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MONITORING OF THE PRESTRESSED CONCRETE SLABS WITH UNBONDED TENDONS DURING ERECTION AND IN USE

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Abstract

The slabs prestressed with unbonded tendons have been successfully used worldwide for several decades. During this time many recommendations dealing with shaping the geometry of such slabs, selection of prestressing method, dimensioning and erection technology were prepared and issued. The recommendations pertaining to the selection of slab depth and the slab geometry were supported by the numerical calculations performed especially for this purpose. However, those recommendations are limited in application to span lengths not exceeding 12÷13 m. During the recent years prestressed slabs of spans and slenderness substantially exceeding recommended values were designed and erected in Poland. Because of conscious breaking the slenderness limits and prototypical character of the structural solutions applied, continuous monitoring of the slab behaviour when subjected to load is strongly recommended during both the erection and service phases. The strains in concrete, slab displacements and forces in prestressing tendons are measured. The response procedures to the results of monitoring have been prepared as well. In this paper the theoretical basis for the measurement technology applying vibrating wire transducers is described. The continuous monitoring system for the structures of this type, and examples of its application are also discussed. Examples of reaction to the measured values exceeding their threshold values are also presented.

1. On the need to apply monitoring

During several decades of effective application of prestressed slabs many design guidelines were prepared and implemented in order to enable the simple engineering approach to the design of selected slab type. The slab thickness, depending on the span length and acting service loads, constitutes one of the parameters determining its capability to safely resist the loads applied. The slab depth is bounded from below by the maximum allowed displacements, stresses in the cross sections and column punching in the column-slab structures. The top bound is defined by the economy of the structural solution and the requirements pertaining to the maximization of the usable space.

Table 1: Recommended span/depth ratio according to [1].

Slab type	**Span/depth**
Solid one-way slab	30÷45
Ribbed slab	25÷35
Solid flat slab	35÷45
Waffle slab	20÷30

Khan and Williams [1], beginning with the crack free condition in the cross section of the slab, and basing on the performed calculations give the required depth to span ratio for the various load levels. The scope of this ratio for various slab types is listed in the Table 1. Moreover, in the FIB Bulletin No. 31 [2], the minimum slab depth and maximum slab span for various support conditions and load levels are listed in a more detailed way. Generally, the highest span to depth ratios identified according to [2] do not exceed the value of 45. The allowed recommended span lengths for continuous slabs are equal to 13.6 m for bidirectional slabs and to 12.5 m for unidirectional slabs, according to [2]. The published recommendations resulted in that the constant depth slabs are erected worldwide with the maximum span limit set at around 12÷13 m.

In recent years several floor slabs having span and slenderness significantly exceeding the recommended values have been prepared and erected by the employees of the Building Materials and Structures Institute of the Cracow University of Technology. Three extremely slender slabs prestressed with unbonded tendons were designed and erected in the building housing the Artistic and Cultural Center in Kozienice, which opened in summer of 2015. Two uniaxilally prestressed slabs were designed directly above the theater hall: S1-1 at the level of +9.68 m, having the span of 11.15 m and depth of 200 mm, as well as S1-2 at the level of +14.08 m, having the span of 12.65 m and depth of 250 mm. Additionally, a bidirectionally presterssed slab P1-3 having the span of 17.65×19.6 m and 350 mm deep was designed over the cinema hall. The span to depth ratios for the prestressed slabs listed above are: 55.8, 51.4 and 50.4, respectively. These values substantially exceed the recommended values, both in terms of slenderness and span. Currently a design for unidirectionally prestressed slab having a record span of 21.0 m is being prepared. Breaking the existing barriers for span and slenderness requires an in depth and continuous monitoring of slab behaviour when subjected to loads. In order to achieve that, continuous monitoring of slab behaviour is performed, both during the erection and the initial phase of service. Three basic values determining the proper plate operation are monitored: deflection, concrete strains and the force in prestressing tendons. Though all erections are preceded by a detailed numerical analysis, the prototypical character of proposed solutions resulted in preparation of user reactions procedures, which shall be applied in the case when the threshold values of the monitored quantities are exceeded. Thus, the tasks of the monitoring may be listed in a sequence:

- identification of the alert states, allowing for remedial actions to be undertaken,

- delivery of information on actual value of the elasticity modulus in the concrete in real structure and information on real drop of the prestressing force. These parameters are subsequently used in formal models verifying the forecast behaviour of slabs and in the modeling of other long span slabs,
- delivery of data on real deflection of slabs and deflection change during service. Data of this type are useful during the follow on design of slabs, usually better than those initially designed.

