A method for piles monitoring using long-gauge fibre optic sensors

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ABSTRACT: Long-gauge fibre optic sensor is basically designed to monitor average ranging strain between two points of the structure. The particularity of the sensor is the long gauge-length, ranged between 250 mm and 10 m, which makes them insensitive to local structural defects like crack openings or air pockets, and allow the collection of data on a structural and not material level. Due to fibre optic nature, the sensors are insensitive to environmental influences such as temperature, humidity, corrosion, and electromagnetic fields. The aim of this paper is to present the long-gauge fibre optic sensors and a monitoring method based on their use which is applicable on wide type of structures. The philosophy of the method is similar to philosophy of the finite element method: the structure is divided in elements, called cells, and each cell is equipped with the appropriate combination of sensors, called topology; if only compression or traction is expected in a cell, then a single sensor is installed within the cell, while the pair of parallel sensors is installed for bending; using appropriate algorithms, the cells are connected and the structure monitored on global structural level. The method was applied and proven and an application on piles subject to axial compression, pullout and flexure test is presented in the paper. SOFO long-gauge sensors were used. The method allowed the determination of the Young modulus of the piles, the occurrence and characterisation of cracks, the normal force distribution, the ultimate load capacity in case of axial compression and pullout tests as well as the curvature distribution, horizontal displacement, deformed shape and damage localization in case of the flexure tests. Moreover, the distribution of the pile-soil friction, the quality of soil and the pile tip force were estimated.

1 INTRODUCTION

The availability of long-gauge fiber optic sensors (Glisic, Inaudi, 2002a) has opened new and interesting possibilities for structural monitoring. Long-gauge sensors allow the measurement of deformations over measurement basis that can reach tens of meters with resolutions in the micrometer range.

Using long-gauge 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-gauge 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-gauge 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 presets a method for piles monitoring based on use long-gauge sensors. The ideal disposition of multiple sensors (topology) in piles to measure different parameters related to compression and bending is developed. The method was tested on-site and results confirmed its excellent performance.

2 LONG-GAUGE DEFORMATION SENSORS

2.1 *Basic notions*

Frequently used construction materials, and notably concrete, can by affected by local defects, such as crack, air pockets and inclusions. All these defects introduce discontinuities in material mechanical properties at a meso-level. 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 insensitive to material discontinuities.

The long-gauge deformation sensor, by definition, is a sensor with a gauge-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 gauge length of long-gauge sensors is to be several time longer than both, maximum distance between cracks and diameter of inclusions. Description of measurement performed by long-gauge deformation sensor is presented in Figure 1 and Equation 1.

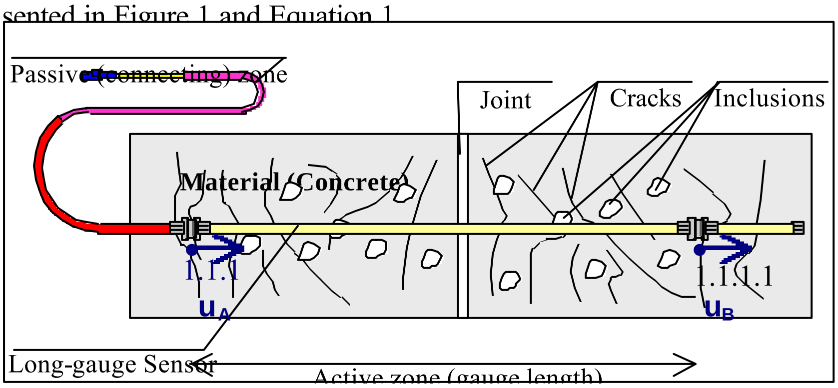

Figure 1: Schema of a long-gauge sensor installed on a material with cracks, inclusions and joints

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 sensor is then expressed as in Equation 1.

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.

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

where m_s = measured value; ε_s = measured average strain; l_{A-B} = gauge length; Δl_{A-B} = change in length 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 sensor; ε = Strain in material; Δw_C = change in size of crack openings; Δw_J = opening of joint; and Δw_I = change in inclusion dimension.

Long-gauge 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. Topologies applied for piles monitoring are presented in Section 3.

2.2 *SOFO technology*

An example of monitoring system that deals with long-gauge sensors is the system called SOFO, based on low-coherence interferometry in optical fiber sensors and developed by SMARTEC SA and the Swiss Federal Institute of Technology in Lausanne (Inaudi 1997).

The SOFO system consists of long-gauge sensors, a reading unit and data acquisition and analysis software.

