4th International Conference on Structural Health Monitoring of Intelligent Infrastructure (SHMII-4) 2009
22-24 July 2009, Zurich, Switzerland

Probabilistic Design Aspects of Jointless Structures associated with Monitoring Information

R. Wendner[1], A. Strauss[1], D.M. Frangopol[2] D. Novak[3] K. Bergmeister[1], M. Reiterer[4]

[1] University of Natural Resources and Life Sciences, Vienna, Austria
[2] Lehigh University Bethlehem, PA, USA [3] Lehigh University Bethlehem, PA, USA
[3] Brno University of Technology, Brno, Czech Republic
[4] RED Bernhard GmbH, Vienna, Austria

ABSTRACT: Recently the construction type "Jointless bridge" has gained much popularity among bridge owners, since reduced costs in maintenance and rehabilitation are to be expected with this design. This is mainly caused by the lack of bearings as well as of expansion joints which generally characterize this construction type together with integral abutments. Nevertheless the acceptance among civil engineers is not that high due to uncertainties regarding numerical modeling, material strength development and structure-soil-interaction. These uncertainties are currently being addressed by (a) monitoring of existing structures to verify existing assumptions, (b) by performing nonlinear finite element simulations and parameter studies, and (c) by probabilistic analyses to determine sensitivity factors in order to efficiently optimize the design. This paper especially deals with probabilistic aspects in nonlinear design of jointless bridges.

1 INTRODUCTION

Due to the international trend towards sustainable and cost-efficient construction work, which is mainly motivated by steadily increasing budgetary constraints, jointless bridges are gaining popularity in Austria as well. The main motivation of using this type of design is the prospect of omitting all details which are especially susceptible to degradation like bearings and expansion joints, thus reducing life-time costs in maintenance. Additionally no traffic obstructions due to construction work concerning this bridge equipment are to be expected.

Since there is little experience in Austria concerning the design of jointless bridges, there is a lot of demand for basic research as well as studies aiming at the verification or adaptation/ improvement of international know-how in order to work out guidelines which meet the national needs. In general, guidelines have to be based on reliability concepts as obtainable from time consuming probabilistic simulations. The simulations have to be based on measured real data as well as on already defined design concepts in order to assure a practice related development of nonlinear structural design.

Such simulations require detailed concepts concerning (a) numerical computations with respect to load cases and material laws, (b) deterministic or probabilistic analyses, (c) the inclusion of geometrical and material nonlinearities, and (d) the incorporation of measured data obtained from real bridge structures via monitoring systems. The incorporation of monitoring information in computational routines and in the design practice will further improve efficiency in design and structural reliability. Subsequently probabilistic aspects in the nonlinear design of jointless bridges as well as uncertainties going along with this approach will be shortly introduced in general and discussed in case of a jointless three-span structure, located close to Vienna.

2 NUMERICAL COMPUTATIONAL CONCEPTS

Generally the design of structures and especially of bridges necessitates computationally intensive numerical simulations which are based on material and load models as specified in current codes like the Euro-Code family (EC0 2002). These models were defined on expert knowledge and usually provide conservative design solutions. Nevertheless, the Euro-Code family (EC0-EC7) allows for more sophisticated nonlinear and probabilistic considerations in order to capture a more realistic structural performance. In general material laws are well researched and defined – e.g. material models implemented in ATENA (Cervenka et al. 2002) – whereas load models often only represent rough estimations of reality thus introducing large uncertainties in the design process. Probabilistic calculations however allow considering uncertainties of all input variables in the simulation and so lead to an estimation of the design parameters which are to be expected as well as their probable variability and the corresponding reliability level. Additionally correlations between input variables like material properties and loads and design parameters like necessary reinforcement area, span length or height of the superstructure are obtained which serve for the efficient optimization of the design. Since nonlinear and probabilistic computational procedures are not too familiar to engineers in practice although they provide the prospect of efficient design and sensitivity based design optimization, the requirement for clearly defined procedures regarding linear and nonlinear probabilistic analyses has to be underlined and will be covered by this paper. Further information concerning code based design is provided in the paper “Nonlinear Design Aspects of Jointless Structures”.

