Piles monitoring using topologies of long-gage fiber optic sensors

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ABSTRACT: Long-gage fibre optic sensors are designed to measure an average strain between two points of the structure. The advantage of the sensors is in a magnitude of gage-length, usually ranged between 250 mm and 10 m, which makes them insensitive to local structural defects like crack or air pockets. The data collected by the sensors is not related to local material properties but rather to structural behaviour of monitored element. The philosophy of monitoring using long gage sensors is very similar to philosophy of finite element method: the structure is divided in elements, called cells, and each cell is equipped with a combination of sensors, called topology. The topology is particularly adapted to efforts expected in the cell, e.g. in case of pure traction or compression the topology consists of single sensor installed parallel to the axis of cell, while in case of bending the topology consists of two sensors parallel to each other and to the axis of the cell. Using appropriate algorithms, the behaviour of different cells is correlated and monitoring at global structural level is performed. Since single topology can cover important volume of the structure, the total number of cells is limited and the total number of sensors necessary for representative monitoring of whole structure is reasonably small. In addition, fibre optic nature of the sensors makes them insensitive to environmental influences such as temperature, humidity, corrosion, and electromagnetic fields. The aim of this paper is to present the application of long-gage fibre optic sensors to piles subject to axial compression, pullout and flexure, and to highlight their performances through the results. Large spectra of parameters such as 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

Structural monitoring is a process aiming at providing accurate and in-time information concerning structural condition and performance. It consists of permanent continuous, periodical or periodically continuous recording of representative parameters, over short- or long-terms. The information obtained from monitoring is generally used to plan and design maintenance activities, increase the safety, verify hypothesis, reduce uncertainty and to widen the knowledge concerning monitored structure.

The availability of long-gage fiber optic sensors (Glisic, Inaudi, 2002a) 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. Using long-gage sensors, it becomes possible to cover the whole volume of a structure with sensors enabling a global monitoring of it.

This contribution presets a method for piles monitoring based on use long-gage sensors and their topologies. The method was tested on-site and results confirmed its excellent performance.

2 LONG-GAGE DEFORMATION SENSORS

The strain occurs in the concrete as a consequence of several influences such as load, temperature variation, creep and different types of shrinkage (Neville 2000). It is local property and is related to geometrical position in the material. Concrete is non-homogenous material and has some local defects, such as cracks, 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-gage deformation (average strain) sensor is, conventionally, the sensor with the gage length long enough to minimize the influence of the material local defects to measurement (Inaudi, Glisic, 2002). 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.

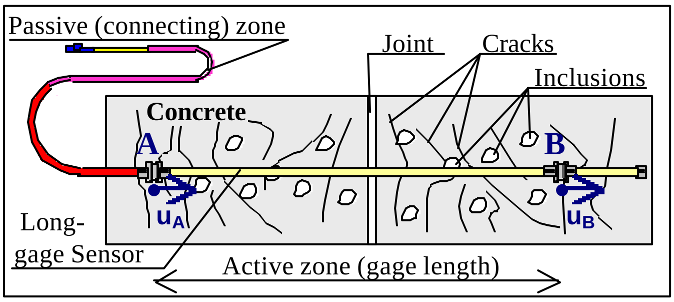

Figure 1: Schema of a long-gage sensor installed on a material with cracks, inclusions and joints.

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 Equations 1 and 2.

$$\varepsilon_s = \frac{m_s}{l_{A-B}} = \frac{\Delta l_{A-B}}{l_{A-B}} = \frac{u_B - u_A}{L_{A-B}} \quad (1)$$

$$m_s = \int_A^B \varepsilon dl + \sum_A^B \Delta w_C + \sum_A^B \Delta w_J + \sum_A^B \Delta w_I \quad (2)$$

where m_S = measured value; ε_S = masured average strain; $l_{A\text{-}B}$ = gage length; $\Delta l_{A\text{-}B}$ = 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.

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.

Long-gage sensors are 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.

3 SENSORS TOPOLOGIES – FINITE ELEMENT STRUCTURAL MONITORING

3.1 Philosophy of "finite element structural monitoring"

To perform a monitoring at a structural level it is necessary to cover whole the structure with sensors. More sensors have been installed more detailed and precise monitoring is performed, but also the cost of monitoring becomes elevated. Therefore, an optimization has to be carried out. Long-gage sensors offer an excellent compromise between the number of employed sensors and performance of monitoring using so-called finite element structural monitoring approach.

