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SENSITIVITY OF DYNAMIC BEHAVIOUR OF THE FE MODEL: CASE STUDY FOR THE IGNALINA NPP REACTOR BUILDING

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Abstract. The 3D thin-walled finite element model of Ignalina NPP Unit 2 reactor building was developed aimed at the evaluation of the global dynamic behaviour with a focus on the seismic response. The model comprises description of the monolithic structures, while prefabricated frame structures are ignored and replaced by external masses. Sensitivity study of the selected dynamic characteristics of the model with respect to data uncertainties is considered. Uncertainty of the model is considered in terms of masses of removed structures and wall stiffness. Seismic input is represented by the site specific free-field ground response acceleration spectra. The sensitivity study concerns variations of frequencies and acceleration of in-structure horizontal response spectra at specified points. Maximal bending moments are also considered. It was obtained that the reactor level is not sensitive to the uncertainties considered, while discernable sensitivity was detected at the top level of the structure.

Keywords: Ignalina nuclear power plant, finite element model, frequency analysis, seismic analysis, free-field spectra, in-structure response spectra.

1. Introduction

The Ignalina NPP located in the north-eastern Lithuania, is one of the biggest power plants in East Europe. It is the only nuclear plant operating in the Baltic States. The plant contains multi-channel graphite-moderated water-cooled so-called RBMK reactors. RBMK is a Russian acronym for "Channelized Large Power Reactor".

Recently an increasing risk of natural and artificial disasters raise up an importance of the safety assessment of nuclear equipment and RBMK reactors in particular. Several important design features of Ignalina NPP, as well as of all reactors of this series are unique and extremely complex with respect to those built in Western countries. They do not have protective shell but are constructed as large interconnected traditional buildings. A detailed description of Ignalina NPP is given by (Almenas *et al.* 1998).

Several important factors urge the safety reassessment. The original designing and safety analysis of NPP structures have been performed by applying simple methodologies on the basis of oversimplified assumptions, which do not correspond to the modern computational technologies.

Ignalina NPP is located in west of the East European Platform at the boundary of two large-scale structural elements – the Baltic depression and the Mazur-Belorus heights (Šliaupa 2002; Šliaupa *et al.* 2006a; Marcinkevičius 1995; Assistance Programme… 2004). Consequently, the probability of occurrence of the active fault zones and related seismic risk near the Ignalina NPP is rather high.

Seismic analysis of buildings and equipment is a significant part of the safety assessment of NPP's. The previous seismic analysis of building structures was basically performed applying one-dimensional column discrete-mass models (Clough & Penzien 1999; Kačianauskas & Kutas 1995). This approach was also used in evaluation of the Ignalina NPP response spectra (Popov 2004). Nowadays, the existing finite element methodologies (Zienkiewicz & Taylor 2000, Kačianauskas 1995, Miedziałowski *et al.* 2007) and universal software codes (ABAQUS; ANSYS; Dundulis *et al.* 2003, 2005, 2006) provide possibility of performing the structural analysis of different complexity, including volume and plate or shell elements of continuum as well as various engineering one-dimensional elements in a unique assembly. The existing requirements for design (IAEA 2000, 2003a, 2003b) recommend the application of 3D modelling techniques in order to simulate the realistic structure behaviour.

The presented paper addresses the development and case study of sensitivity of 3D thin-walled model of the Ignalina NPP Unit 2 reactor building to be used for the global dynamic analysis. It is realised that due to a high complexity a certain degree of simplification and uncertainties are inevitable, but essential dynamic features of the building must be retained. Uncertainty of the model is considered in terms of masses of removed structures and wall stiffness.

Sensitivity study of the selected dynamic characteristics of the model with respect to data uncertainties is considered in this paper. In recent years, a number of different methods of global sensitivity analysis and stochastic sensitivity analysis have been presented (Sobol *et al*. 2007; Campolongo *et al*. 2007). The sensitivity analysis makes it possible to determine the dominant properties that require more attention, especially during the preparation of input values and when considering the improvement of technological processes and the checking process.

The seismic input is represented by the site specific free-field ground response acceleration spectra. Sensitivity study concerns variation of frequencies and acceleration of in-structure horizontal response spectra at specified points.

The model is examined by considering sensitivity of eigenfrequencies, spectra and applied masses. Finally, it is used in the seismic analysis performed. The deterministic approach (BRIGADE/Plus Version 1.2, Peters *et al*. 1977) instead of probabilistic was applied because of the lack of data on the seismic events in the Ignalina region, while seismic input is provided by site specific free-field ground response acceleration spectra (Šliaupa *et al*. 2006a).