2.1 Nonlinear simulations

Advanced finite element simulations generally are based on a suitable and efficient discretization of the modeled structure. Depending on the level of detail necessary and the scale of the application 2D or 3D models are preferable. An additional choice regards the type of element used. Typically volumetric or shell elements can be chosen, with differing advantages. Depending on the mesh generator used during discretization ordinarily brick or tetras and in 2D models quadrilateral or triangular finite elements are obtained, influencing computational time and quality of results. After having discretized the structure/ model, material laws have to be chosen. In this step simple elastic behavior or more realistic but also more complex laws can be applied. The second paper mentioned in section 2 refers to different material definitions which are available in the engineering software solution SOFISTIK (2004). Other software packages like ATENA (Cervenka et al. 2002) focus more on realistically modeling actual structural response including complex material models such as the fracture-plastic cementitious material, the microplane material model or the Drucker-Prager plasticity model. Of high importance for advanced nonlinear calculations are suitable solution methods for finding the equilibrium like

Newton-Raphson or arc-length. The line-search method accelerates the convergence of the solution which is controlled by energy-based and residua-based criteria (Pukl et al. 2007).

Structural design considering geometric and material nonlinear characteristics has to be based on few critical load case combinations due to computational demands and the fact that superposition can not be applied. Usually the critical load case varies depending on (a) the cross section and even cross-section property, and (b) the limit state (bearing capacity or serviceability). Consequently a strategy to reduce the number of necessary calculations to minimum has to be derived. One such strategy can be summarized by the following steps. First the usual linear code based design and calculations are performed. Based on those, critical cross-sections for the limiting structural properties like deflection or crack width and corresponding load cases can be identified. Finally the nonlinear design is done taking only the identified load cases on the permanent loads into account.

2.2 *In-depth monitoring*

In order to ensure cost-efficient maintenance and a reduction of life-cycle-costs the current as well as the future condition of existing structures need to be known. Consequently the inclusion of monitoring data within the structural performance evaluation is to be addressed, as is the extrapolation of the current condition by prediction functions. Bayesian Updating procedures provide together with probability based quality acceptance methods efficient and powerful tools. These methods can even serve as decision elements for adapting the necessary level of monitoring or even the possible interruption of monitoring.

The in-depth monitoring covers increased traditional visual inspection strategies as well as completely automated permanent monitoring systems. Monitoring systems which are able to capture mechanical (static and dynamic) structural properties (Santa 2004) together with systems monitoring chemical properties (Budelmann et al. 2008) serve as Structural Health Monitoring systems, SHM (Frangopol et al. 2007). For this application the design of the monitoring system itself and of concepts for the evaluation of short as well as long-term data are of high importance (Strauss et al. 2008b, Frangopol et al. 2008). Ultimately the information obtained via monitoring is to be included in detailed numerical models for instance based on probabilistic concepts (Bergmeister et al. 2007, Strauss et al. 2007).

This paper mainly deals with probabilistic aspects of nonlinear design which will supplement in-depth monitoring concepts. The nonlinear design and probabilistic optimization techniques are essential to the efficiency of the construction type “jointless bridge”. In the following, the presented concepts are applied on an integral bridge system, called “Marktwasser Brücke SR 33.24”, located close to Vienna. Information about the state-of-the-art monitoring system installed on this structure as well as first results concerning the comparison of real and assumed structural response are given in “Fibre-Optic Monitoring Systems: Application on a 3-span Jointless Bridges”.

3 APPLICATION

In order to verify current design criteria and improve know-how about jointless bridge design a three-span RC-bridge which is currently being built was instrumented with fiber-optic sensors. Parallely a finite-element model of the structure was set-up and used to reevaluate the design considering material and geometrical nonlinearities as well as the load model according to Eurocode 1 (2004a), see paper “Nonlinear Design Aspects of Jointless Structures”. In this paper the uncertainties in all input variables are accounted for in a probabilistic calculation, the statistical properties of the main design parameters are obtained and sensitivity factors determined.

3.1 Structure – Marktwasser Bridge S33.24

In order to explore the possibilities of a jointless design the operator of Austria's highway network decided to built a prototype of a three-span jointless bridge as foreshore bridge leading to a Danube crossing. The structure is called "Marktwasserbrücke S33.24" and located close to Vienna.

Marktwasser bridge is a three span continuous plate structure with spans of 19.50 m, 28.05 m and 19.50 m respectively. Figure 1 shows the top view as well as the longitudinal cut of structure. The main aspects of the design are a crossing angle of 74° between center-line and integral abutments, a deck width of around 19.37 m excluding two cantilevers of 2.5 m each and a construction height of 1.0 m. Around both middle supports the deck shows a haunch going from 1.0 m to a total of 1.6 m to account for the negative bending moment.

