IOP Conference Series: Materials Science and Engineering

About Distributed Internal and Surface Strain Measurements within Prestressed Concrete Truck Scale Platforms

To cite this article: Rafal Sienko *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **471** 052074

About Distributed Internal and Surface Strain Measurements within Prestressed Concrete Truck Scale Platforms

Rafal Sienko [1], **Lukasz Bednarski** [2], **Tomasz Howiacki** [3]

[1] Cracow University of Technology, Warszawska St. 24, 31-155 Cracow, Poland
[2] AGH University of Science and Technology, Mickiewicza Al. 30, 30-059 Cracow, Poland
[3] Cracow University of Technology, Warszawska St. 24, 31-155 Cracow, Poland

rsienko@pk.edu.pl

Abstract. Distributed optical fibre measurement technology provides new possibilities in structural technical condition assessment in comparison with traditional spot measurements. It is not only possible to analyse strains continuously over structural member length with spatial resolution starting from as fine as 5 mm, but also the cracks and displacements state within reinforced concrete structures. The article presents pilot studies regarding prestressed concrete track scale platforms with a length of 8 to 16 m. Optical fibres were glued within composite rods attached to the stirrups inside the cross section of the slab on the height of lower and upper prestressing tendons, as well as they were glued to the concrete surface after bonding. That allows for comprehensive analysis of concrete strains state including all local nonlinearities (cracks) starting from hydration process (thermal-shrinkage strains), through prestressing tendons activation (strains regarding the transfer of compression forces from the tendond to the concrete) and finally during laboratory tests, when slabs were mechanically loaded until destruction. The ways of installation and exemplary results from selected phases of the research were presented as well as data interpretation was described and discussed.

1. Introduction

1.1. Truck Scale Platforms

Truck scales are mainly used for trade and inspections weighting of car vehicles. Their main structural element is a platform (deck, slab) which transfer the loads from vehicles into foundations through measuring devices. On Polish market producers offer the platforms with load bearing capacity up to 80 tons. The crucial aspects during their design phase are durability, bending stiffness and the dead weight. The most popular solutions include the scales with steel, reinforced concrete ore combined platforms. Steel decks have the lowest weight, but they are mainly susceptible to corrosion and need a lot of expenses during operation. Reinforced concrete slabs are characterized by the lower operational costs and the higher durability in comparison to the steel ones, but the important disadvantage is their weight, which impede the transportation and thus increasing its costs.

However, another solution which will fulfill these three main requirements more effectively would be a prestressed concrete, which idea is to conscious interfere into the structural member internal forces by providing compression. This approach means "*the higher level of dominating the nature by technique*" [1] and allows for designing slabs which are slim, light, stiff and durable. For this reason, in the years 2012-2014 some partially prestressed (where is a possibility of cracks development under short-term load [2]) truck scales were designed and implemented in Poland with load bearing capacity of 30 [3] and 60 tons [4]. Due to the possibility of prefabrication of prestressed concrete truck scales, which would enable the mass production, it seems reasonable to carry out detailed tests of structural members made on a natural scale in order to optimize adopted technical solutions, for example geometry of the deck, the area of reinforcing and prestressing steel, prestressing forces as well as the concrete class. This optimization would be the more effective the better we get information about structural response and so the better tools we will apply to estimate this response. The main limitation of traditional extensometers is that they provide information locally (for example the strain value is averaged over the measuring base in the middle of the slab span). This information is incomplete as we do not obtain knowledge about the state of the rest part of the structure. Furthermore, because of the cracks and local increase in stiffness due to the presence of the aggregate, the interpretation of such results should always be done with high precaution. It should also be emphasized that theoretical considerations including even advanced mathematical models, especially with respect to the heterogenous materials, could lead to the significant errors [5] and always remain imperfect.

However, nowadays we have the possibilities of applying much more advanced measuring tools, including distributed optical fiber sensor technology [6], which provide comprehensive and much more useful information in comparison to traditional measuring and numerical solutions. This tools with reference to a specific case study of prestressed concrete truck scales were described hereafter.

