RELIABILITY OF BRIDGE IN OPERATION BASED ON STRUCTURAL HEALTH MONITORING SYSTEM DATA

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SUMMARY

The paper presents the author's concept of probabilistic safety assessment of the bridge structure components in the operation phase. The probabilistic models of live loads (traffic loads and thermal actions) were based on the measurement results derived from the SHM system. The developed procedure of using the measurements which enables carrying out the reliability analyses is described. The results of the analyses led to reaching some interesting conclusions about the safety level of the long-span arch bridge in operation.

Keywords: *Steel arch bridge, structural health monitoring system, live loads, thermal actions, reliability analyses.*

1. INTRODUCTION

Continuous increase in number of implementations of structural health monitoring systems on engineering structures, particularly in the last decade, along with the developing technology and monitoring techniques gives a potential of carrying out comprehensive research in many aspects of life-cycle civil engineering. Long-term continuous electronic measurements provide large amount of detailed information related to structure's condition and performance. Therefore, there are many purposes such systems can serve and it seems to be of high significance that the aims of using monitoring system in each specific case are defined and known before designing and implementing such system so that it is both reasonable from the economic point of view and practical in terms of the predicted use of gathered data. Once the aims to be achieved based on the measurements are established, it is crucial to apply suitable tools and procedures.

In the paper, the author's procedure of probabilistic safety assessment of bridge structure components in the operation phase is described. The dead load as well as the live loads were taken into account as the primary operational actions to influence the effort of the structure under exploitation. Those quantities were assumed as random and were treated in probabilistic terms. The main emphasis however was put on live actions models which relied on the measurements obtained from the structural health monitoring system of one selected bridge. The developed procedure enabled carrying out the reliability analysis.

The paper focuses most of all on the key parts of the conducted analysis which refer to probabilistic modelling of the effects of traffic loads and thermal actions. The main assumptions, the results and the conclusions of the preceded reliability analysis are presented as well. As mentioned above, all the research refer to real structure being in operation – the Puławy Bridge, the construction and SHM system details of which are introduced too.

2. PUŁAWY BRIDGE – CONSTRUCTION AND SHM SYSTEM

2.1. Construction of the Puławy Bridge

The Puławy Bridge over the Vistula River is located along the ring road of the town of Puławy, Eastern Poland. The total length of the crossing is 1038.2 m (a fourteen-span continuous bridge) and the main arch river span is 212.0 m being the second longest span among the arch bridges in Poland. The composite deck (22,30 m wide) consists of four plate girders grouped into two tandems (constant height of 3.0 m) and of a reinforced concrete slab. The deck is supported by two steel arch girders by means of 28 bar hanger assemblies. The depth of the box arch girders varies from 2,0 m in the crown to 3,5 m in the thrust and the rise of the arch is 36,0 m. The general view of the bridge is presented in Fig. 1.

***Fig. 1.** General view of the Puławy Bridge (www.vistal.pl).*

2.2. SHM system

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. The system is composed of three subsystems: monitoring of the structure, meteorological monitoring and video monitoring.

The structure's monitoring system gathers 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 and 2D accelerometers, 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 Fig. 2.

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.

