# The SHM system as a data source for durability assessment. Case study of Rędziński Bridge stay cable system

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**Abstract.** The paper is an introduction to a durability assessment algorithm based on the data collected by a Structural Health Monitoring (SHM) system of a cable-stayed concrete bridge. It contains basic information about the structure of the Rędziński Bridge and its monitoring system. The collected data from the first years are described and analysed. Later the algorithm to assess the durability of stay cables based on probabilistic method is presented.

## **1** Introduction

Important and innovative structures have been built over last decades. The usage of new materials and technologies allowed to create forms that have never been seen before, but working with innovative or improved materials brings some risk in the process of designing, constructing and maintenance, namely the assessment of its durability after years.

Nowadays a lot of older structures detect a number of some damages. The major example [1] is the cable-stayed bridge (1965) in Leverkusen in Germany where the traffic caused fatigue damages in the steel structure. Not only steel structures are sensitive to the effect of time. The Koror-Babeldaob Bridge (1978) collapsed in 1996 [2] because of project changes and the influence of rheology effects. Both examples show how a wrong assessment of loading after many years can affect the durability of a structure.

In the course of structural design the designer is given information about loadings and material properties taken from standards and laboratory experiments. The sources of information about real behaviour of the structure are long-term observations and unfortunately some failures or collapses. But in the last decades things have changed, namely Structural Health Monitoring (SHM) systems have become more common. At the beginning of that technology groups of sensors were installed in some old structures where visible damages had occurred [3]. After years also newly built objects have been equipped in that kind of systems, which have become more reliable and easy to use by the development of the internet. Nowadays SHM systems have become a convenient tool for engineers to supervise all kind of structures, not only bridges but also roof toppings

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of stadiums or motorways. The system provides not only the information how the structure behaves at one moment, but it is also collecting the data and saving it, so the user may enter the SHM application to perform a long-term overview of a chosen structure element and values like stress, temperature or acceleration. At the turn of the 20<sup>th</sup> and 21<sup>st</sup> centuries a lot of major bridges were built in Poland, most of them have been connected to a SHM system, e.g. : the Solidarity Bridge over the Vistula River in Plock (2007) and the John Paul II arch bridge in Puławy also over the Vistula River (2008). After few years operation SHM systems brought data sets fir the researches to work with [4].

The paper presents the SHM system of the Rędziński Bridge. Furthermore an overview of the collected data will be presented and also the first attempt to use the data for durability assessment will be introduced.

## 2 SHM system of the Rędziński Bridge

#### 2.1 The bridge structure

The Rędziński Bridge was built in 2011 and it is the main bridge on the Wrocław ring road motorway. The structure is a concrete cable-stay bridge with spans 49.00 m + + 256.00 m + 49.00 m. The H-shaped pylon is 122.00 m high. The characteristic feature of the bridge are two separate box girder concrete decks under each road suspended to one pylon with 160 stay cables [5].



Fig. 1. General view of the Rędziński Bridge [5].

#### 2.2 The bridge SHM system

Because of its size and outstanding structure the Rędziński Bridge was equipped with 222 sensors. Figure 2 shows the localization of sensors.

The connection with the system is possible by an internet browser application [6] that provides an overview of each sensor. It allows to see alerts and notification if some sensors are not working properly. Furthermore the application makes it possible to create diagrams of the measured values and to export them as .csv files compatible with calculation software.

The data in the system is measured with the frequency of 1 Hz, but only the maximum value form a 5 minutes period is saved on the server. For a long term analysis, a huge database was required, therefore first calculations based on the SHM system have been done after 5 years of use. In this time each sensor has saved on the server over 500000 values of the measured data – forces in cables, accelerations, stress values and temperature values.



## 3 Data analysis

In the years 2016 and 2017 a first complex report about the SHM system was made [7]. The data collected by each sensor was precisely analysed and a comparison with the border values was carried out. The bridge behaves after 6 years unreservedly, but some characteristic phenomena were observed. As anexample, Figure 3 shows how the cable force changes during a month. There is a visible influence of temperature changes on the structure. Figure 4 describes how the global force in cable has changed for the last 5 years. It may have been caused by rheology processes in the decks and pylons. A more particular analysis of force changes is presented in the part 4.



**Fig. 3.** Force changes in cables during December 2017. A diagram taken straight from the SHM application.

Another important observation was made about the temperature differences in elements of the bridge. Figure 5 shows the temperature course in the deck, pylon and a random cable.

