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# LONG-GAGE FIBER OPTIC SENSORS FOR GLOBAL STRUCTURAL MONITORING

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## Abstract

The long-gage deformation sensor, by definition, is a sensor with a gage-length several times longer than the maximal distance between discontinuities or the maximal diameter of inclusions in monitored material. E.g. in case of concrete, the appearance of discontinuities is mainly in form of cracks or air pockets, and aggregate grains can be treated as inclusions in hardened cement paste.

Main advantage of this measurement is in its nature: since obtained by averaging the strain over long measurement basis it is not influenced by local material discontinuities and inclusions. Thus, the measurement contains information related rather to global structural behavior and not to a local material behavior.

Long-gage sensors can be combined in different topologies and networks, depending on geometry and type of monitored structure, allowing monitoring and determination of important structural parameters such as average strains and curvatures in beams, slabs and shells, average shear strain, deformed shape and displacement, crack occurring and quantification as well as indirect damage detection.

The aim of this paper is to make an introduction to fiber optic long-gage sensors, to present their performances and highlight advantages of their use. Simple mathematical models describing behavior of long-gage sensors embedded in the structure are presented along with real on-site applications.

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## LONG-GAGE (DEFORMATION) SENSORS – BASIC NOTIONS

Basic notions concerning long-gage deformation sensors are presented in this section. First the notion of deformation sensor is developed and further promoted to long-gage deformations sensor.

Sensor designed to measure relative displacement between two pre-defined points of a structure is called deformation sensor in this paper. The distance between these two points is called gage-length of the sensor.

Frequently used construction materials, and notably concrete, can be affected by local defects, such as cracks, air pockets and inclusions. All these defects introduce discontinuities in mechanical material properties at a meso-level. But, more indicative for structural behavior are material properties at a macro-level. E.g. reinforced concrete structures are mainly analyzed as built of homogenous material – cracked reinforced concrete. Therefore, for structural monitoring purposes it is necessary to use sensors that are insensitive to material discontinuities.

The long-gage deformation sensor, by definition, is a sensor with a gage-length several times longer than the maximal distance between discontinuities or the maximal diameter of inclusions in monitored material. E.g. in case of cracked reinforced concrete, the gage length of long-gage sensors is to be several time longer than both, maximum distance between cracks and diameter of inclusions. Description of measurement performed by long-gage deformation sensor is presented in Figure 1 and Equation 1.

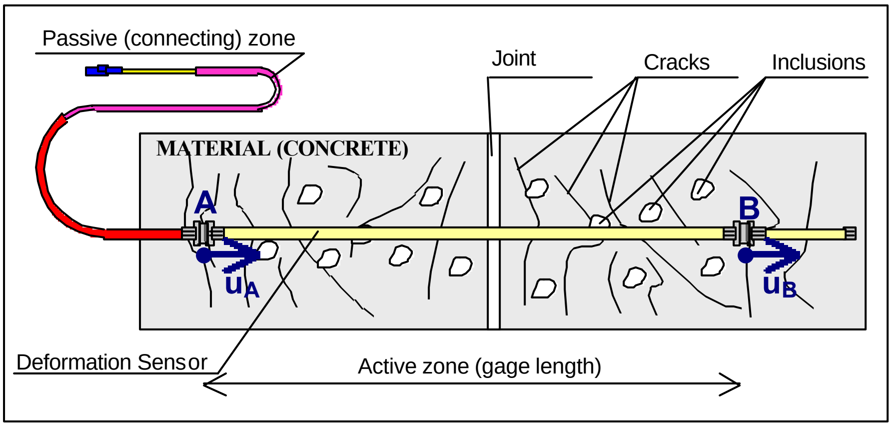


Figure 1: Schema of a long-gage sensor installed on a material with cracks, inclusions and joints (e.g. concrete)

