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STRUCTURAL HEALTH MONITORING SYSTEM OF A CONCRETE CABLE-STAYED BRIDGE

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Abstract
In this paper a system of the Rędziński bridge will be described. The Rędziński bridge is the biggest object along the A8 motorway around the city of Wrocław and the biggest concrete cable-stayed bridge in Poland. For the purposes of the bridge monitoring a system of 222 sensors was installed. Results from the first 5 years of work of the SHM will be presented below.

Keywords: **Bridges; Structural health monitoring; Durability assessment; Maintenance.**

1. STRUCTURAL HEALTH MONITORING SYSTEMS IN POLAND

For over the last decade an intensive development of SHM systems has appeared in Poland and some of them are installed in the following bridges:

- the Solidarity Bridge over the Vistula River in Płock (2007), which is the biggest cable-stayed bridge in Poland, made of steel;
- the John Paul II Bridge over the Vistula River in Puławy (2008) – one of the largest arch bridges in Poland, made of steel;
- the Rędziński Bridge (Fig. 1) over the Odra River in Worcław (2011), which is the biggest concrete cable-stayed bridge in Poland, constructed along the motorway A8.

Furthermore SHM systems are not only installed on bridges. Under a constant observation is also the roof structure of the National Football Stadium in Warsaw or the road surface on motorway A4 which is built in the region of underground mine damages.

2. DESCRIPTION OF THE RĘDZIŃSKI BRIDGE AND ITS SHM SYSTEM

The Rędziński Bridge [2] was open to traffic on 31st August 2011 and is the biggest bridge along the motorway ring-road of Wrocław. It is a four-span cable-stayed bridge situated over the Odra River. The spans are 50 m + 2 x 256 m + 50 m long (Fig. 2) The two separated concrete decks are connected to a single 122 m high concrete pylon located on the Rędziński Island. The stay cable system consists of 160 stays. The decks were built with the longitudinal launching method [3].

For the purposes of the bridge monitoring a system of 222 sensors was installed (Fig. 4). The system is saving data concerning stresses in the concrete elements like

Figure 1.
View of the Rędziński Bridge [www.golowersilesia.pl]

