LONG-GAGE SENSOR TOPOLOGIES FOR STRUCTURAL MONITORING

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1 INTRODUCTION

The availability of long-gage fiber optic sensors [1] has opened new and interesting possibilities for structural monitoring. Long-gage sensors allow the measurement of deformations over measurement basis that can reach tens of meters with resolutions in the micrometer range. The SOFO sensors [2] developed by SMARTEC SA and the Swiss Federal Institute of Technology in Lausanne constitutes a good example of such a sensor system.

Using long-gage sensors, it becomes possible to cover the whole volume of a structure with sensors enabling a global monitoring of it. This constitutes fundamental departure from the standard practice that is based on the choice of a reduced number of points, supposed to be representative of the whole structural behavior, and their instrumentation with short-gage sensors. This common approach will give interesting information on the local behavior of the construction materials, but might miss behaviors and degradations that occur at locations that are not instrumented. On the contrary, long-gage sensors allow the monitoring of a structure as a whole, so that any phenomena that has an impact on the global structural behavior is detected and quantified.

This contribution discusses the use of long-gage sensors for structural monitoring. The response of these sensors in inhomogeneous material like concrete, possibly including defects (e.g. cracks), is analyzed. The paper also presents the ideal disposition of multiple sensors (topology) to measure different parameters including compression, bending and shear. In particular, an algorithm for retrieving the vertical displacement of bridges instrumented with pairs of horizontal sensors is introduced and analyzed. Finally a number of application examples show how interesting this technique is for the monitoring of different types of concrete structures including bridges, piles and high-rise buildings.

2 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.

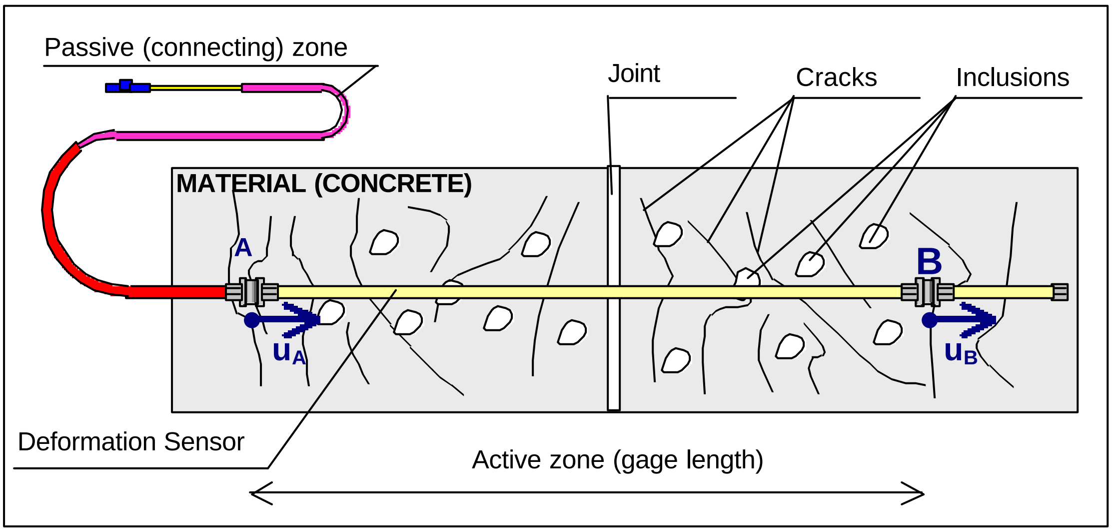

Fig. 1 Schema of a long-gage sensor installed on a material with cracks, inclusions and joints (e.g. concrete)

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:

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

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
ε – Strain in material
Δw_C – Change in size of crack openings (if any crack)
Δw_J – Change in joint opening (if any joint)
Δw_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.

$$\varepsilon_s = \frac{m_s}{l_s} \tag{2}$$

Where:

m_s – Measured value
$l_s = l_{A\text{-}B}$ – Gage length (distance between points A and B)
ε_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. Figure 2 illustrates this statement.