If A and B are the sensor anchoring points as shown in Figure 1, the measurement of the sensor represents a relative displacement between them. The measurement of the sensor is then expressed as follows:

$$m_s = \Delta l_{A-B} = u_B - u_A = \int_A^B \varepsilon dl + \sum_A^B \Delta w_C + \sum_A^B \Delta w_J + \sum_A^B \Delta w_I \qquad (1)$$

Where:

$m_s$ – Measured value; $\Delta l_{A\text{-}B}$ – Change in total distance between points A and B (elongation or shortening); $u_A$, $u_B$ – Total displacements of points A and B in the direction of the active zone of the sensor; $\varepsilon$ – Strain in material; $\Delta w_C$ – Change in size of crack openings (if any crack); $\Delta w_J$ – Change in joint opening (if any joint); $\Delta w_I$ – Change in inclusion dimension (if any inclusion).

Since the long-gage sensor measures relative displacement between two points in a structure, the measurement represents an integral of strain over the sensors length added to a sum of crossed discontinuity dimensional changes (see Equation 1). Finally, the average strain over a length of the sensor is calculated as ratio between the measured relative displacement and the gage length, as presented in Equation 2.

$$\varepsilon_s = \frac{m_s}{l_s} \qquad (2)$$

Where:

$m_s$ – Measured value; $l_s = l_{A\text{-}B}$ – Gage length (distance between points A and B); $\varepsilon_s$ – Measured average strain in material over a gage length of the sensor.

Main advantage of this measurement is in its nature: since obtained by averaging the strain over long measurement basis it is not influenced by local material discontinuities and inclusions. Thus, the measurement contains information related rather to global structural behavior and not to a local material behavior. The example presented in the next section better illustrates this statement.

## GLOBAL, STRUCTURAL MONITORING – BASIC NOTIONS

Monitored parameters can be observed on material or structural level. Main difference between these two levels is in used monitoring strategy and monitoring system: material monitoring provides information related to material behavior, but poor information concerning the structural behavior; structural monitoring provides information related to structural behavior. The difference between the material and structural monitoring is highlighted in Figure 2.

Strain of a bended concrete beam is monitored using four discrete short-gage sensors ($g_{1t}$, $g_{1b}$, $g_{2t}$ and $g_{2b}$) and two long-gage sensors ($s_t$ and $s_b$). All sensors placed in the top of the beam ($g_{1t}$, $g_{2t}$ and $s_t$) measure the same value, while the bottom sensors ($g_{1b}$, $g_{2b}$ and $s_b$) measure different values, due to the crack openings. Short-gage sensors ($g_{1b}$ and $g_{2b}$) are highly influenced by crack presence and they provide information related only to their locations in beam. The long-gage sensor ($s_b$) measure an average value of the strain combined with the crack openings, which is related to the structural behavior. E.g. it is possible to determine structural behavior of the beam by calculating its curvature as ratio between measurement difference and distance between sensors [1]. There is no simple technique that allows determination of structural behavior using results obtained from short-gage sensors. Hence, for the monitoring strategy presented in Figure 2, long-gage sensors allow monitoring at structural level, while the short-gage sensors allow monitoring on material level.

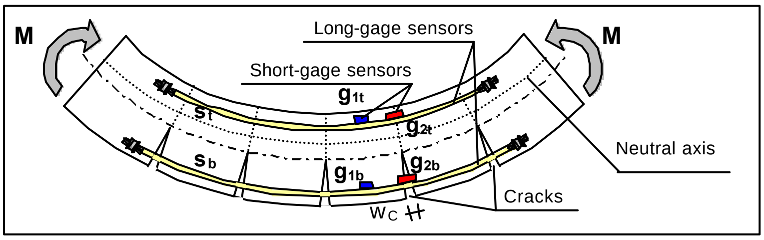


Figure 2. Difference between material and structural monitoring and parallel topology of long-gage sensors

The conclusion carried out from previous example can be summarized by statement that short-gage sensors measure the local behavior of the material while the long-gage sensors monitor structural behavior of the observed element.

