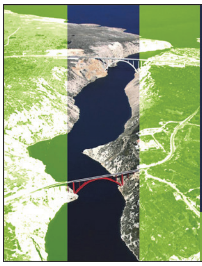

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STEEL BRIDGE WITH THE LONGEST ARCH SPAN IN POLAND – STRUCTURAL MONITORING

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Abstract: *This paper presents selected data obtained from the monitoring system, installed on a steel arch bridge over the Vistula River along the ring road of Puławy, Poland. The total length of the crossing is 1038.2 m (a four-span continuous structure) and the main arch river span is 212.0 m, the longest among the arch bridges in Poland. Due to the great length and the complex structure of the river span, it was decided that a monitoring system should be designed and implemented. The system thoroughly measures various physical quantities at 35 test points. The system is composed of three subsystems: monitoring of the structure, meteorological monitoring and video monitoring.*

The monitoring of the structure, one of the three subsystems of the monitoring system, is designed to control the behaviour of the bridge by means of continuous electronic measurement of the following parameters: changes in strains, deflections, accelerations, temperature of the structure, wind speed and direction. Force changes in hangers are calculated on the basis of strain measurements with the use of sensors installed on ten hangers. Force changes in three selected hangers have been analyzed. Stress changes in arches are calculated on the basis of strain measurements with the use of sensors installed at 14 points.

Gathered data suggest that the main factor to influence the response of the structure in service is thermal action. Data obtained from the systems can give an overview on the real level of the live and/or environmental loads on bridges. It is believed that this information should be included in the Polish National Annex of Eurocodes.

1 INTRODUCTION

Many bridge structures nowadays are provided with the exploitation and technical condition monitoring systems. These systems provide crucial information about: stress states in the elements of the structure, occurring deformations and vibrations, temperature of the structure and environmental conditions. The results obtained from the monitoring system are useful in the verification of the design assumptions and helpful in the maintenance of the structure.

Structural monitoring systems have already been installed in several road bridges in Poland. This paper presents the monitoring system, installed on the steel arch bridge over the Vistula River along the ring road of Puławy, eastern Poland. The total length of the crossing is 1038.2 m (a fourteen-span continuous structure) and the main arch river span is 212.0 m, the longest among the arch bridges in Poland. The composite steel and concrete deck is supported by steel arch girders by means of 28 bar hanger assemblies.

Due to the great length and the complex structure of the river span, it was decided that a monitoring system should be designed and implemented. The system thoroughly measures various physical quantities. Since its elements were installed after the structure had been opened for use, the system takes measurements of changes of particular quantities from the live and environmental loads. The system is composed of three subsystems: monitoring of the structure, meteorological monitoring and video monitoring.

The monitoring of the structure, one of the three subsystems of the monitoring system, is designed to control the behaviour of the bridge by means of continuous electronic measurement of the following parameters: changes in strains, deflections, accelerations, temperature of the structure, wind speed and direction.

The system obtains data from 35 test points. It consists of five types of sensors: string sensors integrated with temperature sensors, inclinometers integrated with temperature sensors, a 1D accelerometer (one channel), a 2D accelerometer (one and two channels), a sensor measuring the wind velocity and direction above and under the bridge deck. The scheme showing the location of test points is presented in Figure 1.

