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CRACK MONITORING IN CONCRETE ELEMENTS USING LONG-GAGE FIBER OPTIC SENSORS

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Abstract

The cracks can be automatically monitored using either short-gage crack sensors or long-gage deformation sensors. The first approach offers accurate monitoring of crack opening evolution, but requires the use of a large number of sensors and the database results is rather bulky. Measurements reflect local crack condition and not global structural behavior.

Since the structural cracks can be considered as local defects that are more or less homogeneously dispersed over structural segments, it is possible to monitor them using long-gage sensors that cover the observed segments. In this way the total number of required sensors is significantly decreased, measurements are directly related to global structural behavior and storage, handling and analysis of measurement are simpler and easier.

A method designed to characterize the cracks in concrete structures using the SOFO long-gage fiber optic sensors is presented in this paper. The method is based on comparison of measured values of two sensors, placed in the observed segment of structure in a manner that they are parallel to each other and both perpendicular to the cracks. The time of crack occurring, average crack depth and average sum of crack width can be determined using the model. In addition a successful on-site application in case of reinforced concrete pile under flexure test is presented in order to highlight the performances of the method and the monitoring system.

INTRODUCTION

Cracks monitoring of concrete structures is of large interest, since the cracks properties reflect not only condition of concrete as material but also the condition of the structure at structural level. Several methods for crack monitoring are developed, and are mainly based on visual inspection and surface measurements of already opened cracks. In the first case on-site intervention is required while in the second case the system can only be applied after the cracks are opened, thus it is not possible to register the moment of cracks occurring. In both cases it is necessary to have direct access to cracks.

The use of long-gage fiber optic sensors, embedded in the fresh concrete, make possible to overcome presented inconveniences and allows measurement of several structural crack parameters. First, it is possible to determine the time of cracks occurring. Second, the average depth of cracks can be calculated and finally, the sum of width of cracks can be estimated.

If the monitoring of these parameters is automatically performed and in long-term, it is possible to retrieve the evolution of mentioned parameters and to register their extreme values. Using the modem connection with the monitoring system, the data is available at any time, and an on-site intervention is not necessary.

In this paper a method for monitoring of structural cracks at global, structural level is presented. It is assumed that structural cracks are consequence of structural behavior of the structure, i.e. they are provoked by mechanical action – bending moments and normal forces. Term global or structural monitoring indicates that a set of cracks in the totality of structural element is observed and not a single crack at certain location.

LONG-GAGE SENSORS MONITORING OF CONCRETE BEAMS

The strain occurs in the concrete as a consequence of several influences such as load, temperature variation, creep and different types of shrinkage [1]. 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 [2]. 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.

If A and B are anchoring points of the long-gage sensor to the concrete structure as shown in Figure 1, 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, as presented in Expression 2.

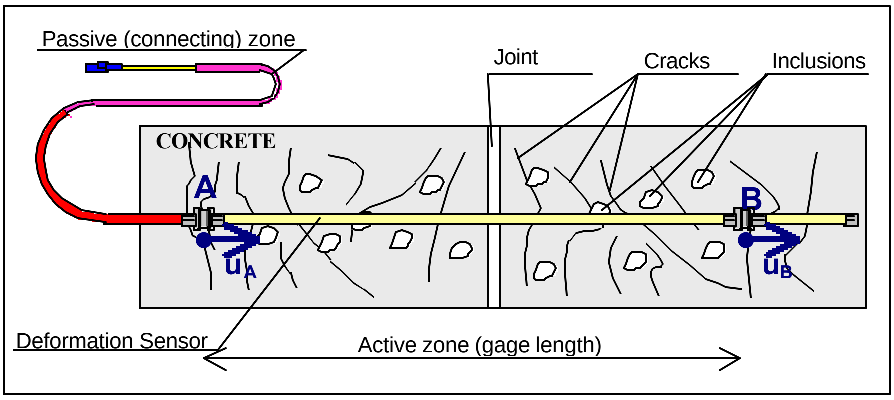

Figure 1: Schema of a long-gage sensor installed on a concrete beam with cracks, inclusions and joints

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

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

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_s^* - 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, and can be presented in a simplified way as shown in Expressions 3 [1].

$$\varepsilon_t = \frac{\sigma_t}{E_t} \cdot (1 + K_{\varphi t}) + \alpha_T \cdot \Delta T_t + \varepsilon_{sh,t} \qquad (3)$$

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.

