PROBABILISTIC NONLINEAR ANALYSIS OF STEEL FRAME SAFETY UNDER EXTREME WIND IMPACT

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Abstract. *This paper describes the methodology and the results of the safety analysis of the Nuclear Power Plant (NPP) structures under impact of the extreme climatic loads. In the case of the NPP structures, the design criteria are stronger. The requirements of the international agency IAEA and NRC standards are based on the probability of mean return period equal to one per 10^4 years. This probabilistic assessment of NPP structures for Probabilistic Safety Analysis (PSA) level 2 of VVER 440/213 in the case of the extreme wind impact is presented. On the base of the meteorological monitoring of the locality the extreme load parameters were defined for the return period 10^4 years using the Monte Carlo simulations. There is showed summary of calculation models and calculation methods for the probability analysis of the structural resistance. The wind load was determined using the fluid analysis in software FLUENT in ANSYS and experimental analysis in wind tunnel. The general purpose of the nonlinear probabilistic analysis of the NPP structure resistance was to define the safety level of the critical structure elements. The numerical simulations on the base of the LHS method were realized in the system ANSYS and FReeT.*

Keywords

Safety, reliability, risk, fragility, nuclear power plant, probability, experiment, wind, ANSYS, FLUENT, FReeT.

1. Introduction

This paper deals with the resistance of the steel hall frame of the nuclear power plant (NPP) in Slovakia. The international organization IAEA in Vienna [1] set up the design requirements for the safety and reliability of the NPP structures. The extreme environmental events (e.g. wind, temperature, snow, explosion...) [2, 3] are the important loads from the point of the NPP safety performance.

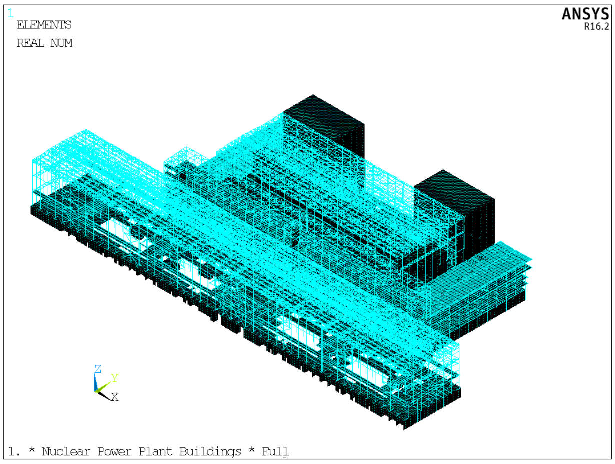

Fig. 1: FEM model of NPP with reactor VVER440/213.

The extreme loads are defined with the probability of mean return period equal to one per 10000 years [1-7]. U.S. Nuclear Regulatory Commission and Nuclear Regulatory Authority of the Slovakia published a set of the regulatory guide to the risk analysis of NPP [6-7]. The NPP buildings with the reactor VVER 440/213 consist of the turbine hall, middle building, reactor building and bubble condenser (Fig.1). The building of the power block was idealized with a FEM model consisting of 996 917 elements with 2 666 556 DOF (Fig.1) in software ANSYS [12, 13].

2. Extreme design situations

There are presented the loading action due to the extreme wind [12, 13]. The load combination of the deterministic and probabilistic calculation is considered according to EN 1990 [8] and IAEA [1] for the ultimate limit state of the structure as follows:

A) Deterministic design method

$$E_d = \gamma_g G_k + \gamma_q Q_k + \gamma_a A_k \ , \tag{1}$$

B) Probabilistic design method

$$E = G + Q + A_E = g_{\text{var}} G_k + q_{\text{var}} Q_k + a_{\text{var}} A_{E.k} \ , \tag{2}$$

where G_k is the characteristic value of the permanent dead loads, Q_k - the characteristic value of the permanent live loads, A_k - the characteristic value of the extreme loads, γ_g, γ_q, γ_a are the loading parameters ($\gamma_g = \gamma_q = \gamma_a = 1$ for the extreme design situation), g_{var}, q_{var}, a_{var} are the variable parameters defined in the form of the histogram calibrated to the load combination in compliance with Eurocode [8] and JCSS requirements [10].

