Analysis of post-tensioned girders structural behaviour using continuous temperature and strain monitoring

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Abstract. This article presents the possibility of using structural health monitoring system data for the analysis of structure’s operation during its life cycle. Within the specific case study it was proved, that continuous, automatic and long term monitoring of selected physical quantities such as strains and temperatures, can significantly improve the assessment of technical condition by identifying hazardous phenomena. In this work the analysis of structural behaviour of post-tensioned girders within the roofing of sport halls in Cracow, Poland, was performed based on measurement results and verified by numerical model carried out in SOFiSTiK software. Thanks to the possibility of performing calculations in real time and informing the manager of the object about abnormalities it is possible to manage the structure in effective way by, inter alia, planning the renovations or supporting decisions about snow removal.

1. Introduction

Application of restressed concrete technology in the opinion of professor Olszak “undoubtedly means the higher level of dominating the nature by technique” [1]. The use of stressed tendons in concrete allow for increasing the length of spans, reducing the cross sections of structural members and taking more efficient advantage of material strengths.

Already in the middle of last century in Poland, lightweight, prefabricated KBO and KBOS post tensioned concrete girders were developed. They were introduced into catalogues [2] and recommended for widespread use. In a short time about 850 objects were built in the country, which means that more than 10,000 girders have been put into operation as structural members of roofs [3]. Unfortunately, mainly due to the low quality of performance on sites as well as the aggressive chloride environment [4] and high humidity in the production halls, the technical parameters of the girders was significantly reduced. Unfavorable operating conditions and the lack of adequate tendon protection have caused pitting corrosion of steel, which in turn caused the breaking of the tendons, sometimes even one year after the girder was built into the structure! Several structural failures in the 1960s caused a decrease in trust top restressed concrete structures.

Nowadays, due to decades-long operation, variable environmental conditions, influence of humidity, progressive corrosion of restressing steel and other factors, one can expect a decrease in the overall bearing capacity of this girders. Furthermore, it should be noticed that the current standard requirements for the structural safety are stricter than before. Thus, it is necessary to properly control the condition of these structures to provide their safe operation. Periodic inspections are carried out, but thanks to advanced structural health monitoring (SHM) we are able to observe the girders behavior.
continuously. In addition, by estimating the bearing capacity of specific girder [5] and preparing the appropriate calculation procedures, it is possible to assess the stress-strain state in the material in real time.

This article presents analysis performed for real case: girders within roofing of “Study Centre for Physical Education and Sport” of Jagiellonian University, Cracow, Poland (see figures 1, 2).

![Figure 1. The monitored hall - view from outside.](image1)

![Figure 2. The view of monitored post-tensioned girders.](image2)

Thanks to the appropriate selection of beam profiles, it is possible to reduce the consumption of concrete and steel. The KBO and KBOS girders have been designed in such a way that the longitudinal configuration has been adapted to the course of bending moments. Thanks to this, materials are used effectively in every cross section, which allow us to include them into the group of economical girders [6].

Considered post-tensioned girders are consisted of eccentrically-compressed upper flange, eccentrically-tensioned bottom flange and vertical braces, which cause bending moments in flanges. They work should be analysed in two stages: before and after bonding with roof panels. In the second case the girders cooperate with panels, providing additional spatial stiffness, which cannot be considered in the 2D model. Obviously, three-dimensional analysis will more accurately reflect the actual state of the structure under operation, and the calculated bearing capacity will be greater than in the case of two-dimensional analysis [6,7]. In view of the threats presented above, the resulting supply is particularly important. In some cases, percentage difference between load capacities obtain from theoretical 2D and 3D model is even more than 50%.

2. Structural health monitoring

Structural health monitoring system of considered girders is based on continuous control of their work by automated and remote measurements of strain and temperature changes in selected measuring points within the structure, in reference to zero readings.