2. Monitored values and monitoring systems applied

During the monitoring of long span prestressed slabs the following values are controlled:

- **slab deflection** – the basic parameter determining the proper operation and the suitability for service,
- **concrete strains –** a secondary parameter. Excessive strains in concrete are really not very dangerous for the structure, but result in slab deflection increase. Concrete strains growth in excess of the critical values result in cracking, and this in turn substantially increases the slab deflections,
- **forces in the prestressing tendons** – a secondary parameter. The forces in tendons tend to decrease in time due to rheological losses. These values do not have any limiting minimum values, but the prestressing is applied to introduce the negative slab curvature and excessive loss of prestressing force results in larger slab deflection.

During slab monitoring continuous measurement of monitored parameters is used, with the variable time interval between measurements equal to 5 minutes during the prestressing phase and to 30 minutes during the service phase. Depending on available means and local conditions on the construction site, the following may be applied:

- **full monitoring** – all three parameters (deflection, concrete strains and force in the tendon) are recorded in continuous mode. This type of monitoring yields continuous information on all three parameters and change of those parameters in time. Continuous control of the deflection – a basic parameter, constitutes an advantage here. Data on concrete strains and prestressing force allow for identification of interdependencies between the measured values.
- **incomplete monitoring –** only two secondary parameters (concrete strains and force in the tendon) are recorded in continuous mode. As the continuous registration of deflections is the most difficult one due to the on-site conditions, character of the structure and the specifics of the service, it is often performed only during the prestressing process and initial phase of the service. During the later time the deflections are monitored with the surveying methods only in the key moments. Often only the surveying methods are applied to register the deflections. When the incomplete monitoring is applied, the possible emergency states indicated by the secondary measurement results may be used as an indicator to initiate the deflection survey.

3. The measurement technology

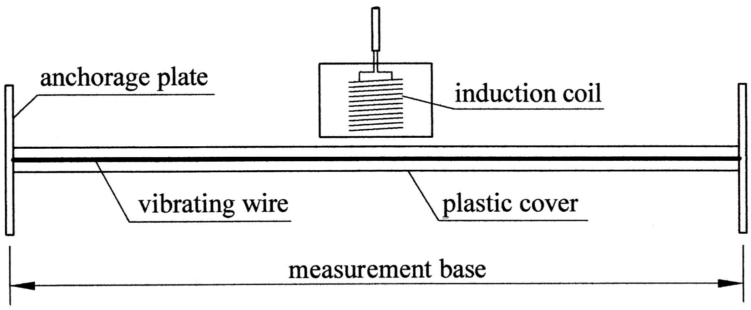
The vibrating wire transducer technology is used to measure the parameters of interest [3]. In such a transducer deformation of a wire (constituting a basis for evaluation of changes in measured variables) is determined via the measurement of the vibration frequency change. The equation of the second law of Newton for a vibrating string takes the form:

$$\varepsilon = f^2 \frac{4L_w\rho}{E \cdot g} \quad , \tag{1}$$

where f is the string vibration frequency, L_w – string length, ρ – string material density, E – modulus of elasticity for string material, g – gravity constant. Thus the strains in the string are directly proportional to the square of its vibration frequency.

The structure of a typical deformation sensor immersed in the concrete is shown in the Fig. 1a. Each such sensor is equipped with an induction coil exciting the string vibrations and measuring the vibration frequency. Additionally, each sensor is accompanied by a thermistor to measure the temperature. The sensors with a measurement base of 50 or 150 mm are used to measure the strains in concrete.

The sleeve sensors mounted under the anchorages (Fig. 1b) are used to measure the force in prestressing tendons. Three vibrating strings, located every 120°, are mounted in the sensor wall. The magnitude of the force is determined based on the average of vibration frequencies in all three vibrating wires.