The load on a structure due to the wind will depend on both wind velocity and terrain roughness [9]. According to Slovakia standard [9] the terrain corresponds to terrain category I, with the basic wind velocity $v_{b.o} = 24$m/s, which correspond to basic wind pressure $q_b = 0.36$kNm^{-2}. These values correspond to the design requirements valid for the civil engineering structures. In case of the NPP structures the extreme wind load (EWL) must be considered for the probability of recurrence once every 10000 years.

The mean wind velocity v_m should be determined from the basic wind velocity v_b which depends on the wind climate and the height variation of the wind determined from the terrain roughness and orography. The characteristic value of the wind load for the return period 10000 years is $p_{\_EWL} = 0.936$ kPa (for the mean velocity 38.7 m/s during 10 min) [9]. This value was determined from the probabilistic analysis of the wind velocity in this region by SHM Institute [11]. In case of the standard civil engineering the characteristic value is determined for the return period 100 years.

3. Experimental analysis of extreme wind impact

The extreme wind impact to the NPP buildings was considered in wind tunnel of STU Bratislava [12]. The models of the NPP buildings were considered without and with the surrounding buildings (Fig.2). The objects were assembled on a 3D printer in a scale of 1: 300.

These directions were supplemented by wind directions 14°, 104°, 194° and 284° to consider the perpendicular wind directions to the individual walls of the halls.

The results from the experimental analysis were used for the evaluation of the numerical analysis of the wind impact in software ANSYS-FLUENT [13-16].

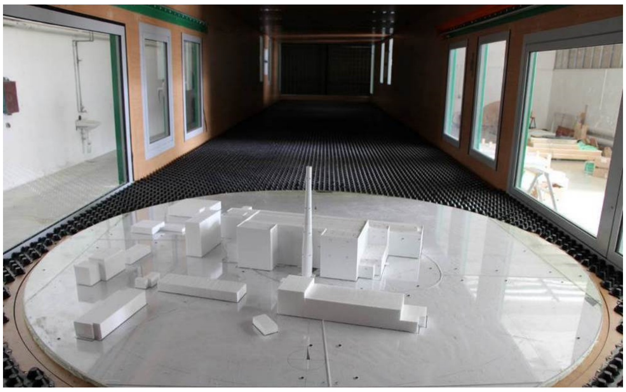

Fig. 2: Experimental model of NPP structures in the wind tunnel.

4. Numerical analysis of extreme wind in ANSYS-FLUENT

The computational fluid dynamics is based on the numerical solution of a system of partial differential equations that express the law of conservation of mass (continuity equation), the momentum conservation law (Navier-Stokes equations) and the law of conservation of energy (energy equation - heat transfer by convection, conduction, or radiation). This basic set of equations can be extended by others that express the transfer of impurities (gaseous liquid or solid). The whole system is then solved by one of the numerical methods, most often by the finite volume method [13-16].

The model represents a flow simulation using Reynold's equations, and even with significantly lower computational complexity, it retains a sufficient solution quality. Therefore, it is the most widely used method for flow simulation in practice.

There are three basic approaches to analysing turbulent flow:

- DNS (Direct Numerical Simulation)
- LES (Large Eddy Simulation)
- RANS (Reynolds Averaged Navier-Stokes Simulation)

DNS and LES methods have high demands on computer memory, number of processors and computational time. The RANS method is effective, which models all types of turbulent vortices and solves time-averaged flow values. For 3D analysis, a powerful 16-processor Dell computer with 64GB of RAM was used. 3D model was created in the AUTOCAD program, which was imported into the program ANSYS-FLUENT. This program has various turbulent calculation models (Spalart - Allmaras, k-ε model, and k-ω model). After considering all the influences, as well as the complexity and accuracy of individual turbulent models and previous experience with individual turbulent models [13, 14], SST k-ω and Standard k-ω turbulent models were selected and used for 3D simulation of air flow around NPP objects [16].

The size of the computational domain was chosen to cover the entire flow in front of, around and above the object so that this flow was not affected by the boundary conditions defined on the domain surfaces. In the case of a 3D model, the following dimensions are recommended - in front of the 5H model, behind the 10H model, above the 4H model and on the 5H. The overall dimensions of the computational domain are 1172x2154x750 m. A total of 14 characteristic computational models in 2D and 3D space were created for the flow direction in the ZX and YZ planes.