1.2. Specimens on a natural scale

Specimens under consideration were prefabricated in the production hall in the technology of pre-tensioned concrete, where prestressing tendons were tensioned prior between the anchor points over the 100 m track and then the slabs were concreted. After the concrete bonds to the tendons as it cures, tendons were released and then the compressing forces were transfer into the concrete by static friction [7]. This construction method allows multiple elements to be constructed end-on-end in the one pre-tensioning operation, allowing significant productivity benefits. Truck scales under consideration were design as fully prestressed, i.e. operating in a non-cracked condition. Providing compressing forces in whole deck sectional area is a very favorable in terms of durability, as it protects the reinforcing and prestressing steel from corrosion, what is especially important for truck scales operating in difficult external conditions.

Further only construction of 8-meter scales, operating as statically determined beam, is described – see figure. 1. To reduce weight of the platforms five oval Styrofoam inserts were placed along its length. Eight prestressing tendons were applied for the lower part of the cross section, and two for the upper. Moreover, reinforcing bars and stirrups were used. Cross sections of the analyzed platforms in the middle of the span and within the support area are presented in figure 2. It should be noticed that examined platforms are only the part of the final version, where the sectional width will be 3 m.

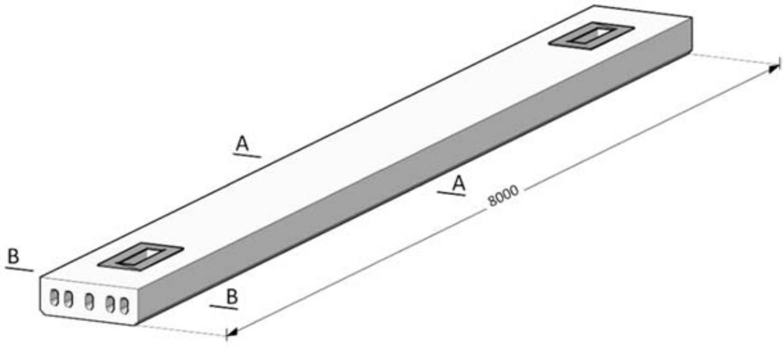

Figure 1. Geometry of analysed truck scale platform prototype

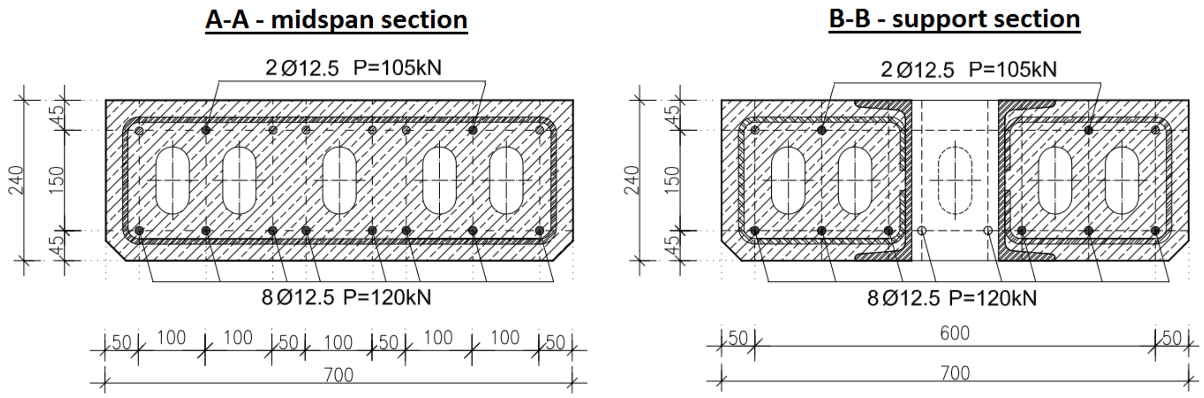

Figure 2. Cross sections of considered truck scale platform prototype

Several tests during different phases of the platforms lifecycle were carried out, starting from hydration process (thermal-shrinkage strains), through prestressing tendons activation (strains regarding the transfer of compression forces from the tendons to the concrete) and finally during laboratory tests, when slabs were mechanically loaded in four-point bending test until destruction. Distributed optical fiber measurement technology was used to record strain and temperature changes along selected measuring paths.