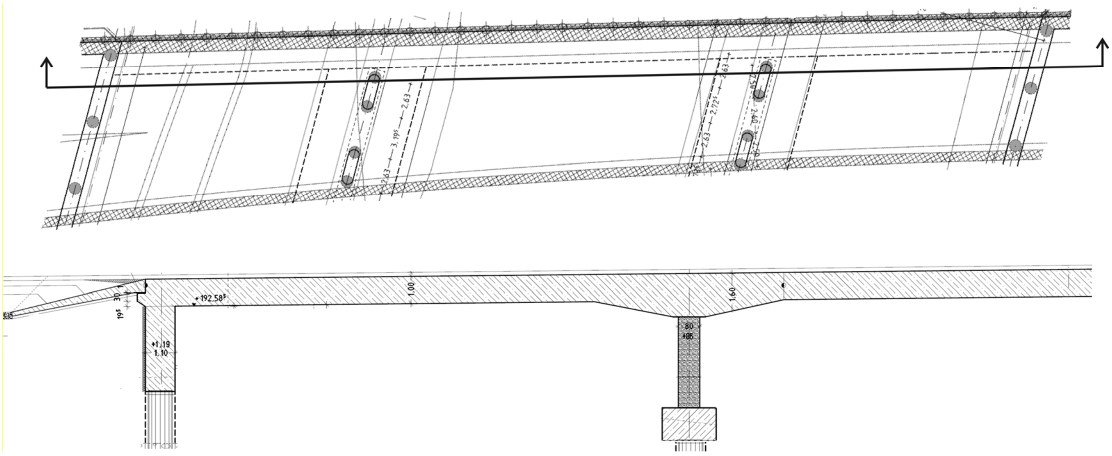

Figure 1. Top View and longitudinal cut of Marktwasser-Bridge S33.24

3.2 Nonlinear simulations - SOFISTIK

Aiming at a realistic study of different design aspects of Marktwasser bridge, a nonlinear 3D model was set up in Sofistik (SOFISTIK 2004) mainly based on beam and shell elements as shown in Figure 2. In order to ensure good convergence and realistic results an automatic mesh refinement in critical areas was applied. The used non-conforming shell elements (quads) are defined by four nodes only, thus reducing computational demands. The performance of the model will be verified with an independent second non-linear model set-up in ATENA.

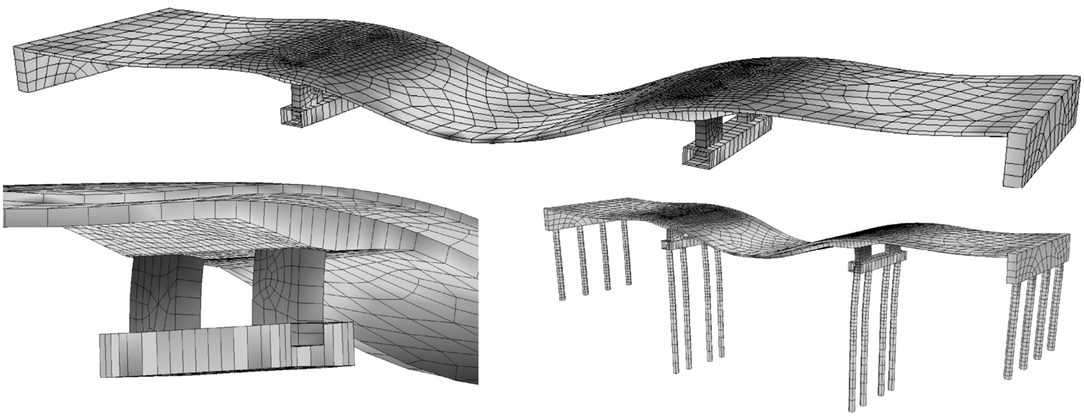

Figure 2. Meshed Finite Element Model in Sofistik (2004)

Material properties were modeled as indicated in Eurocode 2 (2004b) – bilinear law with hardening for steel and a parabolic stress-strain relation for concrete. The tension-stiffening effect is accounted for in the model too.

Due to the fact that Marktwasser bridge is part of the Austrian highway network, apart from deadload, earth pressure, temperature and shrinkage loading mainly is defined by traffic loads according to load models specified in EC1 (ÖNORM EN1991-2 2004a). Consequently trucks, a special purpose vehicle and a crawler vehicle had to be considered. Fortunately, based on linear calculations for various load combinations and load placements only one critical combination of load cases could be determined for both serviceability-related limit states (crack width and deflection). This set of load cases was used for the non-linear calculations and design and included solely the special purpose vehicle with respect to traffic loads. The necessary reinforcement areas which were obtained by nonlinear design are shown in Figure 3. More details regarding the nonlinear design and a comparison with code-based linear design are given in "Nonlinear Design Aspects of Jointless Structures".

