MONITORING AND METHODS OF ENSURING THE SAFETY OF LONG-SPAN POST-TENSIONED SLABS

Rafał Szydłowski[1] and Barbara Łabuzek[2]

[1,2] Faculty of Civil Engineering, Cracow University of Technology, Cracow, Poland
[1,2] TCE Structural Design & Consulting, Cracow, Poland

Corresponding author email: rszydlowski@pk.edu.pl

Abstract

Post-tensioned concrete slabs have been used in building construction since several decades in many countries. Due to the presence of active reinforcement, this kind of concrete slabs can be constructed with larger span and higher slenderness than one with ordinary reinforcement. Most commonly, unbonded tendons are used to prestress the slabs. In this prestressing system the steel is separated from concrete by the plastics casings and grease. As a result of lack of friction, the steel has the possibility of sliding in the structure. Thus, the force from the steel tendon is transmitted on the concrete element by anchorage only. Accidental cut of the tendon or damage of anchorage causes tendon slip on the duct and its total elimination from work. For this reason, the need to ensure safety has led to withdrawing this type of prestressing from use in some countries. However, it is still commonly used in many countries as a cheap and useful construction solution. The authors of this work have designed several slabs with the span and slenderness significantly higher than those recommended as maximum values. Due to the unique sizes of these slabs and controversial type of prestressing used, the contractual security levels have been defined and a monitoring system has been developed. This paper presents the adopted assumptions, critical thresholds to appropriate security levels as well as the results of several-year monitoring showing that the relevant safety levels have been met.

Keywords: Post-tensioned slab, unbonded tendons, monitoring.

1. Introduction

Post-tensioned concrete slabs have been used in building construction in many countries for several decades. Prestressing allows to design the slabs with significantly larger span than in the case of the slabs with ordinary reinforcement. Prestressing (initially tensioned reinforcement) introduces an initial set of loads and preliminary stresses into the structure. They are opposite to those arising from external loads and they reduce later concrete stretching. It has taken several decades to prepare and issue many recommendations dealing with shaping the geometry of such slabs, selection of prestressing method, dimensioning and erection technology. 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.

Khan and Williams (1994), basing on the crack free condition, and basing on the performed calculations give the required depth to span ratio for the various load levels (Table 1). Moreover, in the fib Bulletin 31 (2005), 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 these recommendations do not exceed the value of 45. The allowed recommended span lengths (Fig. 1) according to fib Bulletin 31 (2005) for continuous slabs are equal to 13.6m for two-way slabs and to 12.5m for one-way slabs. The published recommendations resulted in that the solid cross-section slabs are erected with maximum span limit set around 12÷13m all over the world.

Table 1. Recommended span/depth ratio according to Khan and Williams (1994).

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

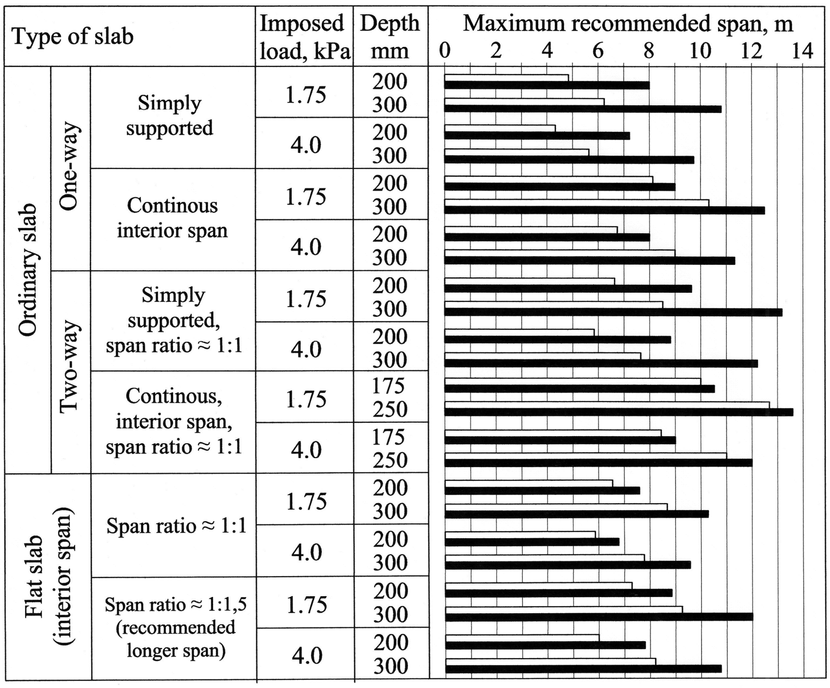

Figure 1. Examples of slab thickness and indication of maximum span for solid slabs with ordinary (□) and prestressed (■) reinforcement according to fib Bulletin 31 (2005).