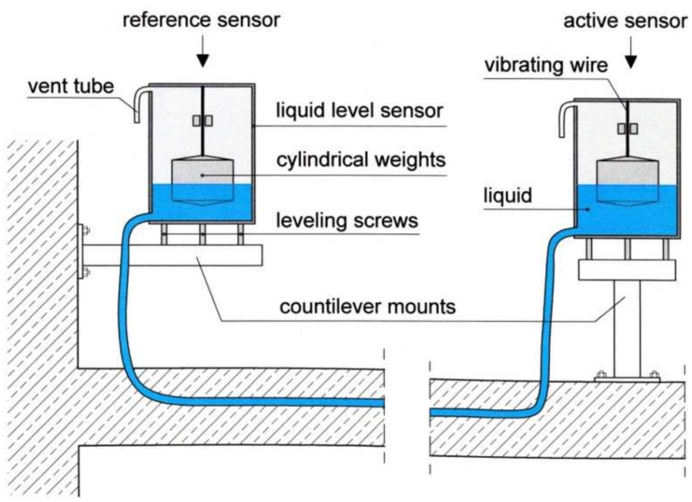
a)

b)

Fig. 1 Structure of a typical vibrating wire deformation transducer (a), external view of the string force transducer for a tendon (b).

Measurement system used for continuous monitoring of slab deflection is depicted in the Fig. 2. This system consists of two transducers having the form of steel vessels filled with liquid (usually glycol) [4], of which one constitutes a reference point and is mounted on the support and the other one (active) is mounted at the deflection measurement point.

The vessels in the Fig. 2a are connected by a pipe hidden within the slab or running outside of the slab. A float suspended on a taut wire is contained within each vessel. A change in relative location of the vessels results in change in liquid levels and thus in the location of floats. This in turn changes the tension in the strings, which is monitored via the measurement of the vibration frequency. The active transducer installed in the middle of the slab span is depicted in the Fig. 2b. During the measurements the transducers having the smallest available measurement range of 150 mm are used. The vessel made of stainless steel is equipped with three mounting screws and a circular level for precise rectification. The system of pipes connecting the vessels filled with glycol is equipped with ventilation port, which at the beginning is used to fill the system with liquid, and subsequently serves to ensure the trouble free operation of the system.



a) b)

Fig. 2 Structure of the slab deflection measurement system (a), view of the system transducer (b).

Table 2. Parameters of string transducers used to monitor the deflections.

Parameter	Value
Range	150 mm
Accuracy (% of range)	± 0.1%
Temperature range	-30 to +80°C
Frequency range	1400÷3500Hz
External diameter	180 mm
Total height	420 mm

The basic technical parameters of the transducers applied are listed in the Table 2. The measurement precision for the transducers having the measurement base of 150 mm is equal to 0.15 mm. The manufacturer declared range of admissible working temperatures allows for the installation of the transducers on the outside of a building and safe operation during the whole year.

4. Interpretation of the results, threshold values and procedures for action

In the evaluation of the behaviour of prestressed slabs subjected to loads, several threshold values of the measured quantities have been assumed as indicators for the need of corrective actions. It was assumed, that:

1) for the strains in concrete:

- $\varepsilon_c > 0$ (decompression in the cross section) – the deflections are reduced mostly through the introduction of permanent compressive stresses in the bottom part of the slab. Total reduction of these stresses, confirmed in strains may result in excessive growth of deflections,
- $\varepsilon_c > \varepsilon_{cr} = 0{,}00010$ – the strains have reached the threshold value of concrete crack resistance.

2) for the prestressing force:
   - $P < P_{obl.}$ – the computationally determined value of the prestressing force constitutes the basis for theoretical estimation of deflections. The excessive rheological loss of this force due to the uncontrolled concrete shrinkage or creep may be worrisome and may result in cracking or exacerbate the slab deflections.
3) for the slab deflection:
   - $u > u_{lim}$ – the code value is assumed as the threshold one (for instance L/250 or L/180 for the total deflection, L/500 for the deflection accumulated after the erection of the slab).

