PAPER • OPEN ACCESS

A Short Review on Numerical Modelling Approaches for Seismic Evaluation Performance of Nuclear Power Plant Structures

To cite this article: Van-Tien Phan *et al* 2021 *IOP Conf. Ser.: Earth Environ. Sci.* **822** 012047

A Short Review on Numerical Modelling Approaches for Seismic Evaluation Performance of Nuclear Power Plant Structures

Van-Tien Phan[1], Xuan-Hung Vu[1], Trong-Cuong Vo[1], Duy-Duan Nguyen[1*]

[1] Department of Civil Engineering, Vinh University, Vinh 461010, Vietnam
[*] Corresponding author, email: duyduankxd@vinhuni.edu.vn

Abstract. Nuclear power plant (NPP) structures play a crucial role in protecting the safety of the whole plant. Overall, NPP structures have complex shapes and large dimensions. Therefore, the decision of an appropriate finite element model for seismic response analysis is important. This study presents a brief review of various numerical modelling approaches for seismic evaluation performance of NPP structures. Different conventional models, i.e. lumped-mass stick model (LMSM), full three-dimensional finite element model (3D FEM), elastic solid element model (ESM), and multi-layer shell model (MLSM), which have been applied in modelling nuclear structures, are introduced. Also, the advantages and drawbacks of those models are analysed. Furthermore, a new model namely, beam-truss model (BTM), which is recently proposed, is highlighted. It reveals that LMSM is the most simplified approach for structural modelling of NPP structures. However, it is normally used for linear analyses and not able to simulate the local behaviours and vertical responses of the complex NPP structures. Even though 3D FEM is the most sufficient method for nonlinear seismic response analyses, this approach is very time-consuming and costly computation. MLSM and BTM are recommended as practical and efficient models for nonlinear analyses of NPP structures.

Keywords: nuclear power plant structure; numerical modelling; seismic performance; beam-truss model; multi-layer shell model.

1. Introduction

Nuclear power plant (NPP) structures have been known as the crucial parts of nuclear engineering. Even though those structures are designed strictly, however some accidents around the world showed that NPP structures can be vulnerable to earthquakes. Therefore, the seismic performance evaluation of such structures is always needed.

The finite element method has been the most popular approach for evaluating seismic responses of nuclear structures. Since NPP structures have complex forms and large dimensions (Figure 1), thus, selection of an efficient numerical model is very important [2]. It is dependent on the computational capacity and purposes of the analyses, a simplified or a sufficient model is employed. So far, the analysts and researchers in the nuclear engineering field have commonly applied two kinds of numerical modelling: (1) lumped-mass stick model (LMSM) and (2) full three-dimensional finite element model (3D FEM). The LMSM approach has been widely used in the last few decades since it is the simplest method [3-23]. Meanwhile, 3D FEM is also applied for evaluating seismic performances of various NPP structures [24-38].

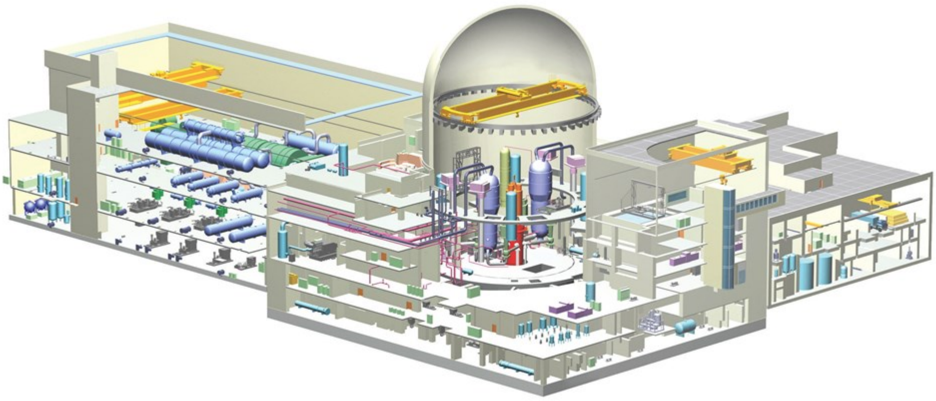

Figure 1. Cutting view of Advanced Power Reactor 1400 NPP [1].

Some other numerical approaches including elastic solid model (ESM), multiple layer shell model (MLSM), and beam-truss model (BTM) can be also used for seismic performance analyses of NPP structures. This paper presents a short review on applying various numerical modelling schemes for the seismic response analysis of NPP structures. Also, the applicable capacity of each model is assessed.

