IS NONLINEAR ANALYSIS BECOMING A STANDARD TOOL FOR DESIGN OF CONCRETE BRIDGES?

Jan Červenka, Ph.D., Červenka Consulting s.r.o, +420 220 610 018, jan.cervenka@cervenka.cz
Jiří Rymeš, Dr. Eng., Červenka Consulting s.r.o, +420 220 610 018, jiri.rymes@cervenka.cz

INTRODUCTION

Nonlinear analysis and simulation within the framework of the finite element (FE) analysis can provide engineers with an insight into the real structural performance and behavior. Contrary to the traditional design protocols based on the elastic beam theory, the nonlinear models can evaluate complex 3D stress states within the material and simulate real material behavior, including crushing of concrete in compression, cracking in tension or yielding of the steel reinforcement as well as long-term rheological phenomena. By these means, not only the ultimate state but various construction stages and environmental loads can be evaluated.

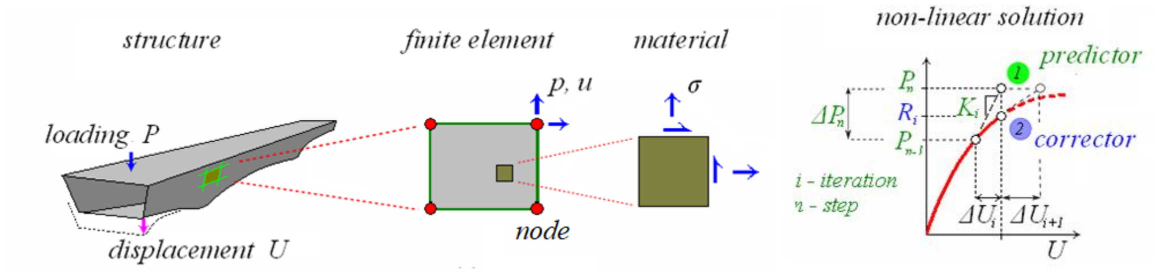

Fig. 1. Typical incremental and iterative solution scheme of nonlinear FEA

Design guidelines and suitable safety formats for nonlinear analysis are becoming available in the new design codes such as the latest fib Model Code 2010 (1) and the new generation of Eurocodes. In addition, nonlinear analyses are quite commonly used in seismic analysis and assessment of civil engineering structures. An important aspect of the application of nonlinear analysis and simulation in design is the consistent treatment of model uncertainties. In fib Model Code 2020 (1) several methods are proposed based on the partial safety factor method, global resistance, and full probabilistic methods. These safety formats are briefly described along with their extension to ASCE and ACI standards.

Case studies from engineering practice are presented to demonstrate the feasibility and advantages of nonlinear analysis in the design of new and assessment of existing bridges.

SAFETY FORMATS FOR NONLINEAR ANALYSIS OF REINFORCED CONCRETE

The design condition is generally formulated as:

$$R_{\mathrm{d}} \leq E_{\mathrm{d}} \tag{1}$$

where R_{d}, E_{d}, represent the design values of strength and load, respectively. They must include the specified safety margins (i.e. safety, load or strength reduction factors) as required by the corresponding design code. Two types of uncertainties are included in the safety factors. The first one, referred as “aleatory” uncertainty, is due to inherent random properties of material and dimensions given by the concrete technology and is referred in the further discussion as the material uncertainty. The second one, referred as “epistemic”, is reflecting the knowledge level of the background theoretical model, and is called as the model uncertainty.

The design condition in Eq. (1) in the standard design practice is applied to critical cross-sections. The inconsistency of this concept is well known because different assumptions are used for the calculation of the load effect of internal forces E_d (obtained usually by linear analysis) and, the cross-section resistance R_d (nonlinear material model). In general, the section forces may change due to a stress redistribution during the non-linear response. Furthermore, the local safety checks do not reflect a reliability of the entire system. In the nonlinear analysis a nonlinear material response is implicitly in the solution process (Fig. 1). Therefore, a local check of the condition in Eq. (1) is satisfied by definition. However, a global check is required. The load effect E_d in the Eq. (1) is considered at the global level. It represents a level of the relevant load combination. Analogically the resistance R_d is the ultimate load level at failure for the given load combination imposed on the structure.