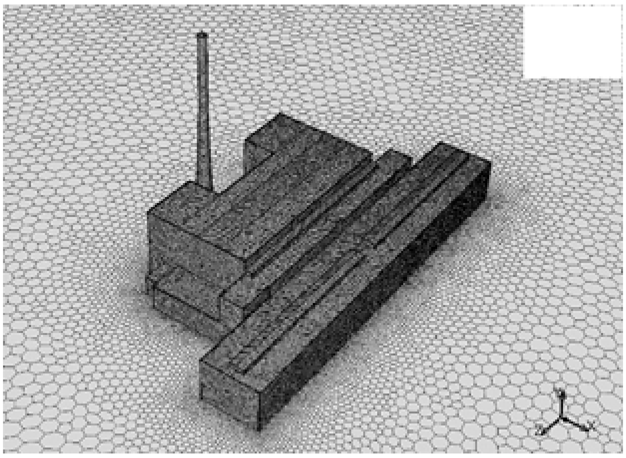

Fig. 3: 3D FE model with the polyhedral meshing.

The specific FEM mesh was created for all four flow directions in the same way. The size of the spatial elements on NPP was chosen 1 m without "inflation" (Fig.3). The size of the surface elements was 1 m as well as for the chimney of NPP. This size of elements came from several iterations. Several FEM meshes were created and each of them was subjected to an ongoing simulation, where it was determined how long the total simulation would take. Some of the possibilities offered by FLUENT in the mesh creating could not be applied to the NPP model because the generation of mesh did end with an error. FLUENT was not able to generate layers of inflation due to the complexity of the model. So, given the possibilities offered by FLUENT, the size of the spatial elements on NPP was chosen 1 m without "inflation" (Fig.3). The element dimensions were defined with an increase of 10 %. The bottom area of the domain was defined as a wall with an element size of 10 m, as the total domain had length dimensions of 2154 m.

This adjustment was to allow FLUENT to calculate the flow profile at the bottom boundary of the domain (practically close to the ground). "Smoothing" was defined as "high" and "Transition" as "slow". The maximum size of the element was defined at 60 m with a maximum area of 30 m^2.

The FE model was created with 1 122 685 nodes and 6 340 840 tetrahedron elements type (Fig.3). Subsequently, the entire domain within the "tetrahedron" elements was transformed into "polyhedral" type of elements, which represent a volume element with 12 nodes. In this way, a reduction in the number of elements to 1 193 211 was achieved, which represents a reduction of the number of elements by 5.3 times.

All simulations were performed with the same solver settings. It was a "Pressure-Based" model and a time-varying "transient" task. Two turbulent models, Standard k-ω and SST *k-ω*, were considered. During the simulation, residues were monitored, namely continuity, *X*-velocity, *Y*-velocity, *Z*-velocity, parameters *k* and *ω*.

The convergence of the solution was defined by setting the maximum residual value

All simulations were performed with the same solver settings. It was a "Pressure-Based" model and a time-varying "transient" task. Two turbulent models, Standard

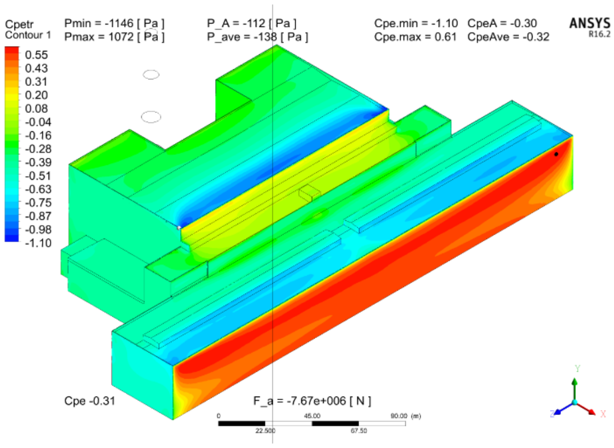

Fig. 4: The average pressures on the surface of the NPP buildings, windward side, flow direction -X.

Based on the above assumptions, defining boundary conditions and parameters of the calculation method on the turbulent model SST "k-ω" in the FLUENT program [13, 14], values of air flow velocity over the object surface were obtained, average pressure coefficients $c_{pe.10}$ on the object surface were determined according to Eurocode requirements [9], as well as the resulting pressures. 25 zones were created on the surface of each object, for which average pressure values were obtained, which could be used for subsequent static calculations (see Fig.5-6).

