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Reliability/risk assessment of concrete structures: Methodology, software and case study

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ABSTRACT: The paper describes a complex methodology for statistical, reliability and risk analyses of concrete structures. It describes the virtual simulation used on the way from assessment of experimental results to reliability analysis. The whole approach is based on randomization of nonlinear fracture mechanics finite element analysis of concrete structures. Theoretical as well as practical application aspects are presented emphasizing the conceptual framework and key points of solution. Efficient techniques of both nonlinear numerical analysis of concrete structures and stochastic simulation methods of Monte Carlo type have been combined in order to offer an advanced tool for assessment of realistic behaviour of concrete structures from statistical and reliability point of views.

1 INTRODUCTION AND METHODOLOGY

The paper presents targets and recent achievements of project RLACS for a complex methodology for statistical, reliability and risk analyses of concrete structures. It describes the virtual simulation concept and tool used on the way from assessment of experimental results to reliability analysis. The whole approach is based on randomization of nonlinear fracture mechanics finite element analysis of reinforced concrete structures. Efficient techniques of both nonlinear numerical analysis of concrete structures and stochastic simulation methods have been combined in order to offer an advanced tool for assessment of realistic behaviour of concrete structures (e.g. bridges) from reliability and risk points of view

The stochastic response requires repeated analyses of the structure with stochastic input parameters, which reflects randomness and uncertainties in the input values. The system uses the nonlinear computer simulation for realistic prediction of structural response and its resistance. Nonlinear fracture mechanics simulation utilizes state of art techniques including: damage mechanics, fracture mechanics and plasticity material models, smeared crack approach - fictitious crack, crack band method, softening of concrete in both tension and compression, combination of nonlinear concrete behavior with discrete and smeared reinforcement in reinforced concrete and pre-stressed structures. As the nonlinear structural analysis is computationally very demanding, a suitable technique of statistical sampling should be utilized, which allows relatively small number of simulations. Final results are: statistical characteristics of response (stresses, deflections, crack width etc.), information on dominating and non-dominating variables (sensitivity analysis) and estimation of reliability using reliability index and theoretical failure probability).

In order to use appropriate parameters of material laws in the computational model, an inverse analysis based on experiments in a laboratory or in situ has to be performed. A suitable technique for the inverse analysis is the stratified sampling scheme for the modeling of uncertain model parameters combined with artificial neural networks.

The procedure can be outlined as follows:

- experiment (laboratory, in situ)
- development of a deterministic computational model to capture the experiment
- inverse analysis to obtain parameters of the computational model
- deterministic computational model of a structure
- stochastic model of a structure
- statistical, sensitivity and reliability analyses of a structure.

2 SOFTWARE

2.1 General remarks

The authors combined efficient techniques of both nonlinear numerical analysis of engineering structures and stochastic methods to offer an advanced tool for the assessment of the realistic behavior of concrete structures from the reliability point of view. Within the framework of this complex system attention is also paid to the modeling of degradation phenomena, such as carbonation of concrete, corrosion of reinforcement, chloride attack, etc. The combination of all parts (structural analysis, reliability assessment, inverse analysis and degradation modeling) is presented together in a package as the SARA software system. A representation of the program combination within SARA software is presented in Fig. 1. It includes: SARA (Bergmeister et al., 2004, Pukl et al., 2003a,b; Novák et al., 2005) – a software shell which controls the communication between following individual programs: ATENA (Červenka et al., 2007) – FEM nonlinear analysis of concrete structures; FReET (Novák et al., 2010) – the probabilistic engine based on LHS simulation; DLNNET (Lehký, 2009; Novák & Lehký, 2006) – artificial neural network software; FReET-D (Teplý et al., 2006) – degradation module based on FReET.