The structure is first divided in small elements, called cells, as shown in Figure 2.

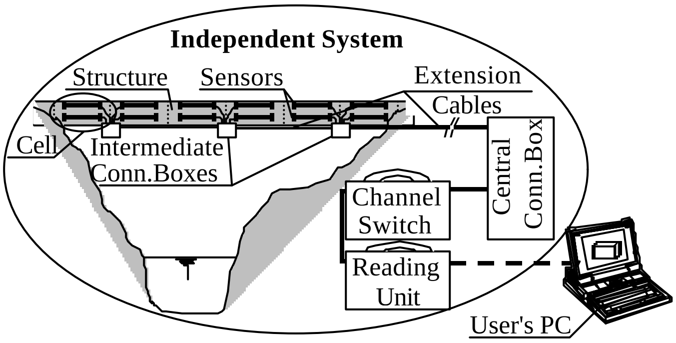

Figure 2: Schema of a structure divided in cells with parallel topologies of long-gage fiber optic sensors of type SOFO.

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 appropriate 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 and therefore they are presented here in more details.

3.2 Introduction to sensor topologies

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 3), 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 3.

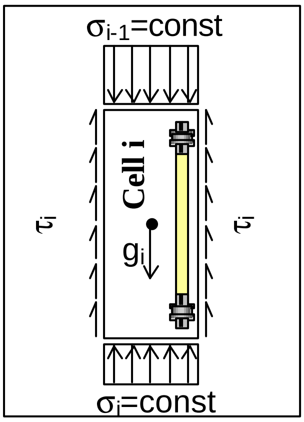

Figure 3: Example of cell with simple topology.

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 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 4.

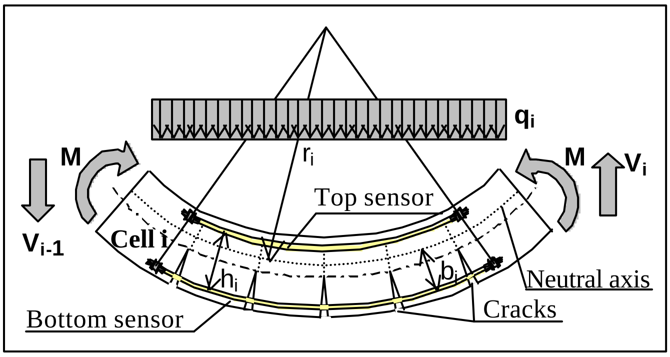

Figure 4: Example of cell with parallel topology.

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:

$$\kappa_i = \frac{1}{r_i} = \frac{m_{i,t} - m_{i,b}}{l_{s,i}} \cdot \frac{1}{h_i} \qquad (3)$$

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; $l_{s,i}$ = gage 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:

$$b_i = \frac{m_{i,b}}{m_{i,b} - m_{i,t}} h_i \qquad (4)$$

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).

3.3 Long-gage sensors topologies applied on piles

Long-gage topologies were tested on piles subject to pullout, axial compression and flexure test (more details are given in Section 6). 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 5. In case of flexure test, a parallel topology was used in all eight cells, as shown in Figure 5. 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 5). The sensors were attached to rebars before pouring and thus embedded in concrete.

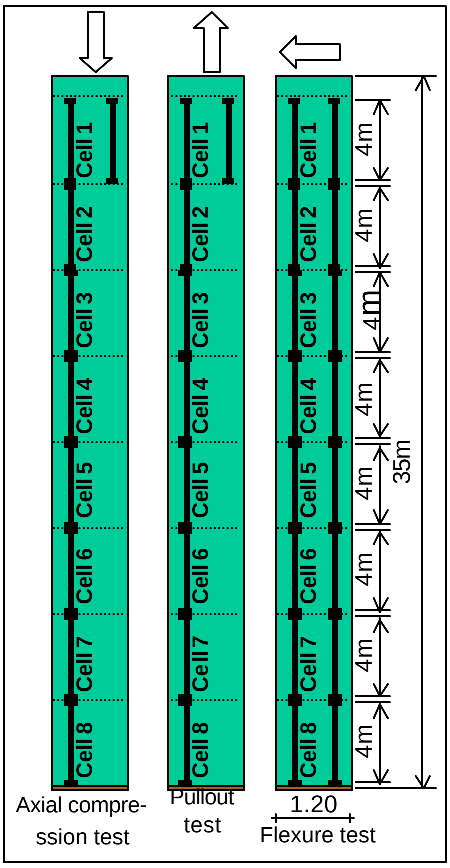

Figure 5: Topologies applied in piles monitoring and dimensions of piles.

