Reliability based assessment procedure for concrete structures

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Summary

The reliability assessment, which goes well beyond the boundaries of codes can bring a significant amount of money savings and provide new insight into bridge administration and decision-making processes. Therefore an engineering software programme has been developed which allows the reliability assessment of existing structures in an easy way. The software programme combines a non-linear FE-Method with probabilistic calculation tools and a database for stochastic models. The conception of this software programme also allows the inclusion of uncertainties due to inspection and the inclusion of degradation models.

Keywords: Reliability Assessment, Existing Structures, Sensitivity Analysis, Safety Target, Monitoring.

1. Introduction

The general approach for the safety evaluation of existing bridges is based on codes and different specific regulations. It has been found that reliability assessment, which goes well beyond the boundaries of codes can bring a significant amount of money savings and provide a new insight into bridge administration and decision-making processes, Casas et al. [1], Enevoldsen [2], Frangopol [3]. Latest developments show that the optimum balance between the cost and safety of concrete structures, e.g. bridges, is becoming a common problem worldwide. Methodologies for use in probabilistic based assessments are available and have been proven to work in practice. But suitable tools for use in design offices are generally missing. This paper shows the combination of efficient techniques, fracture mechanics, monitoring and reliability engineering to achieve this goal: to assess the realistic behaviour of concrete structures from the reliability point of view. The aim of this paper is to present a procedure that allows the probabilistic-based assessment of structures, which can be used in combination with degradation-models and monitoring data for an efficient life cycling planning. For degradation modelling a function will be presented which allows a continuous updating of the degradation line after each inspection. A further question that will be discussed is the demand of safety features for existing structures. Existing structures have already shown their load capacity. Regarding this thematic area, an approach for required safety indexes was worked out by Strauss [4]. However, it is also possible that the demanded safety index – safety standard is subjected to fluctuations due to social or other influences, such as the ruggedness of the structure and the loading situation, over a longer time period.

2. Probabilistic-Based assessment

2.1. Features and requisition of non-linear FE-analysis + stochastic software

The procedure is based on a recently developed integrated system of non-linear fracture mechanics software ATENA and probabilistic module FREET called SARA (Structural Analysis and Reliability Assessment). The Latin Hypercube Sampling technique, which requires a rather small number of samples for accurate results in the opposite to the statistical Monte Carlo simulation shows an efficient technique to solve non-linear analysis which is computationally intensive. The presented approach has been applied recently for several reliability problems, Novák et al. [5], Pukl et al. [6], [7]. This approach was already used at several problem definitions of engineer nature and provides a deeper insight due to the included sensitivity analysis in the structural behaviour. In the necessary modifications of ATENA for implementation into the SARA system it was a crucial point to keep all of the existing features available, as well as for the repeated stochastic analysis. It was enabled due to versatile programming architecture and the construction of the ATENA system, which supersedes the usual finite element packages. ATENA runs on the Microsoft Windows operating system and its code is written in Microsoft Visual C++. The second essential component of the software programme SARA is the software FREET, which allows the probabilistic treatment of the Finite Element problem. FREET (Feasible Reliability Engineering Efficient Tool) is a multi-purpose probabilistic software for the statistical, sensitivity and reliability analysis of engineering problems. It is based on efficient reliability techniques and is focused on computationally intensive problems, which do not allow the performing of thousands of samples. The software programme FREET and the methods utilized in this programme can be found in Novák et al. [8] and Vořechovský & Novák [9]. Some basic ideas and principles are comprehensively mentioned here.

2.2. Latin hypercube sampling

A special type of numerical probabilistic simulation called Latin Hypercube Sampling (LHS) makes it possible to use only a small number of Monte Carlo simulations. LHS uses the stratification of the theoretical cumulative probability distribution function (CPDF) of input random variables. CPDF for all of the random variables are divided into N equivalent intervals, where N is the number of simulations. Centroids of intervals are then used in the simulation process. The representative parameters of variables are randomly selected based on random permutations of integers 1, 2, ..., j, ., N. Every interval of each variable must be used only once during the simulation, Novák et al. [8].

2.3. Statistical correlation by simulated annealing

Statistical correlation among input random variables can be considered. Stochastic optimisation technique called Simulated Annealing, Vořechovský & Novák [9], is utilized to adjust random samples in such a way that the resulting correlation matrix is as close as possible to the target (user-defined) correlation matrix. Note that the approach allows one to also work with a non-positive definite matrix on input, which can be the result of a lack of knowledge of the user. This technique generates samples as close as possible to a positive definite matrix (mathematically and physically correct).