In the case of full monitoring, when all three parameters are controlled in a continuous manner, the deflection constitutes the basic control parameter. The strains in concrete and the prestressing force constitute the secondary parameters. However, the knowledge of these parameters is valuable and may allow for the determination of interrelations between the measured quantities.

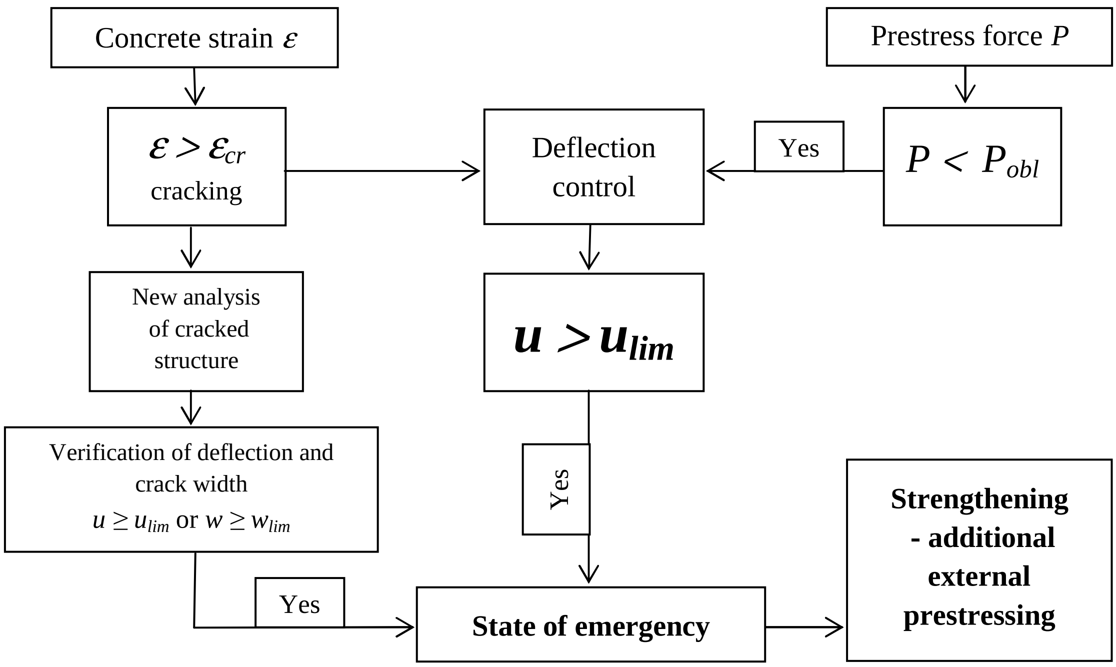


Fig. 3 Algorithm for corrective action in the case of incomplete monitoring.

In the case of incomplete monitoring, the secondary parameters determine the control of the primary parameter, i.e. the deflection. The algorithm for action in such case is shown in the Fig. 3. The prestressing force P determines the emergency state only indirectly, via the excessive growth of deflections. The strains in concrete determine this state both directly, and indirectly via the excessive crack growth.

Table 3. Emergency state levels and the action character.

Emergency level	Threshold value	Action to be taken
0	$\varepsilon_c > 0$ lub $P < P_{obl.}$	Deflection control in an incomplete monitoring.
1	$\varepsilon_c > \varepsilon_{cr}$	Deflection control in an incomplete monitoring. Computational verification of cracks and permanent deflection in the cracked state.
2	$u > u_{lim}$	Emergency state. Strengthening required, for instance by the application of additional external tendons.

The programmed emergency levels and user actions when these levels are reached are listed in the Table 3. The level „0" denotes the harmless state of overcoming the decompression in the cross section or uncontrolled loss of the tensioning force below the preprogrammed value. The level „1" denotes the transition of the structure to the cracked state, indicates the need for computational re-analysis and estimation of permanent deflections. The level „2" denotes the emergency level due to excessive slab deflections. This is a highly undesirable state and requires a thorough intervention in the structure, for instance strengthening by additional external prestressing.