Before starting the experimental work, it was necessary to identify critical areas on the surfaces of individual objects for the placement of measuring points due to the limited possibilities of the number of scanners for measuring pressures in the wind tunnel. After the measurement in the wind tunnel, it was necessary to verify the measured values on a 3D model of wind flow on individual critical surfaces. Such a procedure is generally recommended in the scientific literature [13-16], because, as in the experiment, measurement errors can occur, resp. when evaluating the measured quantities and simulating these phenomena in the ANSYS-FLUENT program [13]. Errors can also occur in defining the boundary conditions as well as in the computational processes during the simulation and processing of the results in the postprocessor.

5. Calculation model of the structural analysis

The resulting pressures from extreme winds were therefore considered (Tab.1) as the best estimate corresponding to the average value of the reduced peak pressures (according to the Eurocode) from the experiment and the values obtained by numerical simulation on a 3D model (Fig.4). We can see the differences between Eurocode simple model and measured results (Tab.1). The maximum difference is 191% at roof of SO 800 BT [16].

The computational NPP model with reactor VVER 440 were compiled in the ANSYS program on the base of project documentation (Fig.5-8). Twelve modified computational models were created, differing in the modelling details.

As part of the preparatory calculations, it was necessary to verify the plausibility of the load-bearing structure model, as well as to fine-tune the model for subsequent dynamic calculations.

The computational models had to be tested for static as well as modal stress. The computational model (Fig.5-8) corresponds to a detailed solution of a steel structure with several details - the model contains 159,037 elements with 139,113 nodes and 444,454 degrees of freedom [16]. The model uses BEAM44 rod elements with all degrees of freedom and shows a slightly higher rigidity than the real structure.

The computational models are a complex model of the whole NPP, i.e., reactor building, bubbling tower, ventilation center, engine room, transverse, and longitudinal electrical building.

The interaction of the building with the subsoil in the case of the subsoil was considered by the SURF154 contact elements.

One from the critical structures was the frame of the transversal gallery (Fig.8) in axis 38. The FEM model was created on base of the methodology of substructure analysis. The stiffness, density and load input were generated from the 3D FEM model (Fig.7). One from the critical structures was the frame of the transversal gallery (Fig.5, 8) in axis 38.

Tab.1: Comparison of coefficients and pressures according to EN1991-1-4 and resulting pressures from experiment and 3D simulations in ANSYS-FLUENT program for flow direction -X and roof zone (Fig.9 and 10).

Roof (Fig.12)	EN 1991, terron II.					3D k-ω + Experiment Mean value		Comparison with EN
SO	Zone	Cpe,10 [-]	Cpi [-]	Peak pressure [Pa]	Mean pressure [Pa]	Cpe,10 [-]	Mean pressure [Pa]	[%]
490	G	-1,3	-0,3	2498	-3997	-0,73	-2573	64
	H	-0,7	-0,3	2498	-2498	-0,7	-2498	100
	G	-1,3	-0,3	2552	-4083	-0,509	-2065	51
	H	-0,7	-0,3	2552	-2552	-0,432	-1868	73
	I	-0,2	-0,3	2498	-1249	-0,481	-1951	156
805	F	-1,9	-0,3	2628	-5782	-0,355	-1721	30
	G	-1,3	-0,3	2628	-4205	-0,016	-830	20
	H	-0,7	-0,3	2628	-2628	-0,314	-1614	61
	H	-0,7	-0,3	2628	-2628	-0,021	-844	32
805 span	F	-1,9	-0,3	2666	-5865	-0,015	-840	14
	G	-1,3	-0,3	2666	-4266	0,133	-445	10
800	F	-1,9	-0,3	2760	-6072	-0,982	-3538	58
	G	-1,3	-0,3	2760	-4416	-0,914	-3351	76
	H	-0,7	-0,3	2760	-2760	-0,565	-2387	87
Vent. Centrum	H	-0,7	-0,3	2760	-2760	-0,322	-1717	62
	I	-0,2	-0,3	2760	-1380	-0,29	-1628	118
Babble tower	I	-0,2	0	2760	-552	-0,382	-1054	191
807	H	-0,7	-0,3	2223	-2223	-0,467	-1705	77
	I	-0,2	-0,3	2223	-1112	-0,618	-2041	184
807 span	H	-0,7	-0,3	2057	-2057	-0,42	-1481	72
	I	-0,2	-0,3	2057	-1029	-0,575	-1800	175