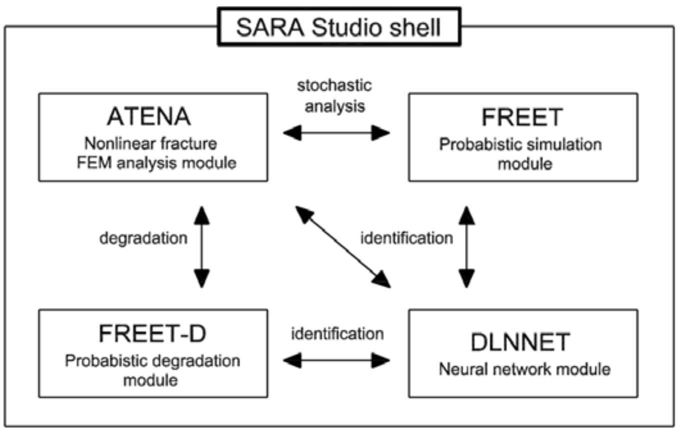

Figure 1. The program combination within SARA software

2.2 FReET – uncertainties simulation

The probabilistic software FReET (Novák et al., 2010) allows simulations of uncertainties of the analyzed problem basically at random variables level (typically in civil/mechanical engineering – material properties, loading, geometrical imperfections). The attention is given to those techniques that are developed for analyses of computationally intensive problems; nonlinear FEM analysis being a typical example. Stratified simulation technique Latin hypercube sampling (LHS) is used in order to keep the number of required simulations at an acceptable level (Novák et al., 1998). This technique can be used for both random variables' and random fields' levels. Statistical correlation is imposed by the stochastic optimization technique – the simulated annealing. Sensitivity analysis is based on nonparametric rank-order correlation coefficients. State-of-the-art probabilistic algorithms are implemented to compute the probabilistic response and reliability. The main features of the software are:

(a) stochastic model (inputs)

- Direct connectivity to the nonlinear analysis input data
- Friendly Graphical User Environment (GUE)
- 30 probability distribution functions (PDF), mostly 2-parametric, some 3-parametric, two 4-parametric (Beta PDF and normal PDF with Weibullian left tail)
- Unified description of random variables optionally by statistical moments or parameters or a combination of moments and parameters
- PDF calculator
- Statistical correlation (also weighting option)
- Categories and comparative values for PDFs
- Basic random variables visualization, including statistical correlation in both Cartesian and parallel coordinates

(b) probabilistic techniques

- Crude Monte Carlo simulation
- Latin Hypercube Sampling (3 alternatives)
- First Order Reliability Method (FORM)
- Curve fitting
- Simulated Annealing
- Bayesian updating

(c) response/limit state function

- Numerical form directly connected to the results of nonlinear FE analysis
- Multiple response functions assessed in same simulation run

For purposes of the RLACS project the FReET software has been enhanced mainly by the possibility of risk/cost analysis. Risk, as the product of theoretical failure probability and cost of failure, and total cost can be calculated for each limit state function defined in task. It enables to compare alternatives of design and to select the best one associated with the lowest risk or with lowest total cost. Total cost calculator consists of summation of cost of planning, cost of execution, cost of maintenance, cost of demolition and restoration to an original state and risk. Number of limit states, associated failure probabilities, risks and total costs is not restricted and they are treated within the framework of one FReET task. The usage of failure probability estimation by alternative techniques (simulation, Cornell´s estimate, FORM, etc.) for risk and cost calculation is fully controlled by the user. Cost/risk table finalizes the usage of software in direction from statistical, sensitivity and reliability analysis towards to risk analysis as decision support tool.

2.3 Nonlinear analysis - ATENA

The existing non-linear finite element code is applied, further developed and combined with tools supplied with other participants. The ATENA software (Červenka et al., 2002, 2007) was developed for realistic simulation of reinforced concrete structures. It is based on the finite element method with non-linear material models, and utilized for analysis of beams and girders, plates and shells, bridges, tunnels, dams, composite structures, strengthenings, structural details, fastenings, fibre reinforced structures, timber and masonry structures etc.

The ATENA software consists of calculating core ensuring the non-linear numerical analysis, and a user-friendly graphical interface for an efficient communication between end-user and program core. The numerical core covers the finite element technology, non-linear material models and non-linear solution. The non-linear material models are based on the orthotropic damage theory and special concrete-related theory of plasticity. As one of the main features the non-linear fracture mechanics is employed for concrete cracking in tension. Based on the fracture energy approach the tensile cracks are modelled as smeared material damage which enables utilization of the continuum mechanics even for the damaged material. Objectivity of the solution is ensured using crack band method. The material law exhibits softening after reaching the tensile strength. The behaviour of concrete in compression is defined by special theory of plasticity (three-parameter model), with non-associated plastic flow rule and softening. This material model for concrete can successfully reproduce also other important effect, such as volume change under plastic compression or compressive confinement. The native graphical user-interface supports all the specifics of reinforced concrete, e.g. input of discrete reinforcing bars, or evaluation of crack patterns in the damaged structural model.