The main purpose of SHM system is to control changes in girders stress-strain state, mainly caused by the snow load. This allows for more effective management of the objects, including supporting those responsible for making decisions about snow removal. Other possible causes of changes in structural effort of girders are corrosion of restressing tendons, the breakdown of roof panels, the loss of bonding between panels and upper flanges of girders or the deformation caused by the temperature. The temperature load, in particular the temperature difference between the girders and the roof panels, has significant impact on girders operation [3]. During traditional geodetic measurements of displacement, special attention has to be paid to the thermal conditions, which should be as close as possible to each other during consecutive measurement cycles. Assessment of girders operation in this case becomes an extremely difficult task. The superiority of the structural health monitoring system
lies mainly in performing measurements continuously over long period of time, what allow for analysis of monthly and annual cycles i.e. when changes in strains are clearly visible against the background of temperature changes. In considered sport halls measurements are made with a frequency of 15 minutes and calculated automatically according to designed procedures. The location of measuring points within monitored objects is presented at figure 3.

Figure 3. Configuration of monitored structures with location of measuring points [courtesy of SHM System].

Within considered sport halls following sensors were installed:

- 28 vibrating wire strain sensors [14], integrated with internal thermistors;
- 20 additional thermistors.

Measuring devices were connected with structural members in a way providing durability of the connection during long-term operation. The location of the sensors within specific KBO-18 girder is shown at figure 4.

Figure 4. Sensors location within KBO-18 girders [courtesy of SHM System].

3. Exemplary results and discussion

At figures 5 and 6 the changes in strain and temperature values were presented between 01.03.2015 and 16.09.2017 for measuring points S2 and S3 within Gym (see figure 3). The blue line corresponds to strains measured at upper edge of bottom flange, and green line to the lower edge of bottom flange. Sign “+” corresponds to the increase of tensile strains in reference to zero reading. The values of strains are presented in microdeformations \( \mu \varepsilon = 10^{-6} \). The temperature changes were marked by dotted lines. Values of temperature are similar within upper and lower edge of bottom flange, as well as the upper flange. The differences did not exceed 1°C in considered period of time, which allows in numerical modelling for assumption of uniform temperature load. It should be noticed, that strain
values calculated and presented in figures 5 and 6 corresponds only to strains, which cause the stress of structural member (they do not include free, thermal strains).

Figure 5. Strain and temperature changes between 01.03.2015 and 16.09.2017 – Gym, S2.

Figure 6. Strain and temperature changes between 01.03.2015 and 16.09.2017 – Gym, S3.

In point S2 we can clearly observe the influence of temperature on strains measured in the bottom flange of girder in annual cycle. This is common situation for almost all analysed girders, except of girder S3 (see figure 6), where strains are insensitive to thermal effects. The reason of this phenomena could be explained by numerical simulations.

The model was created in SOFiSTiK software to analyze girders work in two configurations: as statically determined beam (2D model) and including spatial cooperation with roof panels and other girders (3D model). In the 3D model ribbed roof panels were assumed as areas with equal, averaged thickness, and the upper flanges of girders as monolithically connected with concrete overlay. The visualization of structure’s deformation under the uniform snow and temperature load was respectively presented at figures 7 and 8 (at figure 8 roof panels were deleted to provide appropriate clarity). Figure 7 shows the advantages of bonding girders with roof panels, which provide spatial stiffness and significantly reduces deflections under the snow load in comparison to the free, single beam. On the other hand, while loading the structure with uniform temperature, we can observe that it does not affect the stress in statically determined beam (2D model). This corresponds to the situation presented for girder S3 and suggests the possibility of loss the bonding between the upper flange of girder and roof panels. This could be dangerous for load bearing capacity, because the supplies resulting from spatial cooperation of structural members are reduced.

Getting information about structural behavior in real time based on SHM data analysis is the basis for effective decision making. Abnormalities are visualized for the User in serviceable way, so he is able to start prevent actions immediately, regarding for example with: snow removal, hiring an Expert for making engineering calculations and estimate the actual condition of the building, organizing in-situ inspections or setting a schedule of renovations in long term.
4. Conclusion

KBO and KBOS prestressed concrete roof girders were widely used in Poland in the second half of the last century. Due to their long-term operation in difficult, changeable conditions, they require proper observation and control, preferably by continuous, structural health monitoring. Theoretical analysis of such objects will remain imperfect, so in situ measurements are always very valuable [8,9], allowing for justified and effective decision making in real time. Observation of structural behavior, especially of prestressed concrete structures using SHM systems, is increasingly used in civil engineering [10,11,12] also including construction process [13,15].

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