Modelling of Nonlinear and Uncertain Behavior of Concrete Bridges

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Abstract. The objective of this paper is to present the main project targets: (a) the creation of accessibility to the in-depth numerical statistical building blocks and reliability-oriented assessment methods for the holistic evaluation of bridge systems, (b) the creation of a guideline for the low-risk application of the in-depth procedures, and (c) the development of a sustainable training program. These three integrated approaches have not been prepared to date in any of the European countries and worldwide, therefore, can be considered as highly innovative. The "ATCZ190 SAFEBRIDGE" project, financed by the European Union (INTERREG Austria–Czech Republic), aims to achieve a more realistic analytical modelling of bridges through the consideration of non-linear deterministic and stochastic aspects. The aim of the project is to design in-depth numerical reliability-oriented assessment methods for bridge systems (according to the ÖNORM B4008-2 Level III) and to make them accessible to a larger number of engineering offices, as well as infrastructure operators in the Vienna, Lower Austria and Moravia–Czech Republic regions.

Keywords: Concrete bridges · Nonlinear analysis · Probabilistic analysis · Virtual simulation · Finite element method · Degradation modelling · Life cycle

1 Introduction

The road network in the region of Vienna, Lower Austria and Moravia–Czech Republic faces major challenges: Aging structures, increasing traffic loads, effects of climate change, new quality requirements and a limited budget for road infrastructure. In order to maintain a reliable road network, new, innovative approaches must be pursued, with this particularly applying to bridge structures. Currently, their maintenance management is based on regular structure inspections and damage is not discovered until obvious. This procedure is damage-based and reactive. Damage and problems of the structure, however, often already manifest themselves inside the structure, through their actual but often unknown effects on the structure. The bridges of the future should be able to provide information on their condition and development at an earlier stage and in addition to the structure inspections.

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The "ATCZ190 SAFEBRIDGE" project, financed by the European Regional Development Fund, within the European Union Interreg Austria–Czech Republic program, aims to achieve a more realistic analytical modelling of bridges through the consideration of non-linear deterministic and stochastic aspects. The main project partners are the University of Natural Resources and Life Sciences, Institute of Structural Engineering, Vienna, Austria and the Brno University of Technology, Faculty of Civil Engineering, Institute of Structural Mechanics, Brno, Czech Republic. The remaining project consortium consists of strategic partners, which are the main national and county road and railway bridge operators in Austria and the Czech Republic. The aim of the project is to design in-depth numerical reliability-oriented assessment methods for bridge systems (according to the ÖN B4008-2 Level III [1]) and to make them accessible to a larger number of engineering offices as well as infrastructure operators in the Vienna, Lower Austria and Moravia–Czech Republic regions.

The objective of this paper is to present the main project targets: (a) the creation of accessibility to the in-depth numerical, statistical calculations and reliability-oriented assessment methods for the holistic evaluation of bridge systems, (b) the creation of a guideline for the low-risk application of the in-depth procedures, and (c) the development of a sustainable training program. These three integrated approaches have not been prepared to date in any of the European countries and worldwide, therefore, can be considered as highly innovative.

2 In-Depth Nonlinear Reliability-Based Assessment of Bridges

Nonlinear modelling based on finite element method (FEM) is used nowadays more frequently for design and analysis of structures, along with reliability analysis used in practice. The combination of both procedures is a strong and effective tool for the realistic simulation of new as well as existing structures.

The presence of uncertainty in the analysis and design of engineering systems has always been recognized. Uncertainties are involved in every part of the system: structure–load–environment. Traditional approaches simplify the problem by considering the uncertain parameters to be deterministic and account for the uncertainties through the use of partial safety factors in the context of limit states. Such approaches do not absolutely guarantee the required reliability and they do not provide information on the reliability achieved and/or on the influence of individual parameters on reliability. Therefore, attention is being given today to fully probabilistic approaches and software tools, which can be used for such purposes [2–3]. Important topics can, thus, be treated in an advanced manner, e.g., through the probabilistic vulnerability assessment of civil infrastructure systems followed by efficient decision-making processes.