The seismic analysis and corresponding sensitivity study is restricted to the evaluation of in-structure response spectra in specific selected points and evaluation of maximal values of the seismic bending moments.

The paper is organised as follows. Section 2 describes the Ignalina NPP reactor building, while in Section 3 the used numerical model is considered. Section 4 is devoted to the frequencies analysis, and Section 5 explains some results of seismic calculations.

2. Basic design of NPP reactor building and the equipment

The Ignalina NPP unit 2 consists of 5 buildings: reactor building; demineralised water treatment facilities; reactor gas circuit and special venting system; turbine generators with auxiliary systems, control, electrical and deaerator rooms. These buildings are adjacent, but have separate foundations. Therefore they can be evaluated separately in the seismic analysis. The reactor building was selected for the structural seismic analysis. The cross-section of the reactor building with main components is presented in Fig. 1.

This building contains an RBMK-1500 reactor (pos. 1) with a main circulation circuit (MCC) (pos. 2, 3, 4, 6, 7, 8, 9, 10, 11, 12, 13, 14 and 16), and the following main auxiliary systems of the reactor: emergency core cooling system (pos. 5), accident confinement system (compartments in which is located MCC and towers which contain condensing pools) and Control and Protection System (CPS). The hall above the reactor is a large open workspace housing the refuelling machine (pos. 15). The spent-fuel storage pond is situated in an adjacent hall, but separated from the reactor hall. The reactor compartment consists of a rectilinear structure, the horizontal cross-section of which is 90x90 m and a height of about 53 m.

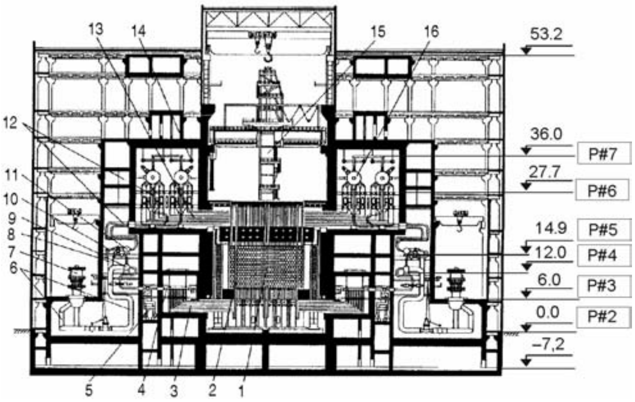

Fig. 1. Cross-section of the reactor building with main components: 1 – graphite stack; 2 – fuel channel feeder pipes; 3 – water pipes; 4 – group distribution header; 5 – emergency core cooling pipes; 6 – pressure pipes; 7 – main circulation pump; 8 – suction pipes; 9 – pressure header; 10 – bypass pipes; 11 – suction header; 12 – downcomers; 13 – steam and water pipes; 14 – steam pipes; 15 – refuelling machine; 16 – drum separator

3. Development of model

Progress of existing computational technologies allows simulation of structures of very high complexity. Nevertheless, it should be noted that certain level of compromise between costly complexity and engineering simplicity should be attained. The presented modelling approach is also based on appropriate compromise. The model is three-dimensional, in order to reflect space distribution of acting forces, while particular details, including equipment and systems, are simplified for the sake of convenience.

The development of model is performed in two stages. The first stage comprises constructing the model geometry. The model is restricted by the monolithic thin-walled concrete structure, while the prefabricated part is removed. Concept of this simplification is illustrated in Fig. 2, where the outline of the monolithic part considered and removed prefabricated structure is shown.

Thus, the geometry of the building is defined by geometry of monolithic walls. To avoid local effects the roof structure is presented in a form of rigid constraints. Finally, the developed model is illustrated by presenting East-West cross-section (Fig. 3).

Influence of the removed prefabricated concrete parts of the auxiliary compartments of the reactor building was compensated by adding the corresponding lumped mass. The point mass is connected to the building by coupling constraints. Mass of all the removed structures of building is 7390 tonnes. The mass of the removed structure is calculated taking into account the number of ceilings, the average number of columns on each level, average thickness of ceilings.