1.3. Distributed optical fibre measurements

The main limitation of traditional extensometers and almost all other measuring techniques is the ability to carry out measurements of a given physical quantity only at a local scale - figure 3a. Sometimes some attempts are made to analysed measured quantity along a given line by installing several sensors within this line – figure 3b, but this approach is expensive and thus occasionally used. Distributed optical fibre technology is based on light scattering and allows for strain and/or temperature measurements to be made with a spatial resolution of 5 mm along the length of the optical fibre [8]. From an engineering point of view, such measurements can be considered as continuous measurements in a geometric sense (figure 3c).

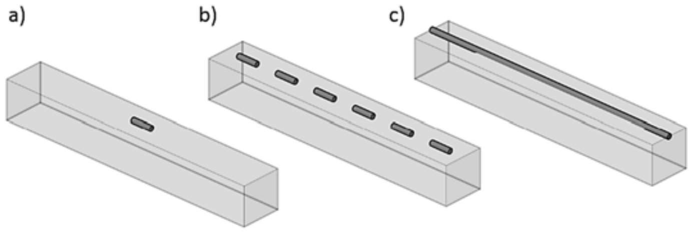

Figure 3. Measurement scheme: a) spot, b) quasi-continuous, c) distributed (geometrically continuous)

A number of studies in this area have been conducted under laboratory conditions over the last few years. There were attempts to embed measuring fibres into a concrete [9], localize cracks within concrete structural members [10] and analyse their strain and temperature distributions [11, 12] using different optical phenomena such us Brillouin or Rayleigh scattering [13].

Glass optical fibres used in the telecommunication field should be as pure as possible i.e. free from micro-imperfections, that cause light wave energy losses over the length. The Rayleigh scattering phenomenon is one of the reason and it occurs in every fibre cross section due to the particle structure of matter (heterogeneity of refractive index at micro-scale). However, this fact is favourable in terms of strain measurements. The light reflected from the imperfection of the glass structure moves backward relative to the original direction of motion. Scattering amplitude is a random but constant property for a given fibre and can by analysed by advanced reflectometers. While changing the fibre length the distance between local imperfections will also be changed and it can be calibrated for mechanical or thermal strains. During the research presented in the following sections of the paper an optical backscatter reflectometer OBR 4600 [14] manufactured by Luna Innovations (based on Rayleigh scattering) was applied for distributed measurements [15]. The selected technical parameters of this device are summarised in table 1.

Table 1. Selected parameters of distributed measurements

Parameter	Value	Unit
Measuring range (standard mode)	70	m
Minimal spatial resolution	5	mm
Temperature resolution	± 0,1	°C
Strain resolution	± 1,0	με

2. Installation of measuring fibres

The main task during installation process is to provide appropriate adhesion between analyzed medium (concrete) and measuring fibre, which enable adequate strain transfer. The second point is to propose some practical ways of mounting very thin and slim fibres without any damages. Within described case study two approaches were discussed and implemented.

First of all, it is impossible to install pure glass optical fibre (Φ = 250 μm) inside the concrete because it will rupture during concreting and compacting the concrete mix. The second argument is that we are not able to control its position along the structural member because of the fibre minimal stiffness. Thus, there is a necessity to provide some intermediary element. In presented case study it was solved by the application of composite rod with measuring fibre glued axially within the prepared groove. Such composite rods were simply tied to the stirrups along the prestressing tendons – see figure 4a. The use of appropriate composite material makes installation easier because of its lightness as well as do not disturb the operation of structural member as its elasticity modulus is similar to the concrete modulus. The main advantage of installation internal optical fibre rods is the possibility of measuring early-age concrete strains and mechanical strains at the height of the prestressing tendons.

However, also surface strain measurements can be useful, especially while examining existing structural members. That is why also this approach was verified during the studies. After the concrete bonding, its surface was cleaned and degreased, and then optical fibres without any external coatings were glued within measuring paths on a two-component epoxy resin – see figure 4b.