After 6 years the extreme values have been noticed and compared to each other, what is shown in Table 1.



Fig. 4. Change of the monthly average force in cables, in each row by the end of 2015.



Fig. 5. The temperature changes in concrete and steel elements in 2017.

Tab.	1.	The	extreme	temperature	values.
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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		

## 4 Durability assessment methods

Bridges are structures that are permanently subjected to moving and changing loads like traffic, wind and temperature. This sorts of loads cause a variable stress in each element, with an influence on the fatigue durability of an entire structure. SHM systems gives the opportunity to create a statistic database for a long-term durability assessment [8]. In a cable-stayed bridge the cables are the most sensitive part. Recently [9] a vast laboratory fatigue tests of cables have been carried out. The work was done under constant force changes and known imperfections in cables, but the diagrams in Figure 3. show how the force in bridge cable is randomly changing. In order to provide a reliable durability assessment not only the value of force is crucial but mostly the force amplitudes. Applying the collected data for a stay cable a diagram of measured stress values was created (Fig. 6). In this case it is one of the shortest cable of the Rędziński Bridge (cable number LZ-W1,

which is the first external cable on the left deck counted from the pylon axis toward Prague). It is visible that the stress range is between 480 [MPa] and 550 [MPa]. After a rain-flow analysis of the force signal a histogram of particular amplitudes was made (Fig. 7).



Fig. 6. Stress histogram.



Fig. 7. Number of occurring amplitudes in the shortest stay cable in years 2011-2016.

According to the Palmgren-Miner rule [10] each cycle  $n_i$  (two amplitudes are a whole cycle) causes a small damage in the steel structure n/N. N is the amount of particular destructive cycles due to the Wöhler curve and n stands for the measured cycles. If D describes the sum of all damages caused by different cycles a simple equation can be formulated, namely:

$$D = \sum_{i=1}^{q} \frac{n_i}{N_i} \tag{1}$$

This equation is used in discret calculations. The diagram in Figure 7. shows obviously the exact amount of calculated cycles, but a more convenient way is to create an amplitude probability density chart  $p(\sigma_a)$  based on the calculated cycles. The probability of each amplitude is described by the equation (2), where  $N_c$  stands for the destroying amount of the cycles that have appeared in the particular cable so far and n is now the function that describes the amount of cycles.

$$P(\sigma_a) = \frac{n}{N_c}$$
 or  $N_c P(\sigma_a) = n$  (2)

In this particular case the probability density equation is described as the exponential one:

$$\frac{dP(\sigma_a)}{d(\sigma_a)} = p(\sigma_a) = \frac{1}{\overline{\sigma_a}} \exp(-\frac{\sigma_a}{\overline{\sigma_a}})$$
(3)

Where  $\overline{\sigma_a}$  is the variable and *s* is the standard deviation of the counted amplitudes. Using a function to describe the course of amplitude values the Palmgren-Miner rule should be described by an integral

$$D = \int \frac{dn}{N} \tag{4}$$

Differentiating the equation (2) by  $d\sigma_a$  a suitable formula is obtained

$$N_c p(\sigma_a) = \frac{dn}{d\sigma_a}$$
 or  $N_c p(\sigma_a) d\sigma_a = dn$  (5)



Fig. 8. Comparison of function *n* with the Wöhler curve [10].

The Wöhler curve is a function that stands for the laboratory assessment of the fatigue endurance for the particular kind of steel. Here Z is the amplitude value reached by  $N_c$  destroying cycles, after which the durability of steel is endless. While the Wöhler curve is described in the logarithmic system the *m* parameter appears in the equations.

$$\left(\frac{\sigma_a}{Z}\right)^m = \frac{N_0}{N} \quad \text{or} \quad \frac{1}{N} = \left(\frac{\sigma_a}{Z}\right)^m \cdot \frac{1}{N_0}$$
(6)

The merging action of the equations (4), (5) and (6) leads to the formula to compute the number of destroying cycles  $N_c$ . Figure 7 shows the function n with the comparison to the Wöhler curve.

$$D = \frac{N_c}{N_0} \int \left(\frac{\sigma_a}{Z}\right)^m p(\sigma_a) d\sigma_a \tag{7}$$

The last equation is a general formula to assess the durability by  $N_c$  cycles that a construction element can stand under current loading conditions. In order to assess the value some assumptions for D and the integration limits should be made. Table 2 shows the chosen values for different durability rules.