2.4. Sensitivity analysis

An important task in the structural reliability analysis is to determine the significance of random variables, i.e. how they influence a response function of a specific problem. The dominating and non-dominating random variables can be distinguished. Sensitivity analysis approach based on nonparametric rank-order statistical correlation with a Spearman correlation coefficient or Kendall's tau is employed, Novák et al. [8]. This technique is distribution free and quite robust. Parallel coordinates' representation in the FREET graphical user environment provides an insight into the statistical structure of the relationship between random input variables and the response output variables.

2.5. Reliability assessment

Cornell's reliability index could be calculated in FREET from the limit state function under the assumption of normal probability distribution for both structural resistance and the acting load. Reliability index is estimated from the mean value and standard deviation of the limit state function. Histogram of the safety margin as specified in the limit state function definition can be visualized. The results can be compared with the target reliability index, e.g. 4.7 for 1 year [10]

3. Non-linear stochastic simulation

The programmes FREET and ATENA, as already mentioned, are integrated into the software package SARA (Structural Analysis and Reliability Assessment) in order to allow for a probabilistic non-linear analysis of concrete structures, Pukl et al. [7]. It also enables the degradation analysis of reinforced concrete structures as shown by Teplý et al. [11].

3.1. SARA Studio

An interactive graphical shell SARA Studio was developed in order to assure a well-arranged data exchange and management, as well as control of both mentioned programmes and additional supporting tools. The entire process of the non-linear stochastic simulation is controlled by the user due to the commands and interfaces that are available in SARA Studio.

3.2. Randomisation of input variables

The material properties and other input parameters used in ATENA's deterministic analysis are defined first. These values are exported to FREET, where they are used as mean values for random distributions of the corresponding variables. Further stochastic parameters (variance, type of the probability density function) for selected variables are defined directly in FREET. The randomness of the input variables reflects the uncertainties and randomness of the input values regarding material properties, geometry of the structure, prestressing etc. An integrated database of stochastic parameters for various structural and material properties (concrete, reinforcing steel, prestressing, and geometrical imperfections) is available in order to support the user in preparation of the stochastic input data. The correlation between random input variables can be introduced in the form of the correlation matrix. The number of samples is selected according to the complexity of the problem to be solved and required quality of the expected results. Already 8 samples could provide a reasonable estimation of stochastic parameters of the structural response and reliability index prediction.

3.3. Repeated non-linear solution

In the next step, sets of input parameters for the required number of samples are generated by FREET. SARA Studio prepares the input data for multiple analyses using ATENA. The single samples are consequently solved in ATENA under SARA Studio control. Selected results from the structural response from the ATENA solution (ultimate load, deflection, maximum crack width etc.) are collected. Finally, the obtained results are transferred to FREET and evaluated in the form of histograms of the structural response and sensitivity plots. The reliability index can then be assessed.

3.4. Solution procedure

The entire solution procedure can be itemized as follows:

Deterministic model of the structure is prepared and checked within ATENA.

Uncertainties and randomness of the input parameters are modelled as random variables as described by their probability density functions (PDF). The result of this step is the setting of input parameters for the ATENA computational model – random variables described by mean value, variance and other statistical parameters (generally by PDF).

Random input parameters are generated according to their PDF using LHS sampling. Statistical correlation among the parameters is imposed using simulated annealing.

Generated samples of random parameters are used as inputs for the ATENA computational model. The complex non-linear solution is performed and the selected results (structural response) are saved.

The previous two steps are repeated for all of the samples.

The resulting set of structural responses from the entire simulation process and is then statistically evaluated. The results are: histogram, mean value, variance, coefficient of skewness, empirical cumulative probability density function of structural response, sensitivity evaluation, and the reliability index assessment.

3.5. Example - Application

The feasibility and outcomes of the stochastic fracture analysis are documented on the Colle Isarco Viaduct. A statistical failure simulation and reliability assessment of this existing bridge structure was performed. It is a cantilever beam bridge on the Brenner Motorway in Italy with a length of 167.5 m, see Figure 6. The mid-span has a length of 91 m, the cantilever beams have lengths of 59 m and 17.5 m. Total length of the bridge is 167.5 m. The lane slab has a width of 10.60 m and its thickness is of about 0.20 m. The lower girder slab has a width of 6.00 m and 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 beam. The bridge is cast from concrete B500 and is reinforced with mild steel BST 500. The post-tension tendons system consists of 211 strands of St 1350/1500.