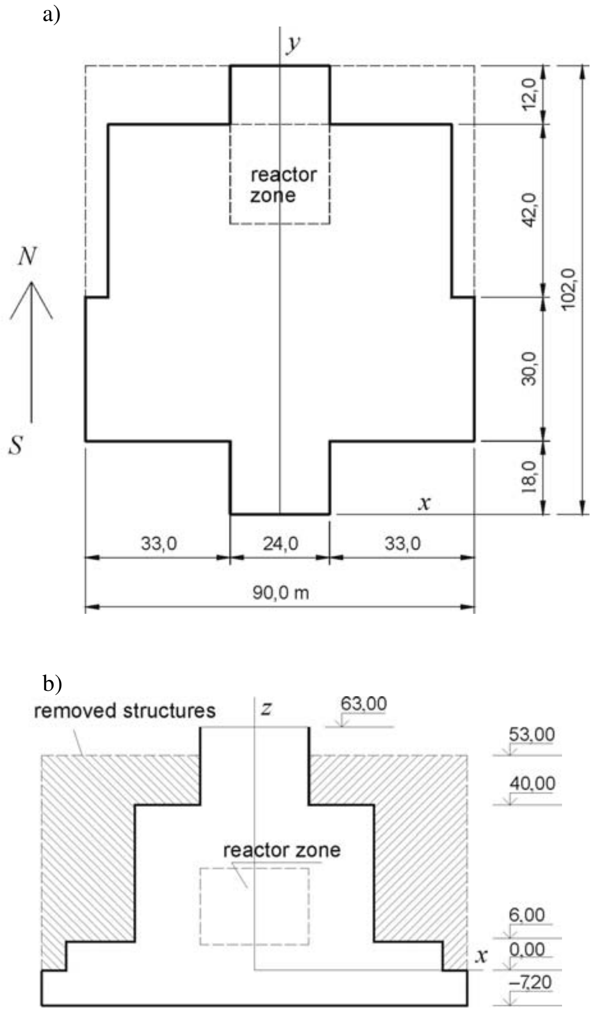

Fig. 2. Schematic illustration of the building: a – layout of the building; b – outline of the monolithic and removed prefabricated structures

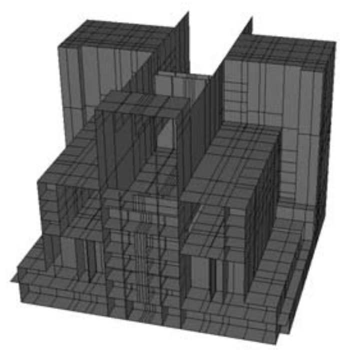

Fig. 3. Model: East-West cross-section (y = 90,0 m)

The scheme of connection of mass of the removed structures of the building to the model walls is in Fig. 4.

The removed structure and assumed simplification provide a certain degree of uncertainty. Consideration of live loads in terms of external mass will be considered in the sensitivity analysis below.

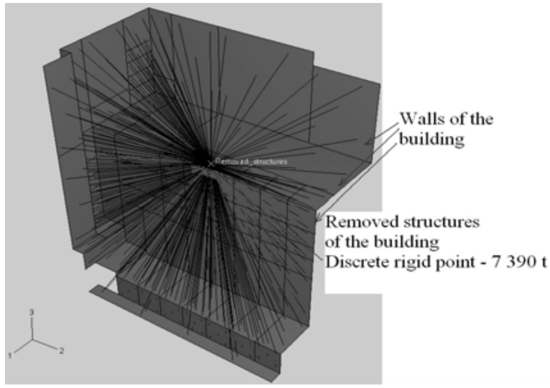

Fig. 4. Illustration of distribution of mass of the removed structures of building to the walls

The following main equipment located in the reactor building in the FE model of Ignalina NPP building was considered in a form of lumped masses (Fig. 1):

- Mass of the reactor (pos. 1);
- Mass of Main Circulation Pumps (pos. 7);
- Mass of Drum Separators (DS) and piping located in the DS room (pos. 13, 14, 16);
- Mass of refuelling machine (pos. 15);
- Mass of the water in the condensing pools.

The reactor mass is 7755 tonnes. It was added in the discrete rigid point located in the reactor core centre and connected with supports of the reactor.

Mass of main circulation pumps is about 440 tonnes, which consists of masses of 4 pumps per loop of 110 tonnes each. Mass of drum separators and piping located in the DM room is about 1665 tonnes. Mass of the refuelling machine is about 450 tonnes.

Mass of the water in condensing pools (290 / 340 tonnes) is attached to the walls in the form of rigid masses (Fig. 5). Mass of water is calculated taking into account the area of condensing pool floor and the water level. The area of floor of the 1st condensing pool is 290 m^2, and the area of the 2nd, 3rd, 4th and 5th is 340 m^2. The average level of water in each condensing pool is 1 m, according to the water mass in the condensing pools 290 t and 340 t. Due to a specific structure of basins, hydrodynamic effects are not taken into account. Total mass of building is $3{,}8 \cdot 10^5$ t.