In case of linear elements (beams), the relation between the long gage-sensor measurement and external forces and temperature at the time t, is presented in Expression 4.

$$\varepsilon^{*}_{st} = \frac{m_{st}}{l_s} = \left(\frac{N^{*}_{st}}{E_t A_t} + \frac{M^{*}_{st}}{E_t I_t} \cdot y_{st} \right) \cdot \left(1 + k_{\varphi t}\right) + \alpha_T \cdot \Delta T^{*}_{st} + \varepsilon^{*}_{sh,t} \tag{4}$$

Where: $N^{*}_{st} = \frac{1}{l_s} \int_{l_s} N_t \cdot dl$ - Average value of normal force over the length of the sensor at the time t;

$M^{*}_{st} = \frac{1}{l_s} \int_{l_s} M_t \cdot dl$ - Average value of bending moment over the length of the sensor at the time t;

$\Delta T^{*}_{st} = \frac{1}{l_s} \int_{l_s} \Delta T_t \cdot dl$ - Average temperature variation over the length of the sensor at the time t;

$\varepsilon^{*}_{sh,t} = \frac{1}{l_s} \int_{l_s} \varepsilon_{sh,t} \cdot dl$ - Average value of concrete shrinkage at the time t;

y_{st} - Distance of the sensor from the neutral axis at the time t;

$K_{\varphi t}$ - Creep coefficient for the time t;

$E_t A_t$, $E_t I_t$ and α_T – Average axial and bending stiffness and the thermal expansion coefficient of the cracked reinforces concrete considered as a homogenous material at the time t.

The Expressions 3 and 4 treats the creep in a very approximate way, but this simplification will not affect the results of the analysis, as we will see in the next section.

CRACK CHARACTERIZATION USING LONG-GAGE SENSORS

In order to determine time of cracks occurring, their average depth and the sum of width, a so-called parallel topology of sensors is employed [3]. Parallel topology consists of two sensors installed parallel to the neutral axis of the beam, as shown in Figures 2 and 3. The segment of the beam equipped with the sensor is called Cell.

Initial position of the sensors (before cracking), concerned geometrical value of the cross-section and the coordinate system are presented in Figure 2. Distribution of strain as well as change in coordinates and displacement of neutral axis due to cracking are presented in Figure 3. Non-cracked concrete is in gray while the cracked concrete is in white in both figures.

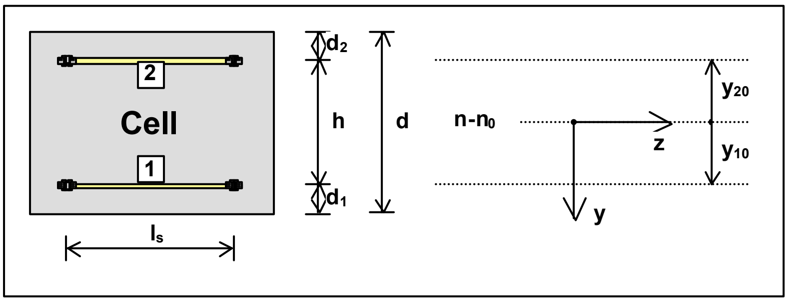

Figure 2: Parallel topology in a segment of non-cracked concrete beam

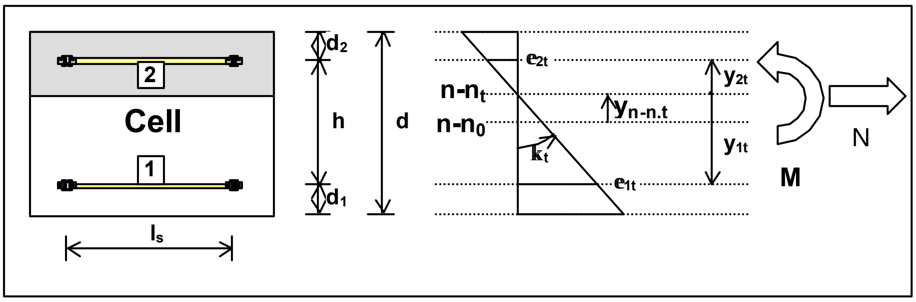

Figure 3: Parallel topology in a segment of cracked concrete beam

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.

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

$$\varepsilon^*_{1t} = \frac{m_{s1t}}{l_s} = \varepsilon^*_{1Ft} + \varepsilon^*_{1\varphi t} + \varepsilon^*_{1Tt} + \varepsilon^*_{1sh,t};$$

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

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. The average thermal strains at position of sensors 1 and 2 are determined using Expression 6.

$$\varepsilon^*_{1Tt} = \alpha_T \cdot \Delta T^*_{1t};\ \varepsilon^*_{2Tt} = \alpha_T \cdot \Delta T^*_{2t} \qquad (6)$$

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 [4,5] 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 [1].

