Reliability analysis based identification for bridge assessment

A. Strauss & K. Bergmeister
Department of Civil Engineering + Natural Hazards, Vienna, Austria

ABSTRACT: A complex interdisciplinary approach to the reliability assessment of reinforced concrete structures is introduced and demonstrated on a real existing structure. The reliability index of the structure drops down during its life cycle due to material degradation. A retrofitting to the desired reliability level should be performed. This procedure is modelled by advanced life-cycle computer simulation. The main feature of the presented approach is the nonlinear finite element analysis of the structure employed for the realistic assessment of structural behaviour. A suitable technique of statistical sampling, which allows relatively small number of simulations, is used in this context. Analytical deterioration models combined with in situ monitoring are used to launch the degradation process. The presented methodology for advanced life-cycle analysis integrated in an innovative decision-making tool that supports maintenance planning of bridges and in general of engineering structures.

1 INTRODUCTION

The life cycle reliability assessment is needed by administration of transport infrastructure network operators. The decision-making tools should intercept the degradation and retrofitting process in order to support the maintenance of engineering structures (Frangopol, 2000), see Figure 1.

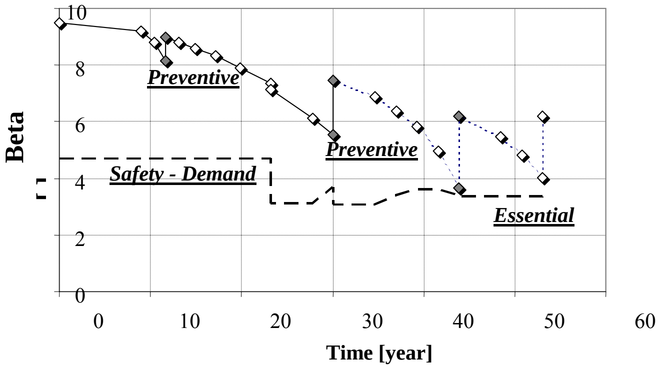

Figure 1. Maintenance – Retrofitting processes

Numerous approaches like the Baysian Updating (Oh et al., 2004), the Monte Carlo Simulation (Petcherchoo et al., 2004) and the Asset Management using multinational Genetic Algorithm (Furuta et al. 2004) have been used for Life Cycle Cost analysis. Since the stochastic models behind these procedures are rather demanding and time consuming, these approaches are commonly based on simplified mechanical models or formulas.

More realistic reliability analysis can be achieved using nonlinear FEM modeling. The life-cycle analysis is a complex task and requires an interdisciplinary approach. It should combine modeling of

- nonlinearities in material
- uncertainties and
- degradation phenomena.

The particular methodologies for the use of probabilistic based assessment are available and have been proven to work in practice (eg. Furuta et al. 2004, fib 2003, Teplý et al. 2003).

The reliability calculation of structures from the stochastically obtained structural resistance and expected load distribution is a transparent and easily understandable concept. The stochastic response requires repeated analyses of the structure with random input parameters to reflect randomness and uncertainties in the input values. A nonlinear computer simulation should be utilized for realistic prediction of structural response and its resistance. As the nonlinear structural analysis is computationally very demanding, a suitable technique of statistical sampling should be used to allow relatively small number of simulations. A special attention is paid to modeling of degradation phenomena, like carbonation of concrete, corrosion of reinforcement, chloride attack, etc.

The main expected results are estimation of structural reliability using reliability index and/or theoretical failure probability during the degradation/retrofitting processes.

The feasibility of the proposed approach is documented on an example of reliability index evolution of an existing highway concrete bridge.

1.1 *Interaction of Methods*

In order to perform a complete life-cycle analysis, a wide spectrum of methods should be used and combined. It must include nonlinear FEM modelling, statistical and reliability techniques and degradation phenomena modelling. The problem is rather complex and requires an interdisciplinary approach and should be accomplished by a health monitoring system. The approach used in this contribution differs from the previous mentioned approaches mainly by the use of nonlinear models describing the real structure. The goal of this approach is a more realistic modelling of the structural behaviour, and consequently of the health index (eg. efficient realistic nonlinear modelling of structures). This method permits a direct link between nonlinear degradation models and nonlinear material behaviour at the “mesoscale”, see Figure.2.