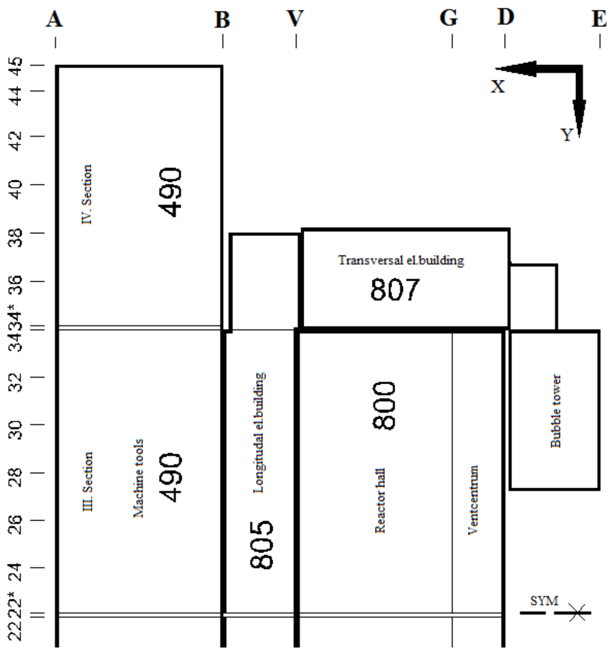

Fig. 5: Scheme of NPP buildings with reactor VVER440.

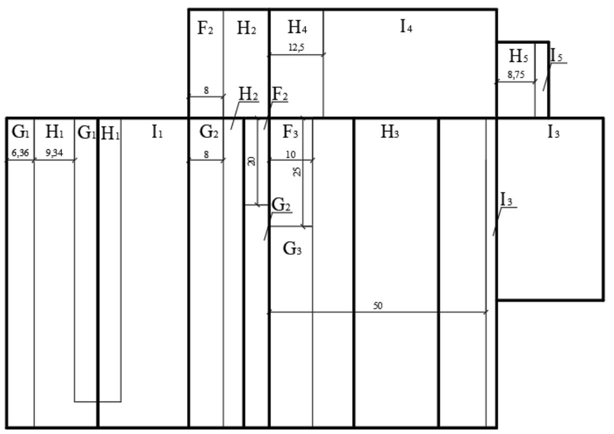

Fig. 6: Surface scheme of NPP roof structures for excitation in the -X direction by Eurocode recommend-dation.

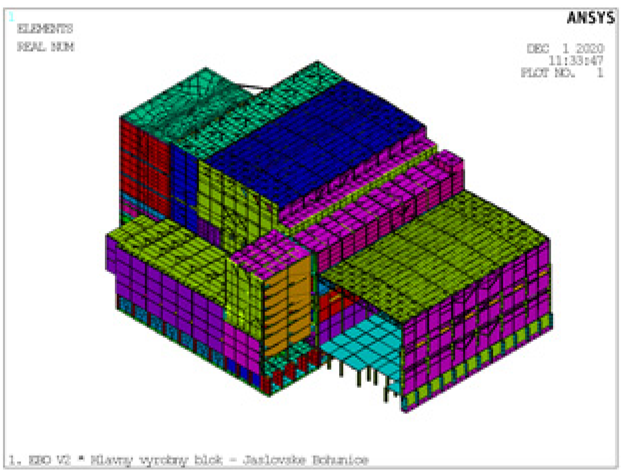

Fig. 7: The axonometric view of the computational NPP model.

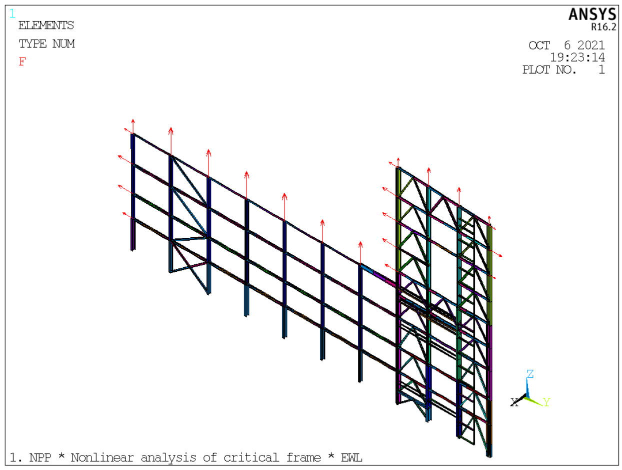

Fig. 8: The view of the critical frame of NPP transversal gallery.