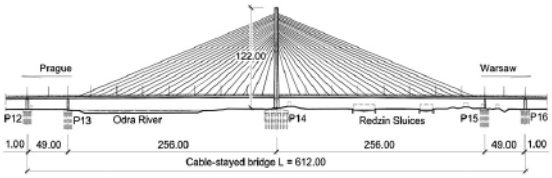


Figure 2.
General view of the Rędziński Bridge

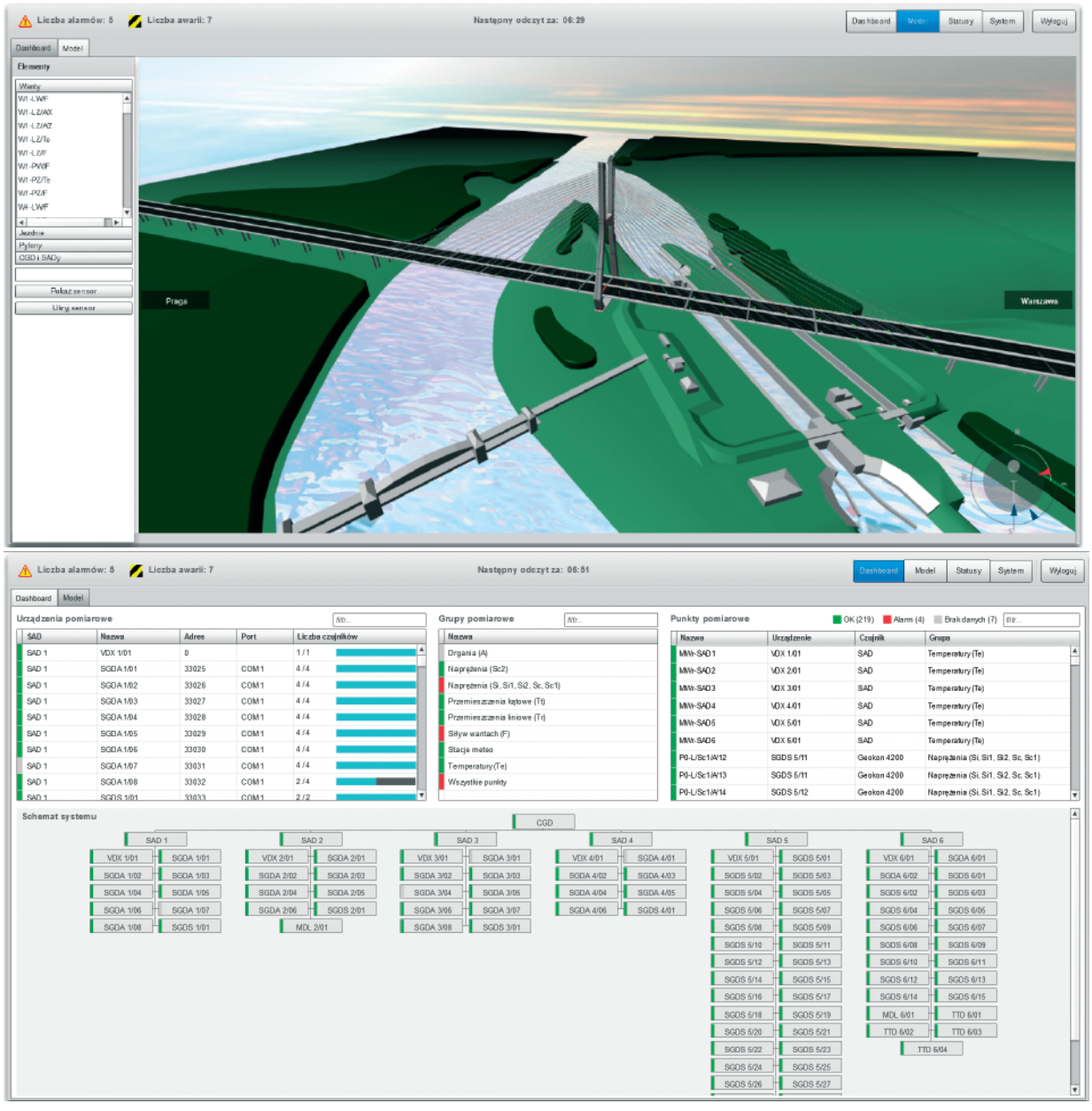
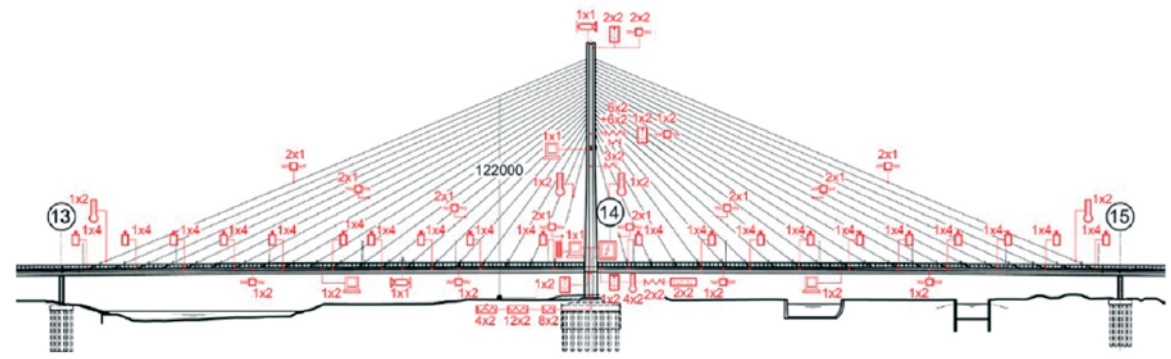


Figure 3.
View of the Rędziński Bridge model in the SHM application. It shows a virtual location of each sensor [1]

the pylon and the decks, it is measuring the forces and accelerations in 80 cable-stays, furthermore it is collecting data about the temperature in the bridge elements with comparison of the current weather