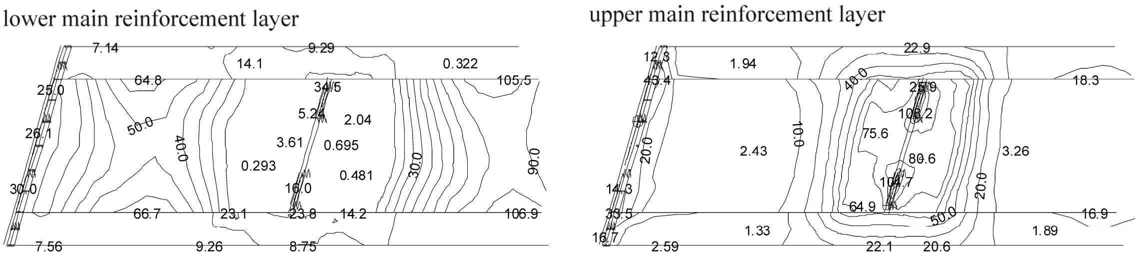

Figure 3. Upper and lower main reinforcement layers

3.3 *Nonlinear simulations - ATENA*

All numerical simulations and models show inaccuracies and only represent reality to a certain extent no matter what the efforts put into the model. Consequently it is advisable to calibrate and check numerical results by real measurement data or at least compare with results originating from an independent second model. To that end the same structure was modelled in ATENA 2D as well as in ATENA 3D, as can be seen in Figure 4. Currently work on these models still is in progress.

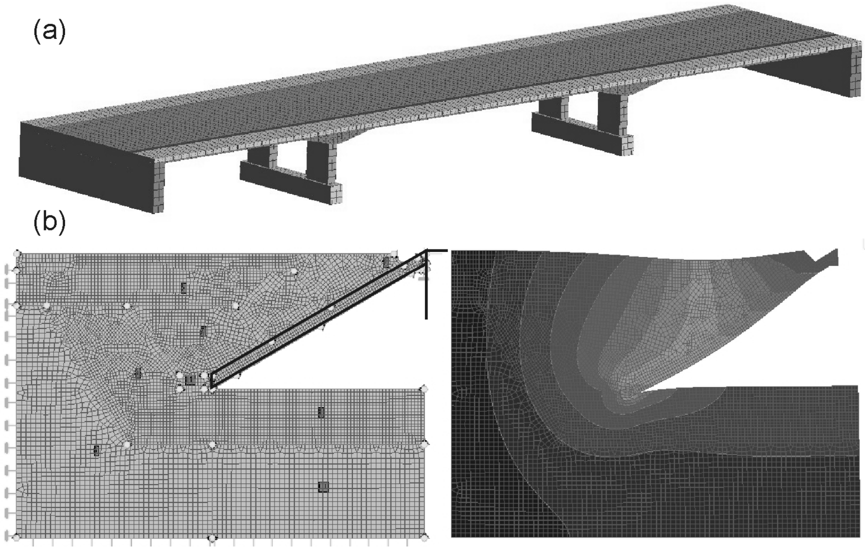

Figure 4. (a) General 3D model of Marktwasser bridge, (b) detailed 2D model of structure-soil-interaction

3.4 Probabilistic model - Sofistik

In order to be able to determine the uncertainties associated with the nonlinear design the input design variables are being considered as random variables described by mean value, coefficient of variation and probability density function (PDF). Since little information is available about the real statistical properties lognormal distributions have been assumed for all variables as well as statistical independence.

Table 1 shows a compilation of the statistical properties of the loads which were considered in the model. All mean values were taken directly from the initial model except of those for wind and the special purpose vehicle. They were recalculated from the initial values using the stated COVs based on the assumption that they represent 90%-fractiles. Solely dead load is kept deterministic.

Table 1. Statistical properties of loads

N°	Description	PDF	Mean	COV
1	Dead load	Det	var.	-
2	Additional dead load	LN	var.	0.12
3	Shrinkage	LN	-15°	0.15
4	Temperature	LN	30°C	0.10
5	Temperature gradient	LN	5°C	0.10
6	Soil pressure	LN	19.78 kN/m²	0.20
7	Wind	LN	9.68	0.15
8	Special purpose vehicle	LN	281,75 kN/m²	0.05

In Table 2 the statistical properties of all random geometrical and material properties are listed. Those include the span lengths L_1 to L_3 which are presumed to be fairly certain resulting in COV=0.02 and the upper h_o and lower h_u concrete cover which are according to JCSS (2000) highly uncertain, thus leading to the assumption of COV=0.18.