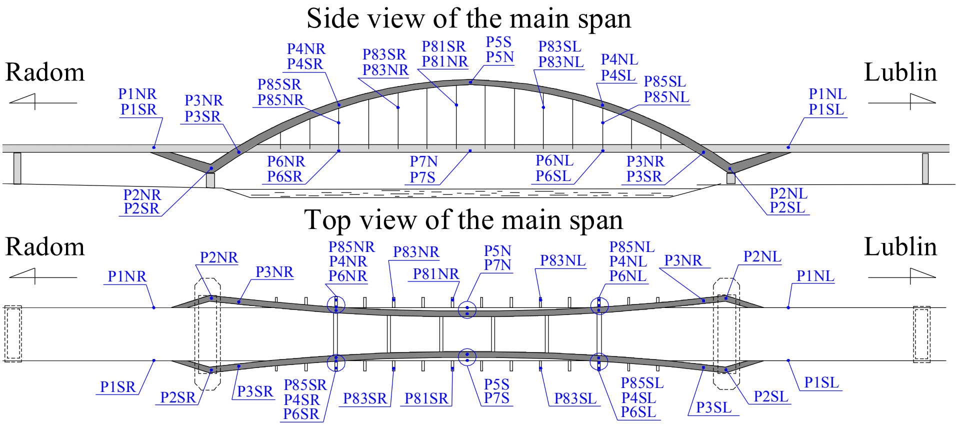

Fig. 2. *Location of the test points on the bridge within the SHM system.*

3. THE METHODOLOGY

3.1. General assumptions

The main aim of the investigations was to develop a procedure of using the measurements obtained from the structural health monitoring system which enables carrying out reliability analyses of the bridge in operation. Within the procedure, the key parts of the research refer to probabilistic modelling of the static effects of traffic loads and thermal actions in the form of normal stresses. What is more, also the effects resulting from the dead load (self weight of the construction) were treated as random (as a result of dimensions' deviations of the component elements of cross sections from the nominal values). The dead load probabilistic model was developed using the Monte Carlo technique for random simulation.

In order to determine the models of the effects of traffic loads and thermal actions, it was necessary, first of all, to identify the values among the derived data resulting from the influence of the mentioned actions and, second of all, to develop algorithms enabling separation of those values from all the gathered measurements. The base for that part of the research were strain measurements in three selected cross sections: crown of the arch, plate girder of the deck (middle of the span length) and central hanger.

The reliability analyses were preceded by determination of the limit state conditions for components in terms of exceeding the material strength parameter by the sum of normal stresses resulting from considered actions.

3.2. Probabilistic model of traffic loads effects

The key part while developing probabilistic model of stresses resulting from traffic loads was to establish which stress changes among all measured values come directly from traffic volume. Initially an assumption was made that those effects manifest themselves in the local peaks noticeable at graphs of stresses (strains), as seen in Fig. 3. In order to verify that assumption, FEM analysis were carried out. Developing the model of real traffic loads occurring on the bridge was necessary for the analysis. The model relied on the literature information referring to classification, stochastic models of vehicle weight, axel weight etc. and to configuration of moving vehicles. It is only to mention that the developed model contains four types of heavy vehicles (trucks) in twelve load schemes. Comparing the results of the numerical analyses with the measured values allowed positive verification of the assumption that the local stress peaks can be evaluated as the result of traffic moving on the bridge.

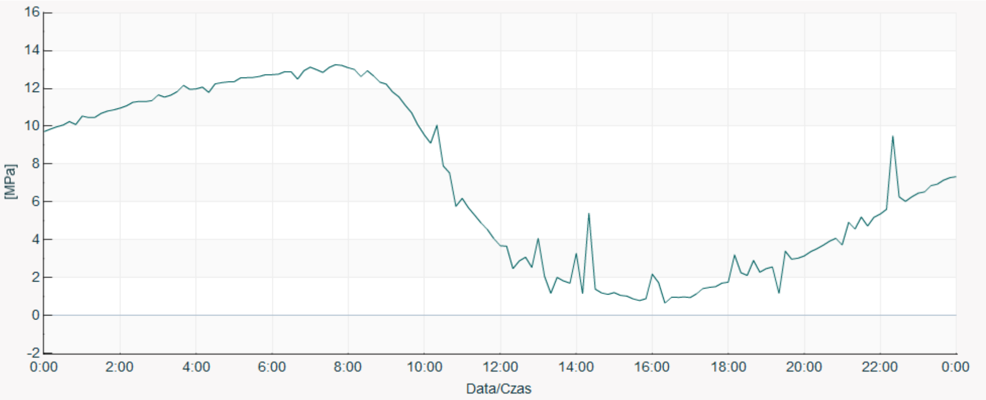

Fig. 3. *The history of the daily stress changes in the deck plate girder.*

The next step was to derive the traffic loads effects from all the gathered data. For that purpose the algorithm of processing data was developed. The identification of peaks was based on finding local extremes in the series of data. In short, the algorithm comprised several steps beginning with exporting measurements from the monitoring system, through deriving identified values and ending with setting them up into the new series of data (respectively for all considered components).

The new series of data were the input for the statistical analyses leading to probabilistic modelling. For two components (crown of the arch and hanger) the traffic loads effects can be approximated with a Gumbel (min.) distribution. The empirical data referring to the deck girder can be fitted equally well to either a gamma or beta distribution.