The influences due to external forces and creep at position of sensors is then calculated as:

$$\varepsilon^*_{1F+\varphi t} = \varepsilon^*_{1Ft} + \varepsilon^*_{1\varphi t} = \frac{m_{s1t}}{l_s} - \varepsilon^*_{1Tt} - \varepsilon^*_{1sh,t}$$

$$\varepsilon^*_{2F+\varphi t} = \varepsilon^*_{2Ft} + \varepsilon^*_{2\varphi t} = \frac{m_{s2t}}{l_s} - \varepsilon^*_{2Tt} - \varepsilon^*_{2sh,t} \quad (7)$$

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:

$$y_{1t} = \frac{\varepsilon^*_{1F+\varphi t}}{\varepsilon^*_{1F+\varphi t} - \varepsilon^*_{2F+\varphi t}} \cdot h\,;\; y_{2t} = \frac{\varepsilon^*_{2F+\varphi t}}{\varepsilon^*_{1F+\varphi t} - \varepsilon^*_{2F+\varphi t}} \cdot h \quad (8)$$

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

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 (Expression 9).

$$t_{ocr} : y_{1tocr} \neq y_{10} \text{ and } y_{2tocr} \neq y_{20} \quad (9)$$

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 (Expression 10).

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

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 $n\text{-}n_t$ (Expression 11).

$$d_{ct} = y_{1t} + d_1 \tag{11}$$

The **average cracks depth at the time t** is obtained improving Expression 11 by taking into account the tensioned part of the concrete next to the neutral axis (Expression 12).

$$d^i_{ct} = d_{ct} - \frac{\varepsilon_{cu}}{\varepsilon^*_{1F+\varphi t} - \varepsilon^*_{2F+\varphi t}} \cdot h \tag{12}$$

Bottom **crack width sum over the length of sensor S w_{ct}** (Expression 13).

$$\sum w_{ct} = \left(\varepsilon^*_{1F+\varphi t} - k_w \cdot \varepsilon_{cu}\right) \cdot \frac{y_{1t} + d_1}{y_{1t}} \cdot l_s \tag{13}$$

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

$$w^*_{ct} = \frac{\sum w_{ct}}{n_{ct}}. \tag{14}$$

APPLICATION IN CASE OF PILE DURING THE FLEXURE TEST

The method carried out in previous section was applied in case of pile loaded by horizontal force [6]. 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 four-meters long SOFO [2, 6, 7] long-gage fiber optic sensors are used. Schema of the test is presented in Figure 4, and is to be observed as rotated for 90° in a clock wise way.

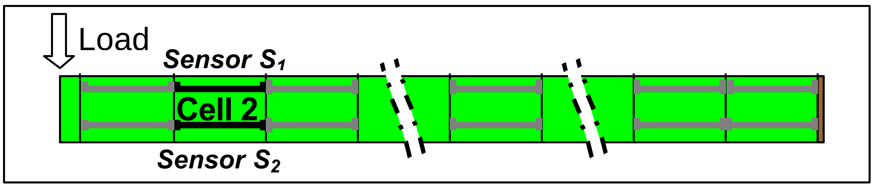

Figure 4: Schema of the pile and position of sensor

The evolution of the load as well as the average strains ε^*_{1t} and ε^*_{2t} measured by sensors S_1 and S_2 respectively are presented in Figure 5.

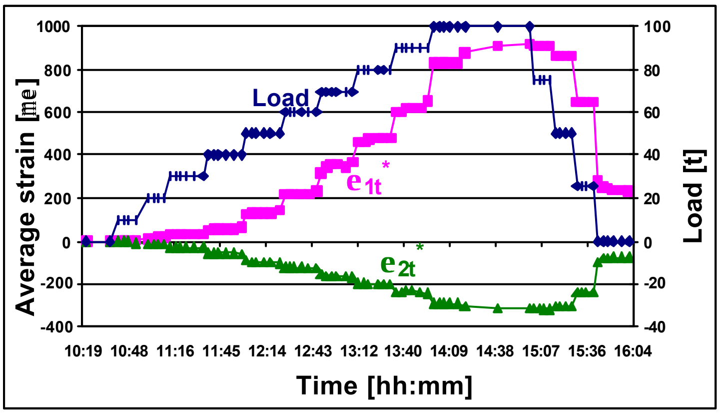

Figure 5: Evolution of load and average strains measured by sensors S_1 and S_2

The initial time t_0 is 10h19. 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. Therefore the following equations are valuable:

$$\varepsilon^*_{1F+\varphi t} = \varepsilon^*_{1t} = \frac{m_{s1t}}{l_s};\ \varepsilon^*_{2F+\varphi t} = \varepsilon^*_{2t} = \frac{m_{s2t}}{l_s} \qquad (15)$$

The time of crack occurring and the ultimate strain of concrete are determined using the Expressions 9 and 10. This operation is presented in Figure 6.

