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MONITORING BASED PERFORMANCE INDICATORS FOR THE ASSESSMENT OF JOINTLESS BRIDGE STRUCTURES

Alfred Strauss
University BOKU Vienna, Austria

Roman Wendner
University BOKU Vienna, Austria

Alexander Krawtschuk
University BOKU Vienna, Austria

Simon Hoffmann
MAGEBA, Bülach, Schweiz

Dan M. Frangopol
Lehigh University, Bethlehem, PA, USA

Konrad Bergmeister
University BOKU Vienna, Austria

In structural bridge engineering, maintenance strategies and thus budgetary demands are highly influenced by construction type and quality of design. Nowadays bridge owners and planners tend to include life-cycle cost analyses in their decision processes regarding the overall design trying to optimize structural reliability and durability within financial constraints. However, efforts to reduce maintenance costs over the expected lifetime by adopting well established design principles lead to unknown risks concerning for instance boundary conditions. Smart permanent and short term monitoring concepts can reduce the associated risk of new design concepts by observing the performance of structural components during prescribed time periods. The objectives of this paper are the discussion of concepts for the effective incorporation of monitoring data in model updating procedures by means of the influence line and the model correct factor concept The proposed methodology will be applied to an integrative monitoring system applied on an existing three-span joint less bridge structure.

Keywords: life-cycle cost, structural reliability, maintenance costs, monitoring concepts, influence line, model correct factor

Corresponding author's email: alfred.strauss@boku.ac.at

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Alfred Strauss[1], Roman Wendner[1], Alexander Krawtschuk[1], Konrad Bergmeister[1], and Dan M. Frangopol[2]

[1] University of Natural Ressources and Life Sciences, Vienna, Austria
[2] Lehigh University, Bethlehem, PA, USA

ABSTRACT: In structural bridge engineering, maintenance strategies and thus budgetary demands are highly influenced by construction type and quality of design. Nowadays bridge owners and planners tend to include life-cycle cost analyses in their decision processes regarding the overall design trying to optimize structural reliability and durability within financial constraints. However, efforts to reduce maintenance costs over the expected lifetime by adopting well established design principles lead to unknown risks concerning for instance boundary conditions. Smart permanent and short term monitoring concepts can reduce the associated risk of new design concepts by observing the performance of structural components during prescribed time periods. The objectives of this paper are the discussion of concepts for the effective incorporation of monitoring data in model updating procedures by means of the influence line and the model correct factor concept The proposed methodology will be applied to an integrative monitoring system applied on an existing three-span joint less bridge structure..

1 INTRODUCTION

In recent years major advances have been accomplished in the design, modeling, analysis, monitoring, maintenance and rehabilitation of civil engineering systems. These developments are considered to be at the heart of civil engineering, which is currently undergoing a transition towards a life-cycle and performance oriented design philosophy, in which monitoring is a key element. One of the main tasks of monitoring is the corrective intervention if all or some of the processes, which are observed, don't develop as assumed, e.g. violating predefined thresholds (Santa 2004). The overall objective is to systematically determine and analyze any potential failure causes, failure effects, and worst case scenarios of concatenated failure events in order to derive measures for the installed monitoring system and definition of performance indicators based on influence line and model correction factor concepts.

2 INFLUENCE LINE AND MODEL CORRECTION FACTOR METHODS

2.1 Influence lines

Influence lines serve for the explicit determination of a structure specific mechanical quantity at a defined location, such as an internal moment, shear force or deformation,

due to a defined load magnitude and position. In other words, influence lines allow the easy determination of mechanical quantities for individual loads and load combinations without the use of complex equilibrium and compatibility conditions as used in classical mechanics for statically determined and undetermined systems (Rubin et al. 1996). The generalization of this approach for statically indeterminate systems was formulated by Land (Hirschfeld 2008) as follows: The influence line for an internal force Z_i (e.g., N_i, Q_i, M_i) in i due to a variable load $P = 1$ in space is equal to the bending line $w(x)$ which is caused by the relative displacement in i, $\Delta\delta_I = 1$ (Δu_i, Δw_i, $\Delta\varphi_i$) at the location of the associated internal force Z_i of interest. Influence lines can be generated numerically (e.g. using the Finite Element Method) by the gradual assignment of the mechanical quantity Z_i in i due to the unit load $P = 1$ to the P associated location. For instance, Figure 1(a) shows the comparison between recorded and simulated influence line values associated with sensor d_{7u}, whereas Fig. 1(b) presents the simulated influence line obtained by the Finite Element Model.