- **F,** force sensors in cable strands (80 pcs.),
- **Tt,** angle rotation sensors (10 pcs.),
- **Tr,** linear displacement sensors (4 pcs.),
- **W,** wind speed and direction sensors (2 pcs.),
- **Te,** temperature sensors (16 pcs.),
- **Sc,** sensors measuring linear displacements on concrete surface (16 pcs.)
- **A,** acceleration sensors (30 pcs.),
- **CGD,** global data server (1 pc.),
- **EN,** power connection (1 pc.),
- **Sc1,** sensors measuring linear displacements inside the concrete structure (24 pcs.),
- **Sc2,** sensors measuring stresses inside the concrete structure (8 pcs.),
- **Si,** sensors measuring linear displacements on steel surface (18 pcs.),
- **Si1,** sensors measuring stresses in the reinforcing rods (16 pcs.),
- **SAD,** Local Data Saver (5 pcs.).

Figure 4.
Measuring scheme of the Rędziński Bridge [4]

Figure 5.
The monthly average forces in case of the longest stay-cables W40-PZ/F and W40-PW/F

conditions. All parameters are measured at the same time and saved in 6 local servers. The dynamic values are registered with the frequency of 100 Hz. The database is available via internet through a professional application. The application (Fig. 5) is equipped with an alert module that informs the user about some dangerous or strange behaviours of the bridge elements. Moreover, it is equipped with a 3D-model of the bridge, where the user can check the precise location of each sensor.

3. MEASUREMENT ANALYSIS

In 2016 a first overview of the registered data from August 2011 till December 2015 was made [5]. The analysed sensors were divided into 3 groups:

– for the cable stayed system: forces, temperatures and acceleration sensors,
– for the deck: stresses, temperatures and acceleration sensors,
– for the pylon: stresses, temperatures, acceleration and displacements sensors.

Some of the results are presented below in detail.