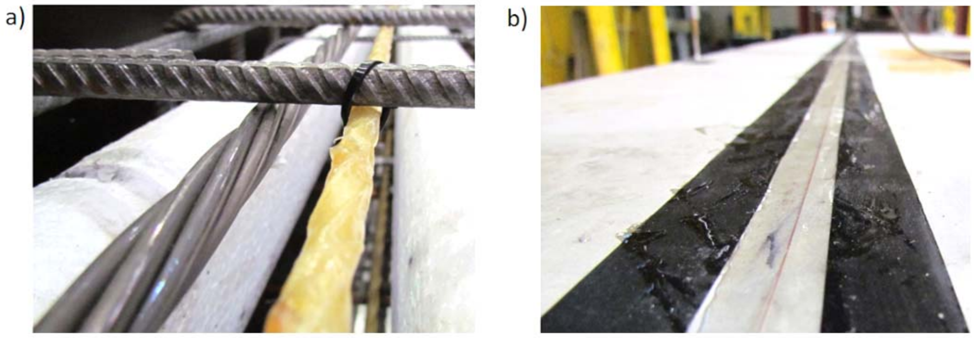

Figure 4. The view of optical fibres for measuring internal (a) and surface (b) concrete strains

The localization and numbering of all optical fibres or optical fibre rods is presented in figure 5. It should be noticed, that in case of surface fibres, their paths were arranged with the loop – they run back (7, 8) and forth (7’, 8’). Optical fibres for measuring temperature (5, 6) were placed freely inside the polyamide tubes, so they were isolated from mechanical strains.

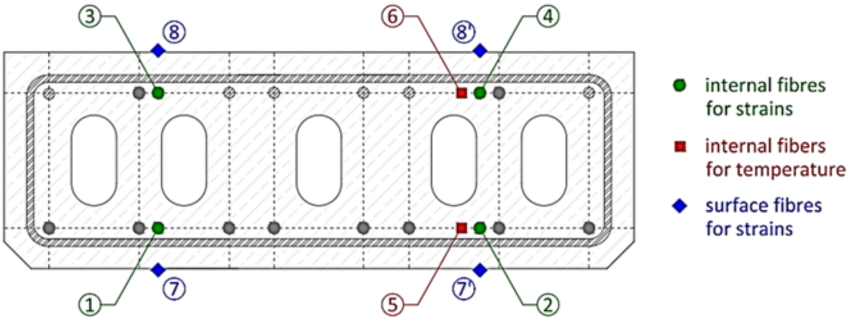

Figure 5. Localization and numbering of measuring fibres within platform cross sectional area

3. Exemplary results

3.1. Early-age concrete strains

The measurements started immediately after platforms concreting. Strains and temperatures were recorded every 30 minutes during first day of concrete hydration. During subsequent measuring sessions the development of thermal-shrinkage strains was observed. It is noteworthy, that the distribution (envelope) of strains along the member length is remarkably stable with respect to the shape from the beginning throughout all the following measurement sessions. Thus the weakest points (those, where the local concentrations of strains occur) may be identified in the early stage, i.e. even then, when the concrete is not yet cracked or when only the micro-cracks invisible to the naked eye occur. The strain distribution plots with spatial resolution of 10 mm along the length of the platform under consideration during first seven hour of hydration are presented in figure 6 for the lower (2) and upper (4) optical fibre rods.

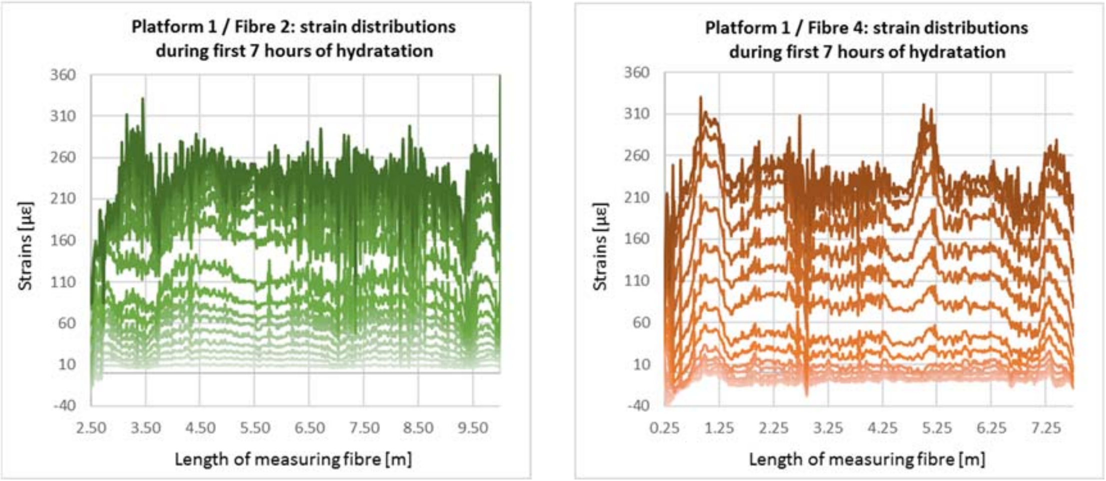

Figure 6. Strains distributions measured by fibre 2 and 4 during first 7 hours of hydration