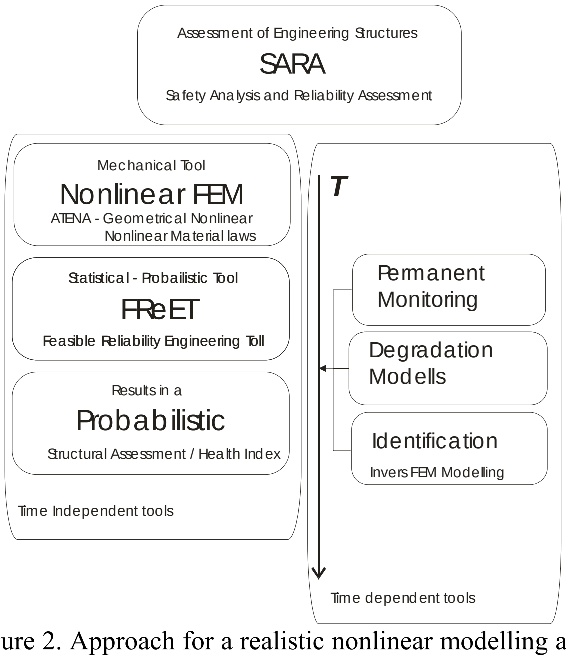

Figure 2. Approach for a realistic nonlinear modelling and reliability analysis

Due to the fact that nonlinear structural analysis is computationally very demanding, a suitable technique of statistical sampling should be used, to allow a relatively small number of simulations. Final results include: statistical characteristics of response (stresses, deflections, crack width etc.), information on dominating and non-dominating variables (sensitivity analysis) and estimation of reliability and theoretical failure probability.

New and/or updated (significantly improved) theoretical statistical and reliability methods, which had to be developed, verified and implemented, are itemized as follows:

- Small-sample simulation (Monte Carlo type) of Latin hypercube sampling for both random variables and random fields
- Statistical correlation using the simulated annealing approach (Vorechovský and Novák, 2003)
- Small number of random variables to represent random fields based on the spectral decomposition of covariance matrix
- Sensitivity analysis based on nonparametric rank-order statistical correlation

The multipurpose probability-based software for statistical sensitivity and reliability analysis of engineering problems FREET (Novák et al., 2002, 2003) is based on the techniques described above. There are three basic parts in the present version of software FREET: stochastic model, sampling and assessment. The basic concepts mentioned above are applied to the example shown in the following.

2 STRUCTURAL ANALYSIS

The nonlinear finite element analysis represents a well established methodology for failure analysis of civil engineering structures in the deterministic sense. The response of the structure under loading and environmental actions can be traced until structural failure. It enables to calculate the structural behaviour under service load (serviceability limit states, SLS) as well as the load carrying capacity of the structure (ultimate limit states, ULS).

Structural concrete is a complex material with strongly nonlinear response even under service load conditions. Therefore, the behaviour of reinforced concrete structures should be analyzed by means of correspondingly advanced technology, taking into account all the important material properties and features: tensile cracking, compressive confinement, reinforcement, including its bond to concrete etc.

One of the most appropriate methodologies for a realistic failure analysis of complex heavy reinforced and pre-stressed concrete structures like bridges seems to be the smeared damage mechanics approach. The main features of the smeared crack modelling of reinforced concrete can be outlined as follows:

- damage mechanics, nonlinear fracture mechanics, enhanced plasticity
- softening in both tension and compression
- smeared crack approach, crack band method
- discrete and smeared reinforcement, bond-slip relationship.