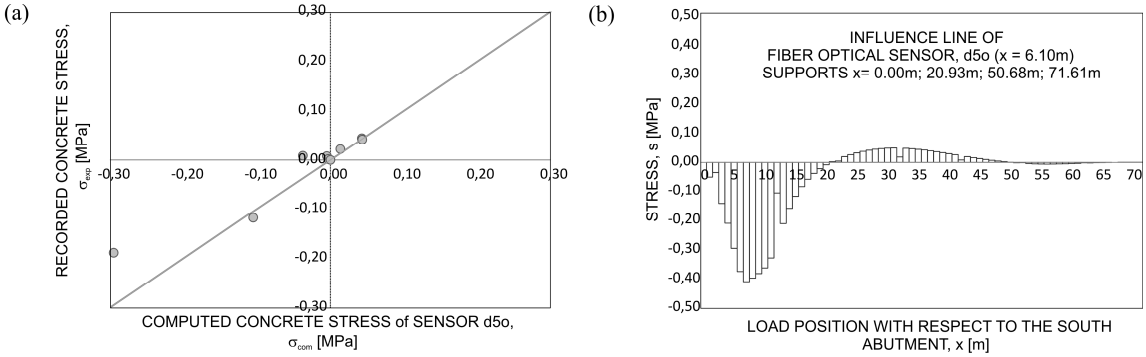

Figure 1:(a) Recorded and computed stress of sensor d_{5o} due to the nine proof loading locations, see Fig. 2(b), on the S33.24 Bridge. (b) Numerically generated influence line for the three span abutment free bridge S33.24 (see Figure 2(a)) along lane 1 for the stress associated with sensor d_{7u} next to the bottom surface of the slab.

2.2 Model correction factors

In general, an initial model layout for the description of e.g. engineering structures will not capture the real behavior due to aleatory and epistemic uncertainties and weak knowledge. These uncertainties can be reduced by engineering knowledge and their experience as well as by computationally intensive model updating procedures using recorded model response. In addition, uncertainties can also be taken into account by model correction factors according to EN1990 Appendix D “Basis of structural design - Design assisted by testing” (2002). The model correction factor based evaluation requires the development of a design model for the theoretical monitored quantity mt of the member or structural detail considered and represented by the model function.

$$m_t = g_{mt}(\mathbf{X}) \tag{1}$$

The model function has to cover all relevant basic variables **X** that affect the design model at the monitoring locations. The basic parameters should be measured or tested. Consequently, there is interest in a comparison between theoretically computed and monitored values. Therefore, the actually measured or tested properties have to be substituted into the design model so as to obtain theoretical values m_{ti} to form the basis

for a comparison with the recorded values m_{ei} from a monitoring system. The representation of the corresponding values (m_{ti}, m_{ei}) on a diagram, as shown in Fig. 1(a) for the recorded and computed stresses due to the nine proof loading locations on the S33.24 bridge, see Fig. 2(b), allows a preassessment of the developed design model. If the design model is exact and complete, then all of the points will lie on the line $\varphi = \pi/4$. In practice the points will show some scatter, as portrayed in Fig. 2(b). However the cause of any systematic deviation from that line should be investigated to check whether this indicates errors in the monitoring system or in the design model. Nevertheless, an estimation of the mean value correction factor b presents the appropriateness of the developed model. The probabilistic model of the monitored quantity m can be represented in the format:

$$m = b \cdot m_t \cdot \delta \tag{2}$$

where b = "Least Squares" best fit to the slope, given by

$$b = \sum m_{ei} \cdot m_{ti} / (\sum m_{ti} \cdot m_{ti}) \tag{3}$$

2.3 Performance indicators in general

It is obvious to assign performance indicators to the recorded quantities of the installed sensors of a monitoring system. In particular, the sensor associated performance indicators, such as the model correction factor b and the characteristic model quantity m_k, provide the basis for (a) the assessment of the ability of the numerical or analytical model to capture the realistic performance, (b) the description of the time variable performance, and (c) the assessment of the performance characteristics with respect to given code specific limit states.

3 THE ABUTMENT FREE BRIDGESYSTEM S33.24 AND PROOFLOADING PROCEDURE (PLP)

3.1 General

The joint less Marktwasser Bridge S33.24 is a foreshore bridge leading to a recently erected Danube crossing which is part of an important highway connection to and from Vienna. The structure actually consists of two structurally separated bridge objects, the wider one of which allows for five lanes of highway traffic. The S33.24 is a three-span continuous plate structures with span lengths of 19.50 m, 28.05 m and 19.50 m orthogonal to the abutment (20.93 m, 29.75 m, 20.93 m parallel to the main axis) as is shown in Fig. 2(a). The top view of the so called "Marktwasser Bridge" shows a crossing angle of 74° between center-line of the deck slab and abutment-axis. Further design aspects of this nonprestressed construction are monolithical connections between bridge deck, pillars and abutments as well as haunches going from a constant construction height of 1.00 m to 1.60 m in the vicinity of the pillars to account for the high restraint moment. The deck width ranges from 19.40 m to 22.70 m excluding two cantilevers of 2.50 m length each. The entire structure is founded on four lines of drilling piles with length of 12.00 m and 19.50 m respectively. Further information about the geometry of the structure is given in (Strauss et al. 2010).

(a) (b)

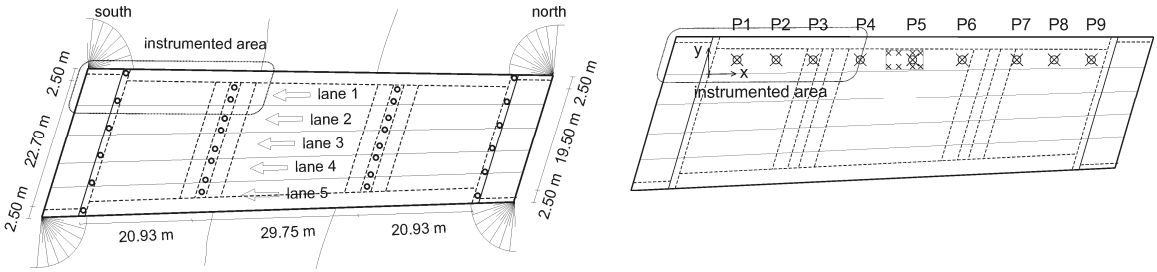

Figure 2: Monitoring installation plan of the Bridge system S33.24; (a) top view indicating the traffic lanes and instrumented area. (b) Static proof loading positions of the vehicles along lane 1 of the bridge system S33.24.

3.2 Proof loading procedure (PLP)

Proof load tests have been performed on Friday, Feb. 19th 2010 between 10:50 a.m. and 14:45 p.m. with ambient temperatures between 0° to 2°C. The results of these proof loadings serve for the calibration of the static linear model and the verification of the assumed structural behavior. The concept for the proof loading procedure was developed with the following goals in mind. Firstly defined load situations with significant structural response were to ensure a proper model calibration mainly with respect to the boundary conditions. As a consequence three 40 to trucks with known axle loads were positioned in 16 static scenarios. The trucks were positioned independently as well as in the most unfavorable configurations on lanes 1 to 3, see Fig. 2. Furthermore dynamic effects and the respective amplification factor should be determined to ensure a proper interpretation of real traffic load effects on the overall performance. To that end in total 35 load scenarios with moving vehicles from walking pace to a speed of approximately 50 km/h were performed. For the model calibration nine static load situations with a single truck of 41.55 to in lane 1 were considered only, see Fig. 2(b). The trucks axle configuration and axle load distribution resulting from deadload and freight is presented in Fig. 2. The stepwise transition along the bridge axis results in an experimental determination of the influence lines for all sensor properties and sensor positions respectively which provide great insight into the system behavior.