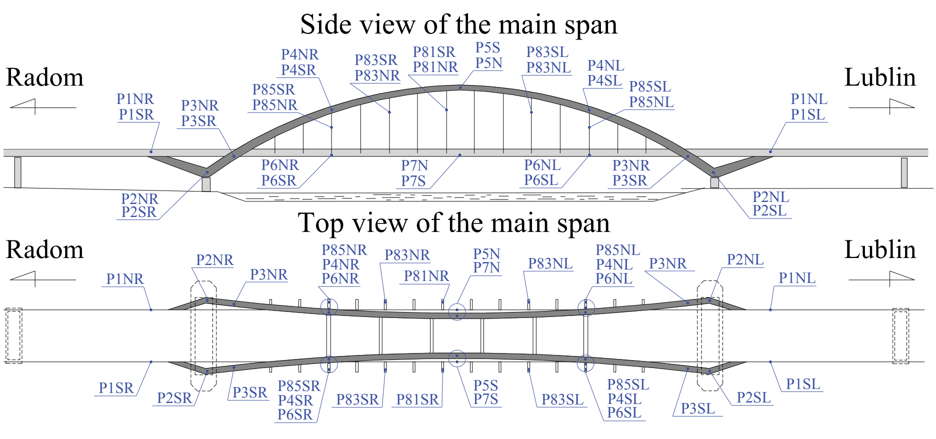

Figure 1: Position of test points on the bridge in Puławy

The Local Server, located on the bridge, gathers measurement data from the subsystems listed above, processes and transfers them to the central database of General Directorate for National Roads and Highways, department in Lublin, which functions as a server. The data obtained are compared with the defined limit values. In the case of any measured value exceeding the limit value, the Operator is automatically notified of such an occurrence.

2 FORCE CHANGES IN THE HANGERS

Force changes in hangers are calculated on the basis of strain measurements with the use of sensors installed on ten hangers. These test points are marked P81÷P85 with symbols: N or S designating the northern or the southern side of the bridge, respectively; R or L designating the part closer to the Radom City or to the Lublin City, respectively.
Force changes in three selected hangers (P81NR, P83NR and P85NR) have been analyzed. In Table 1, the extreme values of measured forces at the point P81NR (central hanger of northern arch) in particular months have been shown together with the time of occurrence. Since the components of the monitoring system were installed after the structure had been opened for exploitation, the system takes measurements of changes of particular quantities from the live and environmental loads. Therefore, positive values of forces in hangers may be recorded, which, however, does not mean that this hanger is under compression.

		F_{min} [kN]	Time	F_{max} [kN]	Time
2009	May	-98.1	05:50	13.6	15:30
	June	-100.9	02:10	-5.8	11:20
	July	-135.5	05:50	-31.2	10:30
	Aug	-151.9	05:40	13.1	11:20
	Sept	-148.0	05:10	-62.9	12:50
	Oct	-156.7	02:40	-82.1	13:10
	Nov	-159.8	04:40	-94.6	12:00
	Dec	-170.4	00:10	-93.2	11:20

Table 1: Extreme values of force changes in central hanger

The largest changes of forces in hangers have been measured at the point P81NR. On average, the force changes are approximately 90 kN, with the characteristic hanger load capacity of 700 kN.
It can be observed (Table 1) that the minimal force values have been measured during the night or in the early morning hours, while the maximal values during the day – round noon or in the afternoon. This phenomenon is assumed to be connected with the change of temperature of the structure. Despite a higher traffic volume, the forces in the hangers decrease during the day. In the night, when the temperature reaches minimal values, the stresses increase. This regularity is confirmed by a graph of changes of stresses and the temperature of the hanger in a daily cycle (Figure 2). The graph allows observation of the occurring changes in a continuous manner. Figure 3 presents the wind velocities from the same day. The wind velocity and direction is measured 1.5 m under the arch (point P5) and 1.5 m under the steel beam deck (P7). Wind velocity measured under the deck did not exceed 2 m/s and can be recognized as less relevant. Wind velocity at the point P5 increased in the afternoon and did not exceed 7 m/s.