This approach is implemented in the nonlinear finite element software ATENA, which is a tool widely used in practice for realistic computer simulations and predictions of damage and failure of concrete and reinforced concrete structures (Cervenka 2000, 2002). It employs realistic nonlinear constitutive models for concrete and advanced technologies to handle them in an objective way within the framework of the continuum discretization by the finite element method.

The deterministic material properties (characteristic values) for the numerical model are initiated according to the compressive strength with a variety of adjustable parameters. The geometry of the structure is defined in the CAD-like graphical environment with automatic mesh generators. Discrete reinforcement bars and pre-stressing cables can be introduced fully independently on the basic finite element mesh. The model is supported by appropriate boundary conditions and can be subjected to various actions: body forces, shrinkage, prestressing, nodal or linear forces, prescribed deformations and temperature.

The loading actions are combined in incremental load steps, which are iteratively solved using advanced solution methods (modified Newton-Raphson, arc-length, line search) with energetic convergence criteria. Like transducers in reality, “monitoring points” can be added to the model to record the evolution of the behaviuor: deflections, forces, reactions, stresses, strains etc. The load-deflection response can be obtained already during the analysis and the crack growth as well as the crack pattern can be traced. After finishing the analysis, the failure mode and ultimate load are evaluated and detailed information concerning the structural response and the stress-strain state at each loading stage is available.

2.1 *Degradation*

The deterioration can be described through a variety of analytical models, whose main difference is their complexity and the number of input parameters necessary. Models describing the carbonation process of concrete as well as chloride ingress and corrosion of mild and pre-stressed steels are used.

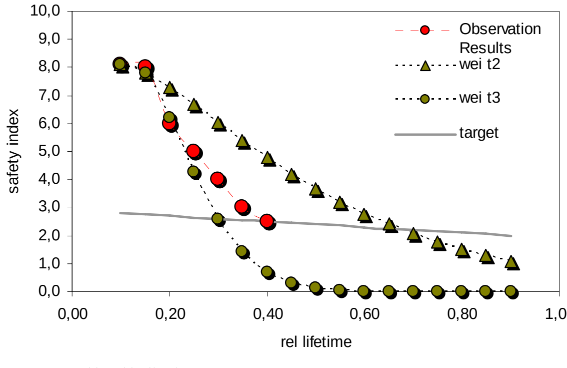

Figure 3. Weibull fitting

The modelling of degradation is focused on simplified models referenced in literature. The exponential distribution is often used as a model of time-to-failure measurements for a structure or parts of an infrastructure, when the failure (hazard) rate is constant over time. When the failure probability varies over time, the Weibull distribution is appropriate. The Weibull distribution is defined as: f(x) = c/b*(x/b)(c-1) * e[-(x/b)^c], for $0 \le x < \infty$, $b > 0$, $c > 0$; where b is the scale parameter, c the shape parameter and e the base of the natural logarithm, sometimes called Euler’s e (2,71). For engineering structures f(x) can be seen as the health index β(t) varying over the time t. Selective results β(t1)… β(tn) from simulations regarding inspection knowledge permit to adapt the parameters b and c. These parameters are continually updated by further simulation and actual inspection results, see Figure 3.

3 RELIABILITY ANALYSIS

The objective of the analysis is to combine nonlinear FEM models taking into account reliability techniques and degradation phenomena, see Figure 1. The whole solution procedure can be itemized as follows:

- The deterministic model of the structure is prepared and checked within ATENA.
- Uncertainties and randomness of the input parameters are modelled as random variables described by their probability density functions (PDF). The result of this step creates the sets of input parameters for ATENA’s computational model random variables described by mean value, variance and other statistical parameters (generally by PDF).
- The random input parameters are generated according to their PDF using LHS sampling. Statistical correlation among the parameters is imposed by using simulated annealing.
- Generated samples of random parameters are used as input sets for ATENA computational model. The complex nonlinear solution is evaluated and selected results (structural response) are saved.
- The previous two steps are repeated for all samples.
- The resulting sets of structural responses from the whole simulation process is statistically evaluated, resulting in: histogram, mean value, variance, coefficient of skewness, empirical cumulative probability density function of the structural response, sensitivity of the structural response to input parameters, reliability index assessment.