2. Unbonded tendons and their threats

Construction of thin post-tensioned slabs of high span is associated with the use of unbonded steel tendons. These have been designed and put into a wide use in the building construction in the 1950s. The application of this solution only in the United States did not encounter difficulties. Hence, in Europe the first application of unbonded tendons dates back to the 1970s. The main reason of reluctance in applying unbonded tendons in Europe was the way of their performance, especially lack of a bond between concrete and steel and hence, the resulting threats. The steel strand is placed in an HDPE (hard polyethylene) duct with grease between the duct and the steel, resulting in the possibility of the strand sliding into the concrete structure. In case of damage of the anchor or cutting of the traditional bonded tendon, the prestressing force is transmitted to the concrete element through the bonding between the steel strand and the concrete. The length of tendon anchorage is formed in this case. Under the circumstances the tendon does not work only in the area of damage. As for unbonded tendons, it is a totally different situation; after damage to the tendon or anchorage, the prestressing tendon does not perform completely in the element.

The example of unbonded tendon failure is shown in Figure 2. Cutting of the tendon during core drilling has caused puncturing of the external plaster and launching of the tendon from the structure.

Additionally, the possibility of sliding tendon in the structure causes its greater elongation than in the case of a tendon bonded with concrete, and in consequence post-tensioned concrete structures are less rigid and more deformable.

Figure 2. The intersection of the strand in the borehole (left picture) and its launch from the structure (right picture).

3. Safety factors

The main parameter decisive of the correctness of post-tensioned slab's performance is its deflection. High rate of slab slenderness informs about any emergencies. The factor, that indirectly determines deflection is state of concrete stresses which is related to prestressing force. The scheme of the impact of particular values shown in Figure 3.

The significant parameter which decides about slab behavior and its emergency states is the stress on the bottom edge of the mid-span cross-section. Taking into account the safety of usage, three levels of stresses should be specified. These safety levels are shown in Table 2.

The first level of stresses is recommended by Eurocode 2 for post-tensioned structures with unbonded tendons. Eurocode 2 allows for presence of cracks with a width of 0.3mm (it is 0.4mm for XC0 and XC1 exposure class). In this case, limiting the width of cracks is dictated by aesthetic considerations. However, the authors dissuade designing post-tensioned slabs in the range of first-level permittable stresses. Although, unbonded tendons are perfectly protected from corrosion, cracking significantly reduces an element's stiffness in bending and it entails a significant increase in deflections. It follows that it is difficult to design cracked slabs with a large span and slenderness. It should be emphasized that the rheology of concrete is a complex and random phenomenon, which makes it very difficult to predict long-time deflection of slab which can increase several times over time. Therefore, allowing such a large cracking is not safe for the structure.

$$P_{eff} \Rightarrow \sigma_c \Rightarrow u$$

Prestress force Concrete stress Deflection

Figure 3. Safety factors and their interaction.

Table 2. Concrete stress levels.

Safety level	Concrete stress limit
I	$w_k \leq 0.4$ or 0.3mm1)
II	$\sigma_\tau \geq -f_{ctm}$ 2)
III	$\sigma \geq 0$ 2)

1) 0.4mm is valid for X0, XC1 exposure classes, 0.3mm is valid for other exposure classes.

These are determinate for quasi-permanent load combination.

2) Under frequent load combination.

w_k – crack width, f_{ctm} – the average concrete strength at axial tension.