3.3. Probabilistic model of thermal actions effects

As in the case of modelling of the traffic loads effects, the identifications of values of stresses (strains) that directly result from the thermal actions played the key role. The starting point was ascertaining the sinusoidal character of the construction's temperature variability, analogically to the air temperature. The relationship between air and construction temperature changes can be best observed graphically on the daily basis. The observed interaction led in consequence to initial assumption that thermal actions influence directly the differences in extreme daily stress changes in specific cross sections. In order to verify that assumption, the following step was to carry out the FEM analysis and for this reason the load model reflecting the maximal daily temperature changes by defining vertical temperature distribution in the cross sections of the considered components was developed. The proposed distributions have been developed according to the long-term observations (which led to gaining valuable experience and provided some interesting conclusions) of the temperature changes of the components of the subjective bridge. Due to both the limited number of sensors installed on the bridge and their location in the considered cross sections, some simplifications and assumptions had to be made. The following distributions reflecting the daily temperature changes were determined: for box arch girder the distribution incorporating a uniform temperature component (representing convection and structure thermal conductivity influence; the value of the component is based on the temperature measurements in the thrust, where the sensor is located on the bottom edge of the box and therefore it is not exposed to direct solar radiation – previous long-term observations showed that temperature values on the bottom edge of all cross sections along the arch at considered time are comparable) and a linearly varying temperature difference component (resulting from the solar radiation influence; it was assumed that the value on the top edge of the box is the difference between the value measured in the considered cross section and the value of the uniform component) was determined; for the composite deck girder a uniform temperature component over the steel plate girder was assumed (due to the higher thermal inertia of the concrete slab in relation to the thermal inertia of the steel plate, the daily increase in the slab temperature was assumed zero in relation to the increase in the plate; it was assumed that the main factor to influence the temperature distribution in the steel plate is its orientation in relation to the slab – the steel girders are hidden under the slab, therefore protected from the direct solar radiation influence and the temperature changes are assumed to be determined by convection and thermal conductivity; the values of the temperature component result directly from the measurements in the considered cross section); for the hanger a uniform temperature component was determined.

In the following step the carried FEM computations, based on the proposed model of thermal actions, were to confirm the direct relation between the daily change of stresses and temperature of the construction by comparing the theoretical (calculated, $\Delta\sigma_c$) values of stresses with those measured ($\Delta\sigma_m$) on a specific day. These computations were based on the data derived from the system for several days differing with climatic conditions. Tab. 1 presents the input and output data according to measurements recorded on 15.07.2010. As an example, Fig. 4 illustrates the stress and temperature changes measured that day.

Table 1. *The daily temperature and stress changes measured, theoretical values of stresses.*

Structure's component	**ΔT [°C]**	**$\Delta\sigma_m$ [MPa]**	**$\Delta\sigma_c$ [MPa]**
crown	+32	-27.0	-26.4
deck girder	+5.5	7.5	9.2
hanger	+14	5.0	4.8

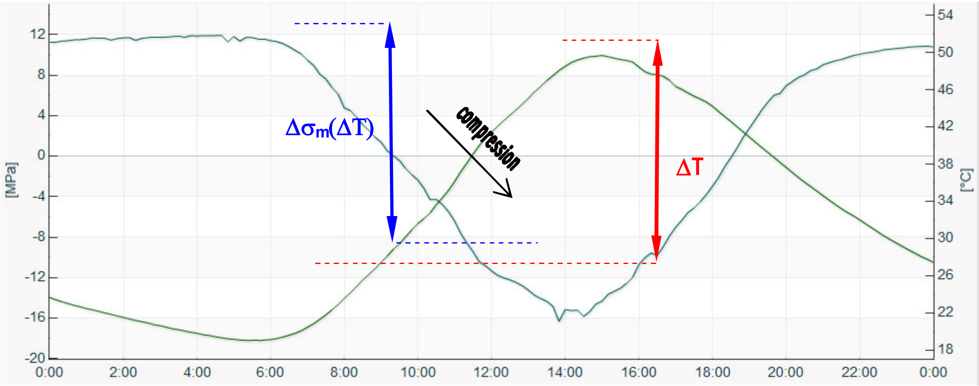

Fig. 4. Stress and temperature measured in crown, 15.07.2010.

For all conducted computations the theoretical values of stress satisfactorily corresponded to the values measured, which allowed positive verification of the assumption of direct relation between the daily change of stresses and the daily change of temperature.