Stiffness properties of the building are predefined by cross-sectional dimensions and material properties. Principally, the conservative approach in developing the initial model was used as much as possible. The openings are neglected in the continuous wall model. Thickness of walls vary in the range of 0,50 and 2,00 m, while the thickness of floor slabs is in the range of 0,30 and 1,80 m. The material properties of the building structures are assumed according to code *СНиП 2.03.01-84*, as they were used in the original design. Linear elastic material model has been used for the reinforced concrete; the changing in the stiffness because of cracking is neglected, following the recommendations by code *ASCE 4-98* (ASCE 2000). The elasticity modulus $E = 27\,000$ MPa, while Poisson's ratio $\nu = 0{,}2$ were applied in the model.

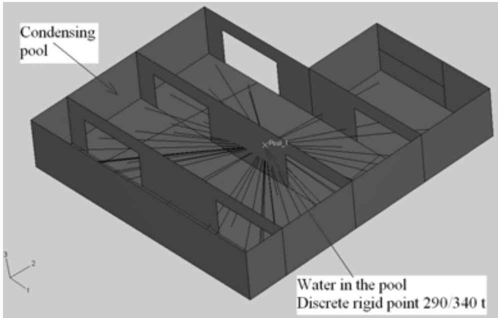

Fig. 5. Modelling the water mass in the condensing pools

The second stage comprises development of the finite element model. The thin-walled structure is described mainly by the linear four-node shell elements of ABAQUS code. The model is generated by BRIGADE/Plus (2003) software. General view of the finite element model is presented in Fig. 6, which has 40 019 elements and 208 008 degrees of freedom.

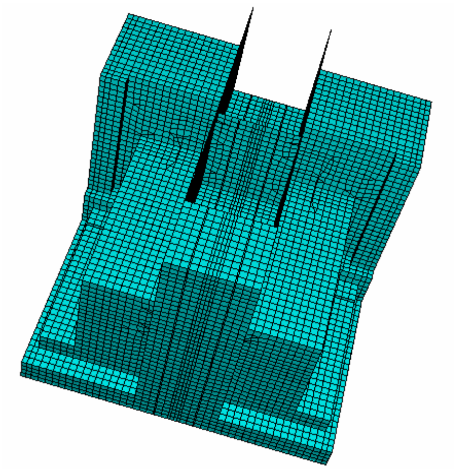

Fig. 6. Three-dimensional finite element model of the INPP reactor building

4. Frequency analysis and sensitivity study

The above described finite element model was employed for dynamic analysis of NPP Unite 2 reactor building structure. Dynamic properties of the building may be reflected by considering eigenmodes. On the other hand, the result of the frequency analysis performed provides the basis for succeeding dynamic analysis including various natural and technological hazards.

The 900 eigenmodes were calculated by solving frequency analysis as a eigenvalue problem. From the structural point of view, the magnitude of the structure mass participating in the motion indicates the importance of the mode during dynamic loading. Distribution of masses participating in the separate vibration modes considered is presented in Fig. 7.

Fig. 7 illustrates several modes, with a very high level of participating mass. The most important modes are extracted from the entire frequency spectra. They exhibit the most important deformation modes. The simulation results are in Fig. 8 and Table 1.

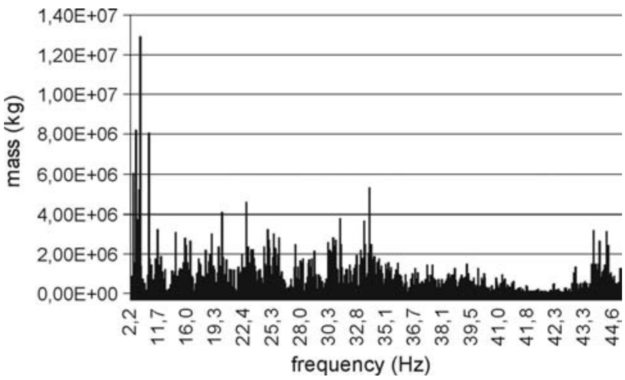

Fig. 7. Distribution of mass involved in individual modes

In order to evaluate assertions involved in the development of the model, a sensitivity study considering the influence of removed mass was performed. Two additional problems with 20 % reduced (RM) and increased mass (IM) of removed prefabricated structures were solved.

The obtained frequency spectra are presented in Fig. 9a. Differences between all 3 models are not considerable in the absolute scale, while absolute differences are presented in Fig. 9b. It can be concluded that uncertainties in the evaluation of mass are not significant.