6. Nonlinear analysis

On base of the linear analysis using 3D calculation NPP model, the critical frame structures were defined. Next, the maximum extreme loads were calculated from the ultimate state of the critical frame. The limit state of the steel frame was considered to utilize the geometric and material nonlinearity in program ANSYS [7, 13, 17, 18]. The geometric nonlinearity is based on the theory of the large strain, which is often used for elastic-plastic elements. The elastic-plastic model of steel material was taken in compliance with the Von Mises yield function *F*(.) and the plastic potential *Q*(.). This model is based on Drucker theorem that the vector of the plastic strain increment is dependent on the plastic multiplier $d\lambda$. Consequently, the stress-strain relations are obtained from the following relations

$$\{d\sigma\}=[D_{\mathrm{el}}]\left(\{d\varepsilon\}-\{d\varepsilon^{\mathrm{pl}}\}\right)=[D_{\mathrm{el}}]\left(\{d\varepsilon\}-d\lambda\left\{\frac{\partial Q}{\partial\sigma}\right\}\right)$$

or $\{d\sigma\}=\left[D_{\mathrm{ep}}\right]\{d\varepsilon\}$ (3)

where $\left[D_{\mathrm{ep}}\right]$ is elastic-plastic matrix in the form

$$\left[D_{\mathrm{ep}}\right]=[D_{\mathrm{e}}]-\frac{[D_{\mathrm{e}}]\left\{\frac{\partial Q}{\partial\sigma}\right\}\left\{\frac{\partial F}{\partial\sigma}\right\}^{T}[D_{\mathrm{e}}]}{A+\left\{\frac{\partial F}{\partial\sigma}\right\}^{T}[D_{\mathrm{e}}]\left\{\frac{\partial Q}{\partial\sigma}\right\}} \quad (4)$$

The hardening parameter *A* depends on the yield function and model of hardening (isotropic or kinematic). Von Mises yield criterion is defined in the form

$$\sigma_{\mathrm{eq}}=\sigma_{\mathrm{T}}(\kappa)\ , \quad (5)$$

where σ_{eq} is equivalent stress and $\sigma_{\mathrm{T}}(\kappa)$ is the yield stress depends on the hardening. The Newton-Raphson iteration method to solve nonlinear equations was taken. The plasticity model is defined as multilinear isotropic hardening material model.

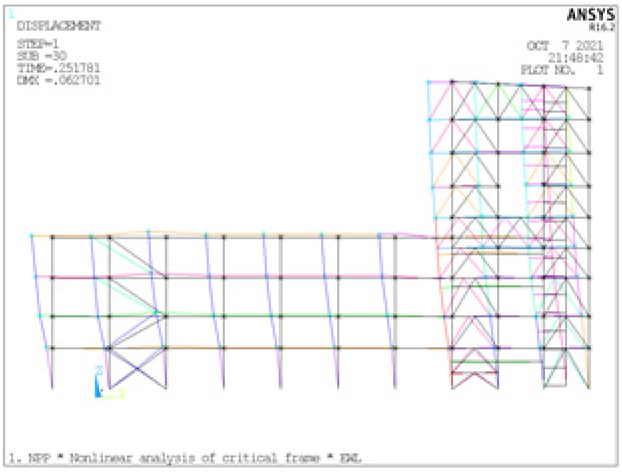

Fig. 9: Deformation of the frame for the py = 23.67.kPa.

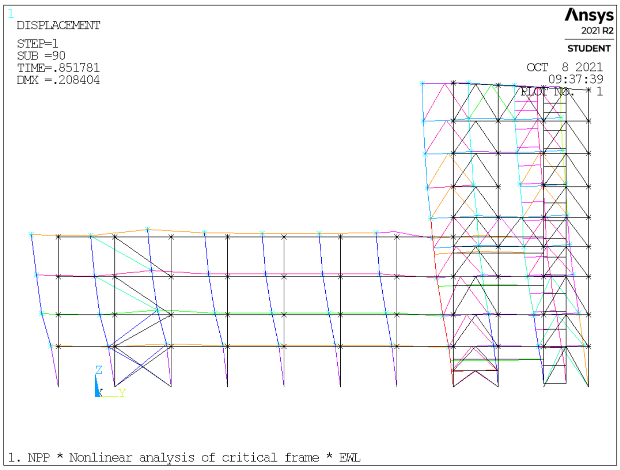

Fig. 10: Deformation of the frame for the pu = 80.kPa.

