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Verificated Techniques for the Numerical Simulation of Extreme Impacts on NPP Constructions

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Abstract

The distinctive paper is devoted to advanced methods of analysis, choice of appropriate and correct methods and software application packages for numerical simulation of external loads and impacts on the basic structures of nuclear power plants (wind hurricane, tornado, plane crash, the impact of the shock wave, seismic and tsunami effect). The article gives examples of representative calculations.

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Keywords: Extreme loads, Nuclear power plants (NPP) structures, Computational fluid dynamic (CFD) methods, Finite element (FE) methods, Program packages, Examples of calculations.

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1. Introduction

Reviewing of significant numbers of actual theoretical and experimental research works and data devoted to the influence of extreme impacts on structures of existing nuclear power plants showed that the existing regulations, corresponding design codes [1] and procedures do not fully take into account the specific definition of extreme loads and impacts on the main building of NPP. That's why they require clarification and development.

The present paper is devoted to advanced analysis methods, choice of appropriate and correct methods and software application packages for the numerical simulation of external loads and impacts (wind hurricane, snow loads, tornado, plane crash, the impact of the shock wave, seismic and tsunami effect) on the basic structures of nuclear power plants. The results of the development of appropriate methodic of definition of loads and impacts on the basic structures of nuclear power plants, its approbation and verification (with the use of universal software application packages) are presented below.

For the purposes of this research the universal software application packages for numerical simulation of continuum mechanics (ANSYS Mechanical, ANSYS CFD, ANSYS AUTODYN, LS-DYNA) were used.

2. Numerical methods

2.1. The implementation of the finite element method (FEM) in the form of displacements

For most structural dynamics problems of a mechanical system, the spatial discretization for the principle of virtual work using the finite element method gives the finite element semi-discrete equation of motion as follows [2]:

$$[M]\{\ddot{u}(t)\}+[C]\{\dot{u}(t)\}+([K]+[K_G])\{u(t)\}=\{F(t)\}+\{R(u,\dot{u})\} \quad (1)$$

2.1.1. Linear structural static analysis

The overall equilibrium equations for linear structural static analysis are:

$$[K]\cdot\{u\}=\{F\} \text{ or } [K]\cdot\{u\}=\{F^a\}+\{F^r\} \quad (2)$$

where: $[K]=\sum_{m=1}^{N}[K_e]$ – total stiffness matrix; $[K_e]$ – element stiffness matrix; $\{F^r\}$ – reaction load vector; $\{F^a\}=\{F^{nd}\}+\{F^{ac}\}+\sum_{m=1}^{N}\left(\{F_e^{th}\}+\{F_e^{pr}\}\right)$ – the total applied load vector; $\{F^{nd}\}$ – applied nodal load vector; $\{F^{ac}\}=[M]\cdot\{a_c\}$ – acceleration load vector; $[M]=\sum_{m=1}^{N}[M_e]$ – total mass matrix; $[M_e]$ – element mass matrix; $\{a_c\}$ – total acceleration vector; $\{F_e^{th}\}$ – element thermal load vector; $\{F_e^{pr}\}$ – element pressure load vector.

2.1.2. Mode-Frequency Analysis

The equation of motion for an undamped system, expressed in matrix notation using the above assumptions is:

$$[M]\cdot\{\ddot{u}\}+[K]\cdot\{u\}=\{0\} \quad (3)$$

For a linear system, free vibrations will be harmonic of the form:

$$\{u\}=\{\phi\}_i\cdot\cos\omega_i t \quad (4)$$

where: $\{\phi\}_i$ – eigenvector representing the mode shape of the i-th natural frequency; ω_i – i-th natural circular frequency (radians per unit time); t – time.

Thus, (3) becomes:

$$\left(-\omega_i^2 \cdot [M] + [K]\right) \cdot \{\phi\}_i = \{0\} \quad (5)$$

The not trivial solution is

$$\left| [K] - \omega^2 \cdot [M] \right| = 0 \quad (6)$$

Rather than outputting the natural circular frequencies {ω}, the natural frequencies (f) are output; where: $f_i = \omega_i / 2\pi$ – *i*-th natural frequency (cycles per unit time).

2.1.3. Thermal analysis

The governing equation of interest is as follows:

$$[C]\{\dot{T}\} + [K]\{T\} = \{Q\} \quad (7)$$

where: [C] – damping matrix; [K] – coefficient matrix; {T} – temperature; $\{\dot{T}\}$ – time rate of the temperature; {Q} – heat flow.