5. Examples of the monitoring applied

Schematic diagram of the prestressed column-slab structure having the largest span of 11.1×12.0 m and 250 mm deep is depicted in the Fig. 4.

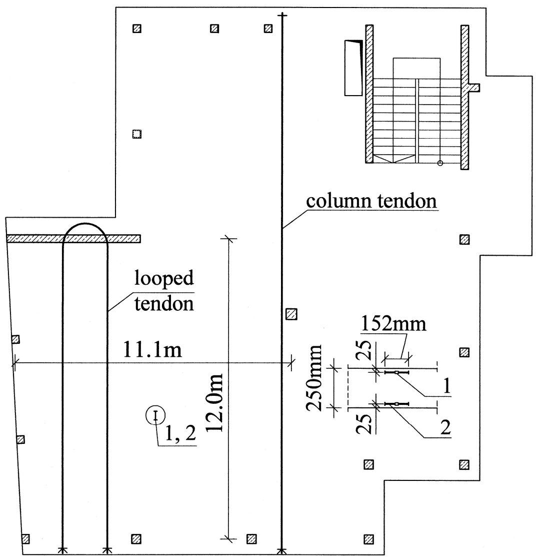


Fig. 4. Application of the monitoring in the column and slab structure having the span of 11.1×12.0 m.

Due to the poor concrete properties during the prestressing phase and the large slab spans, monitoring was applied in order to evaluate the influence of concrete quality on the slab performance. The transducers having the measurement base of 152 mm were used to measure the strains in concrete. Additionally forces in two prestressing tendons in the column and span bands (looped tendon) were monitored. The span deflections were surveyed during the key moments in the building erection phase (installation of additional loads) and sporadically during the first, initial service period. The obtained results are depicted in the Fig. 5.