Table 1. Comparison of frequencies for different models

Description	Type of model			
	Reduced mass (RM)	Initial	Increased mass (IM)	Reduced stiffness (RS)
East-West direction dominated bending mode	6 mode, 4,11Hz	6 mode, 4,08Hz	6 mode, 3,66Hz	9 mode, 3,55Hz
South-North direction dominated bending mode	8 mode, 4,62Hz	8 mode, 4,61Hz	8 mode, 4,05Hz	12 mode, 4,38Hz
Torsion dominated mode	10 mode, 4,70Hz	9 mode, 4,66Hz	9 mode, 4,62Hz	13 mode, 4,52Hz
Axial dominated mode	51 mode, 11,46Hz	50 mode, 11,17Hz	50 mode, 10,89Hz	67 mode, 10,65Hz

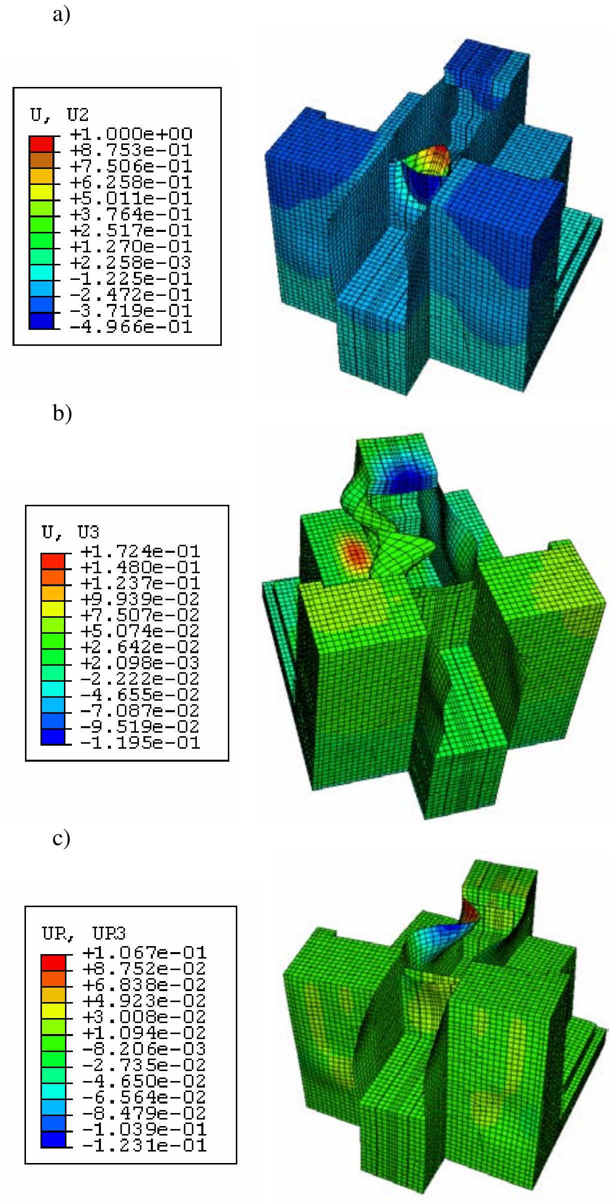

Fig. 8. Typical vibration modes: a – East-West direction dominated bending mode; b – axial dominated mode; c – torsion dominated mode

Sensitivity of the stiffness uncertainty is examined separately by introducing 30 % reduction of the wall stiffness. Variation of the frequency spectrum is presented in Fig. 10a. The absolute difference Δ between frequencies for stiffness model is presented in Fig. 10b, with maximum relative difference of 30 % for the first modes.

5. Seismic analysis

In geological terms, the Ignalina NPP is located in western periphery of the East-European Platform, at the boundary between two large-scale structural elements, i.e. the Baltic depression and the Mazury-Belarus heights. This boundary is marked by a set of tectonic faults identified in the sedimentary cover and underlying crystalline basement.

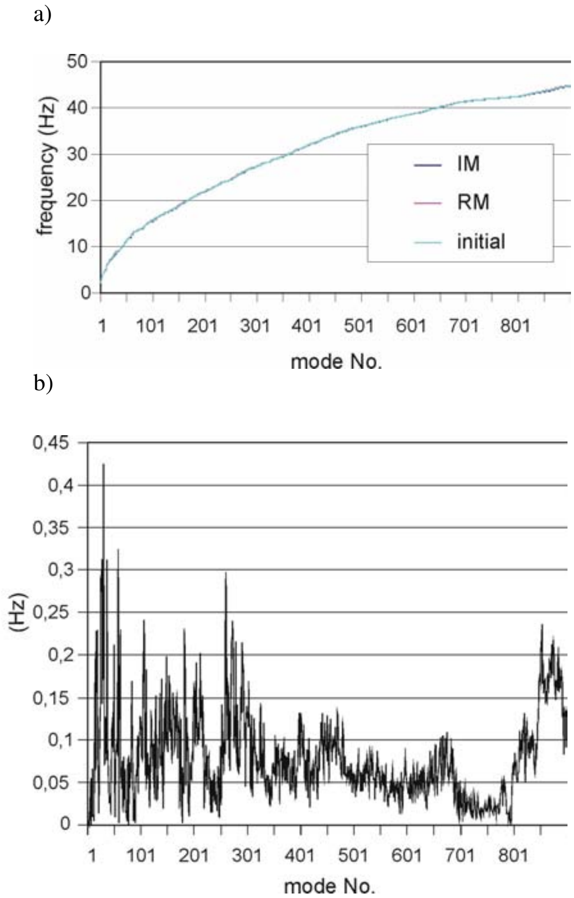

Fig. 9. Comparison of frequencies (a) and absolute difference between frequencies (b) obtained for different models