3.3 Numerical representation of PLP

The recorded strains during the PLP are influenced not only by the well-defined proof loads but also by dead-load and constraint loads due to constant temperature, temperature gradient and possibly the effects of earth pressure against the abutments as well as partial settlements. In order to account for these contributions all the mentioned load situations are analyzed in the finite element model and subjected to a sensitivity analysis. In total 17 load cases were evaluated. Partial settlement of the four individual bridge axes is considered by a magnitude of 5 mm. Earth pressure against the abutments is accounted for by a linear pressure distribution of up to 25 kN/m² (approximation of active earth pressure). The proof loading scenarios are modeled utilizing the spatial distribution of all eight wheel loads and the respective model points.

3.4 Interpretation of IL with respect to modeling and monitoring

The span by span comparison between simulated influence lines and experimental influence values shows deviations of 10 % to 45 % with respect to the finite element

model, see Figs. 3(a) and (b). Apart from divergences between model and reality (degrees of restraint, stiffness distribution, local stress trajectories not covered by the model) the reasons for the observed deviations may be (a) an inaccurate determination of model points during the proof loading procedure (truck positions), or (b) an insufficiently well calibrated monitoring systems. A single monitoring system does not allow a statement regarding the true nature of the deviation. However, influence lines obtained by a second independent monitoring system (e.g., LVDT deflection measurement in southern lateral span) allow an investigation of the above stated aspects and finally the conclusion whether one of the monitoring systems provides inaccurate or biased data. As the FOS influence lines related to sensors d_{7u} and d_{9o} presented in Figs. 3(a) and (b) and the LVDT influence lines related to sensors w1 and w2 presented in Figs. 4(a) and (b) show qualitatively similar deviations it can be concluded that (a) the calibration of both monitoring systems is adequate, (b) no severe or systematic error is present in the measurements, and (c) the likely cause has to be contributed to modeling.

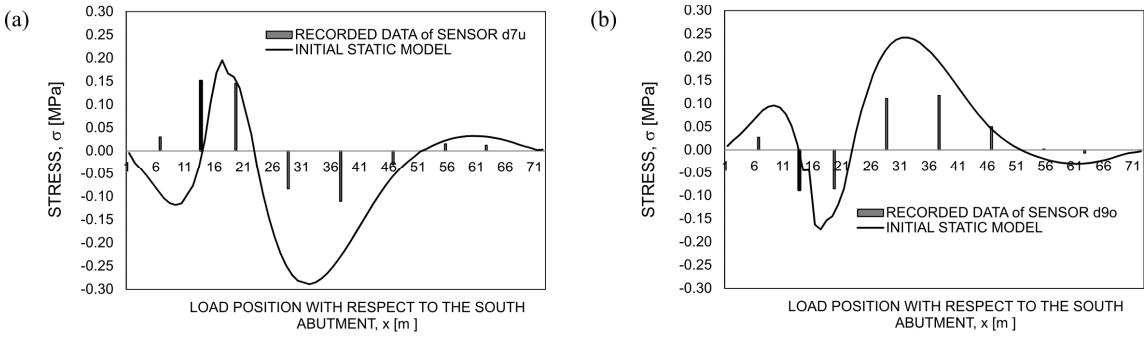

Figure 3: Influence lines (IL) extracted from the Finite Element Model of the bridge system S33.24 (Fig. 4(a)) with respect to the measured values of the nine proof loading positions: (a) IL of stresses associated with the fiber optical sensor d_{7u}; and (b) IL of stresses associated with the fiber optical sensor d_{9o}.

