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STRUCTURAL ANALYSIS AND RELIABILITY ASSESSMENT, SARA PART I

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Abstract

The paper describes a complex methodology for statistical and reliability analyses of concrete bridges. It describes the virtual simulation used on the way from assessment of experimental results to reliability analysis. The 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. In order to use appropriate parameters of material laws in computational model and/or damage assessment, an inverse analysis based on dynamic experiment has to be performed. The applications of the approach are described in consequent papers of SHMII-3 2007 conference – Parts II-VI. This session introductory paper informs on development and achievements of a large long-term project SARA (Structural Analysis and Reliability Assessment).

INTRODUCTION

During the last few decades practical methods for the reliability assessment of structural infrastructure have been developed to assist engineers in probabilistic analysis. A complex interdisciplinary approach to the reliability assessment of reinforced concrete structures is introduced and demonstrated. The reliability index of the structure decreases during its life cycle due to material degradation. A retrofitting to the desired reliability level should be performed. This procedure is modeled by an advanced life-cycle computer simulation. The main feature of the presented approach is the nonlinear finite element analysis of the structures employed for the realistic assessment of structural behavior. A suitable technique of statistical sampling, which allows relatively small numbers of simulations, is used in this context. Inverse analysis is necessary for the knowledge of model parameters and damage identification.

The concept presented here uses the nonlinear computer simulation for realistic prediction of structural response and its resistance. The nonlinear numerical analysis utilizes the current state-of-the-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 (expensive evaluation of the structural response). The 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 experiment in laboratory or in situ has to be performed. A suitable technique for the inverse analysis based on the experimental data is the stratified sampling scheme for modeling of uncertain model parameters combined with artificial neural networks.

In this paper, the description of systematic complex treatment of concrete structures is presented. Keystones of the procedure include:
- health monitoring
- virtual structural nonlinear simulation using deterministic computational model
- dynamic damage identification
- statistical, sensitivity and reliability analyses of a structure.

The first aim of the paper is to describe a conceptual framework of this complex approach. Second, the software package that came into existence is briefly presented. It is represented basically by a combination of reliability package FREET (Novák et al. 2003) and nonlinear software ATENA (Červenka 2003, Červenka & Pukl 2006). The methods were integrated within the complex software system SARA (Novák at al. 2002, 2005, Pukl et al. 2003a b, Bergmeister at al. 2004).

The paper informs on development of a large long-term project SARA (Structural Analysis and Reliability Assessment). Project achievements are summarized and software tools are briefly described. Details and applications are provided in consequent parts II-VI of SHMII-3 2007 conference.

TOOLS

Efficient techniques of both nonlinear numerical analysis of engineering structures and stochastic methods have been combined to offer an advanced tool for assessment of realistic behavior of concrete structures from reliability point of view. Within the framework of this complex system attention is also paid to modeling of degradation phenomena, like 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 under the name of SARA software system. The sketch of program combination within SARA software is presented in Fig. 1. It includes:

- SARA (Novák et al. 2002, Pukl et al. 2003ab, Bergmeister et al. 2004) – software shell which controls the communication between programs listed bellow;
- ATENA (Červenka 2003, Červenka & Pukl 2006) – FEM nonlinear analysis of concrete structures;
- FREET (Novák et al. 2003, 2005) – probabilistic engine of the system based on LHS simulation;
- DLNNET (Lehký 2007) – artificial neural networks software;
- FREET-D (Teplý et al. 2007) – concrete degradation module based on FREET.

Beyond this SARA shell there are also developments regarding alternative ways of damage identification. One of them is STRIDE, an algorithm that is based on sensitivity factor utilization for model updating (Strauss et al., 2004).

ARA has already a history of about 5 years. The main parts within the first development were the nonlinear FEM ATENA (consequent paper – Part II), the statistical package FREET (Part II), the operation of monitoring programs at existing structures, the development of a stochastic database for materials of engineering and the application of these concept on existing structures (Bergmeister et al., 2004) to demonstrate the practicability of this concept. Fig. 2a shows the main parts of this fundamental concept. The experiences obtained during the development processes as well as the responses from users of SARA have given impulses to extend this original concept to a more comprehensive tool including maintenance, inverse analysis, etc.

There have been the requirements for time dependent degradation models (FREET - D presented in consequent paper – Part VI) as well as 3D considerations (ATENA 3D presented in consequent paper – Part II), see Fig. 2b. The emphases were also focused beyond the basic fields of numerical analyses methods on the effective use of monitoring data within the numerical assessment framework. A sensitivity factor and influence line based approach (presented in consequent paper – Part III + Part V) and a neural network based approach (presented in consequent paper – Part IV) have provided in this regard promising results.