The stochastic analysis serves for the instantaneous record of the health condition of a structure. Based on monitoring data, the stochastic analysis will deliver explicit results regarding the time-depending health condition of the structure. If several health conditions at a well-determined time are analyzed, the Weibull fitting will be used for the examination of the remaining lifetime and the degradation process.

By combining the stochastic analysis with analytical deterioration models, an implicit approach is given. Starting from at least one calculated health condition an extrapolation of the degradation behaviour is available.

Both the explicit and the implicit approach are used for retrofitting measurements and consequently lifetime planning. In the case of retrofitting, the stochastic analyses are focused on the point after measurement and the implicit or explicit approach is still valid for the remaining time. The explicit approach seems to be easier to handle, because of the lower number of less necessary input quantities. The solution procedure as described before is implemented in the integrated software system SARA. SARA, together with the implicit and explicit approach, provides a dynamic tool for health evaluation and lifetime planning of engineering structures.

4 APPLICATION ON BRIDGES – STRUCTURAL ANALYSIS WITH INTEGRATED MONITORING

4.1 *Deterministic Model*

The objective of the stochastic fracture analysis for a specific bridge the Colle Isarco Viaduct was to estimate the reliability of the structure and to show the efficiency of the procedures used by SARA. A detailed statistical failure simulation and reliability assessment of this existing bridge structure was performed. The Colle Isarco Viaduct is a cantilever beam bridge in Italy with a total length of 1,000 m. Built in 1969, it is a fully post-tensioned box-girder bridge and is part of the Brenner Highway in Italy.

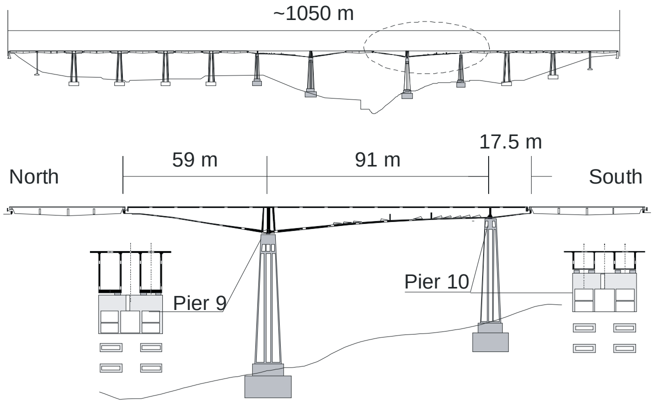

Figure 4. Side elevation of the bridge from the west

The lane slab has a width of 10.60 m and the lower girder slab a width of 6.00 m. Both of them have a thickness of about 0.20 m. The height of the box girder varies from 10.80 m over the middle support to 2.85 m at the end of the cantilever beams.

4.2 *Ultimate limit state*

The assessment of the Ultimate Limit State ULS is based on three structure conditions regarding the degradation degree. The first configuration assumes that the structure undergoes no degradation process. The second case assumes that the area of the prestressing tendons has already been reduced by 17%. The third case presumes a reduction of 33%. The chosen degrees of 17% and 33% damage were estimated without proof from test data. These two damage levels serve as supporting points for interpolating the damage degree.

For achieving a clear defined failure mode, the load history was carried out incrementally. The line load acting on the entire girder has been increased at each step by 10kN/m. The carrying capacity of the structure could be detected by loosing the equilibrium conditions of the simulation process. Consequently, the carrying capacities for each of the calculated individual samples (30) were collected to get a statistical response of the structure. This response is interpreted as the resistance R fitted by a normal distribution. The calculated resistance R was compared with a real traffic loading S to obtain the desired safety index β, see Figure 5.

