Design of Reinforced Concrete Structures by Numerical Simulation

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ABSTRACT

Sustainability of concrete structures can be ensured by deployment of high-tech design tools such as numerical simulations. The author has been involved in the development of new design techniques based on information technologies, namely, numerical simulations, which can bring better expertise to the design process by exploiting advances in material engineering and computational mechanics. Assessment of sustainability was recently performed to existing nuclear power plants in order to check their safety in more demanding design requirements. It is demonstrated, that numerical simulation is well substantiated in cases of complex structures, where an unsafe design has a large impact on the environment.

Keywords. Numerical simulation, non-linear analysis, pushover analysis

INTRODUCTION

Application of numerical simulations have been recently included in the *fib* New Model Code 2010 (Walraven, 2012) where the appropriate safety formats are proposed for this purpose. The paper introduces the features of numerical simulations based on non-linear finite element analysis and its potential for design practice. Its applicability are demonstrated on the assessment of seismic resistance of existing old nuclear power plant in Switzerland based on the pushover analysis.

NON-LINEAR ANALYSIS

The recent developments of structural analysis make it possible to consider material as well as geometrical non-linear behavior and extend the structural analysis into a non-linear range and thus reduce the above mentioned inconsistency. The principles of nonlinear analysis based on a finite element method as illustrated in Fig. 1 are in more detail treated in paper (Cervenka, V., 2013). For concrete the most important material properties to consider are due to a crack propagation in tension and confinement effect in compression. These features are successfully modeled by constitutive laws based on the fracture mechanics and the theory of plastic flow. Material model for concrete in ATENA is based on the smeared crack model for tension combined with plasticity model for compression. Model is described in detail in the paper by Červenka & Pappanikolaou (2008). The material model formulation assumes small strains, and is based on the strain decomposition into elastic (ε_{ij}^{e}), plastic (ε_{ij}^{p}) and fracture (ε_{ij}^{f}) components. The stress be then described by the following rate equations:

$$\dot{\sigma}_{ij} = D_{ijkl} \cdot (\dot{\varepsilon}_{kl} - \dot{\varepsilon}^p_{kl} - \dot{\varepsilon}^f_{kl}) \tag{2}$$

The constitutive equations of the plastic and fracture models can be summarized as follows: the flow rule governs the evolution of plastic and fracturing strains:

$$\text{Plastic model :} \quad \dot{\varepsilon}^p_{ij} = \dot{\lambda}^p \cdot m^p_{ij}, \quad m^p_{ij} = \frac{\partial g^p}{\partial \sigma_{ij}} \tag{3}$$

$$\text{Fracture model :} \quad \dot{\varepsilon}^f_{ij} = \dot{\lambda}^f \cdot m^f_{ij}, \quad m^f_{ij} = \frac{\partial g^f}{\partial \sigma_{ij}} \tag{4}$$