## EXAMPLE OF LONG-GAGE SENSOR – SOFO TECHNOLOGY

An example of monitoring system that deals with long-gage sensors is the system called SOFO (French acronym for Surveillance d'Ouvrages par Fibres Optiques – Structural Monitoring using Optical Fibers), based on low-coherence interferometry in optical fiber sensors [2].

The SOFO system consists of long-gage sensors, a reading unit and data acquisition and analysis software. The sensor consists of two optical fibers called the measurement fiber and the reference fiber and contained in the same protection tube. The measurement fiber is coupled with host structure and follows the deformations of the structure. In order to measure shortening as well as the elongation, the measurement fiber is prestressed to 0.5%. The reference fiber is loose and therefore independent from the structure's deformations; its purpose is to compensate thermal influences to the sensor.

Typical sensor gage-length ranges from 250 mm to 10 m. The resolution (minimal detectable change of optical signal translated in measured deformation) reaches 2 μm independently form the gage length and accuracy of measurement is 0.2% of the measured value (linear correlation between the optical signal and the deformation). The dynamic range of the sensors is 0.5% in compression and 1.0% in elongation, and single measurement typically takes 6 to 10 seconds.

The SOFO system was developed in early 1990's and since 1995 it was commercialized and applied to the monitoring of a wide range of civil structures, such as geotechnical structures, bridges, dams, residential and industrial buildings, just to name a few [3, 4, 5]. The system is insensitive to temperature changes, EM fields, humidity and corrosion, and immune from drift for at least 5 years, making it ideal for both short- and long-term monitoring. Being designed for direct embedding in concrete, the sensors allow easy installation; require no calibration and feature high survival rate (better than 95% for concrete embedding). The long gage-length makes them more reliable and accurate than traditional strain sensors, averaging the strain over long bases and not being influenced by local defects in material (e.g. cracks and air pockets). More information on the SOFO system and its applications can be found in the references [6].

A typical application as well as the components of the system is presented in Figure 3.

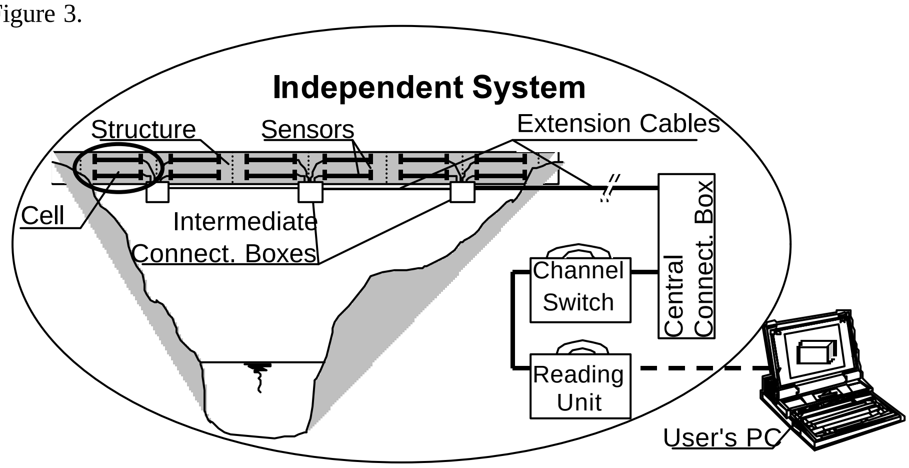


Figure 3: Typical application and components of the SOFO monitoring system

## LONG-GAGE SENSOR TOPOLOGIES

Long-gage sensors can be combined in different topologies and networks [7], depending on geometry and type of monitored structure, allowing monitoring and determination of important structural parameters such as average strains and curvatures in beams, slabs and shells, average shear strain, deformed shape and displacement, crack occurring and quantification as well as indirect damage detection.