Table 1.
Comparison of average monthly forces

Sensor	Average force, August 2011	Average force, December 2015	Difference	Percent change	Sensor	Average force, August 2011	Average force, December 2015	Difference	Percent change
	[kN]	[kN]	[kN]			[kN]	[kN]	[kN]	
W1-LZ/F	1784	1658	-126	-7.0%	W1-PZ/F	-	1524	-	-
W1-LW/F	1433	1237	-196	-13.7%	W1-PW/F	-	1304	-	-
W4-LZ/F	3121	3007	-114	-3.6%	W4-PZ/F	3051.3	3001	-50.1	-1.6%
W4-LW/F	3001	2921	-80	-2.7%	W4-PW/F	3069.3	2993	-76.5	-2.5%
W6-LZ/F	3290	2756	-533	-16.2%	W6-PZ/F	3591.8	3625	33.7	0.9%
W6-LW/F	3229	3254	24	0.8%	W6-PW/F	3253.1	3116	-136.7	-4.2%
W8-LZ/F	3669	3590	-79	-2.2%	W8-PZ/F	3596.8	3643	46.4	1.3%
W8-LW/F	3771	3758	-13	-0.4%	W8-PW/F	3550.4	3595	44.8	1.3%
W10-LZ/F	4572	4675	103	2.3%	W10-PZ/F	4794.7	4823	27.8	0.6%
W10-LW/F	4482	4419	-62	-1.4%	W10-PW/F	4448.6	4368	-81.1	-1.8%
W12-LZ/F	4898	4907	9	0.2%	W12-PZ/F	4869.1	4764	-104.6	-2.1%
W12-LW/F	4441	4384	-57	-1.3%	W12-PW/F	4722.2	3696	-1026.7	-21.7%
W14-LZ/F	5781	5580	-200	-3.5%	W14-PZ/F	5579.0	5599	20.2	0.4%
W14-LW/F	5493	5362	-131	-2.4%	W14-PW/F	5598.2	5455	-143.5	-2.6%
W16-LZ/F	5262	4972	-290	-5.5%	W16-PZ/F	5183.5	4987	-196.8	-3.8%
W16-LW/F	5428	5220	-208	-3.8%	W16-PW/F	5374.6	5241	-133.9	-2.5%
W18-LZ/F	5253	4932	-322	-6.1%	W18-PZ/F	5285.3	5022	-263.5	-5.0%
W18-LW/F	5018	4681	-337	-6.7%	W18-PW/F	5323.7	5072	-251.5	-4.7%
W20-LZ/F	3135	2934	-202	-6.4%	W20-PZ/F	3199.6	2959	-240.4	-7.5%
W20-LW/F	2966	2716	-250	-8.4%	W20-PW/F	2952.4	2701	-251.6	-8.5%
Sensor	Average force, August 2011	Average force, December 2015	Difference	Percent change	Sensor	Average force, August 2011	Average force, December 2015	Difference	Percent change
	[kN]	[kN]	[kN]			[kN]	[kN]	[kN]	
W21-LZ/F	1740	1528	-212	-12.2%	W21-PZ/F	1279	1064	-215	-16.8%
W21-LW/F	1380	1185	-196	-14.2%	W21-PW/F	1455	1266	-189	-13.0%
W24-LZ/F	3111	3033	-78	-2.5%	W24-PZ/F	3088	603	-2485	-80.5%
W24-LW/F	3025	2930	-95	-3.1%	W24-PW/F	3028	2954	-74	-2.4%
W26-LZ/F	3305	3206	-99	-3.0%	W26-PZ/F	3458	3316	-141	-4.1%
W26-LW/F	3229	3006	-223	-6.9%	W26-PW/F	3426	3443	17	0.5%
W28-LZ/F	3714	3572	-142	-3.8%	W28-PZ/F	3610	3619	9	0.2%
W28-LW/F	3670	3614	-56	-1.5%	W28-PW/F	3614	3679	65	1.8%
W30-LZ/F	4744	4658	-86	-1.8%	W30-PZ/F	4532	4641	108	2.4%
W30-LW/F	4570	4438	-132	-2.9%	W30-PW/F	4745	4650	-96	-2.0%
W32-LZ/F	4918	4697	-221	-4.5%	W32-PZ/F	904	4893	3988	441.0%
W32-LW/F	-	-	-	-	W32-PW/F	4942	4849	-93	-1.9%
W34-LZ/F	-	-	-	-	W34-PZ/F	5664	5497	-167	-2.9%
W34-LW/F	5759	5448	-310	-5.4%	W34-PW/F	5668	5460	-208	-3.7%
W36-LZ/F	5263	5005	-258	-4.9%	W36-PZ/F	5437	5172	-265	-4.9%
W36-LW/F	5614	5233	-381	-6.8%	W36-PW/F	5352	4726	-626	-11.7%
W38-LZ/F	5254	4832	-421	-8.0%	W38-PZ/F	5220	4981	-239	-4.6%
W38-LW/F	5281	4928	-353	-6.7%	W38-PW/F	5134	4979	-155	-3.0%
W40-LZ/F	3202	2825	-376	-11.8%	W40-PZ/F	3029	2718	-312	-10.3%
W40-LW/F	3448	3041	-408	-11.8%	W40-PW/F	3303	3010	-293	-8.9%

Figure 6.
The monthly average forces in case of the shortest stay-cables W1-LW/F and W1-LZ/F