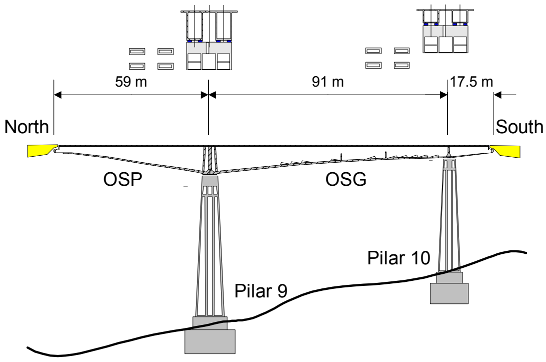

Figure 6 Bridge scheme

3.6. Finite element model

The finite element model was performed with the software programme ATENA. At the first load step the body force and the pre-stressing were applied. In the following loading procedure a prescribed line load – design load taken from the pre-static – of 10 kN/m was increased step by step along the entire lane slab. This process allows one to determine the ultimate failure load ULS. The bridge girder failed typically next to the middle support. First the pre-stressed tendons yielded, tensile cracks developed in the upper flange of the box girder and finally shear failure occurred.

3.7. Stochastic simulations

On the basis of the above-described problem, which was established in ATENA, stochastic simulations with 8 and 30 samples were performed. The material properties, characterized in ATENA, were given as mean values to the SARA Studio. Within the SARA Studio the assignment of statistical parameters such as the standard deviation, coefficient of variation and distribution type regarding the recommendations by CEB, fib, RILEM etc. were performed. Statistical properties of the random variables, see Table 1, originated mostly from the database available in the SARA Studio.

Table 1. Basic random variables.

Variable*	Units	Mean	CoV	Distribution
E_c	GPa	37.0	0.15	Lognormal
f_t	MPa	3.26	0.18	Weibull
f_c	MPa	42.5	0.10	Lognormal
G_f	N/m	85.0	0.20	Weibull
ρ	MN/m^3	0.023	0.10	Normal
E_s	GPa	210	0.03	Lognormal
f_{ys}	MPa	500	0.05	Lognormal
f_{yp}	MPa	1350	0.03	Lognormal

* Notation of random variables
Concrete:
Ec Modulus of elasticity ft Tensile strength
fc Compressive strength Gf Fracture energy
ρ Specific material weight

Table 2. Correlation of random variables.

Variable*	E_c	f_t	f_c	G_f
E_c	1	0.7	0.9	0.5
f_t	0.698	1	0.8	0.9
f_c	0.896	0.798	1	0.6
G_f	0.500	0.892	0.601	1

Prestressed Steel:
E_s Modulus of elasticity f_{yp} Yield strength
Reinforcement:
E_s Modulus of elasticity f_{yS} Yield strength

Since in reality there are interactions between the random parameters it is important to take care of them by the simulation of real behaviours. SARA encourages the formulation of correlations between material parameters. The prescribed correlation matrix is shown in the upper triangle of Table 2. The lower triangle of Table 2 shows the correlation matrix generated by simulating the annealing for 30 samples. In the non-linear simulations (samples) the relationship between the applied line load and the vertical displacement at selected points has been monitored. The ultimate load and post-peak behaviour (descending branch) have been obtained. The bridge girder failed as already mentioned for the deterministic investigation, typically next to the middle support. In the probabilistic consideration another effect could be observed. There were two different failure modes - failure by bending and failure by shear - appeared side to side.

3.8. Selected results

For the reliability analysis of a structure it is necessary to choose certain observation points within the structure. These points are described as monitoring points within ATENA. Every load increment is permitted to represent structure specific values such as stress, strain, displacement etc. in a diagram. The results of the last load level – calculated in ATENA for the randomised problems (10-100 samples) - belonging to the monitoring points are returned to the SARA studio. The statistical analysis and the sensitivity analysis are carried out within the Sara Studio with the help of the programme module FREET. Therefore, the statistical response values and the authoritative influence parameters due to the sensitivity analysis are known in the monitoring points after the probabilistic analysis with SARA.