4 DESCRIPTION OF EMPLOYED MONITORING SYSTEM - SOFO

The monitoring system used in the presented tests is called SOFO (French acronym for Surveillance d'Ouvrages par Fibres Optiques – Structural Monitoring using Optical Fibers) and is based on low-coherence interferometry in optical fiber sensors (Inaudi 1997). The main components of the system are schematically presented in Figure 2. The SOFO system consists of 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. The optical signal (light) is sent from the reading unit through a coupler to the sensor, where it reflects off mirrors placed at the end of each fiber and returns back to the reading unit where it is demodulated by a matching pair of fibers. The returned light contains information concerning the deformations of the structure, which is decoded in the reading unit and visualized using a portable PC. Typical sensor length (gage-length) ranges from 200 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 (SMARTEC 2003). The system is insensitive to temperature changes, EM fields, humidity and corrosion, and immune from drift for at least 7 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 (SMARTEC 2003).

5 INSTALLATION NOTICE

In the presented application the sensors were embedded into the concrete during the construction of the piles. They were attached to rebars just before the pouring using ordinary plastic rings. Pictures taken during installation are shown in Figure 6.

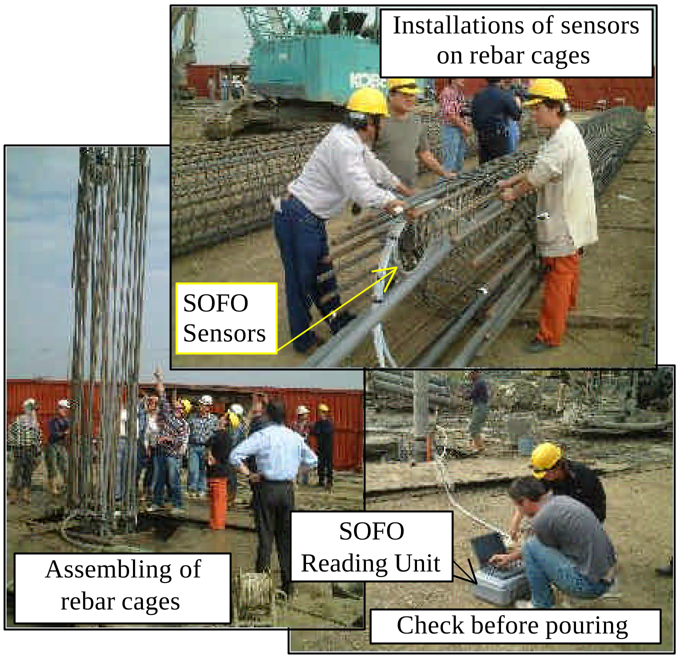

Figure 6: Installation of SOFO sensors or rebar cages.

The rebars cage of these piles was too long to be put into the borehole at once. It was therefore split into three sections, which were lowered sequentially and assembled by welding. The sensors were first installed on each section and the sensors whose position corresponded to a welded region were installed after welding, while lowering the cage (see Figure 6). Even in such a complex condition the survival rate of sensors was very high (>95%) and no retard of works are generated due to installation.

6 TESTS, RESULTS AND ANALYSIS

6.1 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 (ASTM D1143-B1), uplift ASTM D3689-B3) or horizontal force (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.

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).

6.2 Results obtained from compression and pullout tests

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 7, and for decreasing loads in Figure 8.

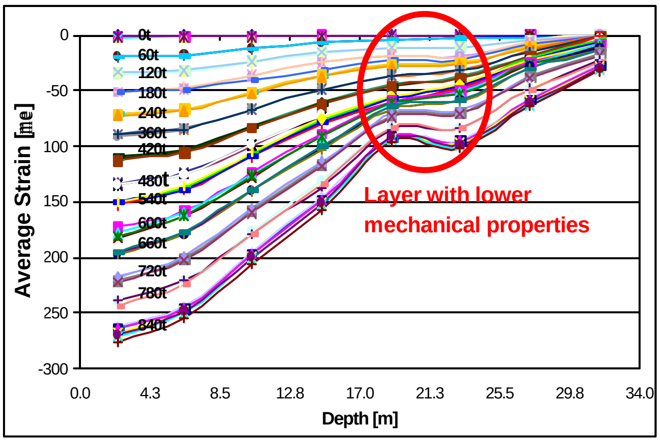

Figure 7. Average strain distribution, increase of load, axial compression test.