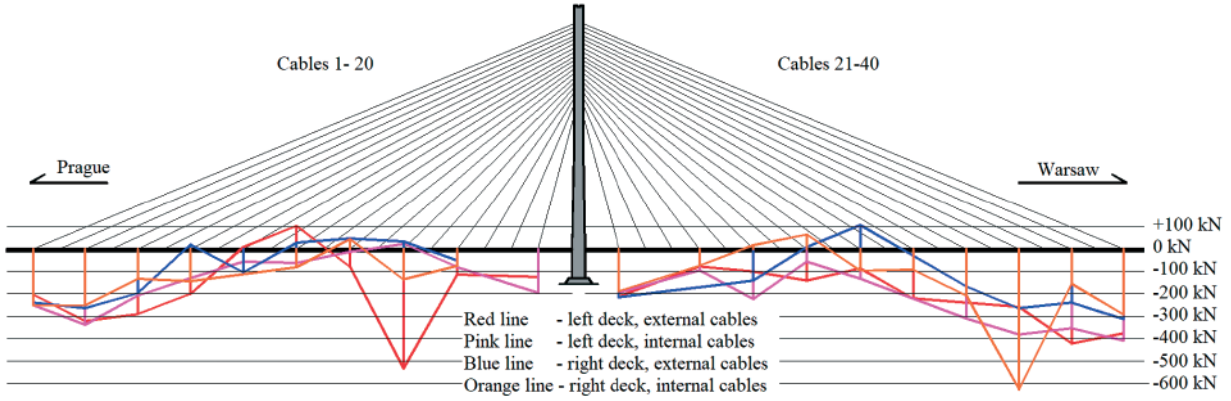


Figure 7.
Change of the monthly average force in cables, in each row

3.1. Cables – forces in strands

The cable stayed system is equipped in 80 force sensors [6]. Over each single deck 20 cables are under the SHM observation. In Table 1 a comparison between the beginning average and the last average force value is presented. Each sensor has its number and code which informs the SHM user about its location. Numbers of the sensors W1-W20 are for the cables from the southern side of the pylon (Prague direction) and numbers W21-W40 are for the northern cables (Warsaw direction; see Fig. 2). The letter L in the sensor code means the left deck, and the P letter means the right deck. Then the letter W means that the sensor is located on the internal cable row of the deck, the letter Z refers to the external cables. The sensor is installed on the reference strand in each cable. The cables were installed using the Isotension method, which guarantees the same force in each strand. If the number of strands in cable is known – a simple calculation allows to define the force in a whole cable.

During the analysis for each measured cable the maximum, minimum and average monthly force value was saved. It was the basis for creating a global overview how the forces in 80 cables have been changing for the first 5 years. Generally a decrease of the force has place. Moreover, during summer the force is increasing, and in winter it is lower again. Figure 6 shows an example how the force in the longest stay-cable is changing. Figure 7 shows the same for the shortest cables.

According to the Figures 5 and 6 and Table 1 it is visible, that the decrease of the force in the longest cables is between 6.4% and 11.8%, whereas in the shortest the differences are between 7.0% and 16.8%. The biggest change had place in the middle cable W12-PW and was about 21.7%. In cables W12-LZ and W28-PZ the change was about 0.2%. Some sensors are not working properly, like W24-PZ/F and W32-PZ/F. The decrease of forces in cables is a natural process caused by shrinking and creeping of the concrete elements of the bridge.

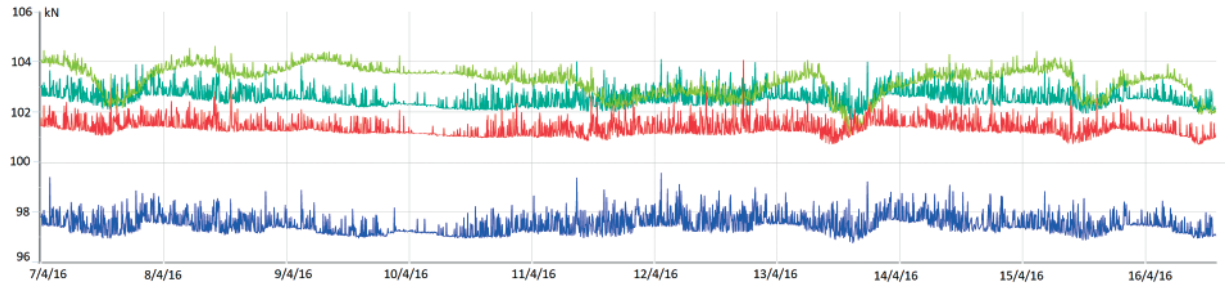
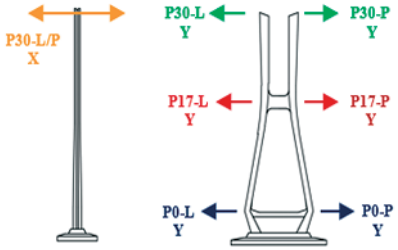