2. Lumped-mass stick model

Known as the simplest approach, LMSM simulates the real structures using a series of beam elements with lumped masses at element nodes, as depicted in Figure 2. Thus, this method reduces the computational effort significantly. Numerous studies highlighted that LMSM can approximate global responses of the sufficient method (i.e. 3D FEM) in linear analyses [20-23, 39-41]. However, to perform nonlinear dynamic analyses, LMSM is still facing challenges, especially considering local behaviours and vertical responses. To overcome this deficiency, Park and Hofmayer [42] proposed a nonlinear flexural and shear model for the seismic design of NPPs. Nevertheless, this approach focused mostly on the nonlinear model for beam elements, meanwhile, the NPP structures (e.g. reactor containment building and auxiliary building) are made by a lot of shear walls.

Typical following steps can be employed to implement LMSM.

- Decide the length of beam elements with consideration of changing sections and connecting to other structural members or critical equipment.
- Calculate the equivalent section properties for each beam element.
- Calculate the lumped masses, which are assigned to nodes.
- Assign boundary conditions and applied load.
- Obtain the structural responses.

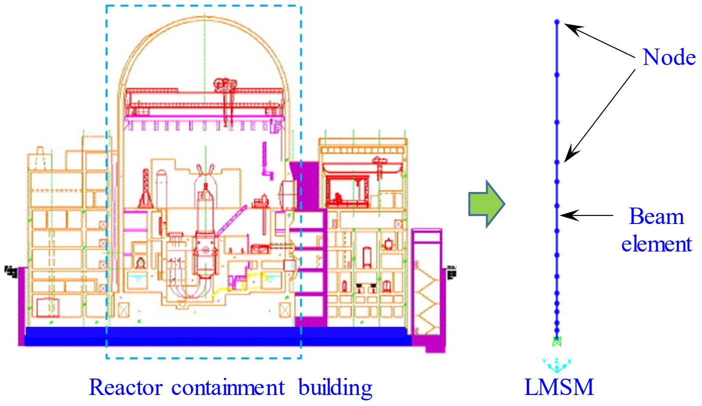

Figure 2. Illustration of the LMSM approach.

3. Elastic solid element model

ESM is one of the most effective models for verifying the simplified models such as LMSM. This approach uses linear solid elements such as tetrahedrons, hexahedrons, or pentahedrons types, as shown in Figure 3. The limitation of this method is only consideration of linear analyses. Some studies utilized ESM in seismic performance analyses and evaluations of NPP structures [20-21, 24-25]. To conduct this model, the following procedure can be used.

- Construct the dimensions of the model.
- Define and assign the material properties.
- Control and determine the mesh size.
- Assign boundary conditions and applied load.
- Obtain the structural responses.

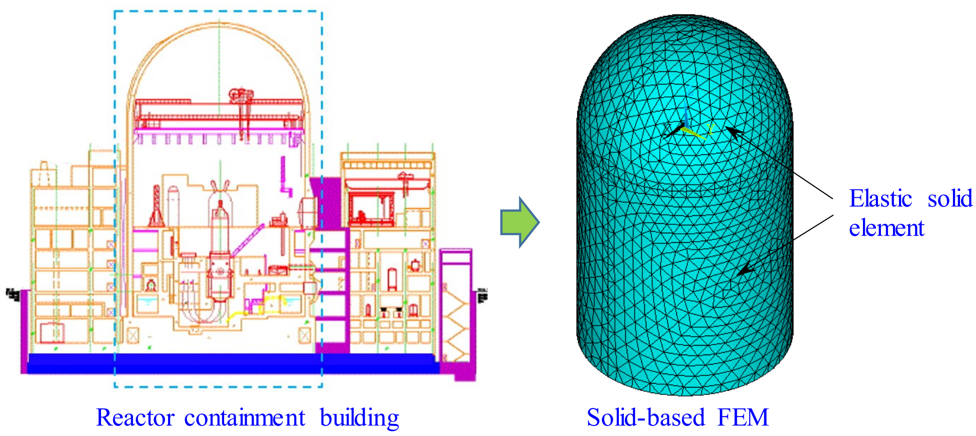

Figure 3. Illustration of the elastic solid model.