The second level of stresses means no cracking for frequent load combination. This is a reasonable recommendation but for post-tensioned slabs with span and slenderness not exceeding the standard sizes. In accordance with the calculations, the elements should not be cracked so their stiffness is equal to that of a dense cross-section. In this way, the deflection does not grow as in case of the first level of stresses. Hence, it can be concluded that the assumptions concerning stresses are appropriate for slender post-tensioned elements. On the other hand, concrete cracking may occur accidentally, as a result of restrained thermal or shrinkage strains. Unpredictably cracked cross-sections are less rigid in tension. For this reason, it is not a good assumption for an extremely large slab.

The third level of stresses is defined as lack of tensile stresses during frequent combination of loads. This assumption is not specified in any guidelines but it was established by the authors of this paper and it is a main design condition for slabs with significantly greater span and slenderness than recommended (see section 5). Assuming compression of whole cross-section during the entire lifetime, the previously-described accidental cracking does not influence the decrease in stiffness (there is no decompression). Maintenance of third-level stresses is recommended by the authors especially for slabs with a large span or slenderness.

4. Measured values and monitoring system

The authors sometimes use full monitoring in their studies. It is the case in which three parameters are measured (prestress force, concrete stress and deflection). Sometimes incomplete monitoring is applied, in which case two parameters are measured – deflection and one of the additional parameters. In the case of limited possibilities, only deflection is measured as a key factor.

4.1. The measurement technology

The vibrating wire transducer technology is used to measure the parameters of interest (Parkasiewicz et al. 2017). In such a transducer deformation of a wire (constituting a basis for evaluation of changes in measured variables) is determined by the measurement of the vibration frequency change. The equation of the second law of Newton for a vibrating string takes the form:

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

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.

4.2. Concrete stress measurement

Due to small thicknesses of the slab, direct measurement of concrete stress is extremely difficult. Stress control is realized through strain measure. Hence, the accuracy of measurement is closely related to the accuracy of the elasticity modulus estimation. It must be noted that precise determination of Young's modulus in the structure is problematic and usually its value is different from the value obtained from laboratory tests on small samples. For that reason, it should be presumed that stress is measured with an accuracy of ±20%.

Considering that it is easier to monitor strain than stress, the best way to perform risk assessment and estimate concrete stress is by using the strain criterion for cracking. Exceeding level III and achieving level II of stress can be identified by occurring of concrete elongation and achieving stress level I is identified by concrete strain higher than $\varepsilon_{cr} = 0.00010$.

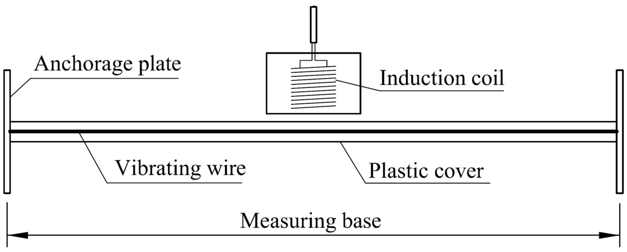

Figure 4. Construction of a typical vibrating wire deformation transducer.

The construction of a typical strain sensor immersed in the concrete is shown in Figure 4. Each such sensor is equipped with an induction coil exciting the wire 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 150mm are used to measure the strains in concrete.

4.3. Prestress force measurement

The sleeve sensors mounted under the anchorages (Fig. 5) are used to measure the force in prestressing tendons. Three vibrating wires, 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.

Figure 5. Construction of a typical vibrating wire deformation transducer.

4.4. Deflection control

Measurement system used for continuous monitoring of slab deflection is depicted in Figure 6. This system consists of two transducers having the form of steel vessels filled with liquid (usually glycol) (GEOKON, Instruction Manual), 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 Figure 6 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 wires, which is monitored via the measurement of the vibration frequency. During the measurements the transducers having the smallest available measurement range of 150mm 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.