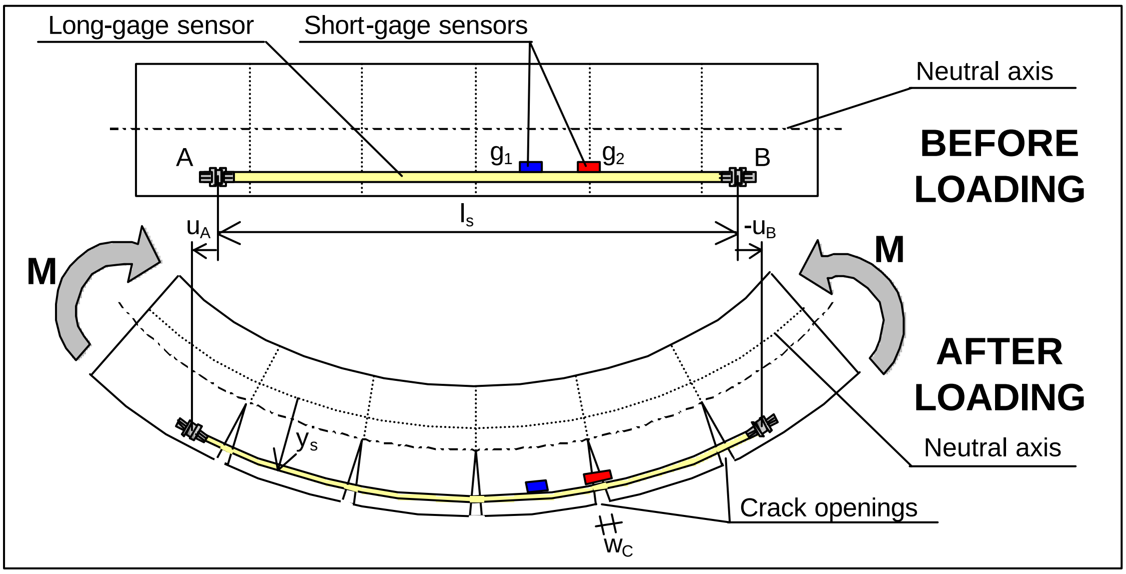

Fig. 2 Difference in deformation measured by the SOFO long-gage and strain (short-gage) sensors

Results obtained by monitoring of concrete structures using long-gage and short-gage sensors installed on a cracked concrete element exposed to bending are compared in Figure 2. The difference lays in fact that short-gage sensors measure the local behavior of the material while the long-gage sensors monitor structural behavior of the observed element.

The measurement performed by the long-gage sensor represents average strain of the cracked reinforced concrete element considered as a homogenous material. This measurement does not make any difference if the source of the measured deformation is in strain of concrete or in width of crack openings. Therefore this measurement shows behavior of element (beam) in a structural level and can be represented as in Equation 3. We note that it follows the philosophy of reinforced concrete.

$$\varepsilon_s = \frac{M}{E_c I_c} y_s \tag{3}$$

Where:

ε_s – Measured average strain over a gage length of the sensor
M – Bending moment
E_c I_c – Stiffness of cracked reinforced concrete
y_s – Position of the sensor with respect to neutral axis of cracked element

On the other hand, the short-gage sensors measure local behavior of material. For example, the sensor g_1 will record the exact strain in concrete at the position where it is placed, while the sensor g_2 will be influenced by crack opening and will record a value very close to the size of the opening. In structural point of view, even if they are at the same level in cross section, they will give a different answer, not related with value of bending moment. Therefore from these measurement it is difficult, or even impossible, to understand structural behavior of the element.

If we analyze the configuration shown in Figure 2, then following relations between measured values and theoretical considerations can be established:

1) $M_{g1}=M_{g2}$, but $\varepsilon_{g1}<\varepsilon_{g2}$ - bending moment in point g_1 is equal to this in point g_2, but measurements are not in accord with this statement;

2) $\varepsilon_{g2} > \varepsilon_s = \frac{M}{E_c I_c} y_c > \varepsilon_{g1}$ - measurement performed by long-gage sensor shows average value related to structural behavior and not to local behavior of material.

