Strain, deformation and crack monitoring in bended structural members using long-gauge fiber optic sensors

Glisic Branko, Inaudi Daniele
SMARTEC SA
Via Pobiette 11, 6928 Manno

Abstract

The availability of long-gage fiber optic sensors 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. This contribution discusses the use of long-gage sensors for structural monitoring of bended members. The response of these sensors in inhomogeneous material such as concrete, possibly including defects (e.g. cracks), is analyzed. The paper presents the ideal disposition of multiple sensors, called parallel topology, to measure different parameters in bended members. The primary monitored parameter is average strain. Using parallel topology, and the presented algorithms it is possible to calculate average curvature distribution and deformed shape of bended members as well as to characterize cracks, i.e. to determine sum of openings, average depth, and time of crack occurring. On-site applications illustrate the theoretical considerations and show how interesting this technique is for the monitoring of different types of structural members.

Introduction

The most interesting parameters to be monitored in case of bended concrete members are deformed shape and crack behavior. Both parameters require monitoring over whole member, but only a limited number of sensors can practically be installed for this purpose. The fundamental departure from the standard practice is based on the choice of a reduced number of points, supposed to be representative of the member 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. Increasing the number of the sensor in order to cover all the parts of the structures will increase costs of material, installation and data analysis and will not necessary solve the problem. On the contrary, using long-gage sensors [1], it becomes possible to cover the whole volume of a structural member with limited number of sensors enabling a global monitoring, so that any phenomena that have an impact on the global behavior is detected and quantified.

In case of the use of long-gage sensors a particular philosophy, is followed: the structure is first divided in cells. Each cell contains a combination of sensors, called topology [1], 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. In case of bending so-called parallel topology is used. An example of beam divided in cells and equipped with sensors combined in parallel topology is presented in Figure 1.

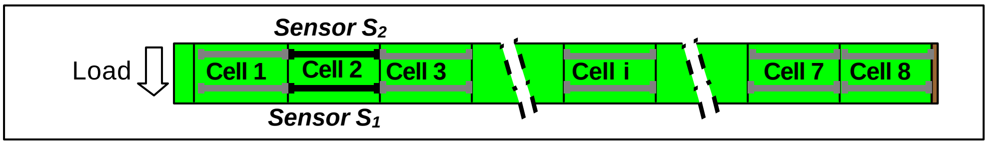

Figure 4: Schema of the pile divided in cells and position of sensors combined in parallel topology (rotated 90° in clock-wise opposite direction)

A method for monitoring bended structural members is developed and presented in this paper. The method was applied and proven on number of structures, and two examples are presented in order to illustrate its power.

Long-gage sensors average strain monitoring

The strain occurs in the concrete as a consequence of several influences such as load, temperature variation, creep and different types of shrinkage [2]. 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. For structural monitoring purposes it is necessary to use sensors that are 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 [1]. 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 2.
If A and B are anchoring points of the long-gage sensor to the concrete structure as shown in Figure 2, the measurement of the sensor represents the relative displacement between these two point, and is given in Expression 1. The average strain between the points A and B is calculated as a ratio between the measurement and the initial length of the sensor.

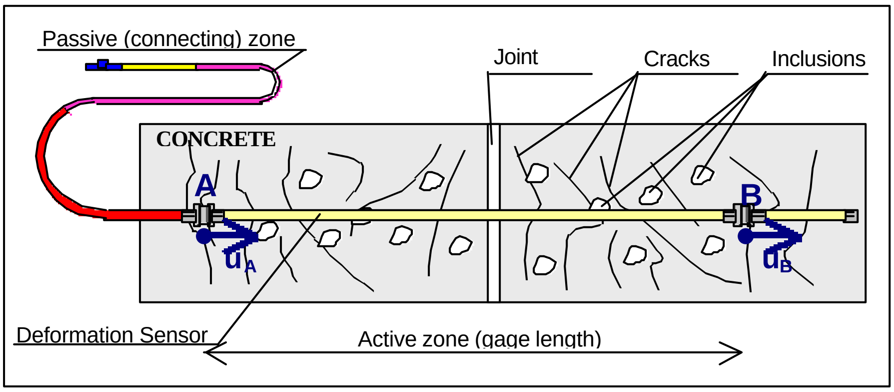

Figure 2: Schema of a long-gage sensor installed on a concrete beam with cracks, inclusions and joints

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

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; 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); ε^* - Average strain over the length of sensor; l_s – Length of the sensor.