Figure 8.
Forces change between 3/04/2016 and 16/4/2016 in four random cable-stays – a diagram generated using the SHM application

Table 2.
Measured and allowed angular displacements



Sensor	Minimum displacement	Maximum displacement	Maximum designed displacement
P0-L/Tt/Y	-0.01°	0.10°	1.09°
P0-P/Tt/Y	-0.01°	0.05°	1.09°
P17-L/Tt/Y	-0.06°	0.08°	2.74°
P17-P/Tt/Y	-0.06°	0.08°	2.74°
P30-L/Tt/X	-0.09°	0.09°	0.85°
P30-L/Tt/Y	-0.06°	0.04°	1.47°
P30-P/Tt/X	-0.11°	0.08°	0.85°
P30-P/Tt/Y	-0.12°	0.12°	1.47°

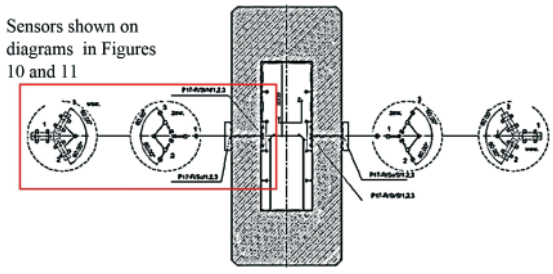


Figure 9.
Sensors in the pylon's cross-beam

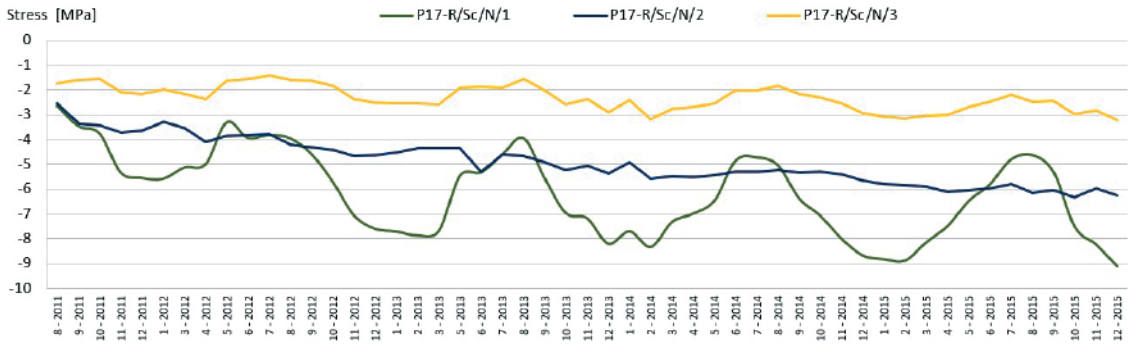


Figure 10.
Monthly average values of stress in concrete for the northern outside cross-beam surface

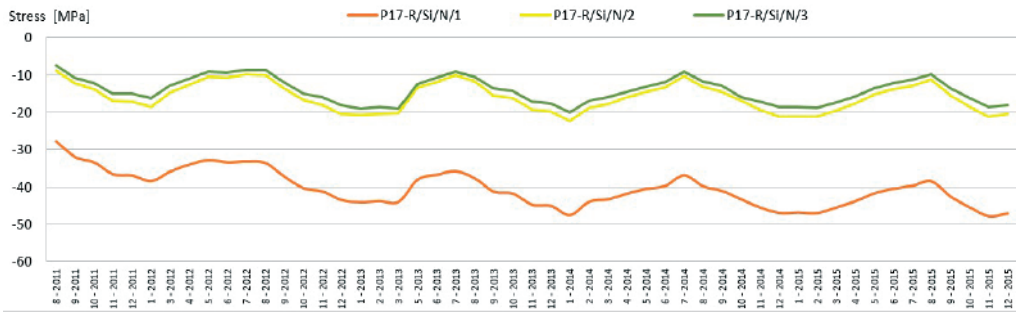


Figure 11.
Monthly average values of stress in steel for the northern outside cross-beam surface