Typical sensor gauge-length ranges from 250 mm to 10 m, wile the resolution reaches 2 μm independently form the gauge 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. The system is insensitive to temperature changes, EM fields, humidity and corrosion, and immune from drift for at least 6 years, making it ideal for both short- and long-term monitoring. More information on the SOFO system and its applications can be found in the references (SMARTEC 2003; Glisic, Inaudi 2003).

3 SENSORS TOPOLOGIES APPLIED IN PILES MONITORING

3.1 *Introduction to sensor topologies*

To perform a monitoring at a structural level it is necessary to cover the structure with sensors. For this purpose the structure is first divided in cells (see further Figure 4). Each cell contains a combination of sensors appropriate to monitor parameters describing the cell's behavior. Knowing behavior of each cell, it is possible to retrieve the behavior of entire structure. The combination of sensors installed in single cell is called sensor topology (Inaudi, Glisic, 2002). 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, shear strain, etc.) and sensor network can contain cells with different topologies. Two topologies used in piles monitoring method are called Simple and Parallel 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 2), e.g. piles or columns. In these cases no bending occurs and the strain is constant over the cross-section of beam. Thus, the sensor can be installed regardless to the position in the cross section, and provide information directly related with structural behavior of 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 2.

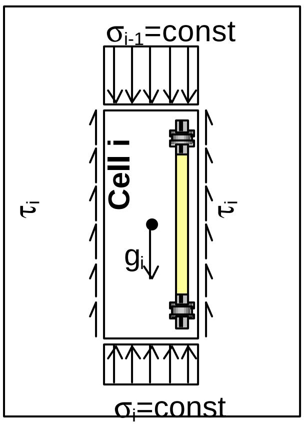

Figure 2: Example of cell with simple topology

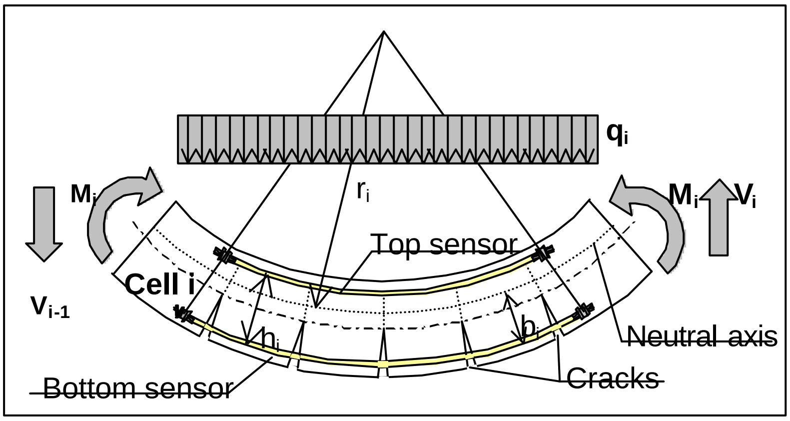

Figure 3: Example of cell with parallel topology

If several cells containing simple topology are enchained and fully cover 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.

Parallel topology consists of two parallel sensors with equal gauge 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 3.

The parallel topology is used for monitoring parts of structure subjected to bending: the sensors installed at different level 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 is satisfied (plane cross-sections of the pile remain plane under loading) using the following expression:

$$\kappa_i = \frac{1}{r_i} = \frac{m_{i,t} - m_{i,b}}{l_{s,i}} \cdot \frac{1}{h_i} \tag{2}$$

where κ_i – average curvature of cell i; r_i = curving radius; $m_{i,t}$, $m_{i,b}$ = deformations measured by top and bottom sensors; $l_{s,i}$ = gauge length of sensors; and h_i = distance between sensors.

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 of curvature (Vurpillot, 1999). 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.

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

$$b_i = \frac{m_{i,b}}{m_{i,b} - m_{i,t}} h_i \tag{3}$$

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 (Glisic, Inaudi 2002b).