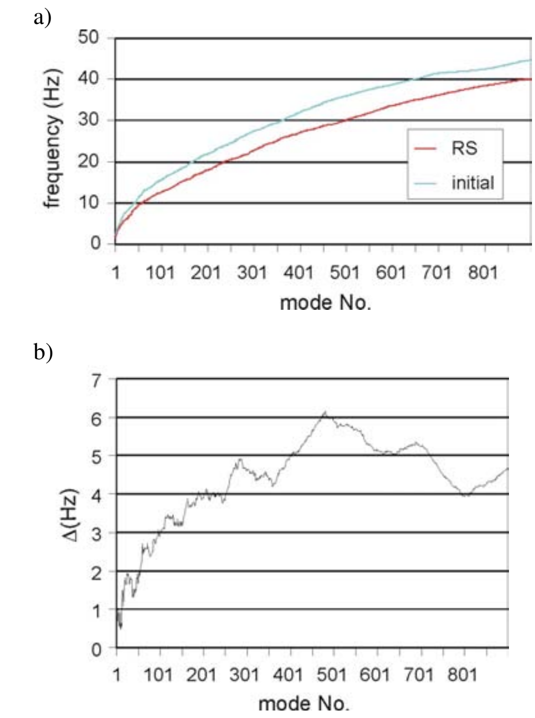

Fig. 10. Comparison of frequencies (a) and absolute difference between frequencies (b) obtained for stiffness and initial models

Therefore, the probability of the recent tectonic activity near the Ignalina NPP is relatively large compared to the adjacent areas. The presence of different-scale faults in the Ignalina NPP area was proved by detailed geological-geophysical mapping (Marcinkevičius et al. 1995 – unpublished report) and the recent vertical and horizontal movements of the tectonic blocks were detected by precise levelling and GPS measurements (Šliaupa et al. 2006b; Zakarevičius 2003) that points to the present activity of the structural gain of the area.

One of the major components related to the seismic safety assessment is derivation of design basis parameters, i.e. seismic input. The free-field ground response spectra used in a frame of this study was evaluated by a deterministic approach (DA).

Recently, the site specific free-field ground response spectra with 5 % of critical damping recommended to the seismic analysis of INPP was updated by (Šliaupa et al. 2006a). It serves the base for other than 5 % damping ratios. 2 % damping is explored in the current study; therefore, the free-field spectra are accordingly recalculated. Horizontal and vertical input spectra are presented in Fig. 11.

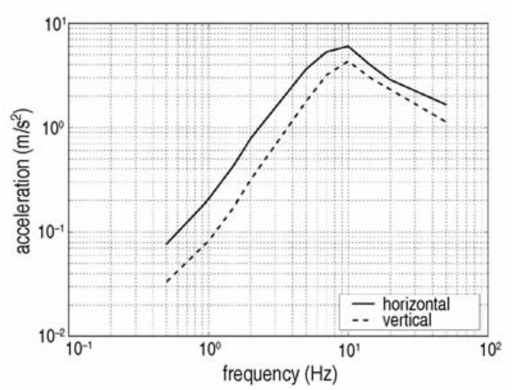

Fig. 11. Free field ground response spectra of INPP area, 2 % damping

Results of seismic analysis in a form of horizontal (East-West) in-structure acceleration response spectra are presented in Fig. 12, where curves IM and RM presents results obtained in increased and reduced mass models respectively.

It is observed that this influence increases with increasing the height of selected point in the building. At lower altitudes ($z = 20{,}0$ m), the in-structure response spectra are almost insensitive to the values of masses, whereas at the higher level ($z = 36{,}0$ m) they exhibit about 15 % difference in the peak values.