4. Multi-layer shell model

Since the NPP structures contain a lot of shear walls, thus, numerical models of those structures can be developed using smeared MLSM, as illustrated in Figure 4. The shell element comprises of different layers, which represent used materials. In NPP structures, reinforced concrete material is predominant. It should be noted that nonlinear material properties are assigned to defined layers. Basically, the concept of MLSM is based on the theoretical background of mechanics of composite materials. One typical advantage of MLSM is that it can consider the in-plane and out-of-plane interaction and the in-plane flexural-shear responses of reinforced concrete walls [43-45].

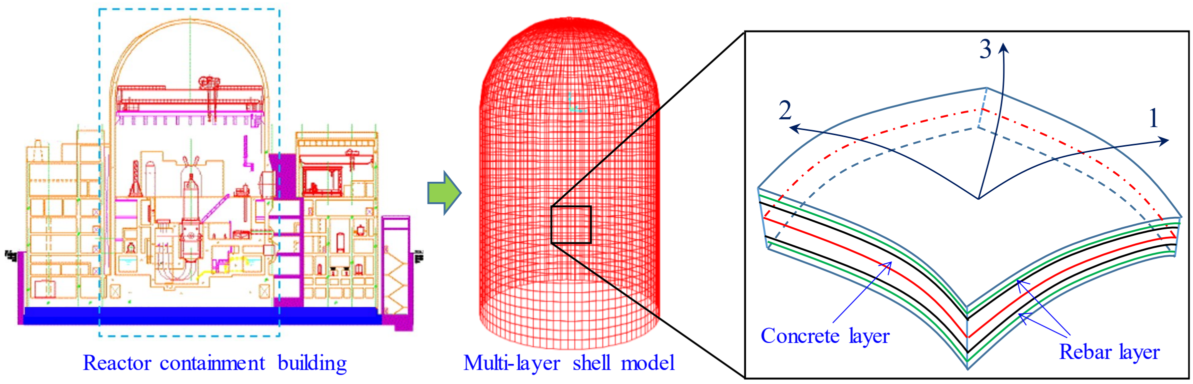

Figure 4. Multi-layer shell model approach.

The typical advantage of this modelling scheme is capable of simulating nonlinear behaviours of wall-type structures. Because this model reduces the number of degrees of freedom significantly compared with those of ESM, the computational effort is lessened. The following steps can be used to implement MLSM.

- Construct the dimensions of the model.
- Define the nonlinear material properties.
- Define the material layers with assigned properties.
- Assign boundary conditions and applied load.
- Obtain the structural responses.

5. Full 3D FE model

3D FEM, which contains details of concrete and reinforcements, is the most accurate method in structural numerical modelling, as shown in Figure 5. We can use typical commercial finite element software such as ANSYS, ABAQUS, or LS-DYNA to construct 3D FEM. Each software has a series of specific models for materials. Since 3D FEM separates concrete and reinforcing bars in meshing, thus, the number of degrees of freedom much higher than that of other models. Additionally, a contact element should be used to connect concrete and rebars. Also, the nonlinearity of material models can be considered in this approach. Accordingly, the computational effort in nonlinear dynamic analyses of full 3D FEM is extremely time-consuming and costly.

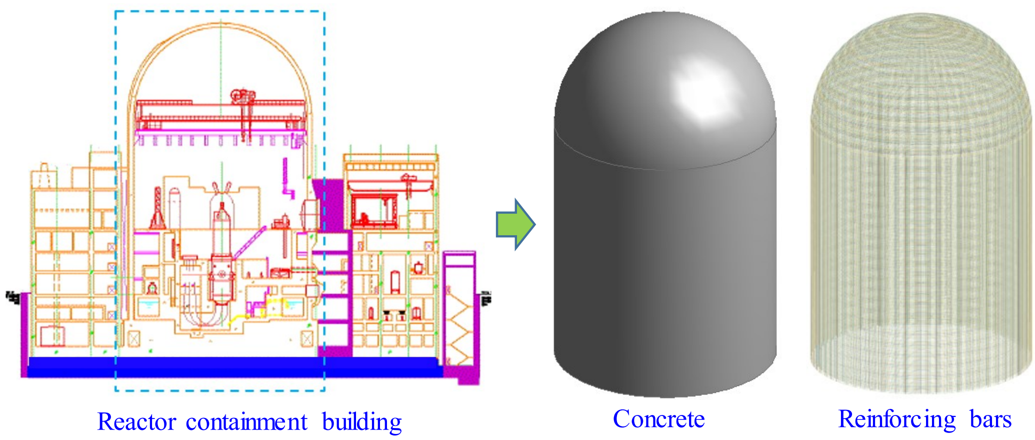

Figure 5. Full 3D finite element model.