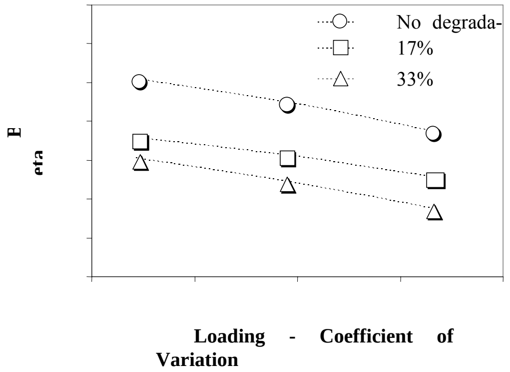

Figure 5. Comparison of the safety index

4.3 *Strengthening measures*

Supposing a safety β-index of 5.6 (4.95 - model uncertainty included) is reached by a damage of already 17%, this safety level will be the trigger for the planning of strengthening efforts to the structure. The simplest way to strengthen a structure is to raise the safety level to the initial safety level. This retrofitting has no direct influence to the proceeding degradation process of the original structure. The increase of the safety level can be obtained by an external pre-stressing system, with 8 tendons 1570/1770 0.6’, as shown in Figure 6. The following procedure summarizes the singular steps for a reliability analysis for bridges in order to achieve a safety level of 4.95 for the next 25 years:

1. Location of the external tendons on the structure
2. Deterministic simulation

3. Quantitative comparison of the deflection behaviour of the undisturbed structure with the deflection behaviour of the retrofitted structure – monitoring points serve as reference points
4. Fitting of the location to balance the quantitative deflection differences
5. Deterministic simulation - in case of poor results repeat point 4
6. Comparison of the loading capacity of the retrofitted structure with the loading capacity of the undisturbed structure
7. Adaptation of tendon cross sections or number of tendons regarding the symmetry to the middle plane
8. Comparison of the loading capacity of the retrofitted structure with the loading capacity of the undisturbed structure - in case of poor results repeat point 7
9. Probabilistic calculation of the retrofitted structure to achieve the safety index of the strengthened structure.

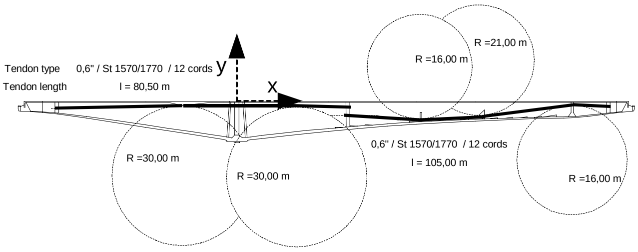

Figure 6. Location of the external pre-stressing system 1570/1770

5 IDENTIFICATION APPROACHES

Additional to the FEM study a permanent monitoring system is recording the strain and deformation conditions at the structure. The recorded data should serve to verify the partly assumed values for the FEM model and to detect the time dependent behaviour of the structure and consequently of the material properties.

Monitoring systems on structures in general only allows to record global structure behaviour, like displacements, vibrations, but not to record directly material or geometrical changes. Based on this weakness a sensitivity based identification algorithm has been developed.

The first steps within this development were based on the comparison of the deformation data from the simulation and the observed data from monitoring.

Due to the sensitivity analyses between the basic variables of the probabilistic simulation and the simulation results the base variables responsible for the differences between the simulation output and the observed data can be derived. Based on this information a tuning of the basic variables for the next simulation can be done.

This iterative process leads to realistic material parameters or geometry parameter for the simulation, which contains the information of monitoring , see Figure 7.