The evolution of average depth of crack openings is calculated according to Expressions 11 and 12 and is presented in Figure 7. As expected, the maximal crack opening occurred for maximal load, and the cracks remained open after the load is moved. The difference between approximate estimation d_{ct} and more accurate d^i_{ct} 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 12).

The crack width sum is calculated using Expression 13 and for different values of coefficient k_w is presented in Figure 8. The coefficient k_w depends of the strain level in concrete and therefore is not constant and cannot be accurately determined. Anyhow, the value of 0.5 can be used as mean value, and values 1.0 and 0.0 as lower and upper limit.

Since the pile was below the earth surface, it was not possible to determine visually the number of cracks over the length of sensor and consequently it was not possible to calculate average crack width according to Expression 14.

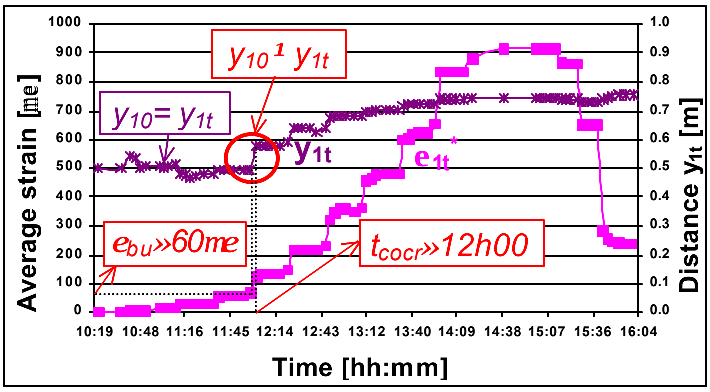

Figure 6: Determination of crack occurring time and ultimate strain of concrete

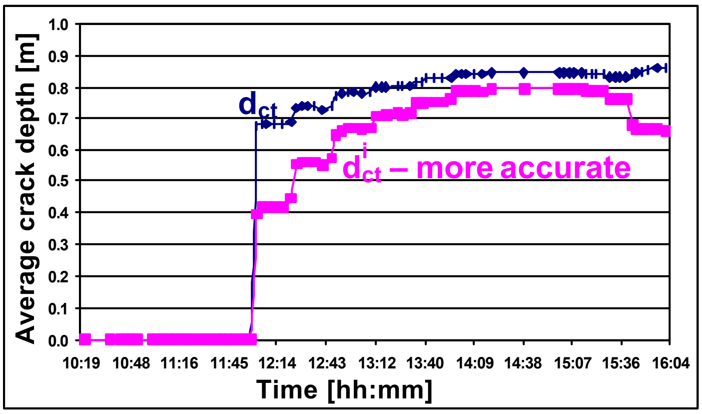

Figure 7: Evolution of average crack depth

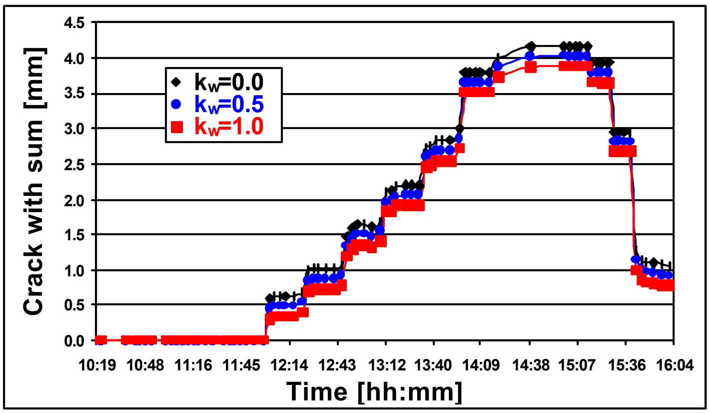

Figure 8: Evolution of crack width sum for different values of coefficient k_w

CONCLUSIONS

Structural cracks characterisation of bended concrete beams using long-gage sensors is presented in this paper. The numerical model is first developed, and then applied to reinforced concrete pile exposed to the horizontal force at the head. The model is based on so-called parallel topology of long-gage sensors, which consists of two sensors installed parallel to the neutral axis in a longitudinal direction of the beam.

Several important parameters related to cracks are determined from monitoring such as time of crack occurring, ultimate strain in concrete, evolution of average crack depth and evolution of crack width sum.

The measurements are performed using the SOFO long-gage sensors. Advantage of the presented model is use of long gage sensors that offers monitoring on structural level, possibility to install the sensors before pouring of concrete, without knowledge where the crack will occur and large number of parameters related to crack that can be monitored.

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