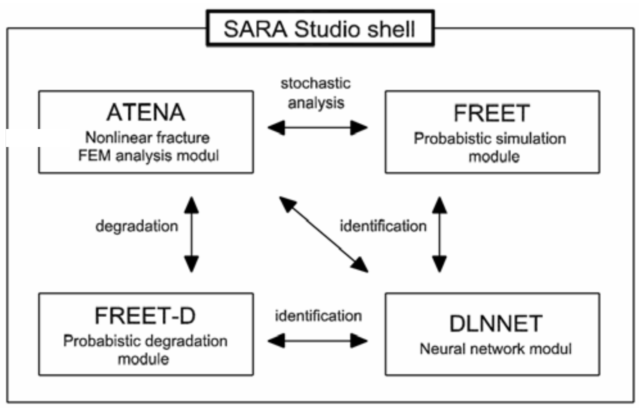

Figure 1. The program combination within SARA software.

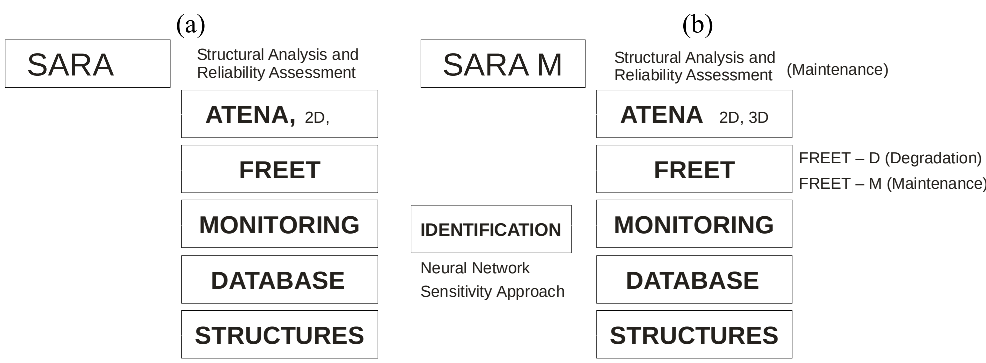

Figure 2. Structural Analysis and Reliability Assessment (SARA) (a) fundamental concept and (b) extended maintenance tool.

These identification approaches initially were only related to static structural responses, with the disadvantage to be dependent on well defined load cases. Since live load of structures are not well defined load cases that causes a variety of mixed structural responses, there have been the ambitions to include in the approaches the information provided by not well defined load cases or in consequence to be load case independent.

Dynamic structural characteristics are physical quantities that seem to fulfil the above mentioned demand to be load case independent. Dynamic identification methods are often used in practice to assess properties and/or damage of the structures (bridges). In consequence there have been the intentions to include the dynamic quantities and the static responses (for defined load cases) in the identification approaches. To meet these demands the framework as well as the basic framework of SARA has to be enhanced for dynamic considerations.

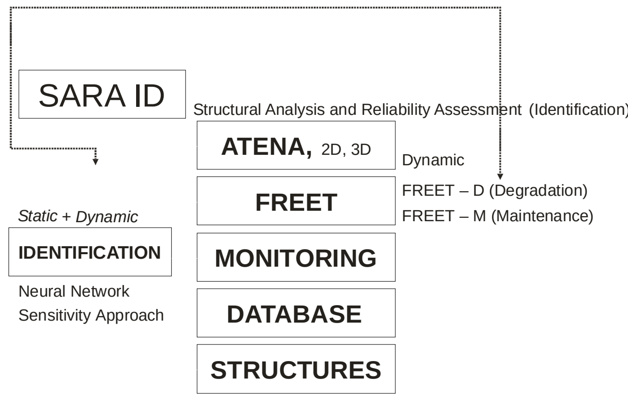

Figure 3. SARA – ID focused mainly on dynamic damage identification.

Figure 3 shows the dynamic enhancement for ATENA and the identification methods within the project SARA ID. However, the assigned tools e.g., FREET–M, FREET–D etc. are also influenced by this development. Interfaces as well as algorithms for dynamical quantities have to be adapted. FREET–D within this development phase acquire a special position, since the nonlinear reliability assessment as well as identification methods (static, dynamic or both) can provide together with prediction models (e.g. degradation models included in FREET-D) effective maintenance planning for engineering structures.

HEALTH MONITORING

During the last few decades practical methods for the reliability assessment of structural infrastructure have been developed to assist engineers in probabilistic analysis. SARA is one of these methods. In general SARA differs from the others by containing highly developed components of the reliability analysis for nonlinear structure analysis (methods presented in consequent paper – Part II), time saving stratified simulation methods and identification methods and degradation models among others. The method helps to quantify reliability within the inspection and assessment, as well as immanent uncertainties by sensitivity analysis. Eventually decision making about the structural resistance is eased.