MC2010 (1) introduces four methods for the global assessment using nonlinear analysis, which differ in estimate of the random parameters of the ultimate resistance. In this study only two most prominent methods will be treated. i.e. the partial factor (PFM) (Section 7.11.3.4) and ECoV method (Section 7.11.3.3 of fib model code 2010 (1)). These two methods are expected to be included in the new version of Eurocodes, and therefore they will be treated in more detail. A full probabilistic approach on the other hand can be used as an exact reference solution. The (PFM) method is most closely related to the classical approach used by engineers for the verification and design of sections of structural elements:

$$R_{\mathrm{d}}^{fib} = \frac{R\left(X_{\mathrm{d}}; a_{\mathrm{nom}}\right)}{\gamma_{\mathrm{Rd}}}, \; X_{\mathrm{d}} = \frac{X_{\mathrm{k}}}{\gamma_M^*}, \qquad \theta = R_{\exp} / R_{\mathrm{sim}}, \; \gamma_{Rd} = \frac{\exp(\alpha_R \beta \times V_\theta)}{\mu_\theta} \tag{2}$$

where X_k is the characteristic (i.e. guaranteed) material strength, a_{nom} represents the nominal geometric parameters, γ_M^* is the material safety factor excluding model uncertainties. α_R is FORM resistance factor, β is reliability index, and γ_{Rd} is the safety factor for model uncertainty. This safety factor depends on the numerical method and model used in the nonlinear analysis, i.e. software, and should be evaluated by a separate study involving simulation of experiments and statistical evaluation the model uncertainty θ of typical structural elements and failure modes, such as: bending, shear or punching with given statistical parameters: average μ_θ and variability V_θ. An example of the calibration of the model uncertainty is for instance presented in Cervenka et. al. (2) where typical uncertainty factors for different failure modes were determined for methods and models implemented in ATENA software were obtained as shown in Tab. 1. Another interesting validation is also presented in the benchmark competition by Collins et al. (3).

Tab. 1: Partial safety factors for model uncertainty (Cervenka et al. (1))

Failure type	μ_θ	V_θ	γ_{Rd}
Punching	0.971	0.076	1.16
Shear	0.984	0.067	1.13
Bending	1.072	0.052	1.01
All failure modes	0.979	0.081	1.16

PFM method could be also extended and applied for ACI design standard. In this case the design strength R_d could be calculated as follows:

$$R_{\mathrm{d}}^{\mathrm{ACI}} = \phi \frac{R\left(X_k; a_{\mathrm{nom}}\right)}{\gamma_{\mathrm{Rd}}} \tag{3}$$

where ϕ is the strength reduction factor, which should depend on the critical element and failure model.

APPLICATION EXAMPLES

The authors have been involved in many applications of nonlinear analysis to engineering structures and bridges in particular. One example is briefly described here as it involves the application of nonlinear analysis to the determination of the load capacity of the bridge. The bridge was built in 1912 (Fig. 2). The bridge is undergoing reconstruction and within this project its load capacity was verified. The classical approach using linear analysis and checking sectional capacities show insufficient capacity even against dead-load, long-term and thermal effects even though the bridge has been working reliably for more than 100 years without any major damages. This can be mainly attributed to the fact that the individual columns and beams were considered as hinged in the original design, but their construction is performed as non-hinged. This discrepancy can be nicely corrected and verified by nonlinear analysis, which can correctly consider the redistribution of forces in the beam column connections as is shown in Fig. 3.

Fig. 2: View of the historical bridge at Nymburg (Czech rep.) with art-neveau artistic features

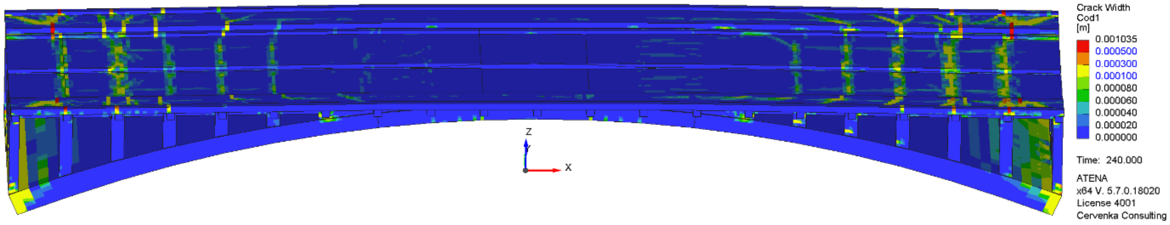

Fig. 3: Calculated crack pattern showing the development of hinges at characteristic load combination

CONCLUSIONS

Nonlinear analysis and simulation have become standard tools for instance in the mechanical or automotive industry and it is starting to be adopted also in the construction industry for construction process planning or the simulation of extreme loading such as earthquakes or blasts. This is supported by the development of new national and international design codes such as the fib model code 2010 (1). It is the opinion of the authors that the simulation will be an important part of the design process, and will be used mainly for final verification whether the structure meets the required performance parameters.

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