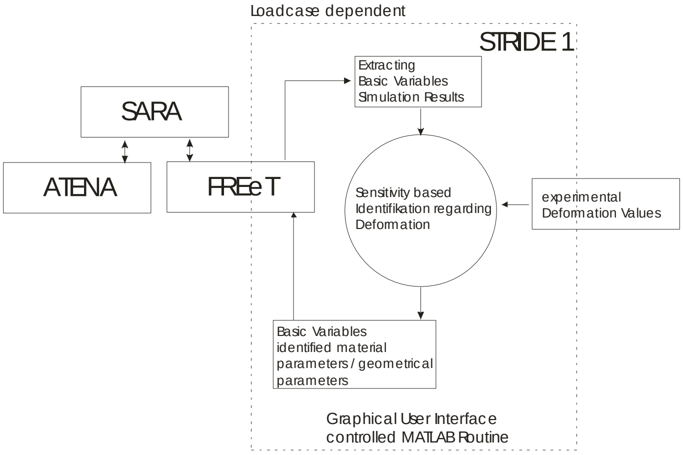

Figure 7. Loadcase dependent identification algorithmen

The disadvantage of this method is that the algorithm need a clearly predefined acting load. The action can be a distribution function but the mean and the standard deviation must be constant. The attempts already carried out to find the real materialparaters from monitoringdaten showed very good results and a high convergence. The search for a burden independent identification possibility led to a correlation coefficient based approach, see Figure 11.

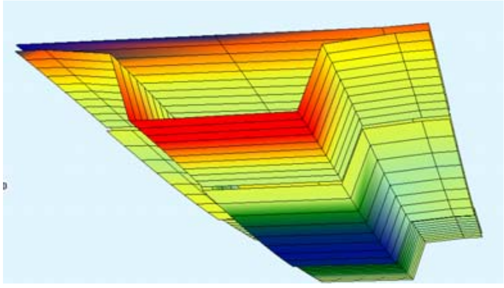

Figure 8. Deformation field of a box girder bridge

Figure 8 shows the strain field of a box girder section. It is obviously that the points of a strain field are in relation which each others. This relations, described by correlation functions are influenced by material properties and damages. Therefore it is evident to use this information to detect the change of material properties or damages at structures.

In the simplest case strain gauges can be applied on a surface within a defined area Ω of e.g. a plate, Figure 9.

These strain gauges are in relation with each other. Therefore a well defined correlation matrix at every time is given. These correlation matrices have a dynamic behaviour over the time, see Figure 11. The dynamic behaviour at an unchanged structure must show a constant process. A sensitivity study referred to the observed correlation fields is used to detect the change of material properties or damages at the structures.

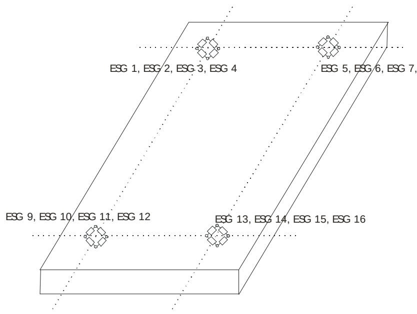

Figure 9. ESG configuration for correlation based identification

Figure 10 shows for the 16 electrical strain gauges the correlation field at a given time. The first plot refers to an undamaged structure, while the second plot shows that some of the correlation coefficients have been dramatically changed.