In order to extend ATENA potential and features, the recent development combines the calculating core with AtenaWin runtime environment and a powerful third-party program GiD for pre- and post-processing. The resulting product ATENA Science covers broad range of structural and material behavior in time. It enables to model geometrically complicated shapes and it is suitable for analysis of complex structural problems, such as:

- dynamic implicit analysis
- dynamic eigenvalue analysis
- static stress analysis
- creep analysis
- transport of heat and fluids
- fire analysis.

3 CASE STUDY

3.1 *Marktwasser bridge*

In the course of the project Traismauer-Danube bridge the bridge object S33.24 was erected, Fig. 2. Approx. 400 m south of the foreshore bridge south the newly traced out S33 expressway crosses a backwater called Marktwasser. The current object was originally designed as a 3-span bridge with bearings at both abutments. Due to reasons of maintenance and economic efficiency the executing company proposed to build the bridge as integral structure (without any bearings and dilatations). The spans measured normally to the abutment axes amount to 19.50 + 28.05+ 19.50 m, the inclined spans 20.93 + 29.75 + 20.47 = 71.15 m total span. The object has 2 separate plate structures, the total bridge width amounts to 41.73 m. The crossing angle (S33 axis in relation to the axis of the Marktwasser) approximately amounts to 71.5°.

Figure 2. Marktwasser bridge; the middle section with supports

3.2 *Deterministic computational model*

Using ATENA software package the computational FEM model was developed, Fig. 3. The integral bridge was solved as 2D plane stress problem incorporating quadrilateral elements. The model consists of about 20 000 nodes and the numerical solution was performed using Newton-Raphson algorithm. The load has been increased step-by-step in small increments and in each increment the equilibrium of internal forces was iteratively achieved (iteration limit 40). To model the real technological process first the bodyweight was applied in few steps, later in combination with settlements, temperature and finally the continuous loading was increased until peak. The loading procedure is documented mainly by the load-deflection diagram, several monitoring points along the structure record the deflection and crack opening values. Crack patterns at ultimate load are shown in figure 3.

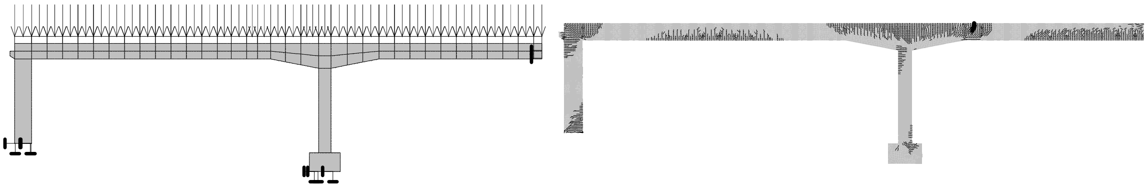

Figure 3. Half-symmetrical topology with constraints and continuous load and crack patterns

3.3 Stochastic computational model

The randomized input variables are presented in Table 1 being described by the mean value, coefficient of variation and probability density function (PDF). Three concrete parameters, elastic modulus, tensile strength and specific fracture energy, including their variability (COV) have been determined by the laboratory tests and the inverse analysis (Lehký et al., 2010). Statistical correlation was considered for selected parameters of concrete, Podroužek et al., 2010. For steel the correlation between elastic modulus and yield stress has been prescribed 0.6. The simulated annealing technique then generated the optimal correlation matrix for 16 random realizations.