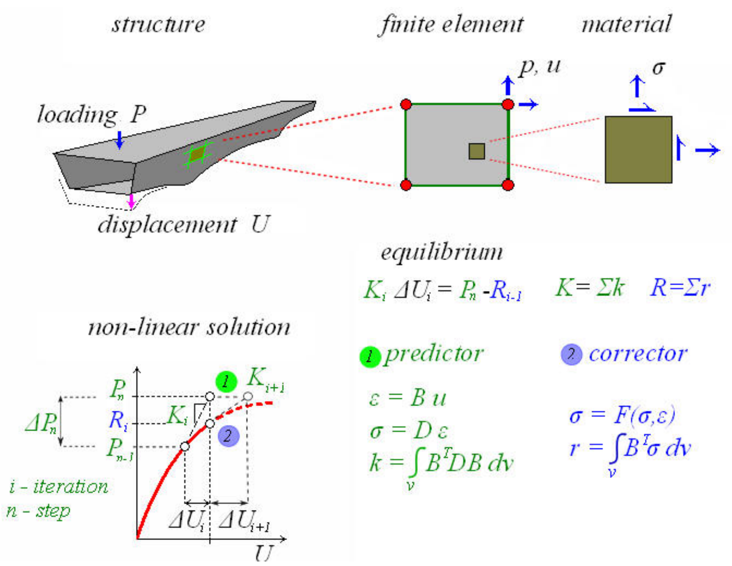


Fig. 1: **Scheme of non-linear finite element analysis**

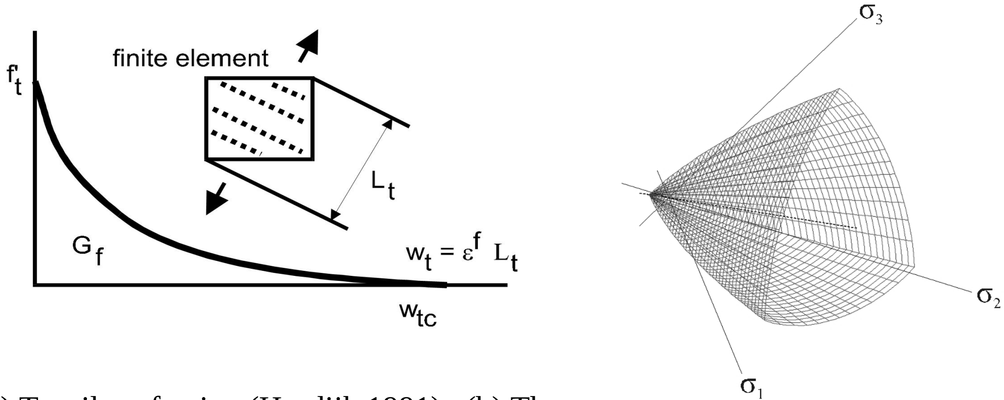
Where $\dot{\lambda}^p$ is the plastic multiplier rate and g^p is the plastic potential function. Following the unified theory of elastic degradation of Carol et al. (1994) it is possible to define analogous quantities for the fracturing model, i.e. $\dot{\lambda}^f$ is the inelastic fracturing multiplier respectively and g^f is the potential defining the direction of inelastic fracturing strains in the fracturing model. The consistency conditions can be than used to evaluate the change of the plastic and fracturing multipliers.

$$\dot{f}^p = n^p_{ij} \cdot \dot{\sigma}_{ij} + H^p \cdot \dot{\lambda}^p = 0, \qquad n^p_{ij} = \frac{\partial f^p}{\partial \sigma_{ij}} \tag{5}$$

$$\dot{f}^f = n^f_{ij} \cdot \dot{\sigma}_{ij} + H^f \cdot \dot{\lambda}^f = 0, \qquad n^f_{ij} = \frac{\partial f^f}{\partial \sigma_{ij}} \tag{6}$$

H^p and H^f are hardening/softening moduli for plastic model and fracturing model, respectively. This represents a system of two equations for the two unknown multiplier rates $\dot{\lambda}^p$ and $\dot{\lambda}^f$, and is analogous to the multi-surface plasticity (Simo et al. 1988). The details of the model implementation can be found in Červenka &

Pappanikolaou (2008). The model is using Rankine criterion for tensile fracture with exponential softening of Hordijk (1991), (see Fig. 2a).



(a) Tensile softening (Hordijk 1991)   (b) Three paramater criterion for concrete (Menetrey & Willam (1995)

Fig. 2: Material low for concrete in tension and compression

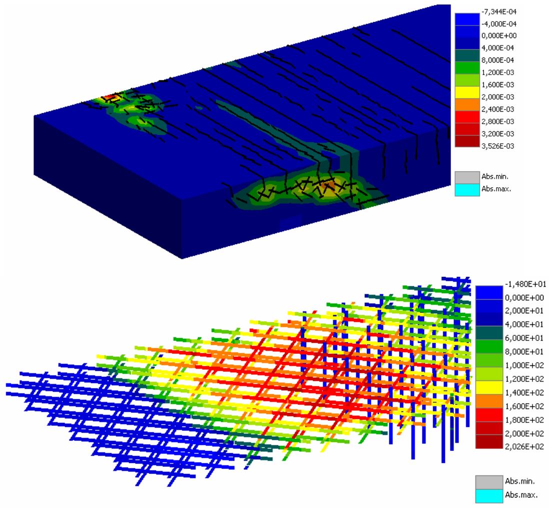
The compressive behaviour is modelled by a plasticity model, which is using the three parameter surface of Menetrey & Willam (1995) (see Fig. 2b). The softening in tension and compression is adjusted using a crack band approach of Bažant & Oh (1983). Concrete constitutive model covers also functions related to the shear resistance of cracks and reduction of compressive resistance due to cracking, which are important for realistic modelling of cracked concrete, Bentz et al. 2006. An example of the model validation is shown in Fig. 3