The long-gage sensor measurement does not make difference if the source of deformation is in strain of concrete or in width of crack openings. Therefore this measurement shows behavior of monitored element (beam) on a structural level, considering the reinforced concrete as a homogenous material. The total strain is a consequence of several sources, but can be simplified and presented as follows [2]:

$$\varepsilon_t = \frac{\sigma_t}{E_t} \cdot (1 + K_{\varphi t}) + \alpha_T \cdot \Delta T_t + \varepsilon_{sh,t} \qquad (2)$$

Where: σ- Stress; K_φ - Creep coefficient; E – Young modulus; α_T – Thermal expansion coefficient; ΔT - Temperature variation; ε_{sh} - Shrinkage; t - indicates time with respect to an initial time t_0.

Long-gage sensors can be combined in different topologies and networks, depending on geometry and type of monitored structure [1]. In this paper we concentrates to parameters related to bended structural members only.

Parallel topology

The parallel topology is used for monitoring of parts of structure subjected to bending. It consists of two parallel sensors with equal gage lengths installed at different levels of structural member cross-section. Direction of sensors corresponds by preference to the directions of normal strain lines. Initial position of the sensors (before cracking), concerned geometrical value of the cross-section and the coordinate system are presented in Figure 3A. Distribution of strain as well as change in coordinates and displacement of neutral axis due to cracking are presented in Figure 3B. Non-cracked concrete is in gray while the cracked concrete is in white in both figures.
The following set of indexes is used for the further analysis: 0 denotes the initial state at time t_0; * denotes the average value; F denotes influence of internal forces and φ denotes influence of creep. Note that the

values of y_{20} and y_{2t} are negative according to coordinate system presented in Figure 2, and that they do not have the same origin since the position of the neutral axis n-n is changed due to cracks.

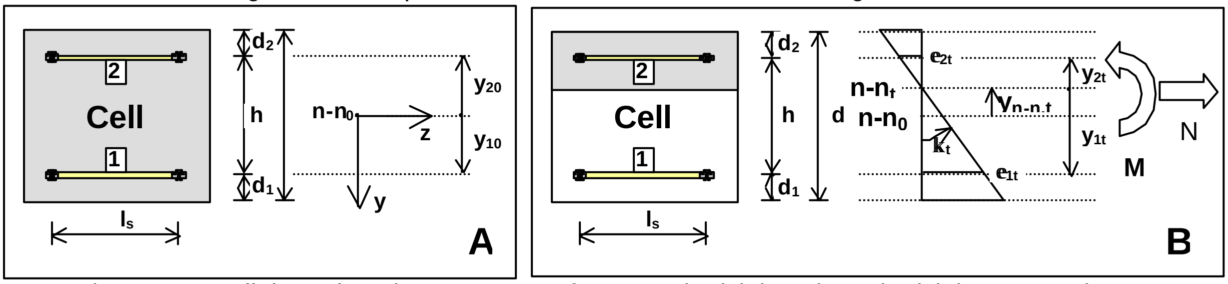

Figure 3: Parallel topology in a segment of non-cracked (A) and cracked (B) concrete beam

The average strain in the Cell at the position of sensors 1 and 2 are expressed from measurements at time t:

$$\varepsilon^*_{1t} = \frac{m_{s1t}}{l_s} = \varepsilon^*_{1Ft} + \varepsilon^*_{1\varphi t} + \varepsilon^*_{1Tt} + \varepsilon^*_{1sh,t}\ ;\ \varepsilon^*_{2t} = \frac{m_{s2t}}{l_s} = \varepsilon^*_{2Ft} + \varepsilon^*_{2\varphi t} + \varepsilon^*_{2Tt} + \varepsilon^*_{2sh,t}\ . \qquad (3)$$