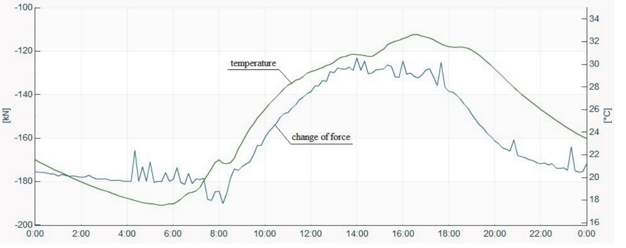

Figure 2: Change of forces and the temperature of central hanger, 12.08.2010

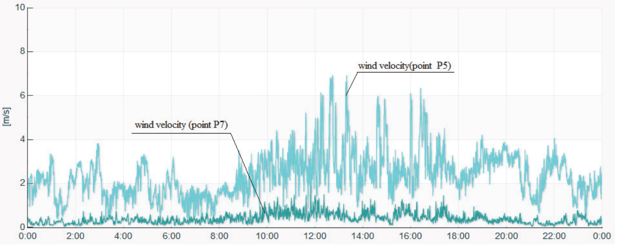

Figure 3: Wind velocity measures at the points P5 and P7, 12.08.2010

Table 2 presents the extreme values of stresses measured in selected hangers and the extreme characteristic values of stresses obtained on the basis of load combinations according to the standard PN-85/S-10030 (C1: live load + wind load, C2: live load + thermal load). Increase in stresses at the points P83NR and P85NR is at the level of 25% of the calculated values. Minimum change of stresses in the central hanger (P81NR) is 65% of the calculated values.

Test point (hangers)	Stresses measured [MPa]	Stresses calculated min{C1 ; C2} [MPa]	Δ [%]
P81NR	-23.3	-35.7	65
P83NR	-9.7	-36.1	26
P85NR	-9.9	-41.0	24

Table 2: Extreme values of measured and calculated stress changes in selected hangers

3 STRESS CHANGES IN THE ARCH

Stress changes in arches are calculated on the basis of strain measurements with the use of sensors installed in 14 points (7 points per arch). These test points are marked P2÷P5 with respective symbols (see Section 2). Strain sensors at the points P3÷P5 are located on the top edge of the box girder (strain measurement parallel to the axis of the bridge) and at the points P2 on the bottom edge. Stress changes in the northern arch in selected points (P2NR, P3NR, P4NR and P5N) have been analyzed. Table 3 presents the extreme values of stresses from particular months at the point P5N. The time of occurrence of each extreme value is given, as well. As can be observed, maximum temperature of the structure is achieved round noon and in the afternoon, which confirms the intuitive approach, as well as data from literature (Zobel 2003). Figures 4, 5 present graphs of stresses and temperature in selected test points on the daily basis. It can be observed that the stress changes are determined by the temperature. Certainly, seasonal temperature amplitudes also influence the range of stress changes. The range of stress changes in of 5-15 MPA, measured in winter of 5-15 MPa ise smaller than 30-40 MPa, measured in summer.

		σ_{min} [MPa]	Time	σ_{max}[MPa]	Time
2009	May	-13.36	13:30	13.69	04:30
	June	-16.15	12:50	13.64	16:10
	Jul	-16.35	12:10	12.95	20:30
	Aug	-11.75	13:30	15.85	17:40
	Sept	-7.03	12:50	12.94	03:40
	Oct	0.57	11:10	13.37	23:00
	Nov	5.87	12:40	13.31	01:10
	Dec	7.18	12:00	14.04	21:30

Table 3: Extreme values of stress changes in the arch (point P5N)

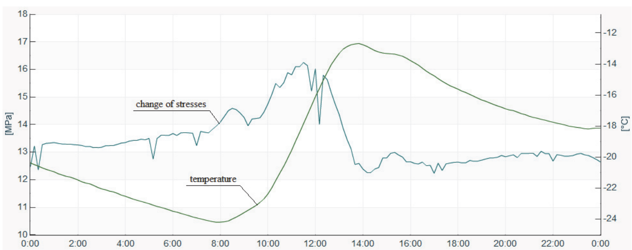

Figure 4: Change of stresses and the temperature of the arch at the point P5N, 26.01.2010