To perform a monitoring at a structural level it is necessary to cover the structure, or a part of it with sensors. For this purpose the structure is firstly divided in cells (see Figure 3). Each cell contains a combination of sensors appropriate to monitor parameters describing the cell's behavior. Knowing the behavior of each cell, it is possible to retrieve the behavior of the entire structure. The combination of sensors installed in single cell is called sensor topology in this paper. Totality of sensors is called sensor network. The most used topologies are simple and parallel topology (see next section).

Sensor topology in each cell is appropriated to the parameter representative for this cell (e.g. strain, curvature, etc.). Sensor network can contain cells with different topologies.

## ON-SITE APPLICATIONS OF SOFO LONG-GAGE SENSORS

### Simple topology

Simple topology consists of single sensor installed by preference in a direction of principal strain (see cells 3 to 8 in Figure 4). It is mainly used for monitoring linear structural elements (beams) subjected to axial compression or traction combined with longitudinal shear stresses and dead load, e.g. piles or columns. In these cases no bending occurs and the strain is constant over the cross-section of the beam. Thus, the sensor can be installed regardless to the position in the cross section, and provide information directly related to the structural behavior of the monitored elements.

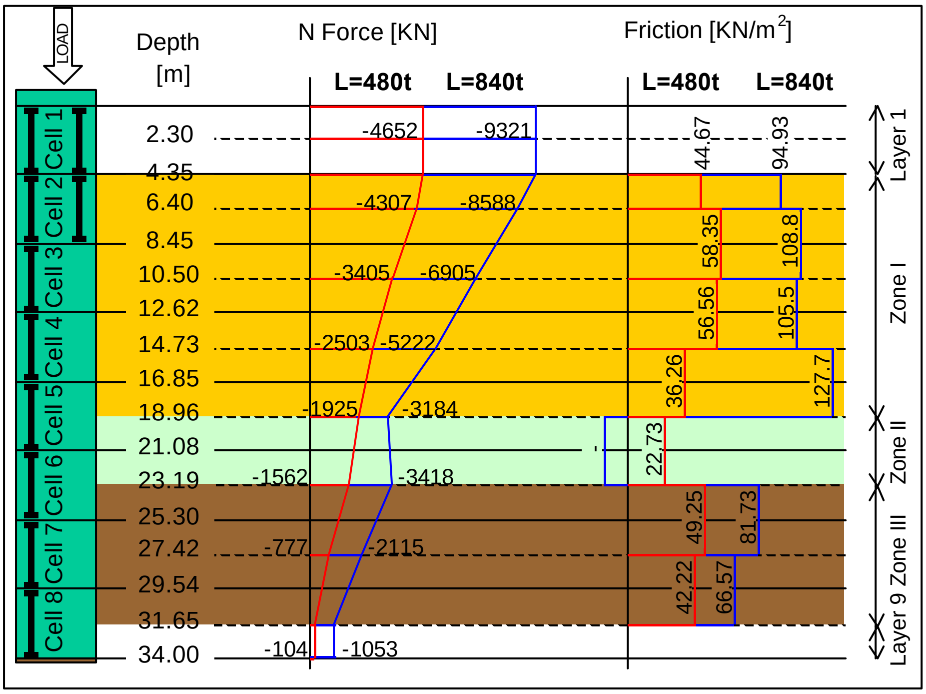


Figure 4: Sensor network and main results obtained using simple topology for pile monitoring

A new semi-conductor production facility in the Tainan Scientific Park, Taiwan, is to be founded on a soil consisting mainly of clay and sand with poor mechanical properties [3]. An adequate functioning of such a facility is possible only if a high stability of its foundations is guaranteed. It was estimated that approximately 3000 piles would be necessary at that site. To assess the foundation performance, it was decided to perform an axial compression, pullout and flexure test in full-scale on-site condition. Since complete analysis of the tests exceeds topic of this paper, only results of axial compression test are briefly presented here.

Length of pile was approximately 35 m and it was divided in eight cells. SOFO sensors with gage length of 4 m were used to monitor the behavior under the test. Two topologies were combined: the first two cells were equipped with parallel topology (see about parallel topology in the next subsection) in order to detect bending created by eccentricity of load; lower cells were equipped only with simple topology (see Fig. 4).