As in many civil structures, deformations are the most relevant parameter to be monitored at bridges and general structures, in both short and long-term. An accurate knowledge of the behavior of bridges or structures is becoming more and more important as new building techniques are introduced and the existing structures are required to remain in service beyond their theoretical service life.

The measurement of deformation can be approached either from the material or from the structural point of view. On the one hand, observation of local material properties made by a series of short base-length strain sensors can be extrapolated to the global behavior of the whole structure and can be included by identification, methods as mentioned above, in numerical tools like SARA to detect critical zones in the structure and in consequence the level of reliability.

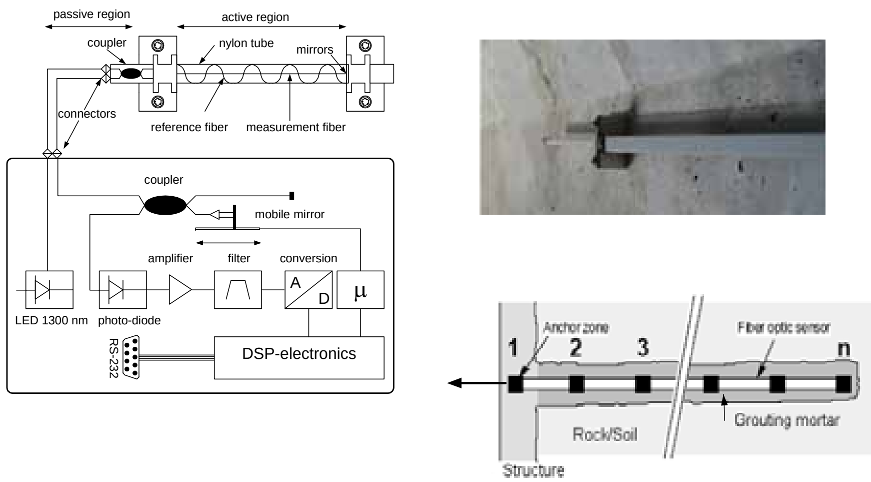

Figure 4. Fiber optical deformation sensor (SOFO): surface mountable version and in a multipoint borehole extensometer configuration.

A lot of experimental techniques exist to measure strain and deformation (e.g. inductive and mechanical extensometers, electrical strain gauges, vibrating wire strainmeters, etc.). In past years, fiber optic sensors have gained importance in the field of structural monitoring (microbending, bragg gratings, Fabry-Perot sensors, etc.), see Fig. 4. They are an ideal choice for many applications, being easy to handle, dielectric, immune to EM disturbances and normally very stable in their long-term behavior. Some of these sensors together with traditional sensors have been used for health monitoring the Colle Isarco Viaduct (Santa et al. 2004). The Colle Isarco Viaduct is a cantilever beam bridge in Italy of the A22 with a total length of 1,000 m. It was built in 1969 and is a fully post-tensioned box-girder bridge, see Fig. 5. One of the first bridges treated with SARA was the Colle Isarco Viaduct. The owner was interested in the current reliability level, in the remaining lifetime and degradation processes of this bridge. The details of these studies can be found in Strauss et al. (2006).

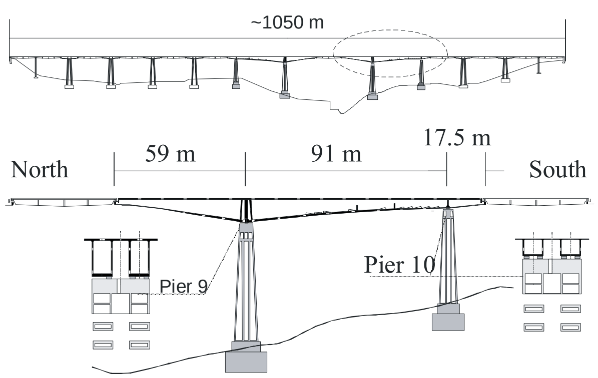

Figure 5. Side elevation of the bridge from the west.