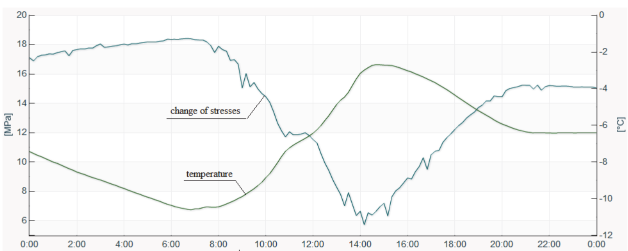

Figure 5: Change of stresses and the temperature of the arch in point P3NR, 08.03.2010

Table 4 presents extreme values of stresses measured in the arch and extreme characteristic values of stresses obtained on the basis of load combinations according to the standard PN-85/S-10030 (C1: live load + wind load, C2: live load + thermal load). Stress increases in the analyzed points are at the level of 62 ÷ 78% of the calculated values.

Test point (hangers)	Stresses measured [MPa]	Stresses calculated min{C1 ; C2} [MPa]	Δ [%]
P5N	16.3	20.7	78
P4NR	16.1	21.5	75
P3NR	18.4	29.5	62

Table 4: Extreme values of measured and calculated stress changes in the arch

4 TEMPERATURE OF THE BRIDGE

4.1 Temperature of the arches

Sensors measuring temperature have been installed on both arches (northern and southern). The sensors at the points P3÷P5 are located on the top edge of the box girder and at the points P2 on the bottom edge.

First of all, the analysis of temperature values in a season scale has been made. The maximal temperature has been measured in a crown segment of the southern arch (point P5S) and its value was 50,01°C. Maximal temperature of the northern arch, which has been measured also in a crown segment (point P5N), is comparable (49,68°C). Those values occurred on 15 July 2010, which is more than twenty days after the longest day in the year. On that day, the maximal amount of solar radiation energy reaches the structure, and the maximal air and structure temperature is reached a few weeks later [3]. The minimal temperature occurred in the northern arch (-24,19°C), however, practically, it can be recognized as equal to the minimal temperature of the southern arch (-24,17°C).

Based on the gathered data concerning extreme temperatures of the arches, relatively large differences between the values depending on the location of the test point along the arch can be noticed. Moreover, the obtained data indicate higher range of maximal temperatures in relation to the range of minimal values, which could have been concluded intuitively. To confirm that regularity, the range of temperature changes on yearly basis, at a particular test point along the northern arch (the part of the arch closer to the Radom City), has been analyzed and presented graphically in Fig. 6. The presented graph has been constructed on the basis of extreme temperatures from particular months. The differences in the range of temperature changes between the points along the arch can be observed. The largest range of changes occurs in the crown segment (P5N) and decreases respectively in the points located lower along the arch. The smallest range of changes occurs at the point P2NR. However, points P2 are less representative in this case as far as the values are concerned, as the sensors in the points P2 are installed on the bottom edge of the arch.

Furthermore, not only the differences in the temperature changes at the points along the arches can be observed, but also differences in changes of the range of extreme temperatures depending on the season. The maximal changes of extreme temperatures within a month at the test points in the analyzed time period were: P5N – 40,2°C (June 2009), P4NR – 37,7 °C (June 2009), P3NR – 32,5°C (June 2010), whereas the minimal changes of extreme temperatures were: 20,3°C, 18,6°C and 15,0°C (all of them measured in January 2011), respectively.

Having analyzed the values of temperatures on daily scale, it can be stated, that during the day, independently from the season, the temperature of the structure rises, which is caused by the dominant influence of direct and diffusive solar radiation that reaches the surface of the structure [3]. The maximal intensity of the solar radiation appears at noon and the