Even if simple topology is used rich information concerning the pile behavior and pile-soil interaction are obtained, such as strain distribution over the pile length, distribution of vertical displacement relative to the pile bottom, Young modulus of pile, forces distribution in pile including the bottom force, failure mode of the pile (sliding), frictional forces in soil, detection of three zones of soil with different mechanical properties and ultimate load capacity of the pile.

Sensor network as well as force distribution in pile and in soil in cases of ultimate load capacity (480t) and maximal applied load (840t) are presented in Figure 4. Identified soil layers with different mechanical properties are also presented in the same figure.

**Parallel topology**

Parallel topology consists of two parallel sensors with equal gage lengths installed at different levels of structural element cross-section. Direction of sensors corresponds by preference to the directions of normal strain lines. Parallel topology is schematically presented in Figure 2.

The parallel topology is used for monitoring of parts of structure subjected to bending: the sensors installed at different levels in cross-section will measure different values of average strain allowing monitoring of average curvature in the cell. The average curvature is calculated assuming that the Bernoulli hypothesis [1] is satisfied (plane cross-sections of the pile remain plane under loading).

If monitored part of structure contains representative number of cells equipped with parallel topology then the average curvature can be monitored in each cell, and consequently the distribution of curvature over entire monitored part of structure can be retrieved. Deformed shape of monitored part of the structure is obtained by double integration of curvature [1]. If, in addition, boundary conditions are known (e.g. displacements in two points or one displacement and one rotation), then it is possible to determinate absolute displacement perpendicular to direction of sensors.

Parallel topology is certainly the most used for monitoring wide type of structure such as bridges, piles, tunnels etc. An example is presented here: monitoring a part of the Versoix bridge in Switzerland (two spans) [4]. 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. 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 optimize the concrete mix and to increase the knowledge on the long-term behavior and performance, the bridge is instrumented with more than hundred SOFO sensors. Position of sensor in the cross-section is presented in Figure 5. Parallel topology is used for monitoring in horizontal and vertical plan.

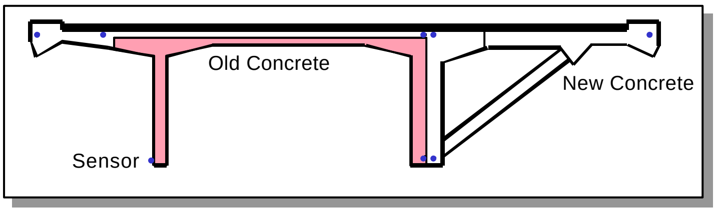


Figure 5: Position of sensors in cross-section of Versoix bridge

The horizontal and vertical displacements of the first two spans of the bridge were calculated using the double-integration algorithm previously cited. Figure 6 shows the horizontal displacement of the two spans of the bridge as calculated by the algorithm, for different times and relative 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.

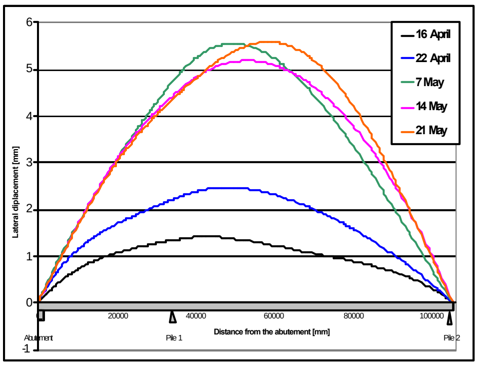


Figure 6: Horizontal displacement evolution due to new concrete shrinkage

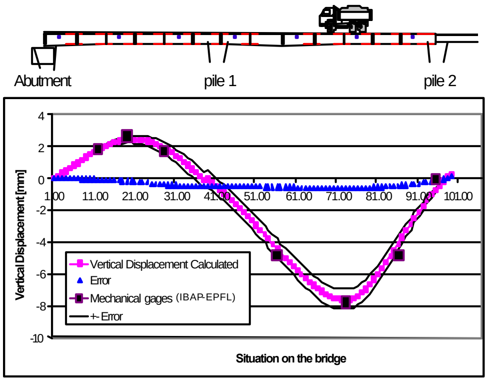


Figure 7: Vertical displacement during the load test and comparison with dial gages