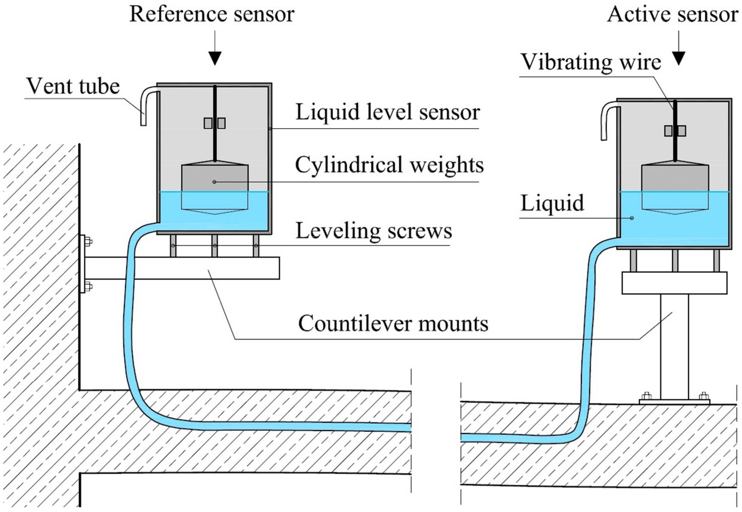

Figure 6. Structure of the slab deflection measurement system (a), view of the system transducer (b).

5. The example of the use of monitoring system and safety assessment of post-tensioned slab

Three extremely slender slabs prestressed with unbonded tendons were designed and erected in the building of the Artistic and Cultural Center in Kozienice (Szydłowski & Łabuzek 2017), which opened in summer of 2015 (Fig. 7). Three post-tensioned slabs were designed (Fig. 8 and 9):

- slab S1-1 at the level of +9.68m, having the span of 11.15m and depth of 200mm directly above the theater hall. The span to depth ratio is 55.8,
- slab S1-2 at the level of +14.08m, having the span of 12.86m and depth of 250mm in the roof above the theatre hall. The span to depth ratio is 51.4,
- slab Sl-3 at the level of +13.68m, having the span of 17.65×19.6m and depth of 350mm over the cinema hall. The span to depth ratio is 50.4.

These values substantially exceed the recommended ones, both in terms of slenderness and span. Slab Sl-3 is probably the largest span slab with a full cross-section in the world. Due to the fact that no slabs with such a large span and slenderness have been erected so far there was a risk of exceeding the permissible deflection. This was the reason for conducting deflection of slab and monitoring of concrete strain during the rise of the building and initially for a certain time of its use. The task of monitoring is to assess the safety of the structure and to show that it is possible to design post-tensioned slabs with spans which have not yet been used. The obtained positive results are to contribute to the design of even more bold structures.

In the mid-span cross-section, four strain gauges were installed, two in one direction and two in another, 25mm from bottom and top surface of the slab. A view of two of them, for which results are described further, is shown in Figure 10a. Embedded vibrating wire trasnducers with a base of 50mm were used in the tests.

Besides concrete strain, slab deflection was measured. The tests were conducted for a year since erection of the slab. Measurements were carried out continuously by the system shown in Figure 6. Deflection transducers installed bellow the slab are shown in Figure 10b. Additionally, deflection is monitored geodetically, from slab construction till now.

Figure 11a shows the development of strain in the mid-span cross-section in the direction of the

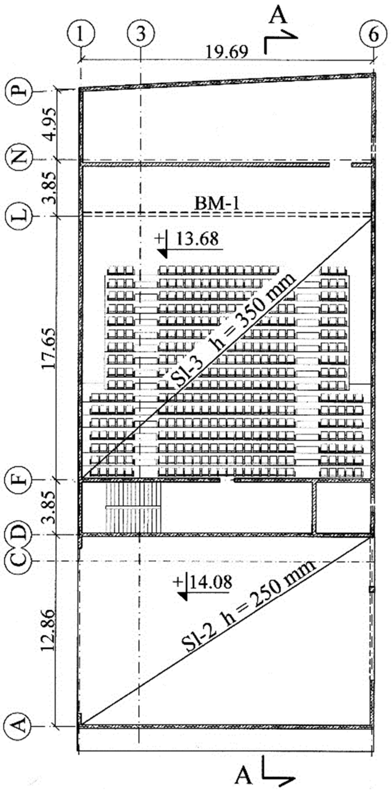

Figure 8. Plan of the building segment with post-tensioned slabs.

Figure 7. Visualization of CKA in Kozienice.