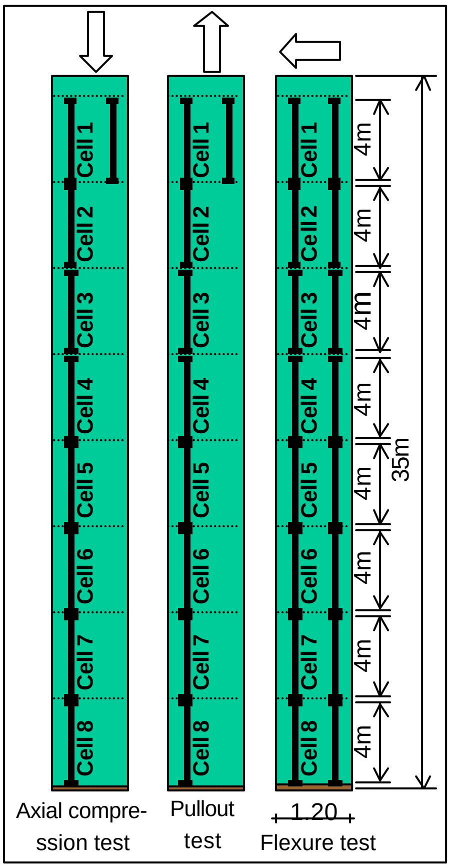

Figure 4: Topologies applied in piles monitoring and dimensions of piles

3.2 *Long-gauge sensors topologies applied on piles*

Long-gauge topologies were tested on piles subject to pullout, axial compression and flexure test (more details are given in Section 4). Four meters long sensors were selected. The piles were divided into eight cells. In the case of axial compression and pullout tests, a simple topology was used, and the parallel topology was used in the top cell only in order to detect and compensate for a possible load eccentricity, as shown in Figure 4. In case of flexure test, a parallel topology was used in all eight cells, as shown in Figure 4. The position of the sensors in the pile's cross-section is selected in such a way that the load direction and the sensors are aligned (see Figure 4). The sensors were attached to rebars before pouring and thus embedded in concrete.

4 TESTS, RESULTS AND ANALYSIS

4.1 *Tests description*

Two sets of reverse, cast-in place piles were tested. Each set consisted of three piles, and each pile in a set was tested to a single load case, i.e. compression (according to ASTM D1143-B1), uplift (according to ASTM D3689-B3) or horizontal force (according to ASTM D3966-90). All piles had the same dimensions: a diameter of 1.20m and length of 35 m, and were designed and constructed in order to have the same mechanical properties. The compressive strength of 3 weeks old concrete samples was 24.5 MPa and calculated compression and uplift capacity was 365t and 220t respectively (Glisic, Inaudi, Nan 2002).

The load was applied step-wise using hydraulic jacks and according to ASTM norms. In addition to SOFO sensors, the displacement of the head of the pile was recorded using LVDT-s.

4.2 *Results obtained from compression and pullout tests*

The full presentation and discussion of each measured parameter largely exceeds the scope of this paper, therefore only the most significant results are summarized and briefly presented. For more details, see (Glisic, Inaudi, Nan 2002).

The average strain in each cell of a pile was determined using Expression 1. The distribution of the average strain over the length of the pile, in the case of the axial compression test for increasing loads is presented in Figure 5, and for decreasing loads in Figure 6.

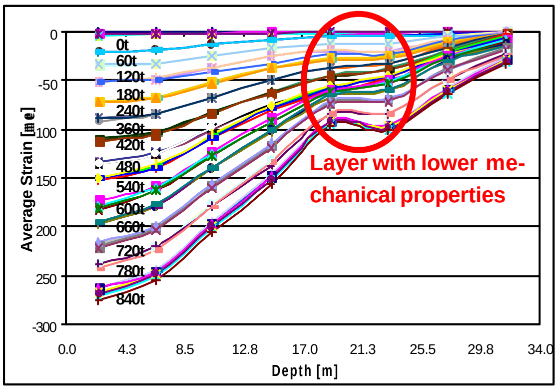

Figure 5. Average strain distribution, increase of load, axial compression test.

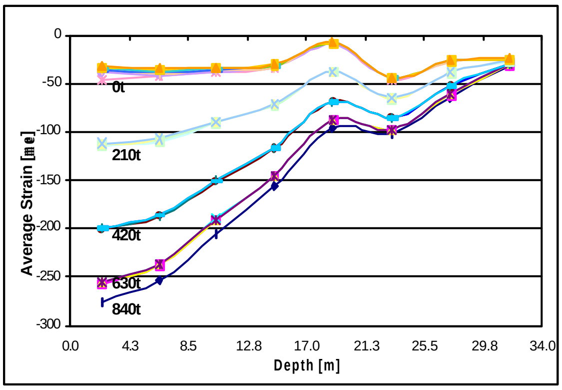

Figure 6. Average strain distribution, unloading, axial compression test.