Some different characteristics are observed in the reduced stiffness (RS) model, as shown in Fig. 13. The peak values are nearly the same as those in the mass models, but peaks are shifted to the right (towards the higher frequencies). Some more horizontal and vertical acceleration spectra present results, obtained for structure point at the level of refueling machine $z = 36{,}0$ m, are presented in Fig. 14. In the case of acceleration spectra into horizontal direction 2 (South-North), as in Fig. 14a, the peak values of frequencies are significantly smaller in the case of stiffness reduction (curve RS), if compared to the mass model. Other tendencies are similar as into the previous horizontal direction.

a)

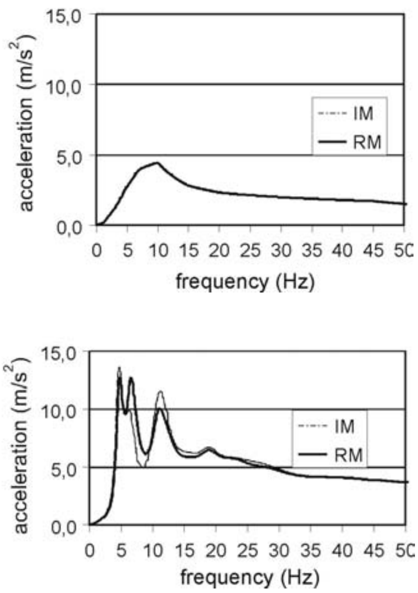

Fig. 12. In-structure horizontal (East-West) acceleration response spectra in selected points at different levels: a – z = 20,0 m,; b – z = 36,0 m

a)

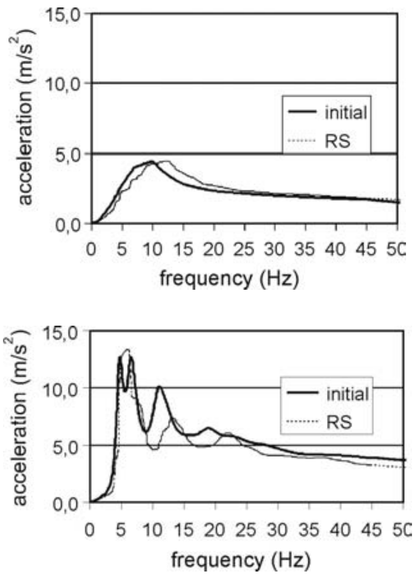

Fig. 13. In-structure horizontal (East-West) acceleration response spectra in selected points at different levels: a – z = 20,0 m; b– z = 36,0 m

The distribution of the seismic bending moments (presented in Nm/m) is illustrated in Fig. 15a, b and Fig. 15c, d for the models of reduced mass and reduced stiffness respectively. The maximum bending moment in the reduced mass model is as high as 978 Nm/m, while the maximum bending moment in the reduced stiffness model is just 265 Nm/m.

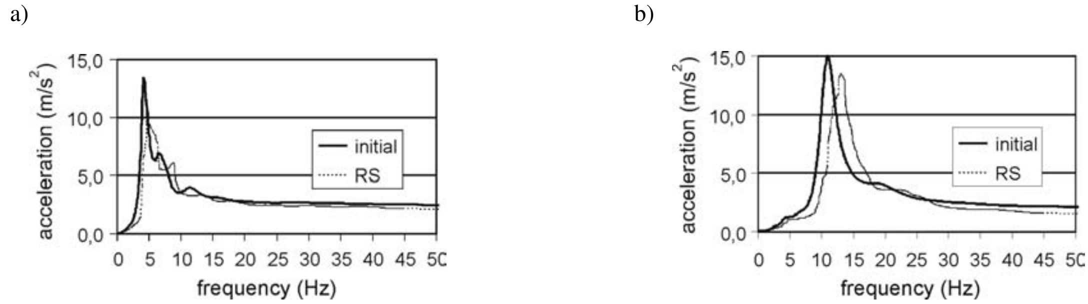

Fig. 14. In-structure acceleration response spectra in selected point at refuelling machine level: a – horizontal (South-North); b – vertical