VIRTUAL NONLINEAR SIMULATION

Structural responses obtained from randomised nonlinear FEM analysis, like ATENA (Fig. 6), together with sophisticated degradation models, shown in the consequent paper – Part VI, are the basis for a rational maintenance planning and life time analysis. The capabilities of ATENA as a virtual nonlinear simulation tool are discussed in the consequent paper – Part II. The reliability analysis, part of the life time analysis, itself has to be based on an efficient advanced Monte Carlo method to allow the handling of nonlinear problems. The reliability analysis procedure of SARA comprised this feature and can be itemized as follows:

1. Preparation and check of the deterministic model within the nonlinear FEM Code.

2. Assignment of probability density functions (pdf) to the input quantities according their nature uncertainties and information uncertainties. The probability density functions are described by statistical moments.
3. Creation of a set of realizations for each input quantity of the nonlinear FEM model, regarding the assigned pdf's, with an advanced Monte Carlo method, the Latin Hypercube Sampling (LHS) method. A prescribed correlation between the input quantities is assured by applying the simulating annealing algorithm.
4. The simulated realizations are sequential transferred to the nonlinear FEM model and processed. For each sequential realization set a structural response is obtained. The complete sequential transfer, adherent with repeated simulations, results in a bundle of structural responses.
5. Selected data (monitoring points) of the structural responses are transferred consequently to a statistical evaluation. The statistical evaluation leads to: histograms, mean values, variances, coefficient of skew ness. The deducible empirical cumulative probability density functions from the histograms of the structural response together with pdf's of actions are the basis for the reliability assessment.
6. The sensitivity analysis, based on Kendal Tau rank order algorithm, demonstrates the relation between input and structural response quantities.

This type of reliability analysis helps to reflect the instantaneous health condition of a structure, it provides the basis for retrofitting measurements and in consequence efficient maintenance strategies.

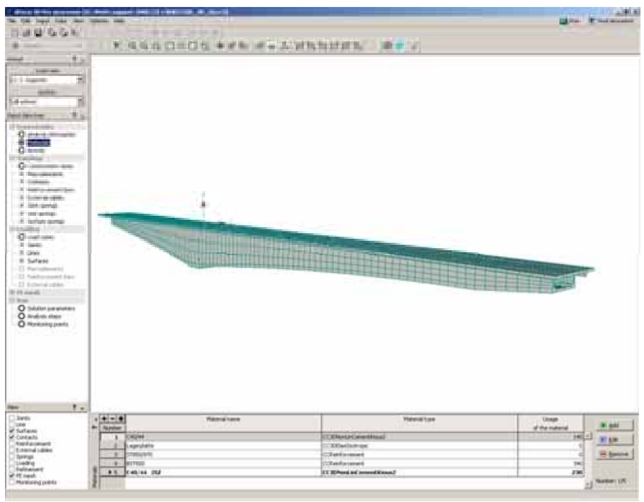

Figure 6. 3D User interface of the advanced nonlinear FE software ATENA.

STATISTICAL, SENSITIVITY AND RELIABILITY ANALYSES

For time-intensive calculations like nonlinear analysis of concrete structures, the small-sample simulation techniques based on stratified sampling of Monte Carlo type represent a rational compromise between feasibility and accuracy. Therefore Latin hypercube sampling (LHS) was selected as a key statistical technique for the SARA project.

The method belongs to the category of stratified simulation methods (e.g. Mc Kay & Conover 1979, Novák et. al 1998). It is a special type of the Monte Carlo simulation which uses the stratification of the theoretical probability distribution function of input random variables. It requires a relatively small (tens or hundreds) number of simulations (repetitive calculations of the structural response) to estimate the requested statistics of response. This technique, used in FREET (Fig. 7), is discussed in more detail in the consequent paper – Part II

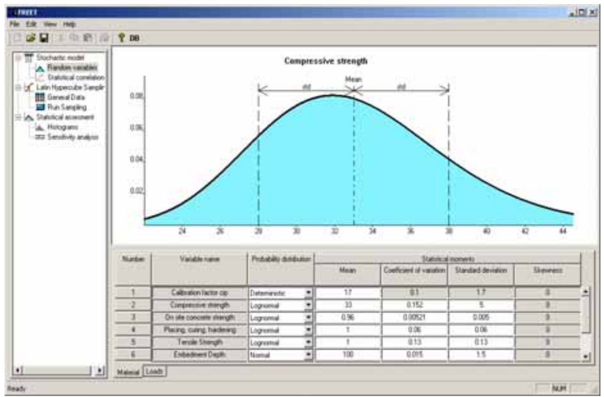

Figure 7. User interface of reliability software FREET.

CONCLUSIONS

A complex methodology including nonlinearities in material, uncertainties and degradation phenomena is proposed for advanced life-cycle reliability analysis of reinforced concrete structures, particularly bridges. Efficient techniques of stochastic simulation methods were combined in order to offer an advanced tool for the probabilistic assessment of complex small or large structures. The presented methodology is implemented into the software tool SARA for instantaneous routine practical applications. 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.

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