The average strain served as a basis to calculate all other parameters. Different algorithms are used in case of different tests and topologies and the rich information concerning the piles behaviors and performances are obtained. As an example of performance of the applied method the diagrams of distributions of normal forces in the pile, friction stress and identification of different zones of soil obtained from compression test are presented in Figure 7.

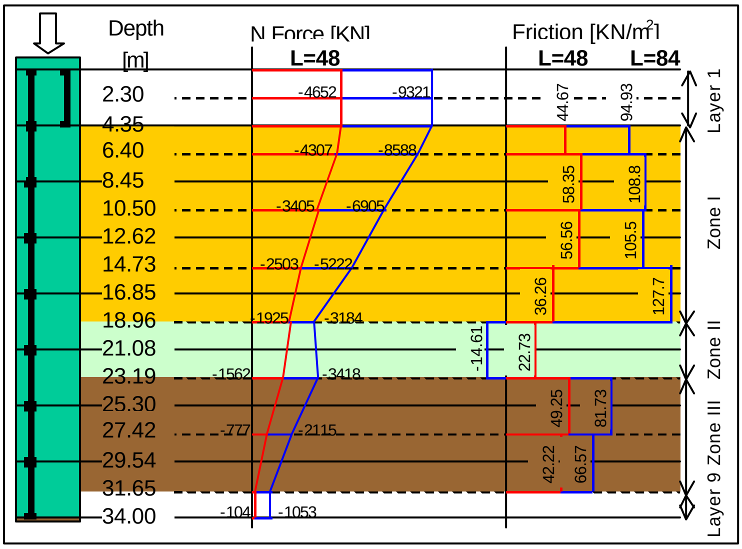

Figure 7. Distributions of normal force in the pile, friction stress and different zones of soil, axial compression test.

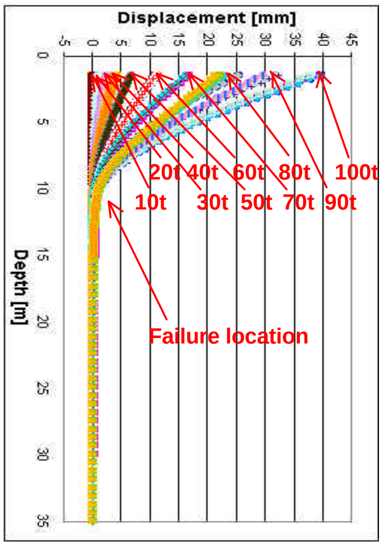

Figure 8. Deformed shapes and failure location, flexure test.

The deformed shape evolution as well as determination of failure location of the pile under the flexure test is presented in Figure 8. The comparison between the results obtained with LVDT has shown excellent agreement with the long-gauge sensor measurements. Other important results are summarized in Table 1.

Table 1. The most important parameters obtained from piles monitoring using long-gauge sensors.

Parameter	Pullout test	Compression test	Flexure test
Young modulus	E=45-50 GPa	E=30-50 GPa	Not calculated
Deformation of pile	Average longitudinal strain distribution Distribution of vertical displacement	Average longitudinal strain distribution Distribution of vertical displacement	Av. long. strain distribution Distribution of curvature Distribution of horizontal displacement
Forces in pile	Distribution of tensile force Bottom force	Distr. of compressive force Bottom force	Qualitative distribution of bending moments
Cracking	At strain of ε=60$\mu\varepsilon$	No crack detected	At strain of ε=60$\mu\varepsilon$
Damaging of pile	Detection, localization and characterization of cracks	No damaging detected	Detection, localization and characterization of cracks
Properties of soil	Qualitative determination of soil strength Identification of zones with different mechanical properties	Qualitative determination of soil strength Identification of zones with different mechanical properties	Qualitative determination of soil strength
Forces in soil	Distribution of pile-soil friction	Distribution of pile-soil friction	Distribution of horizontal reactions of soil
Failure mode	On pile (cracking)	On soil (slip)	On soil (first) and pile (afterwards)
Ultim. load capacity	314.3t to 343.2t	480t to 540t	50t

5 CONCLUSIONS

A method for structural monitoring of piles is presented in this paper. The particularity of the method is use of long-gauge sensors combined in different topologies. The idea is to divide the structure in cells, to equip each cell with topology which corresponds to 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 types of topologies of are presented, simple and parallel topology. Real, on-site application of illustrates the power of the method. Number of parameters related to structural behavior of piles is monitored or determined from monitoring. It is shown that long-gauge sensors offer large possibilities since they provide measurement that is not influenced by local material defects.

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