2.2. The mathematical formulation of the fluid dynamics

To calculate the velocity and pressure fields of fluid flow the nonlinear systems of second order partial differential equations – Reynolds-averaged Navier-Stokes equations (RANS) (8) and continuity equations (9) are solved [2]:

$$\frac{\partial}{\partial t}(\rho \overline{u_j}) + \frac{\partial}{\partial x_i}(\rho \overline{u_i} \cdot \overline{u_j}) = -\frac{\partial \overline{p}}{\partial x_j} + \frac{\partial}{\partial x_i}\left[\mu\left(\frac{\partial \overline{u_i}}{\partial x_j} + \frac{\partial \overline{u_j}}{\partial x_i}\right) - \rho \overline{u'_i u'_j}\right] \quad (8)$$

$$\frac{\partial u_i}{\partial x_i} = 0, \ \frac{\partial u'_i}{\partial x_i} = 0 \quad (9)$$

where: ρ – the fluid density (ρ = const for an incompressible fluid or gas); μ – dynamic viscosity; p – the average pressure, the indices i = 1,2,3 and j = 1,2,3 correspond to the coordinates x, y, z. Shear (Reynolds) stress $\rho \overline{u'_i u'_j}$ are additional six unknowns ($\overline{u_i}$, $\overline{p}$) which are approximated as a rule by the Boussinesq's assumption:

$$\rho \overline{u'_i u'_j} = -\mu_t \left(\frac{\partial \overline{u_i}}{\partial x_j} + \frac{\partial \overline{u_j}}{\partial x_i}\right) + \frac{2}{3}\rho k \delta_{ij} \quad (10)$$

where: μ_t – additional viscosity caused by fluctuations; k – averaged turbulent kinetic energy (TKE).

The system of equations (8, 9, 10) is not closed. To close this system semi-empirical relations (turbulence models) connecting additional unknowns (Reynolds stress) with time-averaged velocity components are imposed.

3. Developed techniques of numerical simulation

3.1. Wind loads and effects

Numerical modeling technique of the wind loads and effects on the basic structures of nuclear power plants was developed. It is based on numerical solution of steady and unsteady three-dimensional equations of fluid dynamics and devoted to the definition and analysis of extreme wind loads (average and fluctuating components of the loads on structures, peak pressures on the building envelope, evaluation of resonance phenomena). Verification of this technique on representative number of verification tests were carried out. Approbation of this developed technique on sample problems, dealing with advanced methods of analysis, definition of loads and impacts on the basic structures of nuclear power plants was done as well.

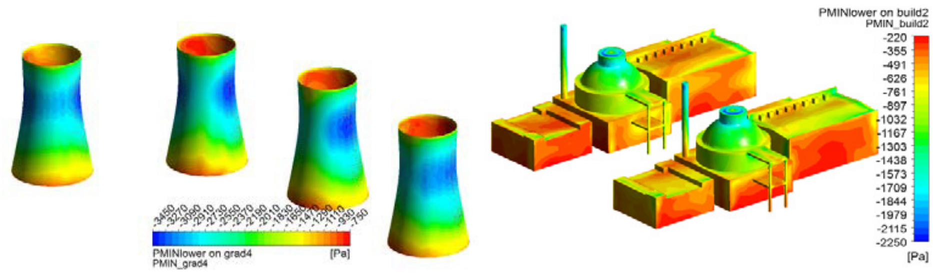

Fig. 1. Lower envelope of the minimum values of wind pressure on the cooling tower (from the bottom) and on the main building NPP(from the bottom) [Pa].

Table 1. Part of the Verification matrix of the numerical modeling technique of the wind loads and effects.

Name of task	Reference[3]	Turbulence model	Number of cells, thousand of cells	Controlled parameters	Time, hours	Error, %
Square prism, two-dimensional simulation	Experiment. Lyn	DES	20	Mean Cx, Cy, Cp, St, Vx, Vy	10	5-20%
Two square prisms interference, two-dimensional simulation	Experiment. S.G. Kuznetsov	DES	50	Mean Cx and fluctuations of Cy	20	5% for mean; 15% for fluct.
Cylinder, two-dimensional simulation (Re=3900)	Simulations. Liaw Experiment. Norberg	DES	40	Mean Cx, Cy, Cp, St, Vx, Vy,	20	5-10% (for Cp 5-20%)
The high-rise building in low-rise buildings	Experiment. AIJ	SST	200 450	Vped (mean and peak values)	1 2	5-10%, for mean 10-20%, for peak
Shinjuku, Tokyo	Measurements. Experiment. AIJ	SST	19 700	Vped (peak values)	15	10-50% (mesur.) 10-30% (exp.)