In this context, several multi-level methods have been developed for the assessment of structures, with the initial assessment levels using deterministic approaches and simplified models, while the higher assessment levels engage semi- or full-probabilistic approaches combined with more accurate and complex FEMs (e.g. non-linear calculations [3–5]). Therefore, the safety level can be increased through the more realistic simulation of the structure [4], however, the detail and the complexity of the models increases accordingly. In the framework of the "ATCZ190 SAFEBRIDGE" project, the multi-level assessment concept proposed in the new Austrian Standard (ÖNORM 4008-2 [1]), which consists of 4 assessment levels, is intensively investigated through a series of selected bridge case studies, which are located within the Vienna, Lower Austria and Moravia region. Each bridge was simulated through linear and non-linear FEM, following deterministic and probabilistic concepts and the results were compared and discussed.

More emphasis was laid on Level III of the Austrian Standard that concerns "Assessment using probabilistic methods". Based on the critical limit states determined from the Level I ("Assessment based on current technical standards") and Level II ("Assessment including in-situ data for actions") validations, an analysis can be performed using the full range of stochastic distributions of the relevant variables. The underlying calculations remain the same but are performed with distributions instead of deterministic values for the characteristic parameters. In practice, this can typically be achieved by generating sets of random variables for the inputs, using these to perform the calculations many times and statistically analyzing the distribution of the results. A characteristic example of concrete mechanical properties and suggested probabilistic values according to [1] are presented in Table 1.

Table 1. Old concrete mechanical properties for good execution, suggested by [1].

Concrete class	f_{cm}	$f_{ck,\ cube}$	f_{ck}	E_{cm}	$covf_{cm}$	$covE_{cm}$
	N/mm^2	N/mm^2	N/mm^2	kN/mm^2	–	–
C12/15	20	15	12	27	0.19	0.20
C16/20	24	20	16	29	0.16	0.16
C20/25	28	25	20	30	0.13	0.13
C25/30	33	30	25	31	0.11	0.11
C30/37	38	37	30	33	0.10	0.10
C35/45	43	45	35	34	0.09	0.09
C40/50	48	50	40	35	0.08	0.08
C45/55	53	55	45	36	0.07	0.07
C50/60	58	60	50	37	0.06	0.06

Where:
f_{cm} mean value of cylinder compressive strength (Ø 150 mm/300 mm).
f_{ck}, cube characteristic 150 mm cube compressive strength (5% fractile).
f_{ck} characteristic cylinder compressive strength (5% fractile) according to [6].
E_{cm} mean modulus of elasticity (secant value $\sigma_c = 0$–$0.4\ f_{cm}$).
According to [6]: $f_{cm} = f_{ck} + 8.0$ (N/mm^2).

The "three-dimensional" multi-level assessment that was applied in the case studies of the current project is depicted in Fig. 1. This figure demonstrates how the safety concept is correlated with the model complexity and the advanced level of analysis, presenting all the available options to the user, based on the available software, modelling ability and computational power, in order to make an informed decision on the level of assessment to perform on a certain structure [7].

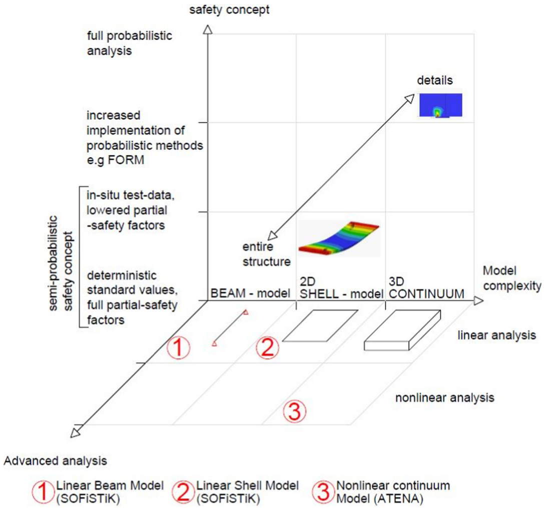

Fig. 1. Overview of different assessment methods' potential roles in multilevel systems [7]

Based on the series of analyses performed for the purpose of the aforementioned process, after the result evaluation and in an effort to bring this philosophy closer to bridge operators and bridge design and maintenance engineering offices, two main outputs are developed: (i) A guideline for the low-risk application of the in-depth procedures, and (ii) a sustainable training program for students, designers, civil engineers and bridge operators and managers.

