condition for the integration) and matches the vertical displacement measured with the dial gages.
The overall precision in the horizontal and vertical

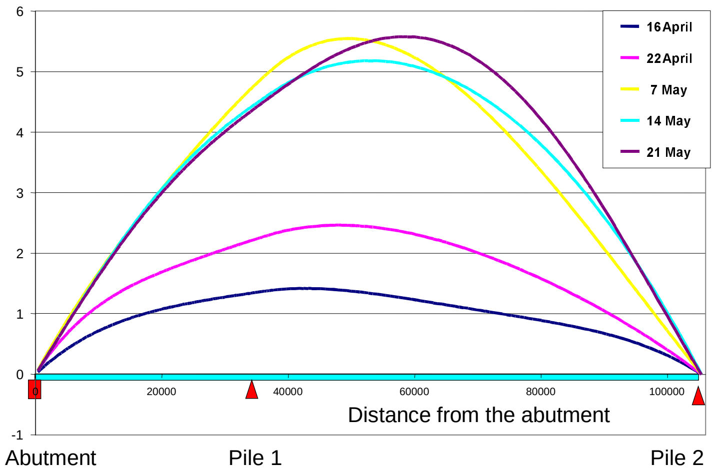


Figure 3: Horizontal displacement of the bridge

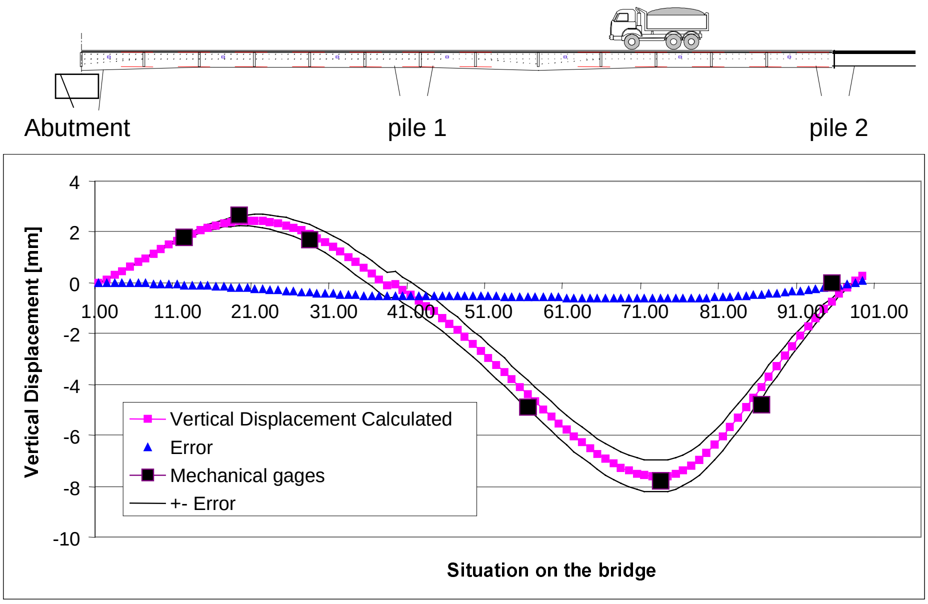
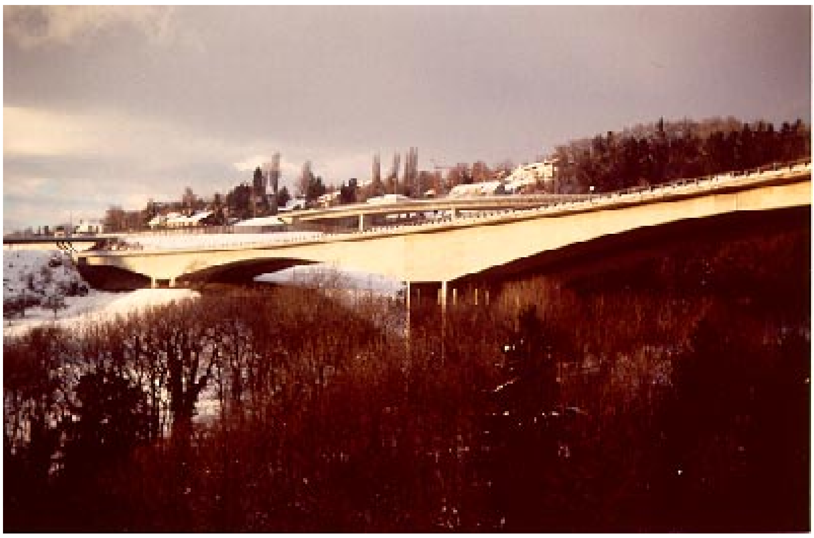


Figure 4: Vertical displacement, load case A

displacements of the two spans can be evaluated to 0.2 mm, a remarkable figure for a total integration length of over 100m. This shows that it is indeed possible to retrieve the global deformations of a bridge using internal horizontal measurements. If the deformations have to be known in an absolute referential and since the internal sensor can not give information on the rigid-body motion of the structure, it is necessary to complement the sensor network with at least two absolute measurements systems, for example inclinometers, GPS systems or additional sensors connecting the bridge to external reference points.

5.2 The Lutrive Bridge

The Lutrive (Switzerland) North and South bridges are two parallel twin bridges. Each one supports two lanes of the Swiss national highway A9 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. Curvatures are measured with sensors placed near to the top and the bottom of bridge web and the vertical displacements can be retrieved by double integration of the curvatures. The sensors were used for quasi-static testing under thermal loading and under a static load-charging test [6], as well as for statistical analysis of the dynamical deformations [8].