Table 2. Statistical properties of geometry and resistance

Property	PDF	Mean	COV
Length of outer spans L_1, L_3	LN	19.50 m	0.02
Length of main span L_2	LN	28.05 m	0.02
upper concrete cover h_o	LN	0.06 m	0.18
Distance between upper reinforcement layers dh_o	LN	0.03 m	0.18
Distance between lower reinforcement layers dh_u	LN	0.03 m	0.18
lower concrete cover h_u	LN	0.06 m	0.18
Compressive Strength f_c	LN	38 N/mm²	0.10
Tensile strength f_t	LN	2.9 N/mm²	0.18
Yield strength f_y	LN	550 N/mm²	0.05

The main material properties affecting design are concrete compressive strength f_c, concrete tensile strength f_t and the yield strength of the reinforcement steel f_y. Scattering of those values was included according to Strauss et al. (2008a).

In order to determine sensitivity factors, a selected number of realizations of all random variables needs to be generated. Due to the computational demands Latin hypercube sampling was chosen, which is ideally suited for the generation of a small number of statistically representative samples (Novák et al. 1998). In this case 60 samples were generated in FREET, a multipurpose software for reliability and sensitivity analysis (Novák et al. 2005). Complete independency between all input variables is assured using simulated annealing.

3.5 Results of probabilistic calculation

The 60 finite element calculations which are necessary for the probabilistic analysis provide an insight in uncertainties included in the optimized design. For instance Table 3 shows the obtained mean values and coefficients of variations, which allows the indication of the uncertainties in results.

Table 3. Statistical properties of design variables

Property	Mean	COV
Max. reinforcement area A_s	108.2 cm²/m	0.09
Max. crack width on upper surface w_o	0.17 mm	0.11
Max. crack width on lower surface w_u	0.09 mm	0.06
Max. deflection in main span u	109.3 mm	0.07

Apart from the determination of uncertainties going along with the optimized nonlinear design it is essential to know to what extent certain input parameters influence the overall result of the design process.

Table 4 shows the variables with the highest impact (by amount) on necessary reinforcement and crack width both on the top and lower side of the plate expressed as sensitivity factors. A_s describes the amount of reinforcement steel, which was necessary at the bottom of the middle of the main span. As can be seen the yield strength of the reinforcement is dominant for all output values followed by the tensile strength for the crack width and the main span length for the reinforcement.

Table 4. Sensitivity factors for reinforcement A_s, cracking w_o/w_u and deflection in main span u_2

Name of variable	A_s	w_o	w_u	u_2
f_y	**-0.80**	**+0.63**	**+0.68**	**+0.46**
f_t	+0.05	**-0.43**	**-0.52**	**-0.45**
L_2	**+0.40**	-0.07	+0.04	**+0.61**
LC 3	-0.03	-0.13	**+0.20**	+0.10
LC 2	**+0.18**	-0.03	**+0.19**	+0.16
LC 5	**-0.10**	**+0.15**	+0.04	+0.05
f_c	+0.04	**+0.14**	-0.01	-0.12
LC 8	+0.08	+0.04	+0.04	**+0.22**

The effects of the random variables on the maximum deflection u_2 in the middle of the main span (see Table 4) the results are not surprising. The main span length L_2 has the most influence, followed by the yield strength f_y and tensile strength f_t. Loads especially the special purpose vehicle (LC8) and additional dead load (LC2) have a higher impact as it is the case for reinforcement and crack width.

Figure 5 provides a visual representation of the scattering data especially showing the positive and negative correlations between input and output variables.