3.2. Tornado and loads of it

Numerical modeling technique of the tornado impact on NPP structures based on numerical solutions of steady and unsteady three-dimensional equations of fluid dynamics (such important factors as the direction of the class tornado relief can be taken into account). Verification and approbation of this developed technique was carried out and showed below.

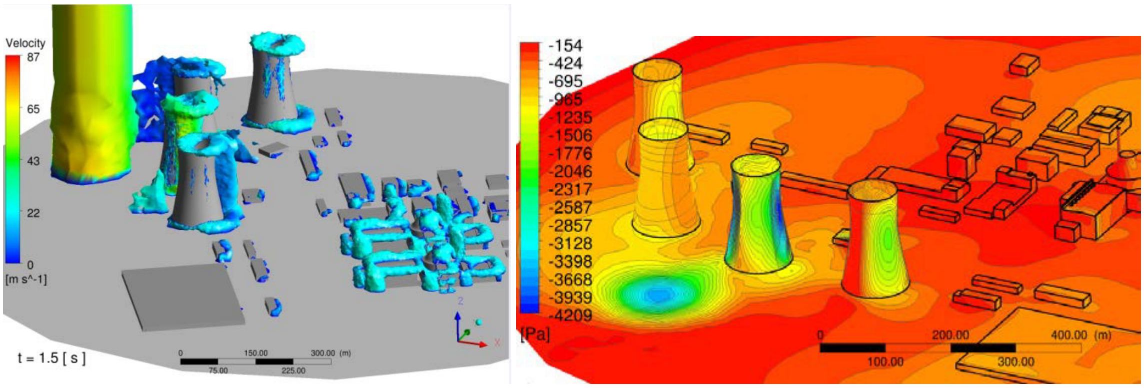

Fig. 2. Top - velocities on the vorticity isosurfaces at time t = 13.5 s; bottom - lower envelope of pressure from a tornado.

Table 2. Part of the Verification matrix of the numerical modeling technique of tornado loads.

Name of task	Reference[3]	Software	Method	Criterion	Error, %
Tornado creation experiment	Measurements Experiment	ANSYS FLUENT	URANS RNG k-e	Wind velociyties	Up to 30% Averaged - < 15%
Project «Shelter»	Expert estimates	ANSYS CFX	URANS SST	The peak pressure	Up to 30%
Impact of the car into the wall	Experiment	LS-DYNA	Explicit	Displacement in points	Up to 10%
Multiphase flow in the pipe	Analytical solution	Fluent	Stationary flow. Inlet flow is fully developed and laminar. The equations of phase transfer are solved.	Comparison of mass fractions of phases A along the axis of the tube	< 0.01%
Impact of metal cylinder in the concrete wall	Experiment	AUTODYN	Explicit	Penetration depth	< 2 %

3.3. The plane crash loads and impacts

Numerical modeling technique of plane crash loads and impacts on NPP structures was developed. It is based on numerical solutions of three-dimensional equations of solid mechanics with the use of finite element method or smoothed particle hydrodynamics method /SPH-method/ (nonlinear properties of reinforced concrete structures, soil foundations, equipment, plane properties (including the analysis of engines behavior, fuel spillage and fire caused by these factors) can be taken into account within coupled design model). Verification of this technique on representative number of verification tests were carried out. Approbation of this developed technique was done as well.