Extracting the daily stress amplitudes from the series of data was the next step in the procedure. For this purpose the rain-flow counting algorithm was applied. However, prior to that it was essential to remove the local extremes (resulting from other actions) from the load history so that they would not be counted into the cycles. This was achieved by using the data smoothing method based on a robust version of local regression that uses weighted linear least squares and assigns lower weight to outliers (Fig. 5). After filtering, the data were set into the new series being the input for the statistical analysis. As a result of the statistical analysis, the thermal actions effects in all considered components were approximated by a beta distribution, the statistical parameters were estimated.

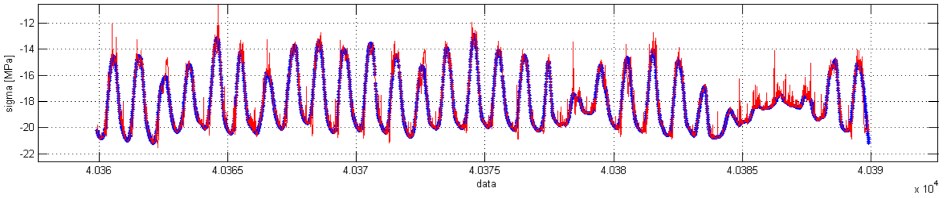

Fig. 5. The history of the monthly stress changes in hanger before and after smoothing.

3.4. Reliability analyses

The reliability analyses (Level 3 probabilistic approaches) were preceded by determination of the limit state conditions in the analyzed sections of the structure in terms of exceeding the material strength parameter by the sum of normal stresses resulting from the concidered loads and actions. The limit state function was fomulated as:

$$Z_i = f_{yi} - \left(\sigma_i(p) + \sigma_i(\Delta T) + \sigma_i(g_o)\right) \tag{1}$$

where f_{yi} is the yield strength of the concidered component, $\sigma_i(p)$, $\sigma_i(\Delta T)$ and $\sigma_i(g_o)$ are the normal stresses resulting from the traffic loads, thermal actions and dead loads respectively.

The probability of occurence of failure p_f as a measure of structure reliability and the corresponding reliability index β were calculated using second-order reliability method as the main one. The relation between p_f and β is given as following:

$$\beta = -\Phi_0^{-1}\left(-p_f\right) \tag{2}$$

where $\Phi^{-1}(\cdot)$ is the standardized normal distribution function. The first-order reliability methods as well as Importance Sampling Monte Carlo techniques were applied for comparison reasons.

The outcomes of the performed SORM analyses indicate larger safety reserves that can be expected in the case of long span bridges taking into account real ranges of operational loads and actions. The obtained values of reliability indexes for all analyzed components considerably exceeded the values for bridges according to the code calibration calculations ($\beta >> 5$). The calculated values of the probability of failure are at the level of $p_f < 10^{-18}$. Obtaining such low probabilities requires precise calculations which in practice are burdened with errors that are commited and compounded in the following stages of calculations. Therefore, the relevant conclusion based on the results is the statement concerning the very low probability of failure and not about the obtained values themselves.

4. CONCLUSIONS

The paper presents the author's concept of bridge reliability assesment based on the measurement data derived from SHM system. The key parts of the proposed methodology refer to probabilistic modelling of effects of traffic loads and thermal actions. In order to reach particular stages, appropriate methods and available tools were used. Furthermore, numerical algorithms were developed, including data identification, data handling, data selection, graphical presentation, statistical analysis, random simulation techniques. The developed procedure combines theorical approach with measurements analyses reffering to real structure being in operation. Therefore, it seems that not only the conducted analyses are of cognitive nature but also the proposed concept can be quite significant from the practical and engineering point of view. The main conclusions based on the performed analyses are as follows:

1) in the case of long span bridges, taking into account the real ranges of operational actions influencing the structure, the higher safety reserves in terms of the exceeding strength parameter can be expected,

2) it seems significant that the minimal values of reliability indexes according to the code calibration calculations, which for bridge structures are at the level $\beta \approx 4$, in the case of long span bridges should be established individually, based on the predicted real ranges of loads and actions on a construction in operation,
3) the experience gained while performing long-lasting measurement data analyses can be the base for the individual calibration of live loads factors for a specific class of bridge construction.