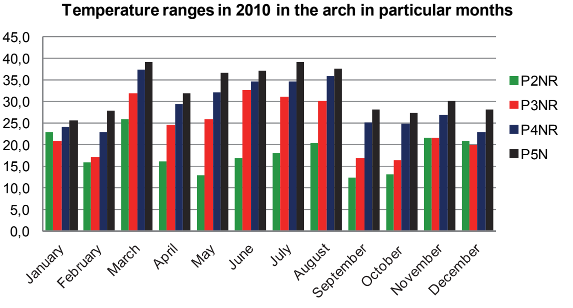

Figure 6: Change The ranges of extreme temperature changes along the north arch

structure reaches the maximal temperature few hours later. The extreme month temperatures at selected test points of the northern arch are shown in Table 5. The precise time of occurrence of these values is also given. Close to dawn or in the early morning hours, the minimal temperature of the structure is observed, as a result of heat exchange processes leading to the energy balance of the configuration structure – surroundings, as well as the balance within the structure itself [3]. 24-hour temperature changes of the structure at selected test point are presented in Figure 4 and Figure 5.

Test point	T_{max} (°C)	Time	T_{min} (°C)	Time
P3NR	43,77	14:50	-21,85	08:30
P3NL	40,55	12:50	-22,14	08:00
P4NR	46,45	14:50	-23,71	07:20
P4NL	44,09	13:00	-23,18	07:10
P5N	49,68	13:00	-24,19	06:50

Table 5: Extreme temperatures in the northern arch

4.2 Temperature of the hangers

It can be noticed that the maximal temperatures of the hangers of the southern arch are slightly higher than the maximal temperatures of the hangers of the northern arch. The maximal value (37,10°C, August 2010) has been measured in the central hanger of the southern arch (point P85SL). The minimal measured value (hanger of northern arch) was -24,66°C (point P83NL, January 2010). Observed differences in the values of extreme temperatures of particular hangers are inconsiderable in comparison to the differences of maximal temperatures at the test points along the arches. They do not exceed the value of 1,81°C for maximal temperatures and 0,75°C for minimal. A conclusion can be drawn that the temperature of the hanger depends to a small extent on the location of this element along and across the deck. The variability of temperature ranges, depending on the season, is noticeable, however, it is not as distinctive as in the case of the arch. As far as the day changes of the temperatures are considered, similar times of heating and cooling up to the extreme values of particular hangers are observed. The maximal temperatures are reached around noon or in the afternoon. The minimal temperatures of the hangers are reached a little bit earlier than of the arches.

4.3 Temperature of the deck beams

The maximal temperature was measured in July 2010 at the point P1SL (southern beam). Its value was even up to 32,99°C. The minimal temperature occurred in the northern beam in January 2010 (-21,72°C). It can be observed that the temperature of the southern beam is slightly lower than of the northern one. The ranges of temperature changes at particular test points in respective months are quite similar to each other. On a daily basis, the extreme temperatures of the deck beams are reached with some delay in relation to the arches and the hangers. This is caused by the fact that the deck beams are hidden under the concrete slab and solar radiation does not reach their surface directly.

5 CONCLUSIONS

Gathered data suggest that the main factor to influence the response of the structure under exploitation is thermal action. Basic change of stresses in particular points of structure is caused by the daily temperature amplitudes. Over a year, influence of air temperature on the range of stresses (smaller in winter, greater in summer) in the structure is noticeable. According to Polish Standard [2] extreme values of temperature of steel structure are determined for -25°C ÷ +55°C and the measured values of the arch, hangers and the beam deck lie in this range. The minimal temperature values of all analyzed elements are very close to the ones indicated in [2]. The important conclusion of the conducted observations regards the observed relatively significant differences between the temperatures of particular elements. Such phenomenon is not considered by the Polish Standard.

Measurements of stress changes in particular elements as effects from live and environmental loads enable to compare real stress values with the ones assumed during calculations (Biliszczuk et al. 2008). Values of these stresses are between 62-78% in the arch (depending on the cross section) and about 65% in the central hanger.

Installed in several road bridges over the past few years, structural monitoring systems provide crucial and valuable information on real response of each of these bridges (usually complex and/or unique in its form) and their particular elements. Data obtained from the systems can give an overview on the real level of the live and/or environmental loads on bridges.

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