The average thermal strain is calculated as: $\varepsilon^*_{1Tt} = \alpha_T \cdot \Delta T^*_{1t};\ \varepsilon^*_{2Tt} = \alpha_T \cdot \Delta T^*_{2t}$ (4)

Thus, to determine the thermal strain it is necessary to measure temperature, e.g. at the middle of the sensors 1 and 2 with assumption that the temperature variation distribution is linear over the whole Cell. It is also necessary to know the value of thermal expansion coefficient α_T. Thermal expansion coefficient depends mainly on concrete maturity and humidity, but approximately 14 hours after the pouring it can be considered as constant with good accuracy.
The deformation due to shrinkage cannot be determined directly. It can only be estimated by comparison with non-loaded samples of the same concrete, or using some prediction formula [2]. The influences due to internal forces and creep at position of sensors is then calculated as:

$$\varepsilon^*_{1F+\varphi t} = \varepsilon^*_{1Ft} + \varepsilon^*_{1\varphi t} = \frac{m_{s1t}}{l_s} - \varepsilon^*_{1Tt} - \varepsilon^*_{1sh,t};\ \varepsilon^*_{2F+\varphi t} = \varepsilon^*_{2Ft} + \varepsilon^*_{2\varphi t} = \frac{m_{s2t}}{l_s} - \varepsilon^*_{2Tt} - \varepsilon^*_{2sh,t} \qquad (5)$$

Curvature and deformed shape determination

In parallel topology, 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 [3] is satisfied (plane cross-sections of the beam remain plane under loading) using the following expression:

$$\kappa^*_t = \frac{1}{r_t} = \frac{m_{1,t} - m_{2,t}}{l_s} \cdot \frac{1}{h} = \left(\varepsilon^*_{1F+\varphi t} - \varepsilon^*_{2F+\varphi t}\right) \cdot \frac{1}{h} + \left(\varepsilon^*_{1Tt} - \varepsilon^*_{2Tt}\right) \cdot \frac{1}{h} = \kappa^*_{F+\varphi t} + \kappa^*_{Tt} \qquad (6)$$

Where: κ – Average curvature of cell; r – Curving radius of cell; $\kappa_{F+\varphi}$ – Average curvature of cell due to internal forces and creep; κ_T – Average curvature of cell due to temperature gradient.

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 [3] 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 next sections). Since the curvature is directly proportional to bending moment, the distribution of curvature helps to qualitatively determinate distribution of bending moments.

Crack characterization

Using appropriate algorithms it is possible to characterize the crack using the parallel topology [4]. The structural cracks will occur only due to stress and creep influence. Therefore, influence of temperature and shrinkage must be subtracted from total strain measured by sensors. If the sensors are installed on a non-deformed structure, before the pouring of concrete, then the initial state is non-cracked and position of sensors with respect to the neutral axis is known (values y_{10} and y_{20}). The neutral axis does not move until the cracks occur. After the cracking, the neutral axis will change position due to redistribution of strain. If the Bernoulli's hypothesis is valid for the cracked beams, i.e. cross-section remains plane and perpendicular to the neutral axis after the deformation, then the position of the sensors 1 and 2 with respect to new neutral axis $n\text{-}n_t$ at the time t (see Figure 3) is determined as follows:

$$y_{1t} = \frac{\varepsilon^*_{1F+\varphi t}}{\varepsilon^*_{1F+\varphi t} - \varepsilon^*_{2F+\varphi t}} \cdot h\,;\; y_{2t} = \frac{\varepsilon^*_{2F+\varphi t}}{\varepsilon^*_{1F+\varphi t} - \varepsilon^*_{2F+\varphi t}} \cdot h \tag{7}$$

When calculated these values we are able to determinate following parameters:

1. **The time of crack occurring t_{cor}** corresponds to the time when the neutral axis starts to move, i.e. to the time when the values y_1 and y_2 change:

$$t_{ocr} : y_{1tocr} \neq y_{10} \text{ and } y_{2tocr} \neq y_{20} \tag{8}$$

2. **The ultimate strain of concrete ε_{cu}** (maximal tensional strain) is approximately equal to the strain at the bottom point of the cross-section at the time t_{ocr-1} immediately before the cracks occur:

$$\varepsilon_{cu} = \frac{y_{10} + d_1}{y_{10}} \cdot \varepsilon^*_{1F+\varphi t_{ocr-1}} \tag{9}$$

3. **The approximate average cracks depth at the time t (d_{ct})** is approximately equal to distance form bottom of the cross-section to the neutral axis $n\text{-}n_t$:

$$d_{ct} = y_{1t} + d_1 \tag{10}$$

4. **The average cracks depth at the time t** is obtained improving Expression 10 by taking into account the tensioned part of the concrete next to the neutral axis:

$$d^i_{ct} = d_{ct} - \frac{\varepsilon_{cu}}{\varepsilon^*_{1F+\varphi t} - \varepsilon^*_{2F+\varphi t}} \cdot h \tag{11}$$

5. Bottom **crack width sum over the length of sensor Σw_{ct}:**

$$\sum w_{ct} = \left(\varepsilon^*_{1F+\varphi t} - k_w \cdot \varepsilon_{cu}\right) \cdot \frac{y_{1t} + d_1}{y_{1t}} \cdot l_s \tag{12}$$

   Where k_w – correction coefficient ($0 \le k_w \le 1$), which takes into account strain in the concrete between two cracks.

6. If the number of cracks over the length of sensor n_{ct} is known, then **the average opening of the crack** at the time t, w^*_{ct} is calculated:

$$w^*_{ct} = \frac{\sum w_{ct}}{n_{ct}}. \tag{13}$$

On-site deformed shape monitoring

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 [5] fiber optic sensors. Position of sensor in the cross-section is presented in Figure 4. Parallel topology is used for monitoring in horizontal and vertical plan.

The horizontal and vertical displacements of the first two spans of the bridge were calculated using the double-integration algorithm previously cited. Figure 5 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.

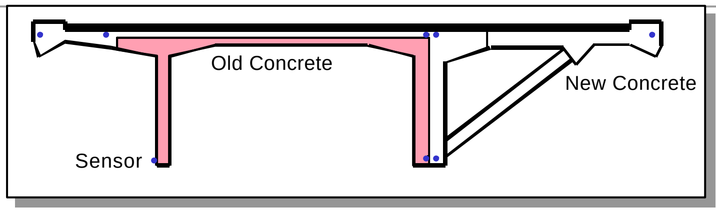

Figure 4: Position of sensors in cross-section of Versoix bridge

During a load test, after the end of construction works, the vertical displacement of the bridge was also monitored using the SOFO fiber optic sensors. Figure 6 shows the measurement with SOFO (Vertical Displacement Calculated) compared to those obtained with traditional invar dial gages. The error of the algorithm is estimated from the deviation from a flat surface of the section deformations. The algorithm (Vertical Displacement Calculated) retrieves within in the error interval the position of the first pile (not entered as a boundary condition) and matches the vertical displacement measured with the dial gages.

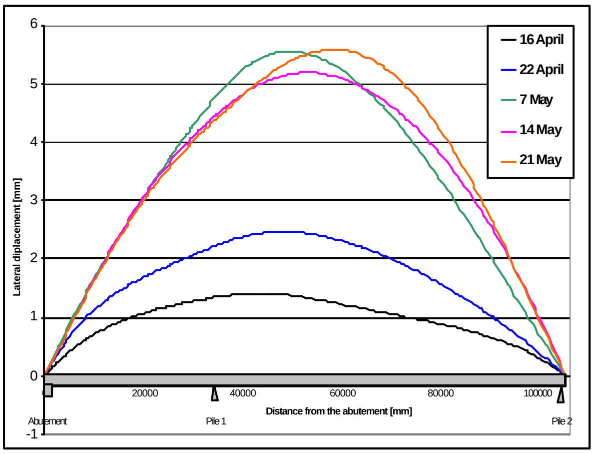

Figure 5: Evolution of horizontal displacement provoked by shrinkage of new concrete