Ultimate Limit State ULS

For the determination of the Ultimate Limit State ULS of this structure the line load of 10 kN/m was, as required for non-linear calculation, increased step by step until the collapse of the structure. At the first calculation cycle the elements are assumed to be in good condition. The stochastic input quantities result from existing test reports from the monitoring information and from the developed database. The formulation of the limit state function for the ULS was made by the confrontation of the response values of the monitoring point 5 with the design line load. The design line load was described by a lognormal distribution, a mean value of 10 kN/m and a coefficient of variance from 0.05 to 0.15. This modelling delivered a safety index β of 11.96, which was far above the values demanded in the codes, see Figure 9. Recent examinations pointed out, however, that a certain percentage of prestressed cables is damaged. This fact was the reason for another simulation of the ULS. Under the assumption of 30 percent damaged prestressed cables the simulation delivers a safety index β of 6.00. This result seems to not be dangerous. However, a detailed view of Figure 9 shows that there is a dangerous development of the safety standard.

4. Reliability based assessment method

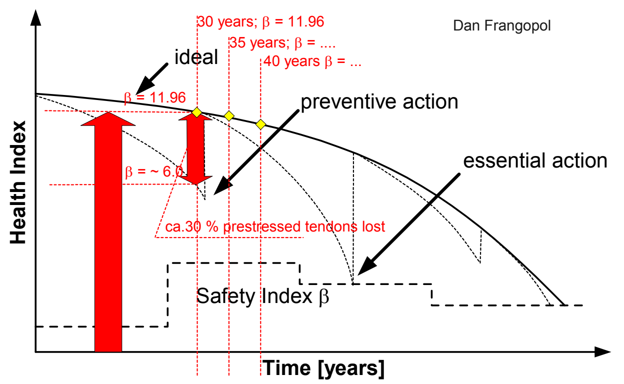

Figure 9. Time dependent safety index β

These degradation-lines are decision tools for the preservation and therefore also for lifetime planning. E.g. the degradation-lines can be described by Weibull-functions in which the information, obtained from every inspection, can be included into the Weibull-parameter. So after each inspection, a continuously updating of the degradation line is possible. For the example discussed here the received results of the SARA calculation were the basis for the following strengthening. As a strengthening measure the external prestressed tendons were arranged.

Table 4. Approach for the safety target regarding the structural conditions

$\beta = 4.7 - (\Delta_M + \Delta_D + \Delta_S + \Delta_L) \geq 3.5$ (ULS) $\beta = 3.0 - 0.8*(\Delta_M + \Delta_D + \Delta_S + \Delta_L) \geq 1.8$ (SLS)	
Monitoring	Δ_M
continuous control of the critical elements	0.5
annual control of the critical elements with a visible early warning	0.25
annual control of the critical elements without a visible early warning	0.1
Control every two years.	0
Ductile	Δ_D
high Ductile	0.5
low Ductile	0
System carrying behaviour, ruggedness	Δ_S
high ruggedness, element failure leads to system-change-System has a redundant behaviour	0.5
middle ruggedness, several elements must fail so that the collapse enters	0.25
low ruggedness, failure of the element immediately leads to the collapse.	0
Loads	Δ_L
(Translate)	0
Sondertransporte – seltenes Ereignis (z.B. 1 mal pro Jahr); maximal 20% über Normbelastung	0.1
seltene und gleichzeitig wirkende Einwirkungen (Sondertransporte + z.B. Wind bzw. Schnee)	0.2

5. Conclusion

The previous considerations have referred to a safety index β of 4.70 for a reference time of one year. These demands are formulated in new structural codes and refer to new structures based on current social needs. However, is it also possible that the demanded safety index – safety standard is subjected to fluctuations due to social or other influences, such as the ruggedness of the structure and the loading situation, over a longer time period, see figure 9.

A further question would be: Is it necessary for existing structures to demand the same safety features as new ones? Existing structures have already shown their load capacity. Regarding this thematic area, an approach for required safety indexes was worked out by Strauss [4], see Table 4.

6. Combination of the monitoring data with the modelling

This simulation method described here needs stochastic models for the description of the material identification values. The information from the monitoring offers the possibility of adapting the stochastic models obtained from the initial quality controls and also receiving closer information about their time dependence. Of great advantage for the facilities of the stochastic models is the execution of loading tests in which are given. The stochastic variable will be emphasised by loading tests and therefore the spread widths can correspond to the burden position of the loading test delimited experimentally.

7. Literature

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