Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 210 (2017) 425–432

Procedia Engineering

www.elsevier.com/locate/procedia

6th International Workshop on Performance, Protection & Strengthening of Structures under Extreme Loading, PROTECT2017, 11-12 December 2017, Guangzhou (Canton), China

Simulation of Severe Accident Scenarios in Nuclear Containments

Jan Cervenka*, Zdenek Janda, Libor Jendele, Radomir Pukl, Vladimir Cervenka

Cervenka Consulting s.r.o., Prague, 150 00, Czech Republic

Abstract

The paper presents the main theoretical backgrounds and application of FE program ATENA to simulation of severe accident in nuclear structures. The software was developed by Cervenka Consulting, Prague, Czech Republic with the aim to offer a tool for numerical simulation of concrete structures subjected to actions in service, ultimate as well as extreme limit states due to mechanical as well as physical effects. Nonlinear behavior of concrete is modeled by theories of damage and plastic flow [1]. Paper outlines the basic features of the used material model. It demonstrates the model accuracy on results from recent blind prediction competitions [2]. In the last section, it shows examples of simulations of severe accidents scenarios in nuclear power plants structures [4].

Peer-review under responsibility of the scientific committee of the 6th International Workshop on Performance, Protection & Strengthening of Structures under Extreme Loading

Keywords: simulation of severe accidents, nuclear containments, reinforced concrete, finite element analysis

1. Introduction

Computer modelling of reinforced concrete structures must reflect all typical features exhibited by brittle cementitious materials, reinforcement and their interactions due to bond. The numerical model of reinforced concrete is usually complex, and is a result of numerous approximations. It is essential to employ a balanced approximation approach, in which the resulting response guarantees a good agreement with the real behaviour. This

* Corresponding author Tel.: +00420604237683;
E-mail address: jan.cervenka@cervenka.cz

1877-7058
Peer-review under responsibility of the scientific committee of the 6th International Workshop on Performance, Protection & Strengthening of Structures under Extreme Loading.
10.1016/j.proeng.2017.11.097

can be assured by a quality control system based on validation. Such validation should include comparison with experiments, blind bench mark tests, effects of numerical methods, namely criteria for iterative procedures and mesh sensitivity.

Validation is briefly discussed in the first part of the paper along with the main principles of the employed material models. An application of ATENA software to containment analysis is presented in the second part of the paper .

2. Material model for concrete

The material model for concrete 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 [1]. The material model formulation assumes small strains, and is based on the strain decomposition into elastic (ε_{ii}^{e}), plastic (ε_{ii}^{p}) and fracture (ε_{ii}^{t}) components. The stress development can be then described by the following rate equations describing the progressive degradation (concrete cracking) and plastic yielding (concrete crushing):

$$\dot{\sigma}_{ij} = D_{ijkl} \cdot (\dot{\varepsilon}_{kl} - \dot{\varepsilon}_{kl}^{p} - \dot{\varepsilon}_{kl}^{f})$$ * MERGEFORMAT (1)

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

Plastic model: $$\dot{\varepsilon}_{ij}^{p} = \dot{\lambda}^{p} \cdot m_{ij}^{p}, \; m_{ij}^{p} = \frac{\partial g^{p}}{\partial \sigma_{ij}}$$ * MERGEFORMAT (2)

Fracture model: $$\dot{\varepsilon}_{ij}^{f} = \dot{\lambda}^{f} \cdot m_{ij}^{f}, \; m_{ij}^{f} = \frac{\partial g^{f}}{\partial \sigma_{ij}}$$ * MERGEFORMAT (3)

Where λ^{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. [5]it is possible to define analogous quantities for the fracturing model, i.e. λ^{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.

$$\dot{f}^{p} = n_{ij}^{p} \cdot \dot{\sigma}_{ij} + H^{p} \cdot \dot{\lambda}^{p} = 0, \; n_{ij}^{p} = \frac{\partial f^{p}}{\partial \sigma_{ij}}$$ * MERGEFORMAT (4)

$$\dot{f}^{f} = n_{ij}^{f} \cdot \dot{\sigma}_{ij} + H^{f} \cdot \dot{\lambda}^{f} = 0, \; n_{ij}^{f} = \frac{\partial f^{f}}{\partial \sigma_{ij}}$$ * MERGEFORMAT (5)

H^{p} and H^{f} are hardening/softening modules for plastic model and fracturing model, respectively. This represents a system of two equations for the two unknown multiplier rates λ^{p} and λ^{f} , and is analogous to the problem of multi-surface plasticity [6]. The details of the model implementation can be found in [1]. The model is using Rankine criterion for tensile fracture with exponential softening of Hordijk [7], see Fig. 1(a).

The compressive behaviour is modelled by a plasticity model, which is using the three parameter surface of Menetrey & Willam [8] (see Fig. 1(b). The softening in tension and compression is adjusted using a crack band approach of Bažant & Oh [9]. The crack band L_t as well as crush band size L_c are adjusted with regard to the crack orientation by , where θ is the angle between crack direction and average orientation of element.

$$L_t' = \gamma L_t \text{ and } L_c' = \gamma L_c, \; \gamma = 1 + (\gamma_{max} - 1)\frac{\theta}{45}, \; \theta \in \langle 0; 45 \rangle, \; \gamma_{max} = 1.5$$ * MERGEFORMAT (6)