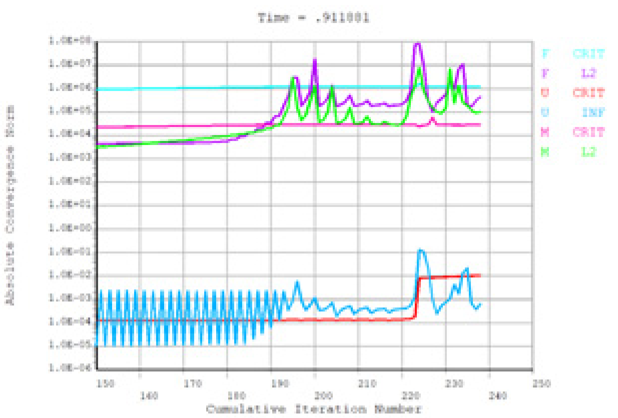

Fig. 11: Absolute convergence criteria at steel frame collapse.

The figures 9 - 11 show results of nonlinear analysis of the critical frame under the elastic and plastic limit wind load. On base of the nonlinear deterministic calculation, we have the median value of the maximum wind load for elastic limit state (f_y) and plastic limit state (f_u) as follows

$$p_{y.m} = 23.67 \text{ kPa} \quad \text{and} \quad p_{u.m} = 80.07 \text{ kPa} \qquad (6)$$

The ductility factor can be determined as the ratio between the maximal horizontal displacement in case the plastic limit state and elastic limit state

$$k_D = u_{hu} / u_{hy} = 0.2084 / 0.0627 = 3.32 \qquad (7)$$

The nonlinear analyze of the critical frames of NPP longwise gallery frame was performed by the Newton-Raphson method in 238 iteration steps of 10 loads increments. The total load was a multiple of the design load from extreme wind of η_y = 25.18 for elastic limit state and η_u = 88.18 for plastic limit state.

7. Probabilistic assessment

Following the Fukushima NPP accident, the IAEA [3], as well as U.S. NRC [4] and NRA in Slovakia [6] defined new increased requirements for NPP safety based on risk analysis of technological processes. This methodology is based on a probabilistic analysis of the safety and reliability of individual elements of the structure, as well as units [7]. Publications from the experience of using probabilistic methodology for structural reliability analysis are appearing more and more in the literature [17-24].

The uncertainties of the input data – action effect and resistance are for the case of the probabilistic calculation of the structure reliability defined in JCSS [10] and Eurocode 1990 [8].

Tab.2: Probabilistic model of input parameters.

Name	Quantity	Mean Value	Variable Paramet.	Histogram
Material	Young's Modulus	E_m	e_{var}	Normal
Load	Dead	G_m	g_{var}	Normal
	Live	Q_m	q_{var}	Gumbel
	Extrem Wind	W_m	w_{var}	Gumbel
Resistance	Steel Strength f_{sk}	F_m	f_{var}	Lognormal
Model	Action Uncertaint	θ_{Em}	Te_{var}	Normal
	Resistance Uncert.	θ_{Rm}	Tr_{var}	Normal

Tab.3: Characteristic input data of the probabilistic model.

Name	Quantity	Mean	Stand. Deviation	Min. Value	Max. Value
Material	Young's Modulus	1	0,120	0,645	1,293
Load	Dead	1	0,010	0,755	1,282
	Live	0,60	0,200	0	1
	Extreme Wind	0,30	0,150	0,500	1,032
Resistance	Steel Strength f_{sk}	1	0,100	0,726	1,325
Model	Action Uncertaint	1	0,100	0,875	1,135
	Resistance Uncert.	1	0,100	0,875	1,135

The input data are defined by the characteristic values and the variable coefficient (Tab. 2, 3). Stiffness of the structure is determined with the median value of Young's modulus E_m and variable factor e_{var}. Loads are represented by theirs characteristic values G_m, Q_m, $W_{E,m}$ and variable factors g_{var}, q_{var} and w_{var}. The resistance of the steel is delimited by the characteristic values of the strength f_{ak} and the variable factor f_{var}. The uncertainties of the calculation model are considered by variable model factor and variable load factor

8. Fragility curve of frame

The fragility curve was calculated for various levels of wind loads using the results from the nonlinear analysis of the steel hall frame. The probability of frame failure was determined by two methods [16]:

A. Analytical analysis based on the FORM method and considering the lognormal distribution of action effect *E* and resistance *R*,

B. LHS simulation methods in software FREeT [23], considering the distribution of Gumbel's wind load, normal self-weight distribution, and lognormal for resistance (see Tab. 2-3).