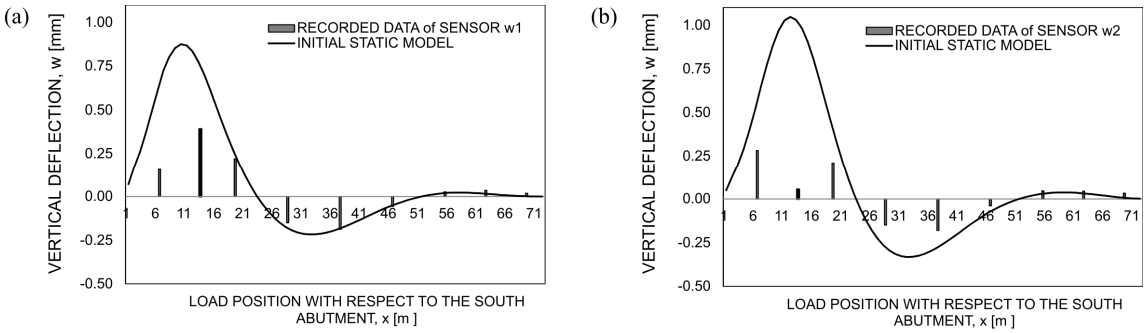

Figure 4: Influence lines (IL) extracted from the Finite Element Model of the bridge system S33.24 (Fig. 2) with respect to the measured values of the nine proof loading positions: (a) IL of vertical deflections associated with the LVDT sensor w1; and (b) IL of vertical deflections associated with the LVDT sensor w2.

3.5 Quantification of goodness of fit – 5 class rating concept

The quantitative comparison of the numerically derived influence line values with the measured values (see previous section) facilitates, as shown in Table 1, an efficient evaluation of modeling concepts and sensor data sensitivity. Table 1 represents a five-class evaluation of the agreement of the measured values with the numerically derived

model values of the sensor properties for the proof loadings. In particular, it shows the evaluation of the influence line values for the measured values of the fiber-optical monitoring system.

3.6 Quantification of goodness of fit – model correction factor approach

A more analytically and statistically based procedure for the quantification of the agreement between numerically generated influence lines and experimentally obtained influence values is provided by the model correction factor concept. The model correction factor allows (a) the assessment of the model behavior with respect to the real structural response, (b) the assessment of the time variable structural performance due to degrading processes based on sensor data, and (c) a limit state analysis with respect to code given requirements. The simulated and recorded sensor characteristics for all nine load proof positions associated with the proof loading of the Bridge-System S33.24 serve for the computation of the model correction factor b as documented in Table 1, which in case of a perfect model (total agreement between numerical and measured quantities) yields $b = 1$. The model correction factor concept facilitates the objectification of the evaluation methods, whose results are shown in Table 1. As advanced statistical analyses are incorporated, the results show minor deviations as compared to the subjective evaluations in Table 1. In agreement with the principles of JCSS a spectrum of values ranging from 0.60 to 1.40 is acceptable due to aleatory and epistemic uncertainties (JCSS 2001, Vrouwenvelder 1997). This corresponds to the limits in between which correlation is usually considered to be significant.

Table 1: Goodness of Fit, given by (a) Subjective assessment, and (b) Model correction factor approach

Sensor	Model Subjective assessment	Model Correction Factor b
d_{2u}	3.5	0.0606
d_{3u}	3.5	0.5819
d_{5u}	3.0	2.1542
d_{7u}	4.0	1.7426
d_{2o}	4.0	0.6418
d_{3o}	4.5	0.1894
d_{5o}	4.5	0.8525
d_{9o}	4.5	1.7072
d_{10o}	3.5	(2.8754)
w_1	2.0	1.1310
w_2	3.0	1.8591
w_3	3.5	2.4504
b_{sys}		0.73