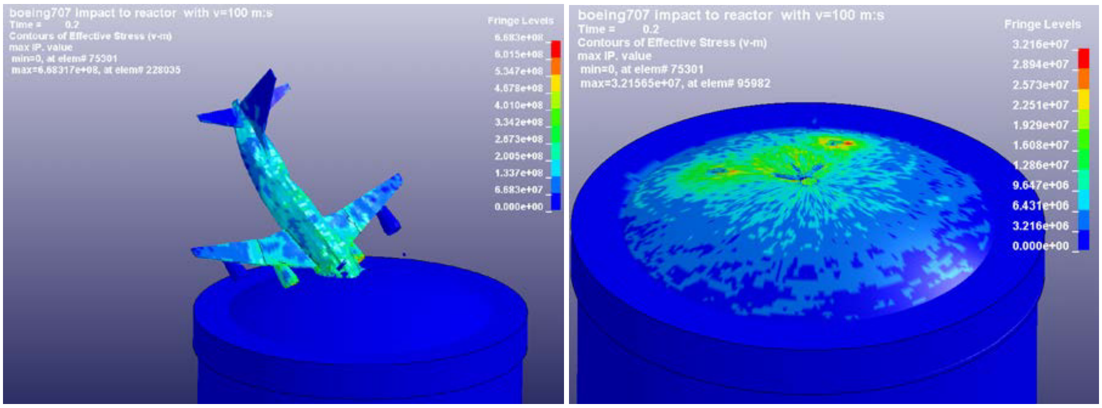

Fig. 3. Contour plots of equivalent stresses [Pa] at time t = 0.2 s.

Table 3 Part of the Verification matrix of the numerical modeling technique of the plane crash loads and impacts.

Name of task	Reference [3]	Sortware	Method	Criterion	Error, %
Collision of non-deformable shell with a reinforced concrete wall	Experiment VTT and empiric formulas	LS-DYNA, ABAQUS/ Explicit ANSYS AUTODYN	explicit	Penetration	10-30%
Wall penetration by the rigid projectile	Measurements	LS-DYNA	explicit	Penetration	< 50%
Collision of F4 with rigid wall.	Riera technique	LS-DYNA	explicit	Overall reaction	< 15%
Stability of spatial geodesic dome	Hangai, Jagannathan, Papadrakakis	LS-DYNA	explicit	Critical loads	0.22–0.5%
Temperature field in reinforced concrete column at a fire	МДС 21-2.2000	ANSYS Mechanical	Newton-Raphson	Temperature	< 9,0%

3.4. Tsunamis and loads of it

Numerical modeling technique of tsunami loads and impacts on NPP structures was developed. It is based on numerical solutions of three-dimensional steady and unsteady fluid dynamics equations within multiphase formulation, (bottom topography and terrain can be adequately taken into account). Verification and approbation of this developed technique was carried out.

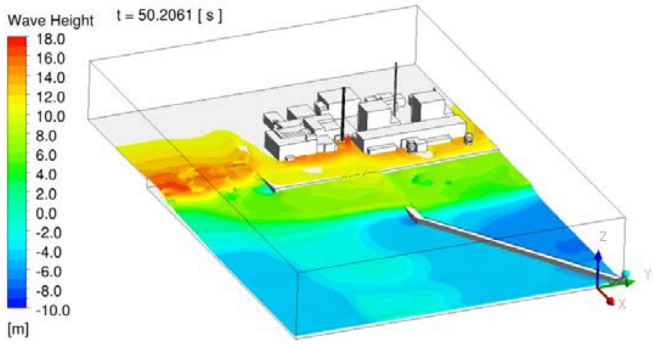

Fig. 4. NPP "Fukushima-1" (Japan). Wave height [m] at t = 50.3 s.

Table 4 Part of the Verification matrix of the numerical modeling technique of tsunami loads.

Name of task	Reference[3]	Software	Method	Criterion	Error, %
Landwash on the obstacle	Experiment	ANSYS FLUENT	RNG k-e VOF	Water level	Up to 40% Averaged – less than 10%
Dam break	Experiment]	LS-DYNA, CFX	SPH	Water level	Up to 15%
Load on the prism at the dam break	Experiment]	ANSYS FLUENT	RNG k-e VOF	Sensors pressure	Up to 15%
Surface waves caused by landslides in the Gulf of Lituya, Alaska	Experiment]	ANSYS FLUENT	RNG k-e DES VOF	Water level	Up to 40%

4. Conclusions

Analysis and synthesis of data on the impact of extreme impacts on structures of existing nuclear power plants (including NPP "Fukushima-1", Japan), and other unique objects, the existing regulations, corresponding design codes and procedures do not fully take into account the specific definition of extreme (special) external loads and impacts on the main building of NPP, and, therefore, require clarification and development.

Considerable number of verification samples, specific to the nuclear industry (Russian nuclear power plants, NPP "Fukushima-1") were used for multistage testing of developed methods and software application packages. The results of analysis showed correctness and effectiveness of the developed numerical methods of advanced analysis and definition of extreme external loads and impacts on NPP structures of a new generation.

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