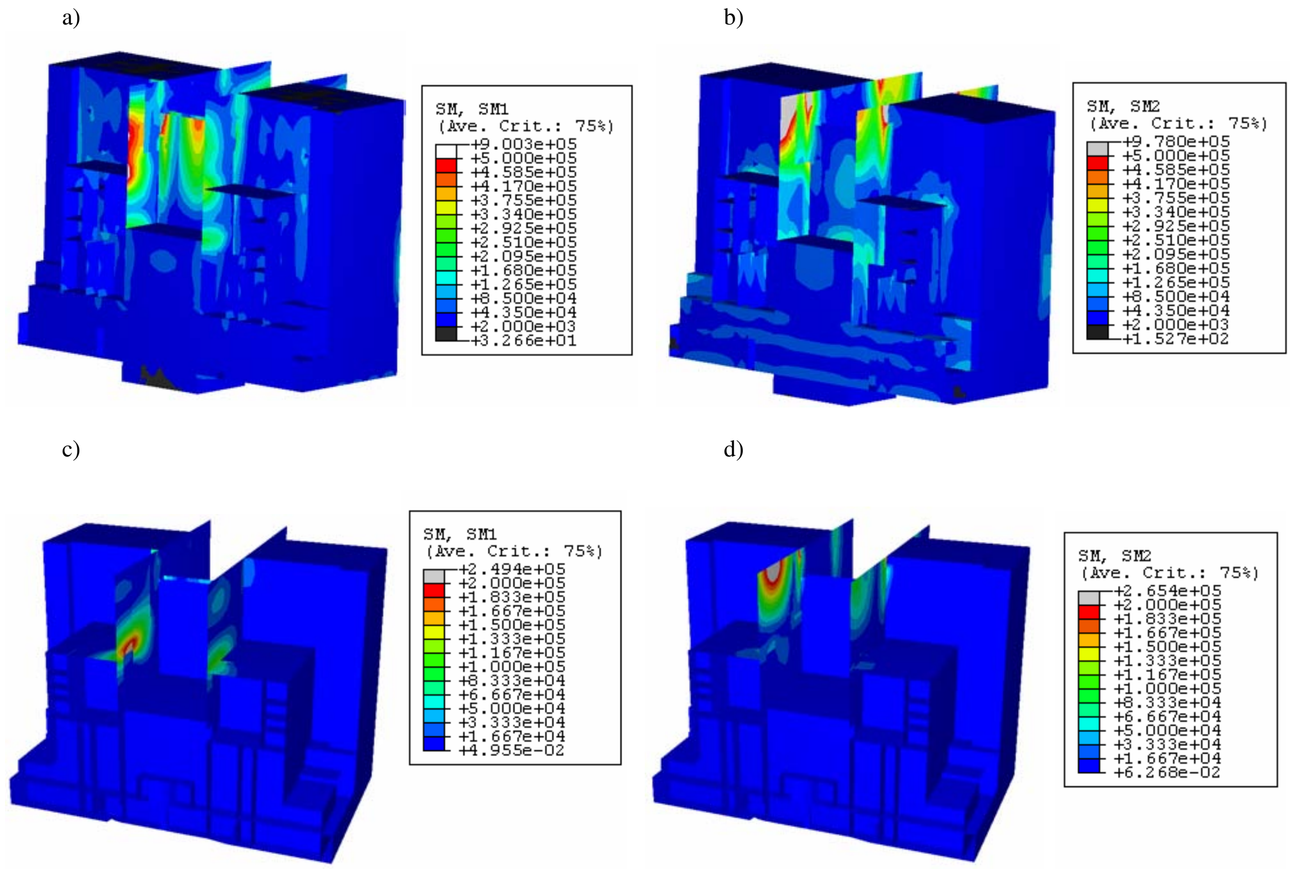

Fig. 15. Distribution of bending moments (Nm / m) in the East-West cross-section: a, c – in the "1" global axis direction; b, d – in the "2" global axis direction of reduced mass model and reduced stiffness model respectively

6. Concluding remarks

The paper presents a case study of dynamic sensitivity for the developed 3D thin-walled finite element model of Unit 2 reactor building of Ignalina NPP. The selected dynamic characteristics of the model with respect to data uncertainties of the model were considered. The results presented in the paper illustrate sensitivity of frequencies, horizontal acceleration response spectra and seismic bending moments to the magnitude of the masses and the stiffness of walls.

It was found that the model is practically insensitive to the uncertainties of mass of removed structures. In contrast, the examined reduction of the wall stiffness associates with considerable reduction of frequencies, the peak values of response spectra are shifted towards higher frequencies and the seismic moments in the walls structure are reduced. The higher sensitivity is recognised at higher structure levels and is insignificant at the level of reactor.

Finally, it is concluded that the modelling approach with respect to stiffness is rather conservative and increases the safety margin.

Acknowledgment

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IGNALINOS AE REAKTORIAUS PASTATO DINAMINIO BEM MODELIO JAUTRUMO ANALIZĖ

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S a n t r a u k a

Pateikta Ignalinos atominės elektrinės pastato erdvinio baigtinių elementų dinaminio modelio kūrimo koncepcija, išnagrinėtas šio modelio jautrumas keičiamoms masėms ir sienų standumui. Parodyta, kaip šie keičiami dydžiai turi įtaką dažniams, horizontaliems tam tikrų nagrinėjamų taškų atsako spektrams, lenkimo momentų persiskirstymui ir jų didžiui.

Reikšminiai žodžiai: Ignalinos AE, baigtinių elementų modelis, savųjų dažnių ir seisminė analizė, plyno lauko spektras, atsako spektras.

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