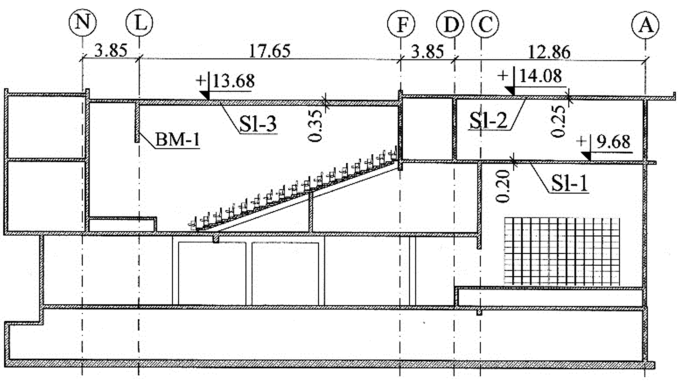

Figure 9. Cross section A-A.

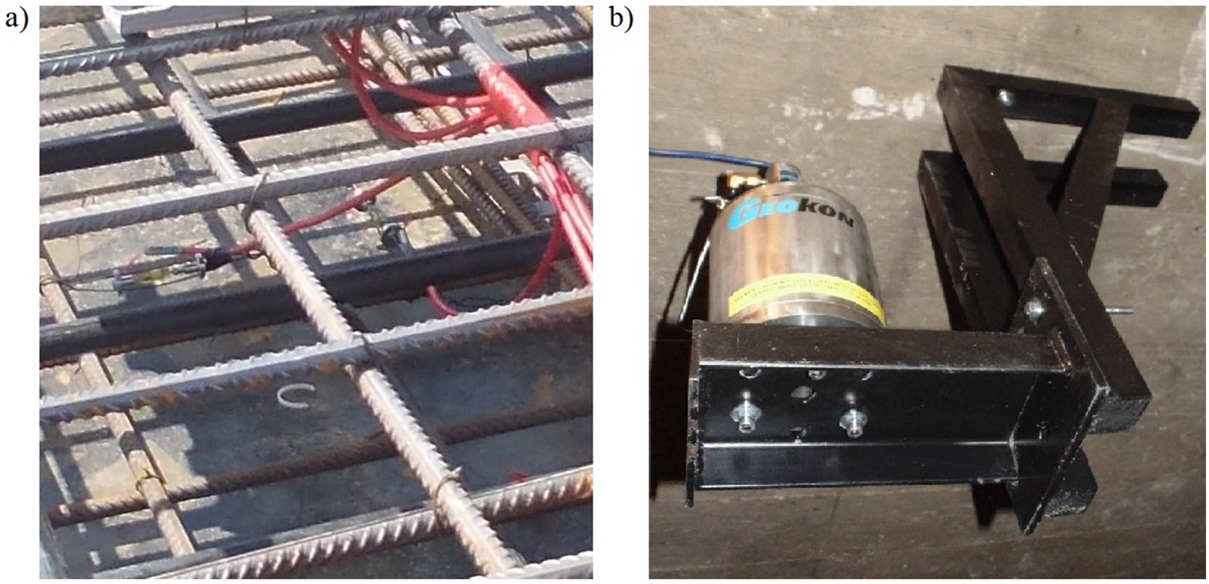

Figure 10. View of the strain transducers installed near the bottom surface (a) and deflection transducers bellow the slab (b).