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

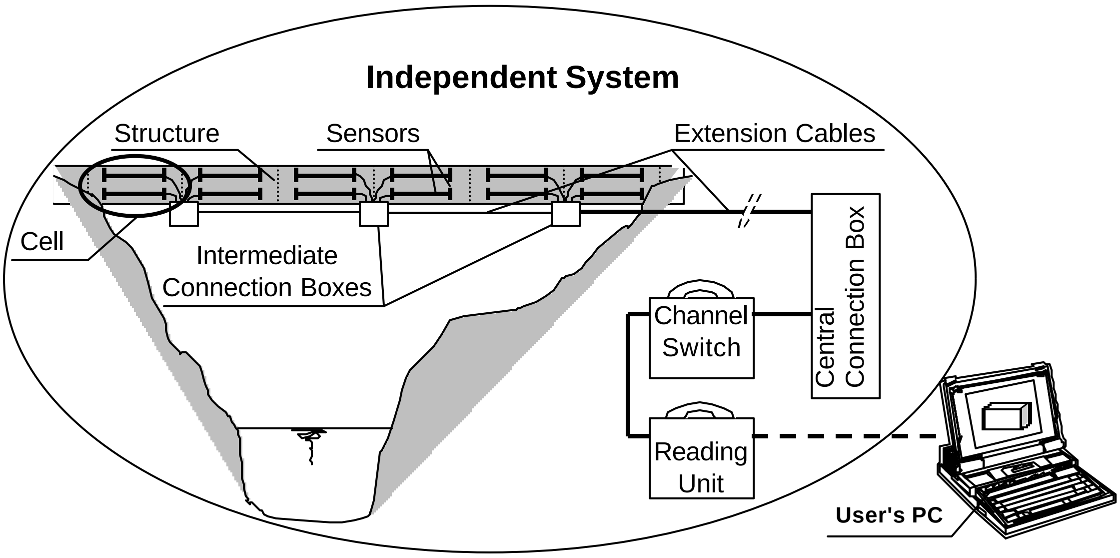

Fig. 3 Typical application and components of the SOFO monitoring system

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, wile the resolution reaches 2 μm independently form the gage length and with an accuracy of 0.2%. The dynamic range of the sensors is 0.5% in compression and +1.0% in elongation.

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 [4, 5, 6]. 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 [2].

4 LONG-GAGE SENSOR TOPOLOGIES

4.1 Basic notions

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.

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.

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 (see Section 5.1).

4.2 Simple topology

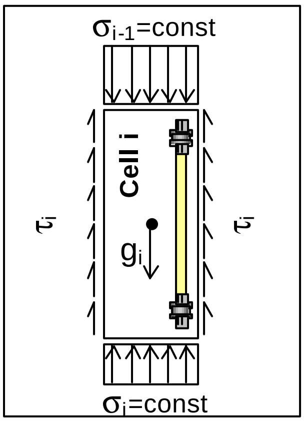

Fig. 4 Example of cell with simple topology

Simple topology consists of single sensor installed by preference in a direction of principal strain. It is mainly used for monitoring linear structural elements (beams) subjected to axial compression or traction combined with longitudinal shear stresses and dead load (see Figure 4), 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. Example of a cell equipped with simple topology subjected to normal stresses (σ_i), longitudinal shear stresses (friction τ_i) and dead load (g_i), is presented in Figure 4.

If several cells containing simple topology are enchained and fully cover the monitored element, then distribution of strain along the element as well as relative displacement in direction of element can be retrieved. The relative displacement is obtained as integral of strain. In addition, if the Young modulus and thermal expansion coefficient of construction material are known, and time dependent strain (shrinkage and creep) can be estimated, then the distribution of normal forces can be qualitatively determined.

An on-site application of simple topology is presented in Sub-section 5.1. We note that simple topology can also be used in cases when the strain field in monitored element is complex, and principal strain is not in direction of the sensor. The sensor will provide information (measure) the average strain in the direction of its gage-length, but no direct conclusions concerning the structural behavior of monitoring element can be carried out.

4.3 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 5.