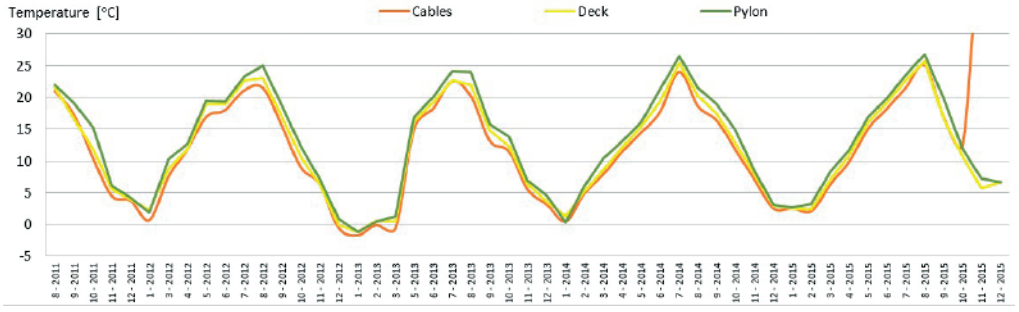


Figure 12.
The monthly average temperature in cables, deck and pylon

Furthermore, the temperature changes of the whole construction in summer and winter are seen as the local extreme values on the diagrams. A similar change is visible in a day/night cycle, which is shown in Figure 8. The change of forces for each cable row is shown in Figure 7.

The measurements from the first 5 years are a basis for an advanced durability assessment of the cable stays in bridges under live loads.

3.2. Pylon – angular displacements

Between August 2011 and December 2015 the extreme monthly values of the angular displacements were measured. In the orthogonal direction (Y in the sensor code) to the pylon surfaces the displacement were measured on 3 levels (Fig. 10):

– on the bottom of the pylon, sensors: P0-L/Tt/Y, P0-P/Tt/Y,
– on the pylon's cross-beam, sensors P17-L/Tt/Y, P17-P/Tt/Y,
– on the top of the pylon, sensors: P30-L/Tt/Y, P30-P/Tt/Y.

In the pylon surface (X in the sensor code) only rotation on the top were measured:

– sensors: P30-L/Tt/X, P30-P/Tt/X.

Table 2 shows the comparison with the allowed values. Measured angular displacements are below maximum designed values.

3.3. Pylon – stresses in the cross-beam

The upper cross-beam of the H-pylon of the Rędziński Bridge is exposed to a big torsion moment. The designer of the bridge decided to construct a steel box inside [2]. Moreover, the cross-beam was pre-stressed with 18 cables. To have a constant overview of the stresses in the structure, sensors were installed inside and outside the box, at the steel and concrete surface. Figure 9 shows the localization of each sensor set. The diagrams in Figure 10 and 11 show, that stresses are slowly increasing in the structure – minus means compressing. The yellow and blue lines describe the values of sensors installed under 60 degrees to the bolt axis. The green line is for the sensor installed in the direction of the cross-beam axis.