Table 1. Selected parameters of concrete

Parameter	Unit	Mean	COV	PDF
Elastic Modulus*	[GPa]	39,5	0.10	N
Poisson's ratio	[-]	0,20	0.05	LN
Tensile strength*	[MPa]	2,90	0.09	Weibull
Compressive strength	[MPa]	28,9	0.10	LN
Specific fracture energy*	[N/m]	178	0.13	Weibull
Uniaxial comp. strain	[-]	0,0018	0.15	LN
Red. of strength	[-]	0,80	0.06	Rect.
Crit. comp. displacement	[m]	0,0005	0.10	LN
Specific material weight	[MN/m^3]	0,023	0.10	LN

* Identification results

3.4 Results

Following the completion of the 16 randomized tasks the statistical evaluation of bridge response has been carried out in the FReET environment. The statistical parameters of response (ultimate load) were estimated and compared. The ultimate load represents the actual resistance of the analyzed structure; the reliability index was assessed under the assumption of normal distribution of load with the coefficient of variation equal to 0.2.

The limit state function for the ultimate capacity was defined as: $g(\mathbf{X}) = R(\mathbf{X}) - E(\mathbf{X})$, where R represents the capacity of the structure, i.e. the calculated response (ultimate load), and E states for the load effect on the structure. Safety index plot (Fig. 4, left) are presented together with the recommended values according to Eurocodes: β = 3.8 as a life time or 50 years target reliability or equivalently β = 4.7 for a one year period with equivalent probability of failure 1.5E-6.

The limit state function for the serviceability was defined as: $g(X) = W_{lim}(\mathbf{X}) - W(\mathbf{X})$, where W_{lim} represents the deflection limit and W states for the calculated deflection corresponding to actual load. Three limiting deflections are compared according to Eurocodes and US Standard Specifications. Eurocodes suggest the deflection limit of span/250 or span/500, respectively. According to the US Standard Specifications the deflection shall be limited to span/360 or span/500, respectively (WSDOT, 2008). Safety index plot (Fig. 4, right) is presented together with the recommended value of β equal to 1.8 from Eurocodes.

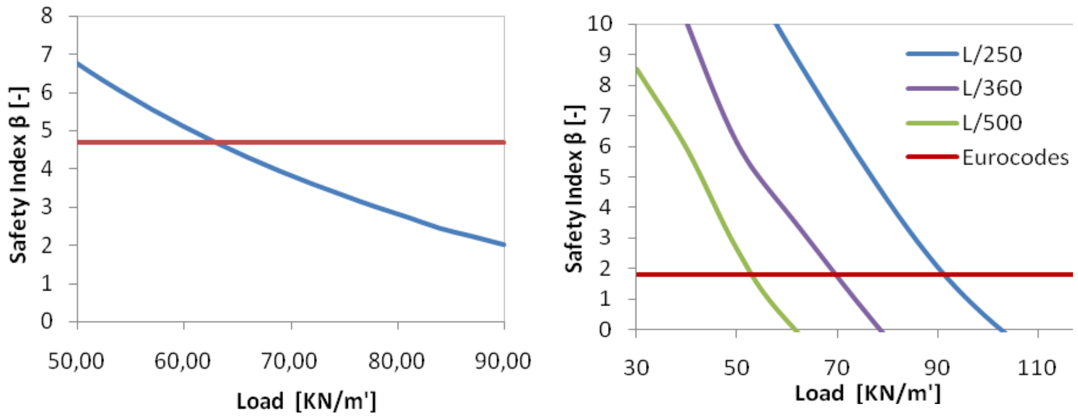

Figure 4. Safety index for ultimate and serviceability limit states

4 CONCLUSIONS

The targets and objectives formulated within RLACS project will be included in a software package usable for the design, management and maintenance of engineering structures. This software will support:

- risk based assessment of structural solutions (e.g., cost optimized components of bridge structures)
- realistic assessment of existing structures within maintenance and cost planning
- predictions of structural performance using identification approaches and monitoring concepts.

The resulting software management tool will allow a cost efficient risk based decision support according to lifetime performance during design and maintenance of structures. The software package developed within the RLACS project will provide a sophisticated tool for an objective risk management in design and maintenance of bridges and other engineering structures. Already during the development partial tools and methods have been used in practical applications (e.g. recently Bergmeister et al., 2010; Strauss et al. 2008, 2009, 2010; Lehký et al., 2010; Podroužek et al., 2010). One of such example is shortly presented in this paper.

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