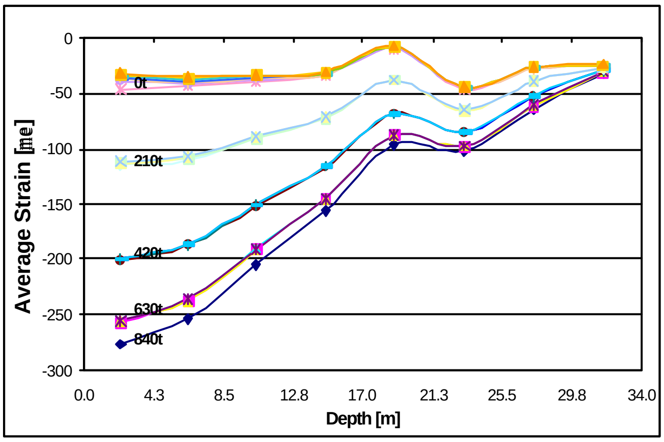

Figure 8. Average strain distribution, unloading, axial compression test.

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 9.

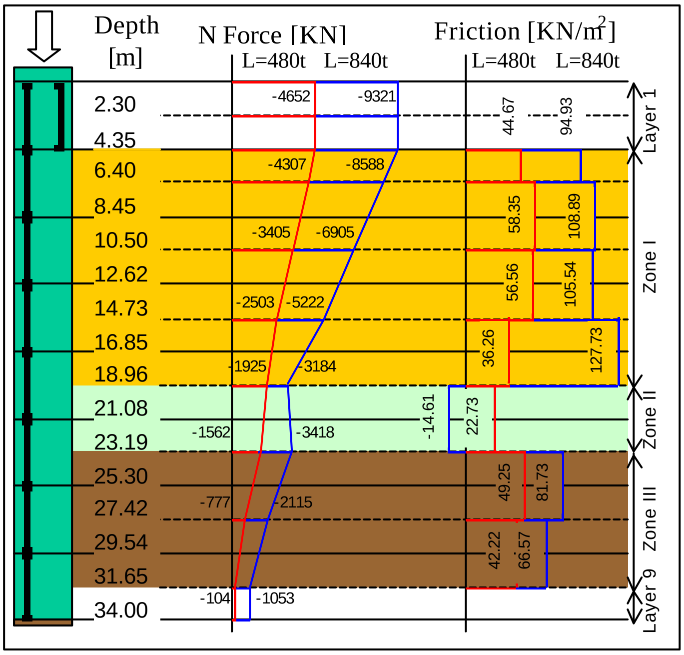

Figure 9. Distributions of normal force in the pile, friction stress and different zones of soil, axial compression test.

6.3 Results obtained from flexure test

The curvature evolution was first calculated from the average strains measured in each cell. Then, the deformed shape evolution was determined using double integration algorithms (Vurpillot 1999). The comparison between the results obtained with LVDT has shown excellent agreement with the long-gage sensor measurements. Finally the failure location was identified.

The deformed shape evolution as well as determination of failure location of the pile under the flexure test are presented in Figure 10.

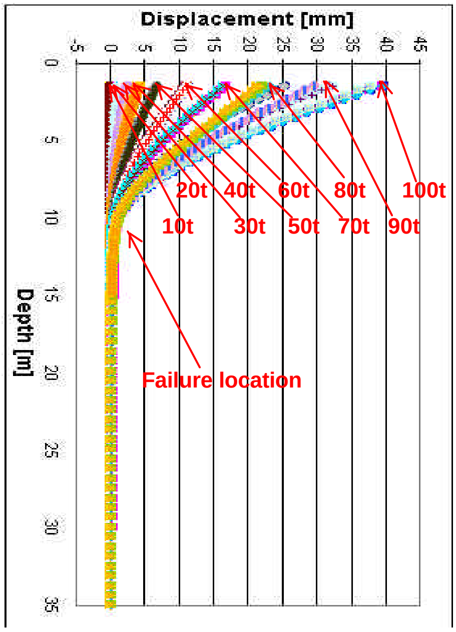

Figure 10. Deformed shapes and failure location, flexure test.