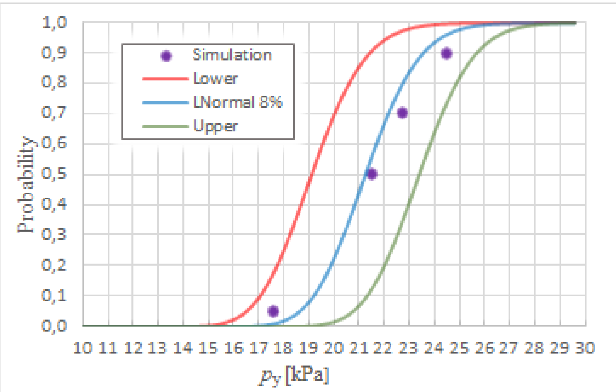

Fig. 12: Idealized fragility curves of the steel hall frame for elastic limit state.

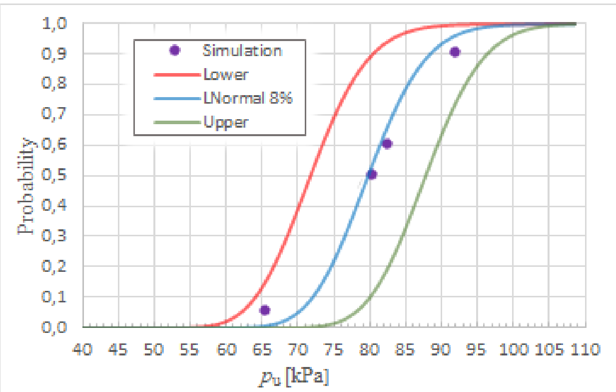

Fig. 13: Idealized fragility curves of the steel hall frame for the plastic limit state.

A) FORM estimation of failure probability:

We have the median value of the elastic load limit effect p_{ym} = 21.3 kPa and the plastic load limit p_{um} = 80.0 kPa according to nonlinear analysis in software ANSYS. The logarithmic standard deviation of load is considered by values β_E = 0.1 and resistance β_R = 0.1. We calculate following critical wind loads for 5% probability

$$\beta_c = \sqrt{\beta_E^2 + \beta_R^2} = 0.141 \quad \text{and} \tag{8}$$

$$p_{y\_0.05} = p_{ym} \exp(-1.65\beta_c) = 16.899 \text{ kPa}$$

$$p_{u\_0.05} = p_{um} \exp(-1.65\beta_c) = 59.549 \text{ kPa}$$

B) LHS simulation using the software FREeT [46]

The elastic $p_{y\_0.05}$ and plastic $p_{u\_0.05}$ limit wind pressure for 5% probability of the exceedance failure of critical frame of the transversal gallery using the LHS simulation method for 1000 simulations in software FREET was obtained as follows

$$p_{y\_0.05} = 17.395 \text{ kPa} \quad \text{and} \quad p_{u\_0.05} = 65.507 \text{ kPa} \tag{9}$$

The wind fragility curves of the steel transversal gallery frame with the 10% envelope are presented in fig.12 in case of the elastic limit and in the fig.13 in case of the plastic limit. These curves were calculated on base of the simulation using LHS method in the program FREET using the lognormal distribution functions.

9. Conclusion

This paper presents the reliability analysis of the steel hall frame of the NPP critical transversal gallery resistance due to extreme wind loads [16]. The extreme loads were defined for mean return period equal to one per 10000 years in accordance with IAEA [1-3], U.S.NRC [4-5] and NRA SR [6] requirements for NPP structures. In this paper were presented the experimental and fluid analysis of the wind impact on the NPP structures. The new methodology of the safety and reliability analysis of the NPP structures were presented.

On the base of the nonlinear numerical analysis of the wind pressure the elastic $p_{y\_0.05}$ and plastic $p_{u\_0.05}$ limit wind pressure for 5% probability of the exceedance failure of critical frame of the transversal gallery using the LHS simulation method for 1000 simulations in software FREET was obtained as follows

$$p_{y\_0.05} = 17.395 \text{ kPa} \quad \text{and} \quad p_{u\_0.05} = 65.507 \text{ kPa} \tag{10}$$

The results of this analysis clearly confirm that considered NPP steel structures have significantly greater resistance to extreme wind effects at the origin of and the development of plastic deformations, considering the conservative linear calculation and assessment of one (weakest) cross-section of the critical element on the simplified wind model according Eurocode requirements [9] for the simple shape of structures.

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