During first hours the higher level of strains was observed for the lower optical fiber rod (2), because the concrete platforms were heated from below within the production line. Upper strains (4) at the very beginning were even slightly on the compressed side because of the external temperature domination before the start of concrete bonding end releasing hydration heat. The values of strains (2,

4) and temperatures (5, 6) at lower and upper edges averaged over 1000 mm base in the middle of the platform span are presented in figure 7 during first 24 hours.

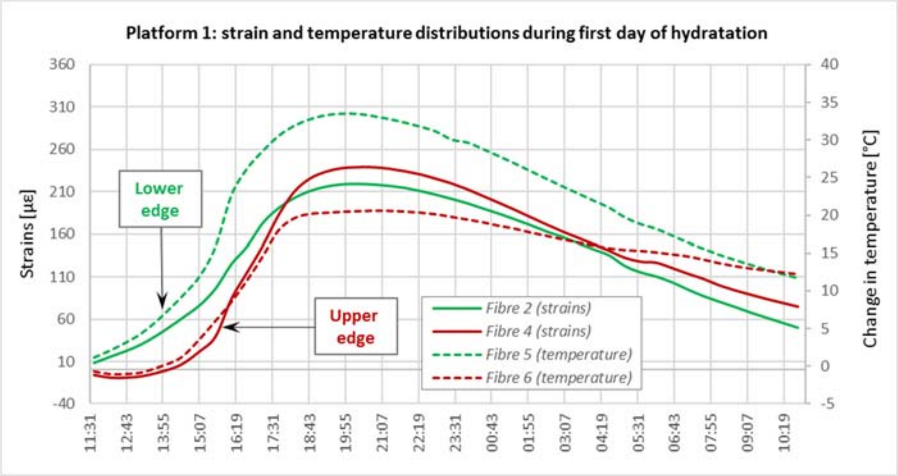

Figure 7. Strain and temperature changes distributions for lower (2, 5) and upper (3, 6) fibres averaged over 1000 mm base during the first day of hydration

3.2. *Tendon activation*

The next phase was to activate all prestressing tendons to provide compression in the concrete platforms. Tendons were cut off in order described in figure 8, where also averaged strains (base equal to 1000 mm) for the lower (2) and upper (4) optical fiber rods are presented for the subsequent tendon releasing T01 – T10. The temperature during this process was constant.

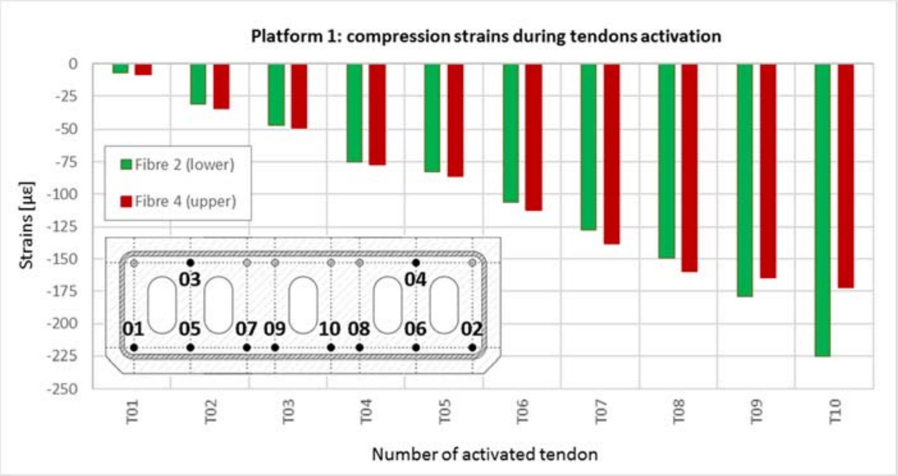

Figure 8. Strains averaged over 1000 mm base for the lower (2) and upper (4) fibres during subsequent activation of prestressing tendons T01- T10

The information from figure 8 could be obtain by applying the standard extensometers, which returns one number after measurement. The more interesting thing is to analyze strain distributions along the structural member, and those are presented in figure 9 with spatial resolution equal to 10 mm. It is worth to notice, that one optical fibre along 8000 mm platform replaces 800 traditional spot sensors. Including all measuring paths, 64 000 virtual optical fiber sensors were applied for the one analyzed platform within this particular case study.