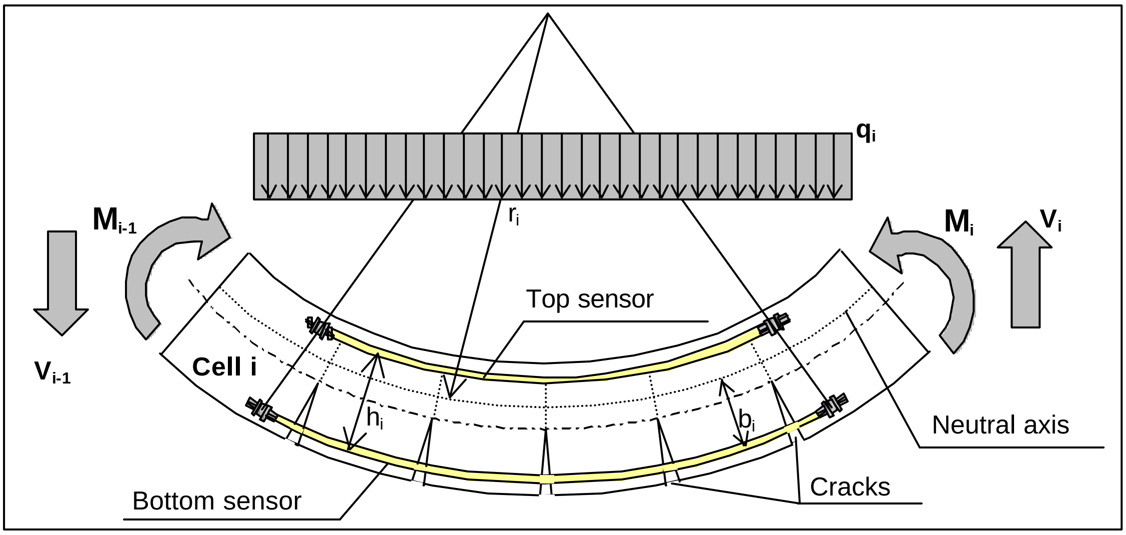

Fig. 5 Schematic representation of a cell equipped with parallel topology

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 [7] is satisfied (plane cross-sections of the pile remain plane under loading) using the following expression:

$$\kappa_i = \frac{1}{r_i} = \frac{m_{i,t} - m_{i,b}}{l_{s,i}} \cdot \frac{1}{h_i} \tag{4}$$

Where:

κ_i – Average curvature of cell i
r_i – Curving radius of cell i (see Figure 5)
$m_{i,t}$, $m_{i,b}$ – Deformation measured by top and bottom sensors respectively (see Figure 5)
$l_{s,i}$ – Gage length of sensors in cell i
h_i – Distance between sensors (see Figure 5)

If monitored part of structure contains representative number of cells equipped with parallel topology (e.g. for beams the minimum number is three) 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 [8] of curvature. If, in addition, two characteristics related to absolute displacement are monitored (e.g. displacements in two points or one displacement and one rotation) and these characteristics are used as boundary conditions for double integration, then it is possible to determinate absolute displacement perpendicular to direction of sensors (see examples in Subsection 5.2).

Since the curvature is directly proportional to bending moment, the distribution of curvature helps to qualitatively determinate distribution of bending moments. If Young modulus, moment of inertia and thermal expansion coefficient are known, and time dependent deformations can be estimated, then the distribution of bending moment can be quantified.

Position of neutral axis with respect to bottom sensor can be determined from measurements using the following expression:

$$b_i = \frac{m_{i,b}}{m_{i,b} - m_{i,t}} h_i \tag{5}$$

If the ultimate strain in concrete is known, then from geometrical proportion and position of neutral axis it is possible to determine depth of cracks as well as sum of their openings in each cell.

Rich information obtained by using parallel topology are presented on real structures in Section 5.

4.4 Crossed topology

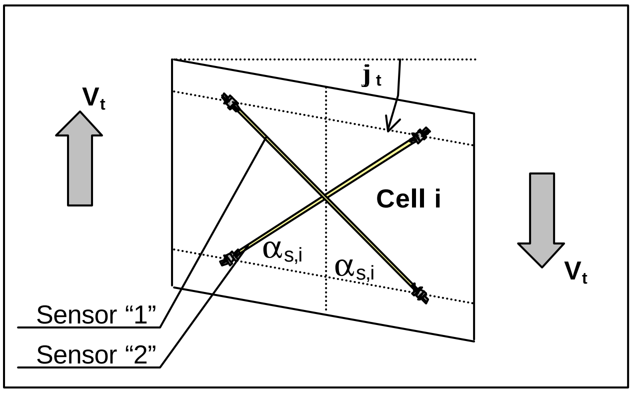

Fig. 6 Example of crossed topology

Crossed topology consists of two crossed sensors installed with a pre-defined angle with respect to direction of normal strain lines. The aim of this topology is to detect and quantify shear strain. The angles of sensors are by preference identical by value, but different by sign. However, it is possible to use sensors with different angles.