2.1 A Guideline for the Low-Risk Application of the In-depth Procedures

A guideline describing the main steps of the procedure for advanced analysis of existing reinforced concrete and pre-stressed bridges is prepared as one of the main outputs of the project. In the guideline aspects of material nonlinearities, FEM modelling of structures, reliability of structures using different safety formats and service life are combined to describe the in-depth nonlinear reliability-based assessment of bridges. For this purpose, a series of bridge case studies are performed in order to verify the procedure and present its usability also in engineering practice.

The following paragraphs demonstrate the steps that were followed through this procedure and correspond to the main chapters of the developed Guideline. The content of each individual chapter summarizes the theoretical background used in the case studies that leads to the desired non-linear assessment of existing bridge structures.

Quality Control Plan in Bridges. In the first chapter of the guideline, a quality control plan in bridges is presented, summarizing the main steps of quality control, damage process and performance assessment, followed by a brief summary of applications in girder and frame bridges. In this context, individual sections of Guideline Chapter 1 are based on [8] and are further reflected with respect to the targets of the ATCZ190 SAFEBRIDGE project. based on certain quality control assessment criteria ten bridges in austria and the czech republic were selected to be studied, modeled and evaluated accordingly.

Monitoring Methods and Data Collection. Engineering structures are designed and built to meet specific requirements and have a limited service life. Above all, the aging of the existing building stock, damage caused by the environment and use, inadequate building maintenance, changing demands on the standard as well as changed usage requirements are responsible for the growth rates in the renovation of buildings [9]. As a rule, visual inspections are used for data collection, which provide an experienced engineer with sufficient information in most cases. If there are any doubts, non-destructive or destructive testing methods are used in practice. By using the latter method, damage of limited extent occurs on the structure under test, which must be remedied after the test has been carried out. The destructively investigated and restored areas are in many cases a future weak point of the construction. Of particular importance for the construction examination is, therefore, primarily non-destructive test methods, which are the main object of Chapter 2 of the Guideline.

Deterministic Computational Modelling. The purpose of Guideline Chapter 3 is to introduce procedures for assessing the structural conditions of existing structures with the help of advanced nonlinear simulation. compared to the MC2010 [10], the chapter elaborates more on specific issues for reassessment assisted by numerical simulations and it expands on modelling, analysis and reporting. A description of best practices for the finite element modelling of planar and slab elements, focusing on numerical approximations, requirements, approaches and the respective results and applications is included as an annex.

Probabilistic-Based Reliability Assessment. In Chapter 4 of the Guideline, the focus is on reliability theory, modelling of uncertainties, statistical simulation, and safety formats. Three main categories of probabilistic analysis, such as statistical, sensitivity and reliability analysis are described with the aim to sum up and refer the most common used as well as advanced methods of structural reliability assessment. The term stochastic or probabilistic finite element method (SFEM or PFEM) is also introduced to refer to a finite element method, which accounts for uncertainties in the geometry or material properties of a structure, as well as applied loads.

Deterioration Modelling for Life Cycle Assessment. In the context of performance-based approaches, sustainability and total life costing of concrete structures, time is the decisive variable and durability issues (service life) are pronounced. The methodology based on the idea of the material potential [11] using the sustainability indicator provides the possibility of mutual comparison of different variants of the proposed concrete mix or the rc structure from the point of view of the sustainability level. Given that one of the basic elements of the structure sustainability is durability, Chapter 5 of the Guideline is devoted to this. Processes and models of concrete carbonation, ingress of chloride ions and corrosion of reinforcement as the main deterioration phenomena are introduced. The software products, which are suitable for efficiently handling the issues of the durability design or assessment of concrete structures, are briefly described and referenced.