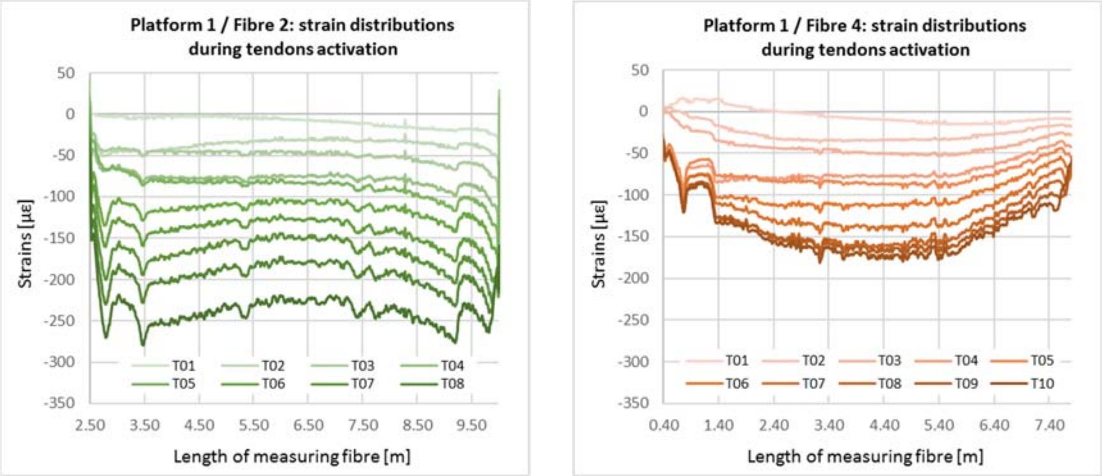

Figure 9. Strains distributions for fibre 2 (lower) and 4 (upper) during the tendon activation phase

It could be observed, that compression level is higher at the lover edge of the cross section where 8 prestressing tendons were placed. Moreover, the strain distribution shapes confirm, that the platforms were bent up after prestressing, which is in compliance with theoretical predictions. Knowing the upper and lower strains along the whole structural length it is possible to estimate the value of vertical displacements (assuming the statically determined beam scheme) and thus exactly verify theoretical design assumptions in every cross section. The results of experiment indicate that continuous fiber optic measurements allow the technical phenomena to be examined much more thoroughly than in the scenarios considered so far.

3.3. Laboratory bending tests

After the concrete bonding and obtaining the adequate compression strength, all analyzed platforms were transported into the laboratory (Cracow University of Technology, Poland) where additional surface optical fibres were installed. Moreover, vibrating wire strain sensors where mounted at lower and upper surface of the platforms as a reference measuring technique.

Platforms were examined in four-point bending test under strength machine, where the load was applied stepwise through kinematic input in the middle of the span. The exemplary view of deflected platform within the measurement stand is presented in figure 10.

The strains distributions were recorded every 10 mm of the midspan deflection. Results for the lower surface optical fiber (7) during subsequent steps of research are presented in figure 11a. The close up in figure 11b includes only the first four steps and clearly shows that platform worked linear and elastic only during the first step (deflection of 10 mm). In the next step we can observe discontinuities on the strain plot relate to the crack occurrence. This cracks were developed during subsequent load steps. Analogous analysis was performed for the optical fiber localized on the upper (compressed) platform surface (8) and results for this case are presented in figure 12. It could be noticed, that within compression zone there are no local strain peaks corresponding to the cracks. However, the weakest place can be identified, which finally decided about the platform destruction.