The algorithm allowing retrieving of shear strain depends on angles of both sensors, their gage-length and strain field in the equipped cell. Since the measurements of sensors are influenced by normal strain too, it is recommended to set the crossing point at neutral line. In such a way the influences of normal strain will be annulled. Example of crossed topology for sensor angles of $+\alpha_{s,i}$ and $-\alpha_{s,i}$, and the crossing point set onto the neutral line is presented in Figure 6. In this case the average shear strain is calculated as follows:

$$\varphi_t = \frac{m_{1,i} - m_{2,i}}{2 \cdot l_{s,i} \cdot \sin\alpha_{s,i} \cdot \cos\alpha_{s,i}} \tag{6}$$

Where:

φ_t – Average shear strain of cell i
$\alpha_{s,i}$ – Angle of sensors in cell i (see Figure 6)
$m_{1,i}$, $m_{2,i}$ – Deformation measured by sensors “1” and “2” respectively (see Figure 6)
$l_{s,i}$ – Gage length of sensors in cell i

Researches on the use and applicability of crossed topology are still going on. Crossed topology is mainly to be used as complement to the parallel topology, but it can also be used in an independent way for monitoring stiffenings, walls etc.

5 ON-SITE APPLICATIONS OF SOFO LONG-GAGE SENSORS

5.1 Simple topology

SOFO sensors in simple topology were successfully used in monitoring of building columns and piles [4]. Results of monitoring performed during the axial compression test of a pile are presented in this subsection.

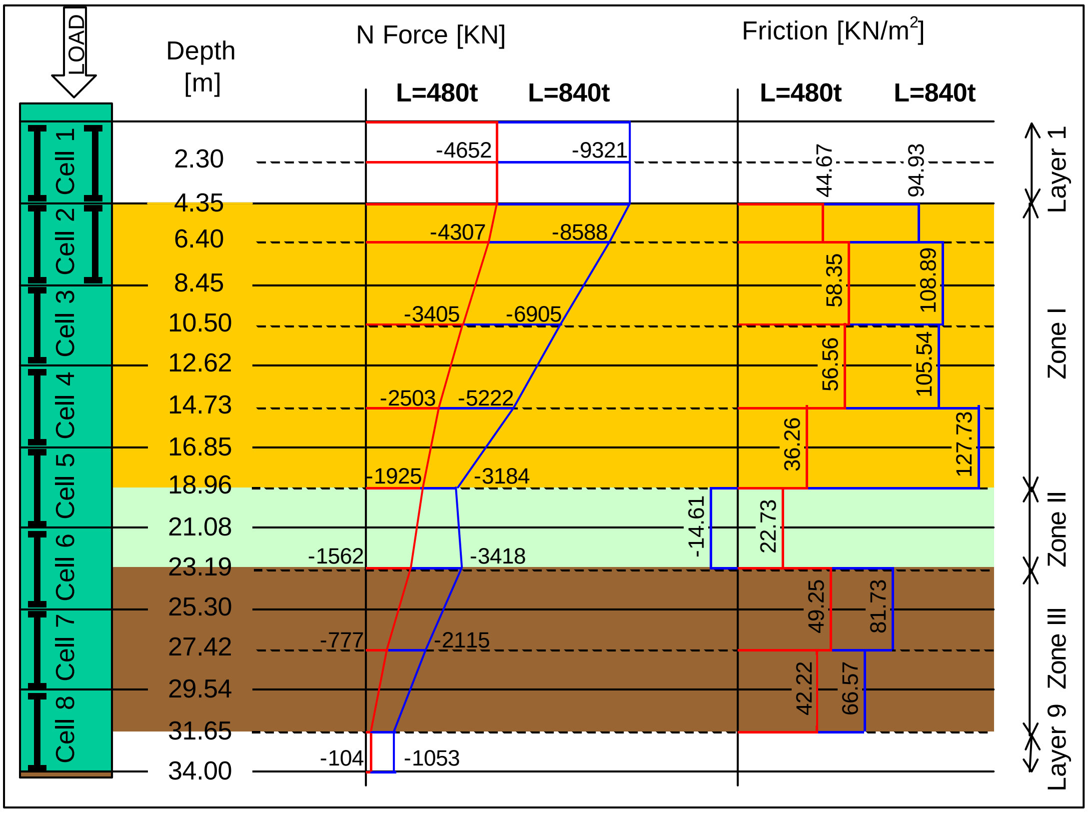

Fig. 7 Sensor network and main results obtained using simple topology for pile monitoring