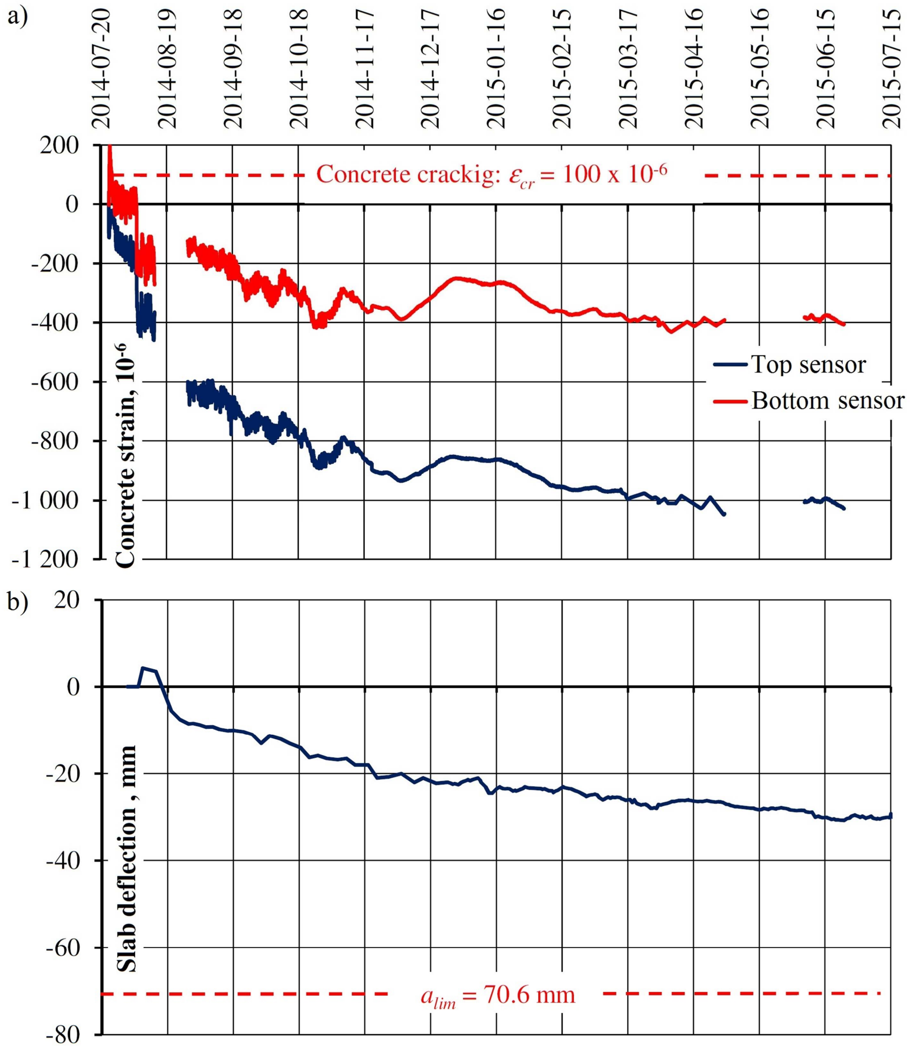

Figure 11. Development of concrete strains in the mid-span cross-section (a) and slab deflection (b) over first year of slab life.

shorter span for the first year. A leap in the first month was caused by prestressing. Further, creep and shrinkage increased concrete strain. After seven months, concrete strains stabilized. The presented results indicate that concrete did not extend which means lack of decompression and maintenance of level III stresses. Increase of strains difference between the top and bottom surface corresponds with the growth of deflection shown in Figure 11b. At the end of continuous monitoring, a deflection of about 30mm was obtained, which is 1/587 of the span.

Maintenance of the compressed cross-section (lack of decompression) was reflected in the value of deflection after four years since slab erection. Total deflection after four years is 54.5mm. The deflection increases since disassembly of formwork (important for brittle elements under and above slab) is 47.5mm. The registered deflection seems to be high but it should be noted that span slab is equal to 17.6m in the shorter direction. The growth of deflection is 1/371 of span. In accordance with Eurocode 2 the limit value of deflection for that slabs is L/250 (if there are no brittle elements on the slab). It is important that the growth of deflection in the last year was 4.5mm, whereas in the previous year it was 7.5mm. Moreover, after three years, the creep, which is one of the main reasons of increased deflection in time, occurs in 80%. Both of these facts lead to the discovery that the limit L/250 will never be achieved.

6. Conclusions

The paper presents the established security levels for post-tensioned slabs as well as the system of their control. The structures of this type are not subject to rapid damage and are not a threat to the lives of people, failures are rather ductile, and exceeding the limit of deflection should be considered a threat. It is the most important parameter for thin concrete slabs which determines the usefulness of the structure. The established security levels and monitoring system described have been tested earlier in simpler slabs with a smaller span. Their implementation was helpful in successful construction of the largest span post-tensioned slab with a solid cross-section in the world by the authors of this work. This slab was described in section 5. Positive results of the behavior of the slab for 4 years of its life became the basis of designing the next unique post-tensioned slab. It is a simply-supported one-way slab in the Busko-Zdrój Cultural Center building. The span of slab is 21.3m and the thickness is 550mm (Szydłowski & Łabuzek 2017).

The presented monitoring system can be also used to inform about the threat created by failure of tendons and their anchorages. However, it is possible after several years of construction life, when rheological phenomena in concrete has stopped.

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