Figure 10. The view of examined platform during four-point bending test

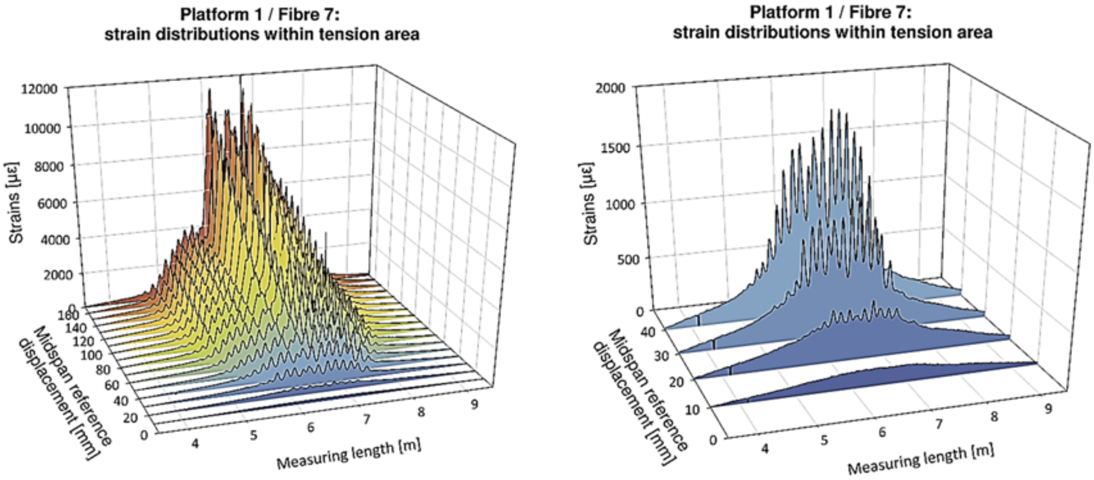

Figure 11. Exemplary plots of strains within tensile area during loading of the slab

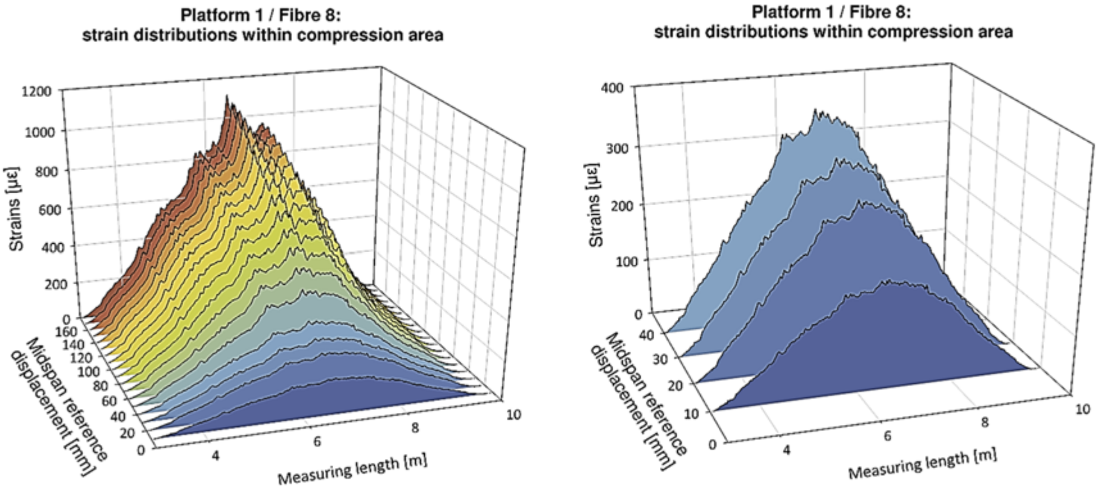

Figure 12. Exemplary plots of strains within compressed area during loading of the slab

4. Discussion and conclusions

The pilot studies described in the article include comprehensive measurements of concrete strains and temperatures during subsequent phases of structural member lifetime. Starting from hydration process (thermal-shrinkage strains), through prestressing tendons activation (strains regarding the transfer of compression forces from the tendons to the concrete) and finally during laboratory tests, when platforms were mechanically loaded in four-point bending test until destruction. Analysis of obtained data will be used to optimize technical solutions for prestressed concrete truck scale platforms before starting their mass production in prefabrication hall.