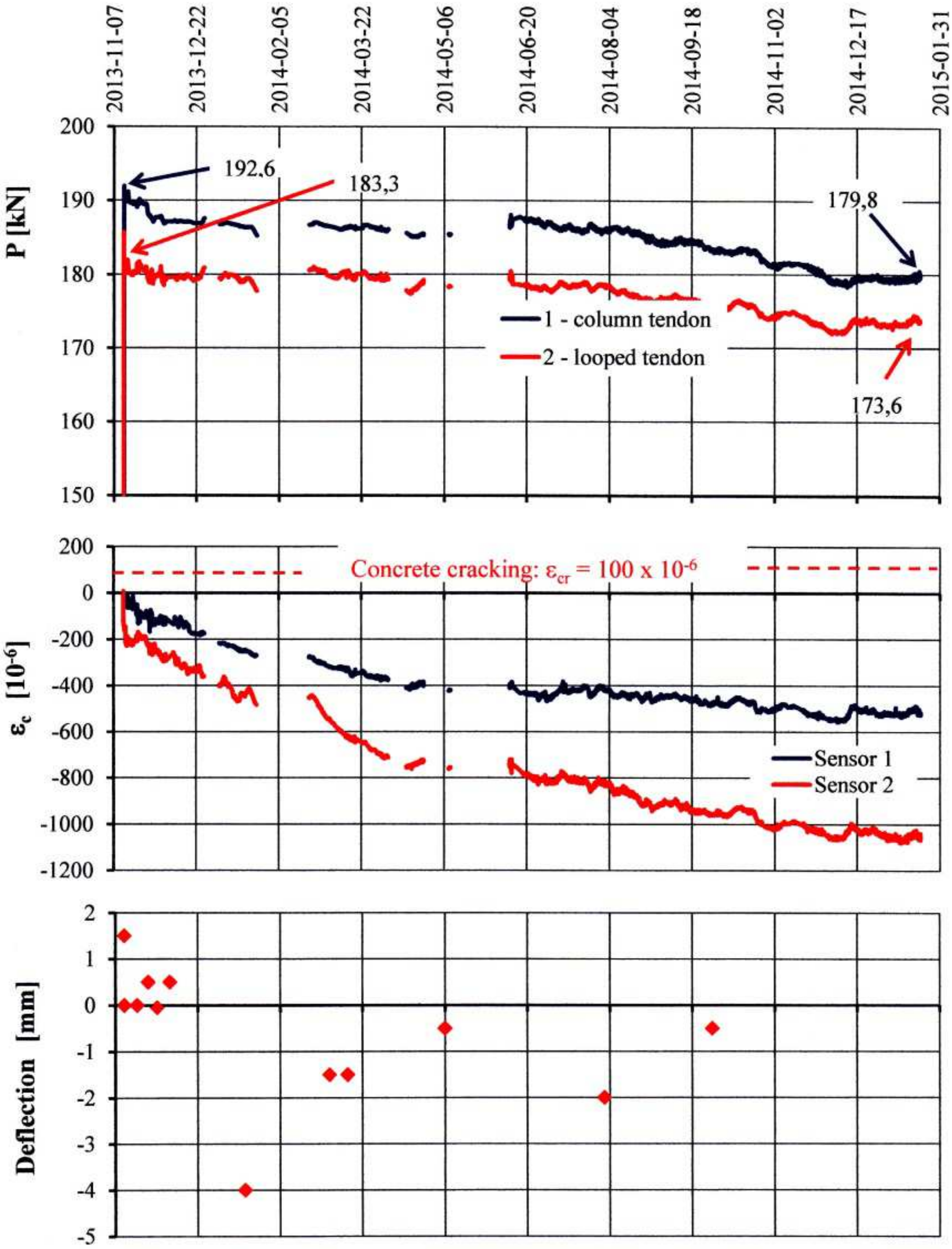


Fig. 5. Results of the monitoring for the slab depicted in the Fig. 4.

In Fig. 6 the plan of the erected prestressed slab having the record breaking span of 17.65×19.7 m and the depth of 350 mm is shown in detail.

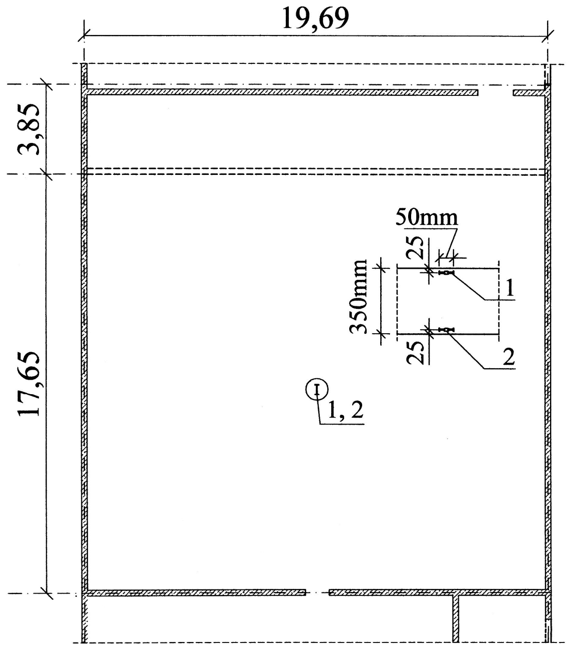


Fig. 6. Prestressed slab having the span of 17.65×19.7 m and 350 mm deep.

In the case of this slab, due to the length and depth exceeding the recommended length and depth, the transducers having the measurement base of 50 mm have been used in the mid-span cross section and the continuous deflection monitoring system was applied. In Fig. 7 the results of continuous deformation monitoring and slab deflection monitoring are depicted, during the first year after the erection of the structure, including the threshold values. In this case, due to the missing third measurement of the force in the tendon an incomplete monitoring was applied. However, the most important parameter, i.e. the deflection was monitored in a continuous manner.

5. Concluding remarks

Monitoring utility substantiation, when applied in the construction of large span slabs, accompanied by the description of the measurement techniques used and brief presentation of the user reaction procedures in the cases of emergency are presented in this paper. Two examples of monitoring applied are enclosed. In both cases the emergency states calling for immediate corrective actions have not been reached. The monitoring confirmed correctness of the structural solutions used, in spite of their innovative character, and slab dimensions significantly exceeding the recommended and applied standards. The obtained results seem to have an important cognitive value and are useful in preparation of new design solutions. Based on the knowledge gained so far through the application of the monitoring an unidirectional slab prestressed with unbonded tendons and having an record breaking span of 21.0 m is currently being designed.