A construction element can keep its durability as long as the *n* curve stays below the Wöhler curve. Table 3 shows the example calulation for the durability assessment of the cable LZ-W1. All calcuations were done after each month according to the shown algorithm. The table presents only the months detecting an amplitude increase. The last column of the table presents the durability assessment as a percent value of caculated cycles number in the first shown month (December 2011).

Rule	Palmgren-Miner	Serensen	Haibach
D	1	$a \sim (a_{max}, Z)$	1
integration limits	$\int_{Z}^{\sigma_{amax}} \left(\frac{\sigma_a}{Z}\right)^m p(\sigma_a) d\sigma_a$	$\int_{Z}^{\sigma_{amax}} \left(\frac{\sigma_a}{Z}\right)^m p(\sigma_a) d\sigma_a$	$\int_{\sigma_{amin}}^{Z} \left(\frac{\sigma_{a}}{Z}\right)^{m'} p(\sigma_{a}) d\sigma_{a} + \int_{Z}^{\sigma_{amax}} \left(\frac{\sigma_{a}}{Z}\right)^{m} p(\sigma_{a}) d\sigma_{a}$

Table 2. Parameters for the durability assessment depending on chosen rule [10].

Year	Month	Average amplitude	Standard deviation	Max. ampltude	Min. Ampltude	Average stress	Max. stress	Min. stress	Nc	
		$\overline{\sigma_a}$	a sigma	$\sigma_{a,max}$	$\sigma_{a.min}$	s sr	s max	s min	Number of	of
		[Mpa]	[Mpa]	[Mpa]	[Mpa]	[Mpa]	[Mpa]	[Mpa]	cycles and its percentage coefficient	
2011	December	0,9915	0,9244	25,6814	0	531,9398	575,1542	517,5746	7,29E+14 1	00%
2012	January	0,9618	0,9301	86,5916	0	531,0057	575,1542	365,9283	7,03E+14 9	96%
2012	April	0,959	0,9444	147,6867	0	529,4223	661,3018	365,9283	6,42E+14 8	38%
2012	May	0,9835	1,0424	248,0442	0	529,6494	862,0167	365,9283	3,56E+14 4	19%
2012	June	1,0094	1,1108	313,0618	0	529,5133	1152,7	365,9283	2,43E+14 3	33%
2013	June	0,9933	1,0567	313,0618	0	521,7808	1152,7	365,9283	3,28E+14 4	15%
2014	June	0,9961	1,0124	313,0618	0	514,6963	1152,7	365,9283	4,24E+14 5	58%
2015	June	1,0042	0,9885	313,0618	0	510,5295	1152,7	365,9283	4,89E+14 6	57%
2016	June	1,0178	0,98	313,0618	0	509,7471	1152,7	365,9283	5,09E+14 7	70%
2017	February	1,035	1,0326	313,0618	0	509,6253	1152,7	365,9283	3,76E+14 5	52%
2017	March	1,0374	1,035	488,9305	0	509,5813	1152,7	365,9283	3,71E+14 5	51%
2017	April	1,0385	1,037	488,9305	0	509,5982	1152,7	365,9283	3,67E+14 5	50%

Table 3. Parameters for the durability assessment according to Haibach modification.

## **5** Conclusions

The first assessment completed according to the algorithm shown for the cables LZ-W1, LZ-W14, LZ-W20 (Fig. 9) proves, that after more than 6 years of servise the durability of cables is preserved. The challenge in this case is to predict the durability after next years and decades today. The future work, based on the presentation above, will contain a specific description of the upcoming forces in the structure elements based on statistical data collected by the SHM system.



Fig. 9. The Rędziński Bridge FEM model.

The algorithm shown above is a simple and fast way to assess the durability of staycables based on the values given by the SHM system. The data used is only the total axial force. For an exact and long term assessment a FEM model should be created as a supporting tool. Creating an influence line for the axial force (Fig. 10) in the cables makes it possible to consider the model with the action of the loads estimated on the basis of the SHM system data. Regarding a vehicle traffic forecast for the motorway an assessment for next years can be made. Additionally not only axial force can be estimated, but also the bending moments in the cable anchorages, the most sensitive point of a cable stay. Furthermore using a FEM model the influence of temperature and wind can be evaluated separately.



Fig. 10. Influence line for the axial force in the shortest stay cable WZ-L1.

The aim of the future work is to create a complete algorithm based on the SHM system data and a FEM model allowing to assess the durability of structural elements, not only the cables, under realistic traffic and weather conditions. Furthermore, the algorithm should be suitable for other bridges equipped in SHM systems.

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