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. 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 in order to detect bending created by eccentricity of load; lower cells were equipped only with simple topology.

Even if simple topology is used rich information concerning the pile behavor 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 7. Identified soil layers with different mechanical properties are also presented in the same figure.

5.2 Parallel topology

Parallel topology is certainly the most used for monitoring wide type of structure such as bridges, piles, tunnels etc. Two examples are presented here, monitoring a part of the Versoix bridge in Switzerland (two spans) [5] and monitoring of a pile under flexure test.

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 8. Parallel topology is used for monitoring in horizontal and vertical plan.

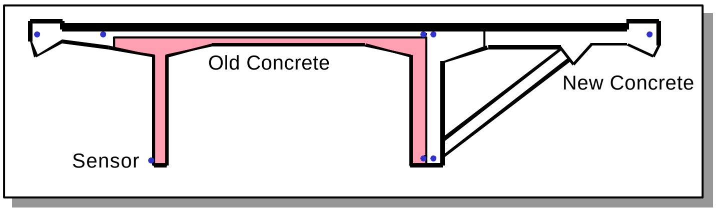

Fig. 8 Position of sensors in cross-section of Versoix bridge

The horizontal and vertical displacements of the first two spans of the bridge were calculated using the double-integration algorithm previously cited. Figure 9 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.

During a load test, performed in Mai 1998 after the end of construction works, the vertical displacement of the bridge was also monitored using the fibre optic sensors. Figure 10 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.

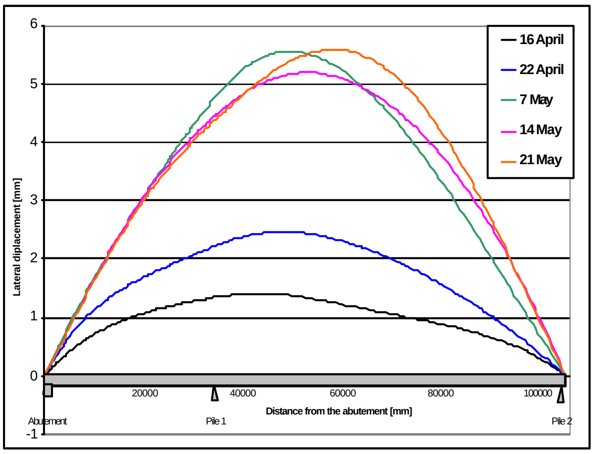

Fig. 9 Evolution of horizontal displacement provoked by shrinkage of new concrete

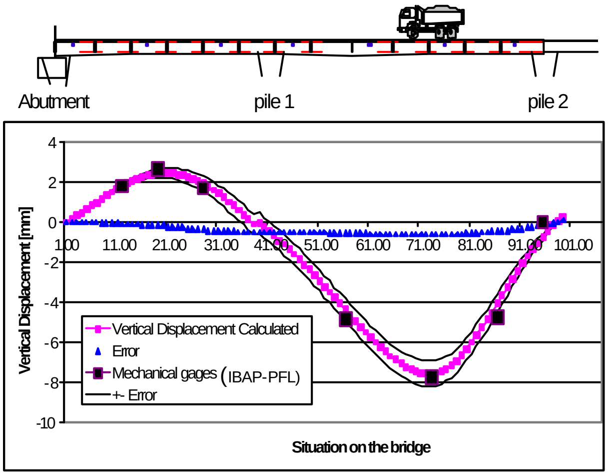

Fig. 10 Vertical displacement during the load test and comparison with dial gages

The second example of on-site application of parallel topology is pile monitoring during the flexure test. The presented pile belongs to the group tested for semiconductor facility in Taiwan. The pile was divided in eight cells as in case of axial compression test (see previous subsection). Each cell was equipped with four-meters long sensors combined in parallel topology. Horizontal force was applied onto the pile's head step-by-step from 0 to 100 tons.