ASSESSMENT OF SEISMIC RESISTANCE

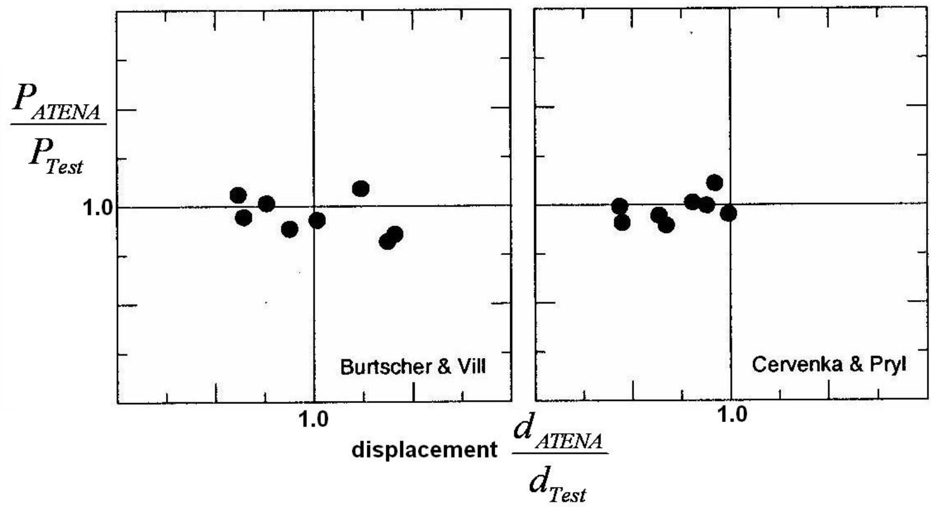
The accident in Fukushima Power Plant in Japan in 2011 spurred activities in energy industry world-wide and opened questions of safety and sustainability of the existing nuclear power plant structures. It is evident that during the life time of existing power plants, the world-wide research effort brought a range of innovations useful for the seismic design. One on them is the push-over analysis method, which is suggested by major design codes but was not a design practice at the time of the constructions of old power plants. Today it serves as a simplified method for the assessment of seismic resistance The investigated reactor building consists of the concrete internal structure, the steel containment and the shield building, i.e. outer wall. More details about the shield building dimensions can be found in Cervenka et al., 2012. The numerical model consisted of the dome, the reinforcing ring with pre-stressing cables and the cylindrical wall. In addition, the steel liner that is attached to the internal surface of the shield building was considered as well. For the safety assessment two models were considered. The „Median model" is using median, i.e. average material properties and the „Characteristic model" with properties of the 5% quantile properties.

A typical deformed shape and crack pattern obtained from the semi-static pushover analysis are shown in Fig. 4. The pushover curve was calculated up to the point when the base shear force dropped below at least 80% of the peak load, see Fig. 5. The pushover curves are transformed into the acceleration displacement diagram, which allows their comparison with the local seismic demand, which is defined by the elastic response spectrum. The result shows very high seismic safety. Furthermore, the idealized curves were be used by the plant owner for a more detailed semi-probabilistic analysis and for the calculation of the fragility curves.

(a) Slab shear test, Jaeger & Marti (2006)



(b) ATENA simulation slab tests,



(c) ATENA prediction results of two teams

Fig. 3: Prediction competition of slab shear resistance

The results confirmed a sufficient seismic safety of this old power plant. Two pushover curves were calculated for the estimation of median and characteristic response. Analogical approach is also applied for the seismic evaluation of other buildings in the nuclear power plant complex (see Fig. 6).

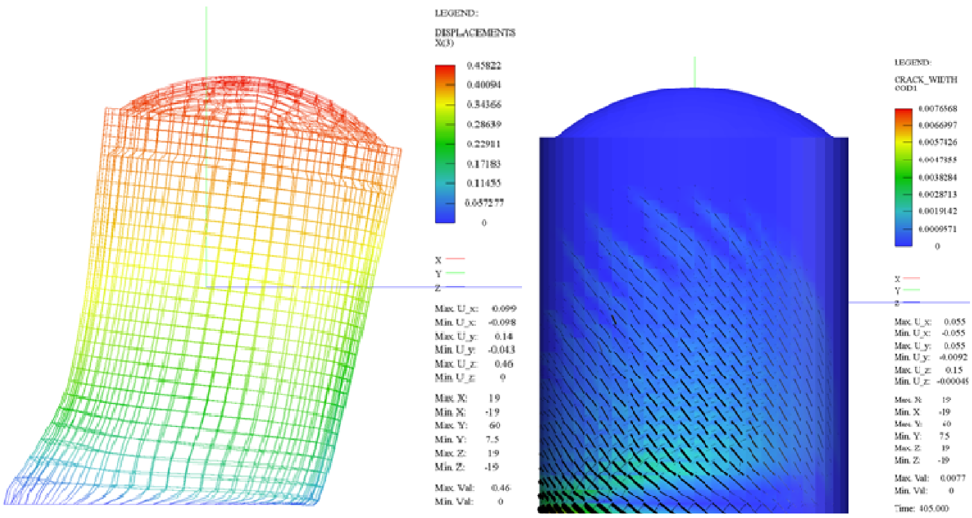


Fig. 4: Deformed form (left) and crack pattern (right) of the characteristic analysis case.