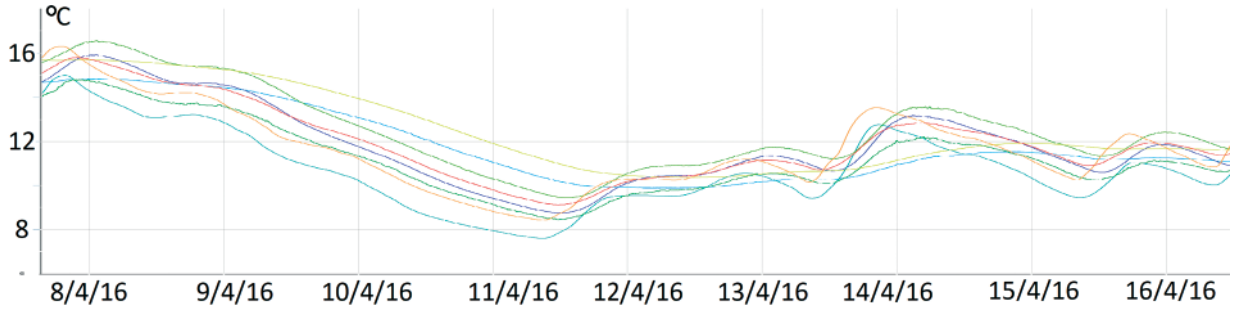


Figure 13.
Two weeks temperature changes in the concrete deck sensors

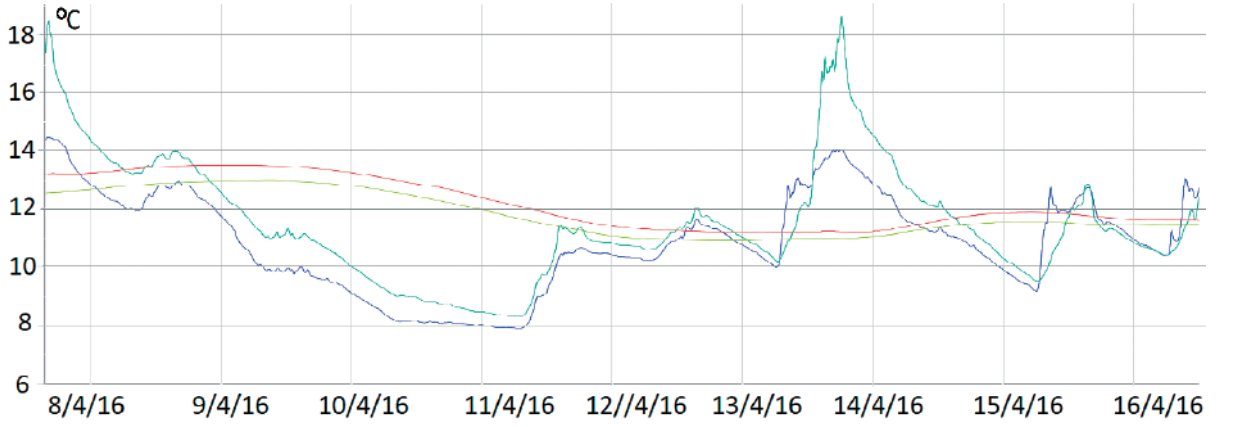


Figure 14.
Two weeks temperature changes in the pylon's cross-beam (in concrete and in steel elements)

Table 3.
Extreme temperatures in each element

Element	Minimum temperature [°C] (February 2015)	Maximum temperature [°C] (August 2015)
Cables	-20.89	44.37
Pylon	-9.05	36.03
Deck	-12.72	33.97

3.4. Temperature comparison between pylon, deck and cables

The 5 years analysis enables a comparison between temperatures in the main structural elements of the bridge. It is an important issue to the Polish Standards, because there is no information about temperature distribution for cable-stayed bridges. Information from the SHM system can be in this case a basis for creating the national attachments for the upcoming Eurocode edition.

A diagram in Fig. 12 shows how the average temperature changed in the cables, deck and pylon. A period of improper work of sensor is visible – the orange line.

In the Polish Standard PN-85/S-10030 for Bridges – the temperature changes for steel elements are from -25°C till 55°C and for the concrete elements from –15°C till 30°C. The Table 3 shows that the temperatures in deck and pylon were higher than allowed. Furthermore short-term temperature changes are also well visible. The diagrams below show how the temperature is changing in the deck structure and pylon between 3rd of April 2016 and 16th of April 2016.

4. CONCLUSION

All measurements were taken in real weather conditions and under real loads by the SHM system. Such an overview gives the opportunity to compare the measured values (stresses in concrete and steel elements, the displacements of the pylon and the deck, the change of forces in cable stays) with each other. A long term observation of the force in cable stays with an additional dynamic analysis made with an FEM-model can be a first assessment of the fatigue durability of steel in these structural elements. SHM

systems are an innovative research method, because they not only give the opportunity to a constant supervision of the bridges, but also enable the engineers and researches to work with reliable measured data. Such investigations are a valuable contribution to modern civil engineering.

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