A high difference in the strain magnitude for the different cells was observed. Cell 2 was the most deformed, followed by Cells 1 and 3 while Cells 4 –8 were practically unaffected, even for the maximal applied load. For loads below 50t, parallel sensors installed in each cell measured approximately the same absolute value of deformation. This means that for those loads the pile was not cracked. For higher levels of load an asymmetry is observed due to cracking and the consequent displacement of the neutral axis.

The average curvature in each pile cell was calculated from the average strain. The average curvature with respect to the load for the first four cells is presented in Figure 11. The curvature of the fourth cell can practically be neglected. The same is true for cells 5-8, and that's why the average curvatures for these cells are not presented in Figure 11.

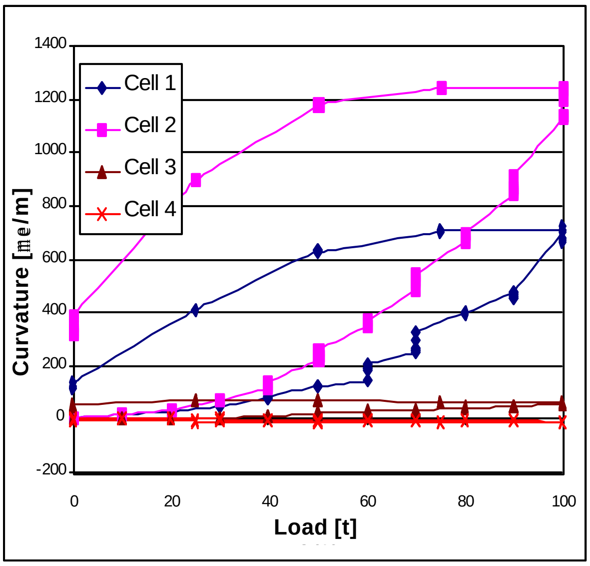

Fig. 11 Average curvature in the first four cells of the pile with respect to load

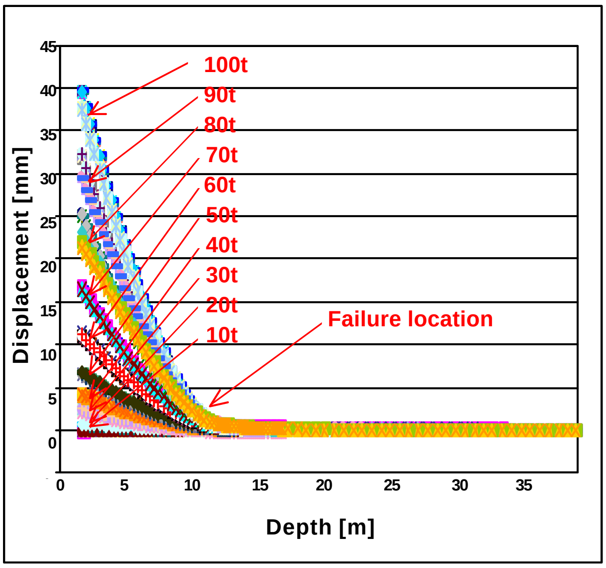

Fig. 12 Deformed shapes and horizontal displacements of the pile for different loads

The deformed shape (horizontal displacement) of pile was calculated using a double integration of the curvature function (7), and is presented in Figure 12. Again, the maximal displacement is observed in the first three cells of the pile. The point with maximal curvature in the Figure 12 corresponds to the failure point of the pile (plastic hinge).

The ultimate lateral load capacity of the pile was identified as the minimal load that generates the cracking in the pile. According to Figures 11 and 12, this load is situated between 40 and 50t. The pile failed at the depth of approximately 10 m, according to Figure 12.

6 CONCLUSIONS

An original structural monitoring method is presented in this paper. The particularity of the method 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.

Three typical topologies of long-gage sensors are presented, simple, parallel and crossed 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. Moreover, they are able to monitor defects such as cracks in reinforced concrete. 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.

7 ACKNOWLEDGEMENTS

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