During a load test, performed after the end of construction works, the vertical displacement of the bridge was also monitored. Figure 7 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 of 6 trucks placed on the second span of the bridge. 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.

### Long-term monitoring

Long-term monitoring of the Vesoix Bridge continues. Monthly quasi-static measurements are performed in order to monitor strain and displacement evolution of the bridge. Five years strain evolution of a cross-section is presented in Figure 8. After the cross-section is bended horizontally due to unequal heat and different time of concrete pouring, all sensors measures approximately same deformation confirming that the cross-section is not exposed to unexpected bending due to damage or delamination.

In Figure 9 diagrams of strain obtained by measurements (sensor A11) are compared with the models (Strain calc., shrinkage + creep) and very good accordance is observed confirming good design and realization of the bridge. The evolution of shrinkage and creep is not finished but it is stabilized (see Figure 9). The seasonal temperature variation influenced behavior of the bridge and can also be seen in Figure 9.

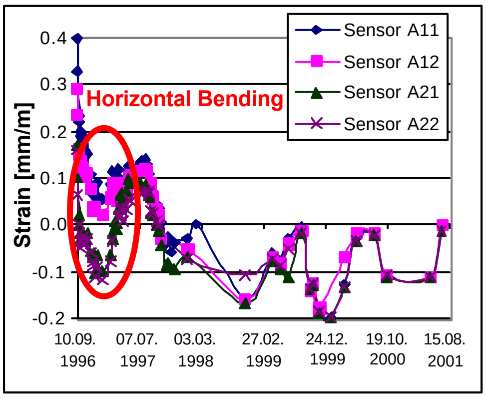


Figure 8: Versoix bridge five-years strain evolution

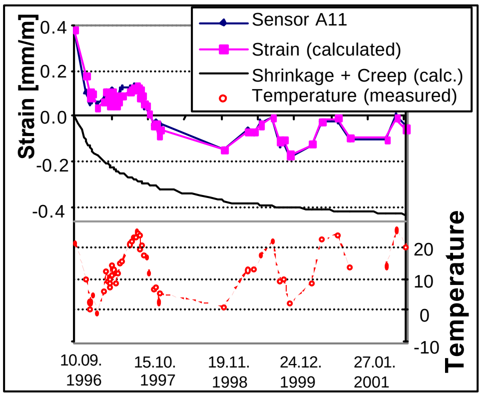


Figure 9: Uncoupling of shrinkage and creep from temperature

## CONCLUSIONS

A structural monitoring system called SOFO is presented in this paper. The particularity of the system is the use of long-gage sensors combined in different topologies. The idea is to divide the structure in cells, to equip each cell with topology which corresponds to the expected strain field and then to link results obtained from each cell in order to retrieve global structural behavior. In that way a kind of "finite element monitoring" is performed.

Two typical topologies of long-gage sensors are presented, simple and parallel topology. Real, on-site application of simple and parallel topology illustrates the power of the method. Number of parameters related to structural behavior is monitored or determined from monitoring.

It is demonstrated that long-gage sensors offer large possibilities since they provide measurement that is not influenced by local material defects. The averaged value obtained by long-gage sensors is fully in accord with philosophy of reinforced concrete where the cracked concrete is considered as homogenous material at macro-level.

Due to their optical nature, the fiber optic sensors are insensitive to environmental influences and provide stable and accurate measurement. Moreover, due to their longevity they are suitable for long-term monitoring, covering whole lifespan of the structure, from construction to the end of service.

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