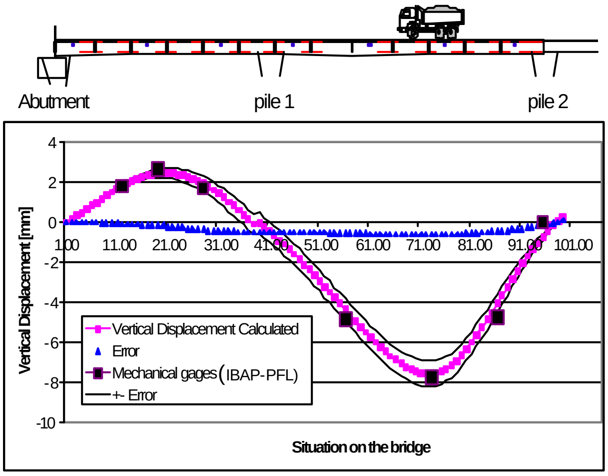

Figure 6: Vertical displacement during the load test and comparison with dial gages

On-site crack characterization

The method carried out in previous section was applied in case of pile loaded by horizontal force. The force was applied at the head of the pile, and the magnitude increased step-by-step. The pile was divided in several cells, and each cell was equipped with the parallel topology. The deformation of the cell 2 was maximal, thus only this cell is presented here, while the analysis of other cells is similar. The SOFO long-gage fiber optic sensors are used. Schema of the test is presented in Figure 1, and is to be observed as rotated for 90° in a clock-wise direction. The evolution of the load as well as the average strains measured by sensors S_1 and S_2 are respectively presented in Figure 7.

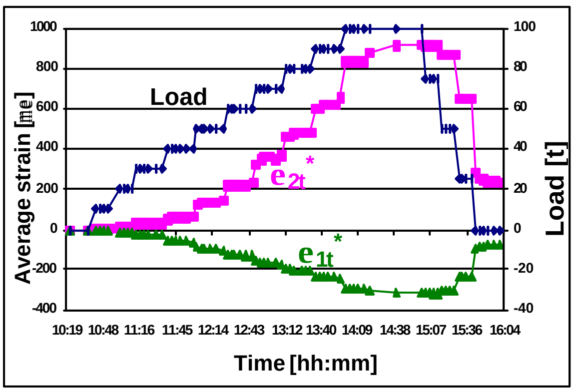

Figure 7: Evolution of load and average strains measured by sensors S_1 and S_2

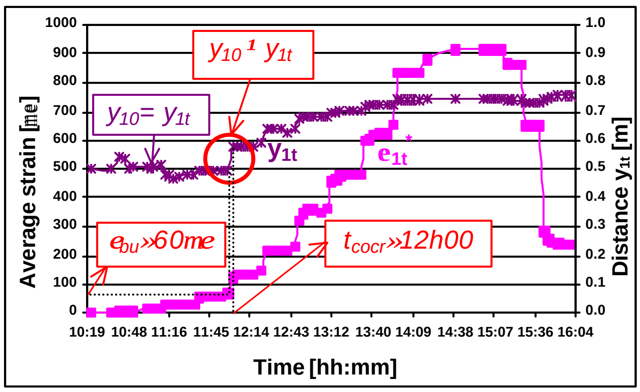

Figure 8: Determination of crack occurring time and ultimate strain of concrete

The test is performed in less than six hours; therefore, the shrinkage and the creep deformation can be neglected. Since the cell 2 was approximately 8 m deep in soil, the thermal influence was minimal and

can also be neglected. The time of crack occurring and the ultimate strain of concrete are determined as shown in Figure 8. The evolution of average depth of crack openings is calculated and presented in Figure 9. As expected, the maximal crack opening occurred for maximal load, and the cracks remained open after the load is moved. The difference between approximate and more accurate estimation is more significant for lower magnitudes of load and proves necessity of considering the tensioned part of concrete near the neutral axis as non-cracked (see Expression 11).
The crack width sum is calculated for different values of coefficient k_w as shown in Figure 10. The coefficient k_w depends of the strain level in concrete and therefore is not constant and cannot be accurately determined. Anyhow, the values of 0, 0.5 and 1 can be used as minimal, mean and maximal.