Using appropriate algorithms it was possible to characterize the crack using the parallel topology (Glisic, Inaudi, 2002b). The time of crack occurring $t_{cocr.}$ and the ultimate strain of concrete ε_{bu} are determined as shown in Figure 11. The evolution of average depth of crack openings is calculated and presented in Figure 12.

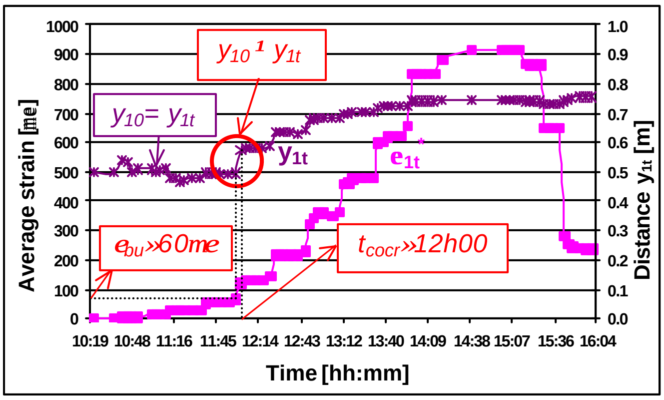

Figure 11. Determination of crack occurring time and ultimate strain of concrete.

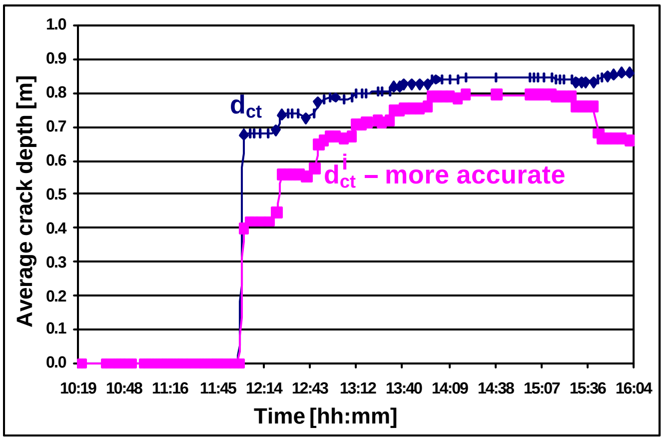

Figure 12. Evolution of average crack depth

Other important results obtained from all the tests are summarized in Table 1.

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

Parameter	Pullout test	Compression test	Flexure test
Young modulus	E=45-50 GPa	E=30-50 GPa	Not calculated
Deform. of pile	• Average long. strain distribution • Distribution of vertical displacement	• Average longitudinal strain distribution • Distribution of vertical displacement	• Average 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$\mu\varepsilon$
Damage in pile	Cracks • Detection, • Localization • Characteriz.	No damaging detected	Cracks • Detection, • Localization • Characteriz.
Propert. of soil	• Estimation of strength • Identification of zones with different mechanical properties	• Estimation of strength • Identification of zones with different mechanical properties	• Estimation of soil strength
Forces in soil	Distribution of pile-soil friction	Distribution of pile-soil friction	Distribution of horizontal soil reactions
Failure mode	On pile (cracking)	On soil (slip)	On soil (first) and pile (afterwards)
Ult. load capacity	314.3t to 343.2t	480t to 540t	50t

7 CONCLUSIONS

Structural monitoring method focusing to strain, deformation and crack auscultation in piles is presented in this paper. The particularity of the method is in the use of long-gage fiber optic sensors combined in topologies. The idea is to divide the monitored structural member in cells and to equip each cell with appropriate topology. In that way a kind of "finite element structural monitoring" is performed.

Two types of topologies of are presented, Simple and Parallel topology. Real, on-site application illustrates the power of the method. Number of parameters related to structural behavior of piles is monitored or determined from monitoring. The basic monitored parameter is average strain distribution. It is shown that long-gage sensors offer large possibilities since they provide measurement that is not influenced by local material defects.

The essential deformation parameters such as average curvature distribution, deformed shape and displacement distribution are determined using the method. In addition, several important parameters related to cracks are assessed such as time of crack occurring, ultimate strain in concrete, and evolutions of crack width sum and average crack depth.

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.

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