Performance Indicators for the Evaluation of the Degradation Processes. The last Chapter 6 of the Guideline aims to give an overview of the performance indicators (PI) used in bridges, describing the process to define key performance indicators (KPI), the establishment of corresponding performance goals, and provide a framework for a quality control plan [7, 12–13]. Some of these terms have already been introduced in Guideline Chapter 1, however, in this part more focus will lean on the identification and classification of pis on degradation processes considering: whether they are measurable, quantifiable, their availability of target value, validity for the ranking, and whether they allow a decision with financial implications.

2.2 A Sustainable Training Program

Within the project a sustainable training program is calibrated with the support of the project strategic partners. The training program consists of three theoretical seminars and three corresponding practical training schools for students, designers and engineers from engineering practice, especially in small and medium-sized enterprises.

The proposed guideline and the correct application of probabilistic nonlinear FEM modelling of real structures are to be shared with the participants to increase the level of education in the field and reduce the risk of undesirable or false results. Technical sheets on partial topics of the procedure of in-depth nonlinear reliability-based assessment of bridges are to be prepared as additional educational material for maintaining know-how and awareness of the suitability of using innovative approaches in engineering and industry.

The presented topics of the program correspond to the individual steps of the in-depth nonlinear reliability-based assessment procedure and can be itemized as follows:

- Seminar and Training School No. 1 – Data collection.

  (i) Regional conditions (climate, traffic density) and input data requirements;
  (ii) Input data: load, resistance, geometry, static system, design method, defects and deterioration (carbonation, chloride ingress, etc.);
  (iii) Current codes and methods for definition of input data (accuracy, advantages and disadvantages): design documentation, construction diary, standard/main bridge inspection, diagnostic research, loading test, probative material tests, on-site and laboratory testing (non-destructive test methods, tests of material parameters, carbonation and chloride profile assessment, cracks detection), etc.;
  (iv) Case studies.

- Seminar and Training School No. 2 – Deterministic analysis.

  (i) Modelling: material characteristics, constitutive models, models of degradation processes, finite elements, prestressing and crack formation, boundary conditions, load;

(ii) Analysis: loading steps, iteration process, convergence criteria;
(iii) Limit states assessment: serviceability limit state, ultimate limit state;
(iv) Actual codes for deterministic analysis (accuracy, advantages and disadvantages);
(v) Case studies.

- Seminar and Training School No. 3 – Probabilistic analysis and lifetime assessment.

(i) Modelling: stochastic material characteristics, stochastic constitutive models, stochastic models of degradation processes, correlation and spatial variability, stochastic finite elements, stochastic load;
(ii) Analysis: Monte Carlo and Latin Hypercube Sampling methods, loading steps, sensitivity;
(iii) Methods for limit states assessment (accuracy, advantages and disadvantages): partial safety factors method, global safety factor method, ECoV methods;
(iv) Case studies.

3 Summary and Conclusions

The "ATCZ190 SAFEBRIDGE" project aims for the nonlinear assessment of existing reinforced and prestressed concrete bridges through the application of multi-level assessment engaging also probabilistic aspects. This targets to demonstrate that multi-level assessment could contribute significantly to the future longevity of structures. A series of case studies, located in the Vienna, Low Austria and Moravia–Czech Republic region, are under assessment, demonstrating that by utilizing increasingly detailed methods of structural analysis, a considerable amount of safety can be gained. The theoretical background used through this process has led to the development of a guideline, including a quality control in bridges, for the low-risk application of the in-depth monitoring methods and data collection, deterministic computational modelling, probabilistic-based reliability assessment, deterioration modelling for life cycle assessment and performance indicators for degradation. Furthermore, to assist the accurate application of the process and the guideline, a training program is designed, consisting of seminars and training schools, where the engineering community is gradually introduced to the above.

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