Strain, crack and displacement analysis of concrete structural members is crucial in the context of the assessment of their technical condition and safety. This is the reason why work and studies are ongoing to improve the methods used in this field. Based on the research carried out and presented in this article, it can be concluded that the distributed fibre optic technology provides new opportunities in comparison with traditional spot measuring techniques (e.g. inductive, electrical resistance or vibrating wire). Thus, it can and should be used not only for laboratory tests, but also as a part of long-term structural health monitoring systems. The attention should be paid to elaborate the best mounting techniques depending on material and application (concrete, steel, buildings, line infrastructure, geotechnics etc.), which will provide appropriate strain transfer from examined medium to measuring fibre, as well as some guidance for data acquisition and processing should be developed in the near future.

Acknowledgments

Authors would like to show gratitude to the SHM System company [16] (Cracow, Poland), currently working on the research project called "*Development of the new fibre optic sensor allowing for the determination of the vertical and horizontal displacements of the studied objects at the distances of up to 120 km*". This project is funded by the grant won at the National Centre for Research and Development within the framework of Intelligent Development Operational Program 2014-2020 (POIR.01.01.01-00-0550/15).

References

[1] W. Olszak, „Theory of prestressed concrete structures" PWN Print, Warsow, 1961, (in Polish).
[2] T. Y., Lin, "Partial Prestressing Design Philosophy and Approach", *FIP Notes 69*, pp. 5–9, July-September 1977.
[3] R. Szydłowski, Ł. Ślaga Ł., B. Łabuzek, „30 tons truck scale platform made from concrete prestressed with unbonded tendons", *Przegląd Budowlany*, 6/2017, pp. 33-39, (in Polish).
[4] R. Szydłowski, B. Łabuzek, "Prestressed Concrete Truck Scale platform with a capacity of 60 tons. Design assumptions and test results", *PCI Journal* (in review).
[5] R. Sieńko, T. Howiacki, S. Jedliński, "Design errors resulting from the adoption of incorrect structure's model", *Technical Transactions,* 2-B/2013 pp 126–136, 2013.
[6] J. M. López –Higuera, L. Rodriguez, A. Quintela et al., "Currents and Trends on Fiber Sensing Technologies for Structural Health Monitoring", *The 2nd Mediterranean Photonics Conference*, Eilat, Israel, 29 November – 2 December 2010.
[7] R. F. Warner, K. A. Faulkes, "Prestressed Concrete (2nd ed.)", *Melbourne, Australia: Longman Cheshire*, pp. 1–13, 1988.
[8] D. Samiec, "Distributed fibre-optic temperature and strain measurement with extremely high spatial resolution", *Photonik International*, 2012.
[9] S. Delepine-Lesoille, E. Merliot, C. Boulay, et al. "Quasi-distributed optical fiber extensometers for continuous embedding into concrete: design and realization". *Smart Materials and Structures*, 15, pp. 931-938, 2006.

[10] Z. Zhou, B. Wang and J. Ou, "Local Damage Detection of RC Structures With Distributive FRP-OFBG Sensors". *Second International Workshop on Structural Health Monitoring of Innovative Civil Engineering Structures*, Winnipeg, Canada, 2004.

[11] W. Li and X. Bao, "High spatial resolution distributed fiber optic technique for strain and temperature measurements in concrete structures". *International Workshop on Smart Materials & Structures, SHM and NDT for the Energy Industry*, Calgary, Alberta, Canada, October 7-10 2013.

[12] R. Sieńko, T. Howiacki, R. Szydłowski, et al. „Application of distributed optical fiber sensor technology for strain measurements in concrete structures". *COST TU1402, Quantifying the Value of Structural Health Monitoring*, Copenhagen, Denmark, 24th August 2016.

[13] A. Barrias, J. R. Casas and S. Villalba, "A Review of Distributed Optical Fiber Sensors for Civil Engineering Applications". *Sensors* 2016; 16.

[14] D. Gifford, B. Soller, M. Wolfe et al. "Distributed Fiber-Optic Sensing using Rayleigh Backscatter". *European Conference on Optical Communications (ECOC) Technical Digest*, Glasgow, Scotland, 2005.

[15] Luna Innovations. User Guide, Optical Backscatter Reflectometer 4600, 2013.

[16] www.shmsystem.pl, access: 06/2018.