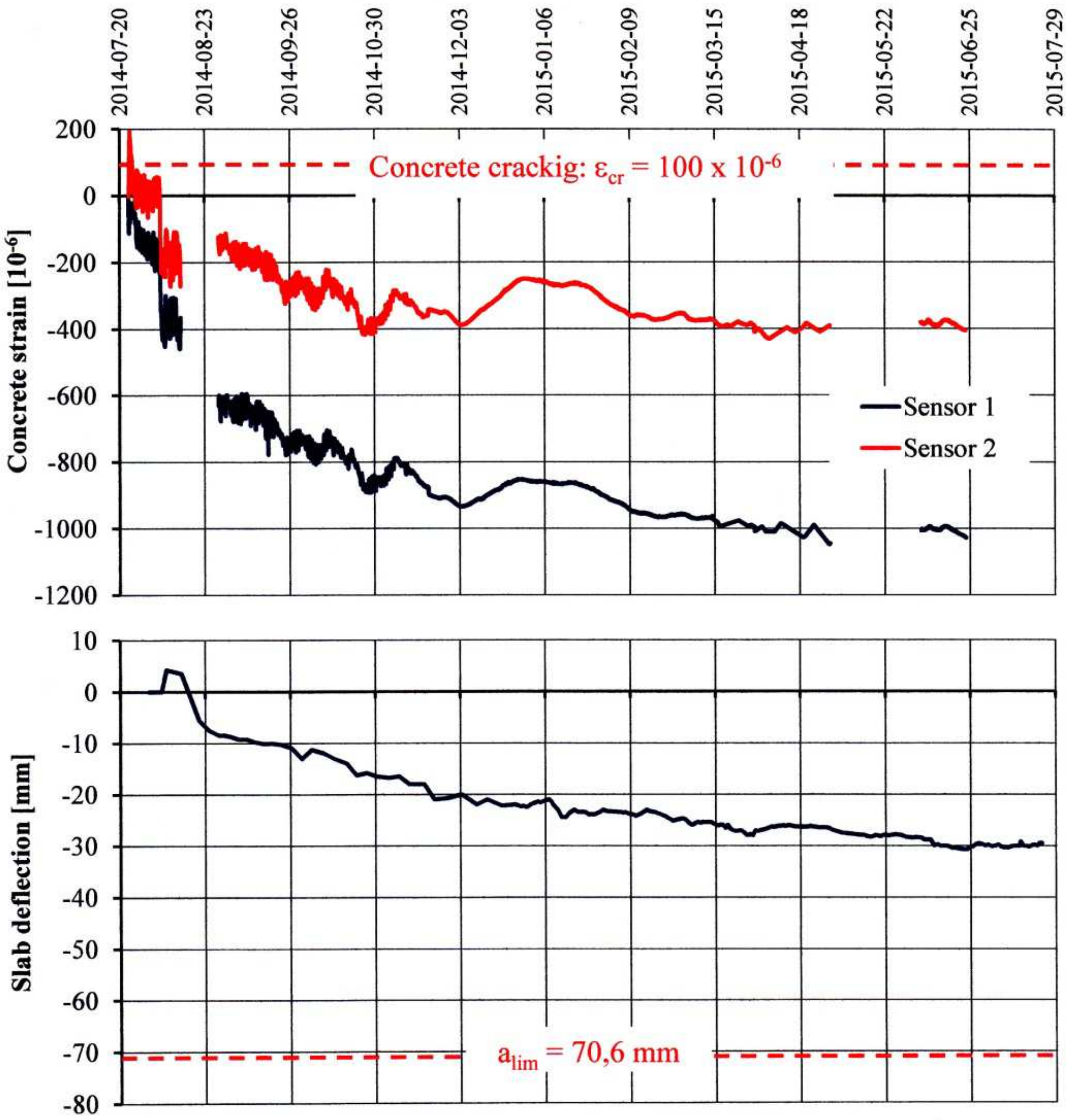


Fig.. 7. Results of monitoring for a large span slab depicted in the Fig. 6.

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