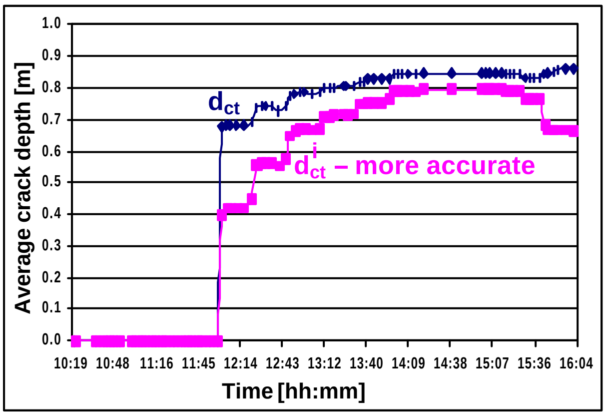

Figure 9: Evolution of average crack depth

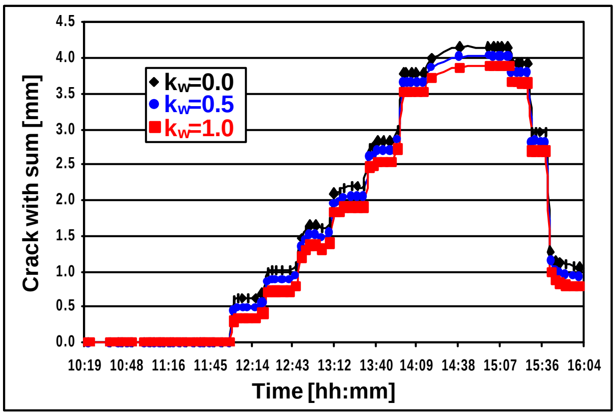

Figure 10: Evolution of crack width sum for different values of coefficient k_w

Conclusions

Structural monitoring method focusing to strain, deformation and crack auscultation in bended structural members is presented in this paper. The particularity of the method is in the use of long-gage fiber optic sensors particularly combined. The idea is to divide the monitored structural member in cells and to equip each cell with co-called parallel topology, which contains two sensors parallel to the member axis. In that way a kind of "finite element monitoring" is performed.
The basic monitored parameter is average strain distribution. 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 theoretical background is presented as well as real, on-site applications. 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.

Acknowledgements

The authors of this paper would like to thank Mrs. Claire Nan and Mr Bing Sen Peng from RoteAero Technology & Engineering, Taipei, Taiwan, for their collaboration and the availability of data for application example. The authors are indebted to Dr. S. Vurpillot, and Mr. P. Kronenberg and the teams at IMAC-EPFL, and IBAP-EPFL for useful discussions and help.

References

[1] Long-gage sensor topologies for structural monitoring, Daniele Inaudi, Branko Glisic, The first fib Congress on Concrete Structures in the 21st Century, Volume 2, Session 15, Pages 15-16, on conference CD, October 13-19, 2002, Osaka, Japan
[2] Neville A.M., "Propriétés des bétons", *CRIB, Sherbrooke–Laval*, Canada, 2000.
[3] Vurpillot, S. : Analyse automatisée des systèmes de mesure de déformation pour l'auscultation des structures. Ph.D. Thesis N° 1982, EPFL, Lausanne, Switzerland, 1999 (in French)
[4] Crack monitoring in concrete elements using long-gage fiber optic sensors, B. Glisic, D. Inaudi, First International Workshop on Structural Health Monitoring of Innovative Civil Engineering Structures, ISIS Canada, Pages 227-236, September 19-20, 2002, Winnipeg, Manitoba, Canada
[5] Inaudi D., "Fiber Optic Sensor Network for the Monitoring of Civil Structures", Ph.D. Thesis N° 1612, EPFL, Lausanne, Switzerland, 1997