The individual b-values can be summarized with respect to (a) the goodness of fit of an individual model, (b) the capability of an entire monitoring system to represent a certain structural characteristic, or (c) to evaluate single sensors. In that context, an average

quadratic deviation from the perfect fit (b_{sys} = 1) is proposed as system indicator, see Eq. (4).

$$b_{sys} = 1 - \frac{1}{n}\sqrt{\sum_{i=1}^{n}\left(1-b_i\right)^2} \tag{4}$$

From the representations in Table 1, it follows that based on the model correction factor concept, the initial model shows an verall agreement with the monitoring data of b_{sys}= 0.73. Although a horizontal shift in the load position could be suspected based on Figures 3 and 4 further analyses show that no such trend can be identified neither for the system indicator b_{sys}, nor for any of the individual sensors model correction factors b_i. However, the proposed concept based on the influence line and model correction factor concept would have been able to identify this type of error and even to determine the most likely position variation, which could have resulted from (a) an erroneous transformation of coordinates between tachymetric survey, documents and model, or (b) an offset in the stationing caused by the inclined abutment axis and the lateral position of the truck.

Nevertheless, the derived model correction factors lead to the requirement of improving the model in order to accurately predict the real behavior. It is necessary to take into consideration that for certain loading situations, certain sensor arrangements may be irrelevant. A few outliers outside of the defined spectrum have to be accepted. Such outliers however can be eliminated from adaptation procedures e.g. by means of outlier statistics, see Ang and Tang (Ang et al. 2007). The interpretation of the individual *b*-values with respect to the performance of the monitoring systems leads to the conclusion that sensor d_{10o} (see Table 1) exhibits the highest deviation ($b_i >> 2$) from the simulation results and should be excluded from all considerations. In general the FOS based monitoring system with an average performance of b_{sys} = 0.73 provides sligthly more accurate information than the LVDT based influence lines with a system indicator b_{sys} = 0.44. At this point it has to be noted that a good statistical agreement expressed in terms of the system indicator does not necessarily mean a good agreement between model and reality, since (a) opposing effects might cancel each other out, and (b) the sensor itself may be insensitive to certain load situations or structural properties.

4 CONCLUSION

The objective of this article was the investigation of monitoring concepts based on influence lines for the evaluation of the real behavior of engineering structures. In particular, the proposed influence line method and the model correction factor method have been used for the evaluation of the modeling of the jointless bridge system S33.24 based on measurement data. (a) Effective incorporation of monitoring data in model updating procedures: The concepts of influence lines and model correction factors have been theoretically presented and combined to an efficient procedure for the incorporation of monitoring data during the processes of modeling and subsequently assessing a structure's real behavior. The presented methodology was successfully applied to a three-span jointless bridge structure utilizing monitoring data of a proof loading procedure obtained by a fiber optic strain and LVDT based deflection

monitoring system.

(b) IL based model correction factors for the short and long term assessment of structural performance: The presented approach combining the influence line concept with the model correction factor concept for the incorporation of monitoring data into modeling concepts does not only provide the basis for efficient and objective model updating strategies but also is quintessential to the performance assessment of structures over time. As investigations show, some sensors are associated with unfavorable data due to an unfortunate location of the sensor, or an insufficiently accurate model with respect to the monitored quantity. Consequently statistically based testing for outliers is mandatory prior to any assessment procedure. In the presented analyses model correction factors have been determined for individual sensors (b_i) as well as the combined monitoring systems ($b_{sys,i}$) based on a proof loading procedure performed at a discrete point in the life time of the investigated jointless bridge. These partially still biased model correction factors can be considered a first estimation of a performance base line for an optimized future model. The development of these *b*-factors over time allows the identification and even quantification of expected and unforeseen processes with respect to code given requirements based on changes between observed and simulated influence lines (utilizing the optimized model). Influence line based model correction factors thus can be regarded as ideal performance indicators, as suggested by Okasha & Frangopol (2011).

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