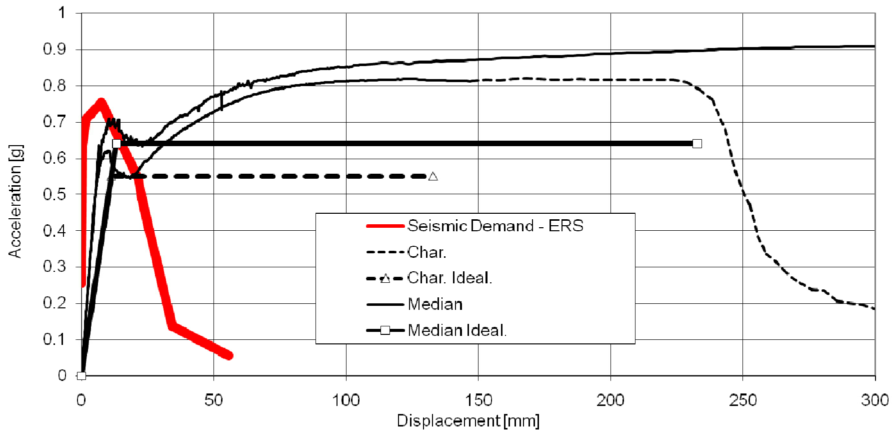


Fig. 5: Pushover curves based on elastic response spectrum of the local seismic demand.

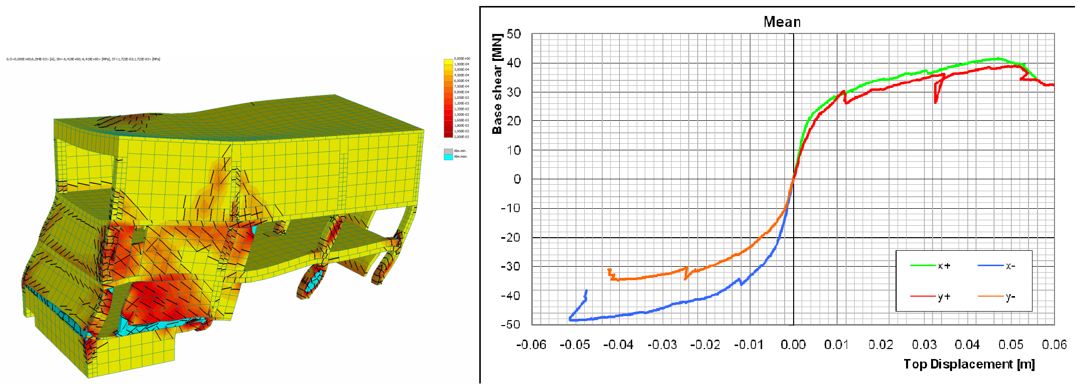


Fig. 6: Pushover analysis of a reinforced concrete building housing the power plant control room

CONCLUDING REMARKS

Advanced simulation tools meet challenges of high structural complexity and extreme load actions and offer an exploitation of state-of-the-art numerical techniques and material models. The nonlinear pushover analysis using advanced material models based on fracture mechanics and plasticity was used to evaluate the sustainability and safety of an existing nuclear containment. The results confirmed very high seismic safety. The calculated pushover curves for median and characteristic response were used for the evaluation of seismic fragility curves.

The numerical tools and methods applied in this work were developed with the support of the Eurostars project SE-Lab E!7521 and project TA01011019 from Czech Technological Agency.

REFERENCES

Walraven, J. (2012). “Model Code 2010. Final draft. Volume 1 and 2.” March 2012. *fib* Bulletin 65 and 66. ISBN 978-2-88394-105-2

Cervenka, V. (2013). “Reliability-based non-linear analysis according to Model Code 2010.” Journal of *fib*, Structural Concrete 14 (2013), No. 1

Cervenka, J., Pappanikolaou, V. (2008) “Three dimensional combined fracture-plastic material model for concrete.” Int. J. of Plasticity, Vol. 24, 12, 2008, ISSN 0749-6419, pp. 2192-2220.

Hordijk, D.A. (1991), Local approach to fatigue of concrete. PhD Thesis, Delft University of Technology, The Netherlands.

Menétrey, P., Willam, K.J. (1995), "Triaxial failure criterion for concrete and its generalization", ACI Structural Journal 92 (3), 311-318.

Bažant, Z.P., Oh, B.H., (1983), "Crack band theory for fracture of concrete". Materials and Structures, RILEM 16

Bentz, E.C., Vecchio, F.J., Collins, M.P. (2006), "Simplified Modified Compression Field Theory for Calculating Shear Strength of Reinforced Concrete Elements". ACI Material Journal, Jul/Aug 2006.

Jaeger, T., and Marti, P., (2006), “Versuche zum Querkraftwiderstand und zum Verformungsvermögen von Stahlbetonplatten (Tests on the shear strength and the deformation capacity of reinforced concrete slabs)”, Report No. 294, Institute of Structural Engineering, ETH Zurich

Cervenka, J., Proske, D., Kurmann, D., Cervenka, V. (2012). “Pushover Analysis of Nuclear Power Plant Structures”. Proceedings of *fib* Symposium, Stockholm, 11-14 June 2012.