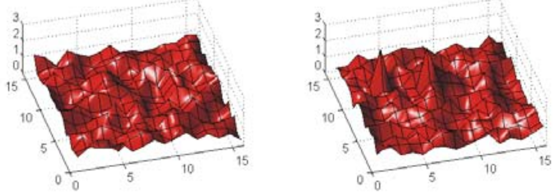

Figure 10. Korrelationsfelder / linkes Bild zeigt Abweichungen

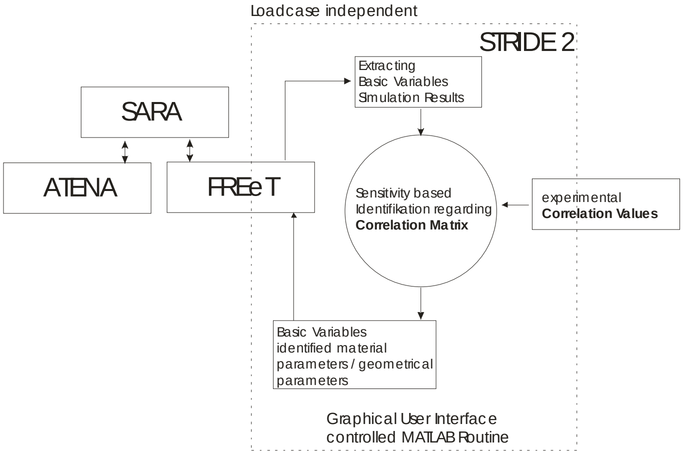

Figure 11. Loadcase independent identification algorithmen

6 CONCLUSION

A complex methodology including nonlinearities in material, uncertainties and degradation phenomena is proposed for advanced life-cycle reliability analysis of reinforced concrete structures. The described methodology is compiled into the software tool SARA for instantaneous practical application. It represents an innovative decision-making tool for the maintenance of structures, which can be very powerful especially in combination with an existing health monitoring system.

Based on selective inspection data, permanent monitoring and degradation models, the phenomenon of degradation and the decrease of the reliability index of bridges in time can be modelled. The concept is powerful to support inverse material detection algorithm to deviate time-dependent material conditions from monitored deflection lines.

7 REFERENCES

Červenka, V. 2000. Simulating a Response. Concrete Engineering International 4 (4): 45-49, 2000.

Červenka, V. 2002 Computer simulation of failure of concrete structures for practice. In The first fib Congress, Osaka, Japan, Session 13: 289-304, 2002.

fib 2003. Monitoring and safety evaluation of existing concrete structures. Bulletin 22, fib, Lausanne, Switzerland. ISBN 2-88394-062-2

Frangopol, D.M. 2000. "Advances in life-cycle reliability-based technology for design and maintenance of structural systems". B.H.V. Topping (ed.) Computational mechanics for the twenty-first century. Edinburgh, UK, Saxe-Coburg Publications, 2000, pp 311-328.

Furuta, H., Kameda, T., Frangopol, D. M. 2004. Optimal maintenance planning of bridge structures based on lifecycle cost and asset management. Bridge Maintenance, Safety, Management and Cost, IABMAS 2004, Taylor&Francis Group, ISBN 041536 336 X.

Novák, D., Rusina, R. & Vořechovský, M. 2003. "Small-sample statistical analysis - software FREET". 9th International Conference on Applications of Statistics and Probability in Civil Engineering (ICASP9), Berkeley, California, USA, July 2003.

Novák, D., Vořechovský, M., Lehký, D. & Rusina, R., Pukl, R. & Červenka, V. 2005. Stochastic nonlinear fracture mechanics finite element analysis of concrete structures. Proceedings of 9th Itn. conf. on Structural Safety and Reliability Icossar 2005, Rome, Italy.

Oh, B.H., Kim, D.W. 2004. Probabilistic Prediction of Structural Performance for Rational Bridge Management System. Bridge Maintenance, Safety, Management and Cost, IABMAS 2004, Taylor&Francis Group, ISBN 041536 336 X.

Petcherdchoo, A., Neves, L. C., Frangopol, D. M. 2004. Combination of probabilistic maintenance actions for minimum life-cycle cost of deteriorating bridges. Bridge Maintenance, Safety, Management and Cost, IABMAS 2004, Taylor&Francis Group, ISBN 041536 336 X.

Teplý, B., Lehký, D., Novák, D., Eichinger, E.M., Kolleger, J., Pukl, R., Cervenka, V. & Stewart, M.G. 2003. Prestressed bridges under corrosion attack. In Nenad Bicanic et al. (eds), Computational modelling of concrete structures (Euro-C 2003), St. Johann in Pongau, Austria:551-558. Lisse:Balkema

Vorechovský, M. & Novák, D. 2003. Statistical correlation in stratified sampling. In 9th International conference on applications of statistics and probability in civil engineering (ICASP9), July 2003, Berkeley, California, USA.