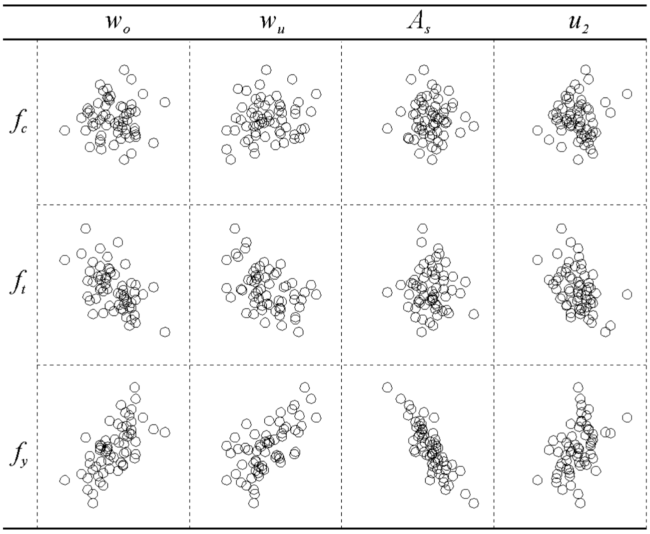

Figure 5. Correlation between material parameters and design variables (A_s=reinforcement area, w_o/w_u=crack width on upper/lower surface, u=deflection)

4 CONCLUSIONS

The paper deals with probabilistic aspects of nonlinear design of jointless bridges. In particular the uncertainties associated with material and load models have been investigated and their effect on different design parameters was evaluated. Furthermore based on probabilistic calculations sensitivity factors between design parameters, loads and structural response were be obtained which could serve for the optimization of the design.

5 ACKNOWLEDGEMENT

The financial aid of the Federal ministry for transport, innovation and technology (BMVIT) as well as ASFINAG are gratefully acknowledged. The authors also want to express their gratitude to ARGE Donaubrücke Traismauer for providing the necessary power supply for the monitoring equipment. The opinions and conclusions presented in this paper are those of the authors and do not necessarily reflect the view of the sponsoring organizations.

REFERENCES

-. 2000. JCSS Probabilistic Model Code Part 3: Resistance Models.

EN 1990. 2002. *Eurocode - Basis of structural design* Brüssel, Belgium

ÖNORM EN 1991-2. 2004a. *Eurocode 1: Einwirkungen auf Tragwerke, Teil 2: Verkehrslasten auf Brücken.*

EN 1992-1-1. 2004b. *Eurocode 2: Design of concrete structures - Part 1-1: General rules and rules for buildings.* Brussels

Bergmeister, K., A. Strauss, N. D. & R. Pukl. 2007. Structural analysis and reliability assessment: SARA part I. In *Structural Health Monitoring & Intelligent Infrastructure, SHMII-3,* eds. B. Bakht & A. A. Mufti. Vancouver, Canada.

Budelmann, H., K. Hariri & T. Starck. 2008. Integration of degradation prognosis of concrete structures into life cycle management. In *IALCCE '08*, 299-304. Varenna, Italy: Taylor & Francis Group, London.

Cervenka, V., J. Cervenka & R. Pukl. 2002. ATENA – A tool for engineering analysis of fracture in concrete. *Sadhana,* 27**,** 485-492.

Frangopol, D. M. & T. B. Messervey. 2007. Integrated life-cycle health monitoring, maintenance, management and cost of civil infrastructure. In *International Symposium on Integrated Life-Cycle Design and Management of Infrastructures*. Tongji University, Shanghai, China.

Frangopol, D. M., A. Strauss & S. Kim. 2008. Use of monitoring extreme data for the performance prediction of structures: General approach. *Engineering Structures,* 30**,** 3644-3653.

Novák, D., B. Teplý & Z. Keršner. 1998. The role of latin hypercube sampling method in reliability engineering. In *ICOSSAR-97*, 403-409. Kyoto, Japan.

FREET program documentation part 2: User manual. Bruno.

Pukl, R., V. Cervenka & J. Cervenka. 2007. Virtual reliability assessment of structures with damage, SARA - part II. In *SHMII-3*. Vancouver.

Santa, U. 2004. Bauwerksinspektion und -überwachung. In *Institut für Konstruktiven Ingenieurbau*. Wien: Universität für Bodenkultur.

SOFISTIK, Statikprogramme, Version 21.0. SOFISTIK AG, Oberschleissheim, Deutschland.

Strauss, A., K. Bergmeister, S. Hoffmann, R. Pukl & D. Novák. 2008a. Advanced life-cycle analysis of existing concrete bridges. *Journal of Materials in Civil Engineering,* 20**,** 9-19.

Strauss, A., D. M. Frangopol & S. Kim. 2008b. Use of monitoring extreme data for the performance prediction of structures: Bayesian updating. *Engineering Structures,* 30**,** 3654-3666.

Strauss, A., S. Hoffmann & R. Wendner. 2007. Structural assessment and reliability analysis for existing engineering structures, applications for real structures. *Structure and Infrastructure Engineering,* 3.