The static measurements under thermal loading extended during 24 hours between the 6th of July 1996 at 14h00 to the 7th of July 1996 at 14h00. The temperature difference 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 difference variations 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 with co-ordinate x for each discrete measure at a time t. ***Figure 6*** shows the temporal comparison between the vertical 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 leveling can be achieved.

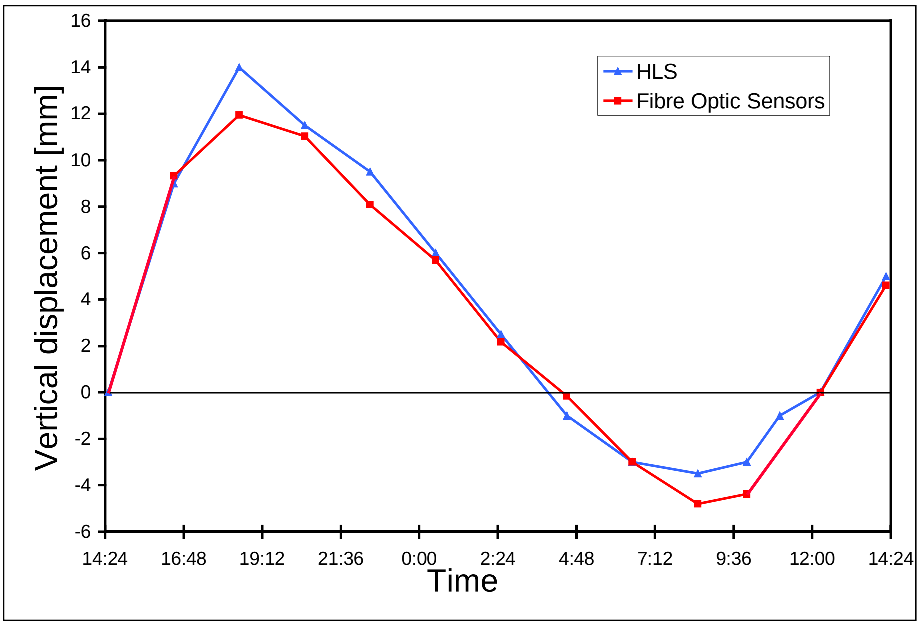


Figure 6: Vertical displacement at quarter span under thermal loading

6. Conclusions

The benefits of structural monitoring are obvious. A continuous or at least regular monitoring of a structure increases the knowledge on its behavior and helps 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 series of sensors (that can be either embedded into concrete or surface mounted on metallic and other existing structures) and of a software package (allowing the treatment of the large 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.
The combination of adequate monitoring techniques and numerical simulations is a powerful tool that enables the understanding of complex structural phenomena. In this way the design of more durable structures can be enhanced.

7. Acknowledgements

The authors are indebted to Prof. L. Pflug, Prof. L. Vulliet, R. Delez, M. Pedretti, R. Passera, P. Colombo, S. Marazzi, J.-M. Ducret, and the teams at IMAC-EPFL, ICOM-EPFL, IBAP-EPFL and IMM for useful discussions and help. This research program is conducted under the partial financing of the Swiss CTI (Commission pour la Technologie et l'Innovation) and of the Board of the Swiss Federal Institutes of Technology.

8. Bibliography

[1] S. T. Vohra, B. Althouse, G. Johnson, S. Vurpillot and D. Inaudi, "Quasi-Static Strain Monitoring During the "Push" Phase of a Box-Girder Bridge Using Fiber Bragg Grating Sensors", European Workshop on Optical Fibre Sensors, Peebls Hydro, Scotland, July 1998

[2] R. Maaskant, T. Alavie, R.M. Measures, M. Ohn, S. Karr, D. Glennie, C. Wade, G. Tadros and S. Rizkalla., "Fiber Optic Bragg grating sensor network installed in a concrete road bridge", Proc. SPIE Vol. 2191, p. 457-465, Smart Structures and Materials 1994: Smart Sensing, Processing and Instrumentation, April 1994

[3] D. Inaudi, N. Casanova, S. Vurpillot, "Fiber Optic Deformation Sensors for Bridges Monitoring", Int. Conf. on New Technologies in Structural Engineering, 2. – 5. July 1997, Lisbon

[4] D. Inaudi, N. Casanova G. Steinmann. J-F. Mathier, G. Martinola, "SOFO: Tunnel Monitoring with Fiber Optic Sensors", Reducing Risk in Tunnel Design and Construction 7. – 8. December 1998, Basel, ITC publisher

[5] P. Kronenberg, N. Casanova, D. Inaudi, S. Vurpillot, "Dam monitoring with fiber optic sensors", Smart Structures and materials, San Diego 5. – 6. March 1997, SPIE Volume 3043,

[6] D. Inaudi, N. Casanova, P. Kronenberg, S. Vurpillot, "SOFO: Monitoring of Concrete Structures with Fiber Optic Sensors", 5th int. Workshop on Material Properties and Design, Weimar, October 1998, Aedificatio Publishers, p. 495 - 514

[7] D. Inaudi, A. Elamari, L. Pflug, N. Gisin, J. Breguet, S. Vurpillot, "Low-coherence deformation sensors for the monitoring of civil-engineering structures", Sensor and Actuators A, 44 (1994), p.125-130

[8] D. Inaudi, J. P. Conte, N. Perregaux, S. Vurpillot, "Statistical Analysis of Under-sampled Dynamic Displacement Measurement", University of California Los Angeles, Symposium on Smart Structures and Materials '98, San Diego 1998, p. 1 - 7