6. Beam-truss model

To overcome the limitations of the aforesaid models, a simplified but efficient model, namely beam-truss model (BTM), is proposed to perform seismic responses of NPP structures [2]. This numerical method divides the wall into a series of beam and truss elements, as depicted in Figure 6 [2, 46-48]. Two superiorities of BTM are identified: (1) the simplicity of the modelling and (2) possible simulation of nonlinear behaviours of large NPP structures. It is a promising approach for numerical modelling of nuclear structures. So far, the first application of BTM for seismic fragility analyses of reactor containment building was conducted by Nguyen et al. [2]. More detailed descriptions and further analyses can be found in the study [2].

7. Qualitative assessment of various numerical modelling schemes

Quantitative assessments of the aforementioned modelling schemes are presented in Table 1 [2]. The qualitative assessment criteria of those numerical models include analysis method, computation time, structural response, and memory consumption. LMSM is a very simple, quick-running, and excellent approach for linear analyses. ESM is simple to construct a model and good at macro and micro simulations, but it is also bounded within linear analyses. Noting that the macro (i.e. global) response represents the floor displacements/accelerations or internal forces. Meanwhile, the micro response characterizes the local simulations such as stresses, strains, or cracking in structural members. 3D FEM is excellent in performing global and local nonlinear behaviours however, it is complicated in modelling process and very time-consuming in computation. Based on the assessments, BTM is recommended as a beneficial modelling scheme since it satisfies the requirement of nonlinear dynamic performance as well as less computational time. Moreover, MLSM is considered as the second option for seismic performance evaluation of NPP structures.

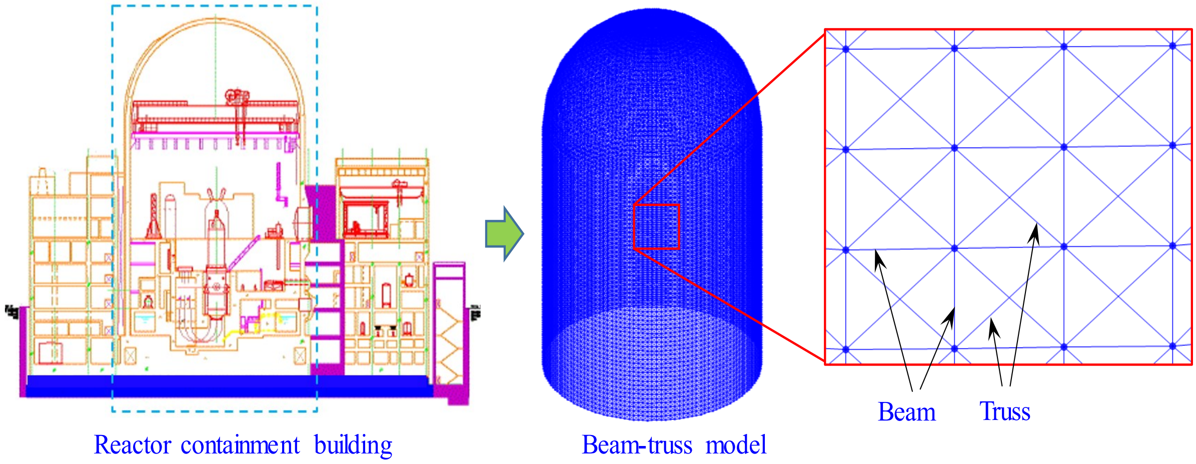

Figure 6. Beam-truss element model scheme.

Table 1. Quantitative assessment of various modelling schemes

Criteria	LMSM	ESM	MLSM	3D FEM	BTM
Linear analysis time	*Quick*	*Medium*	*Quick*	*Medium*	*Quick*
Nonlinear analysis time	-	-	*Long*	*Extremely long*	*Medium*
Global response	*Excellent*	*Excellent*	*Excellent*	*Excellent*	*Excellent*
Local response	-	*Medium*	*Medium*	*Excellent*	*Medium*
Memory consumption	*Trivial*	*Medium*	*Medium*	*Huge*	*Small*

8. Conclusions

Five numerical modelling schemes, which are lumped-mass stick model (LMSM), elastic solid-based finite element model (ESM), multi-layer shell model (MLSM), full 3D finite element model (3D FEM), and beam-truss model (BTM), for using in the seismic performance evaluation of NPP structures are briefly reviewed in this paper. The advantages and limitations of each model are demonstrated. LMSM is the most simplified approach for structural modelling of NPP structures. However, it is normally used for linear analyses, and is not able to simulate the local behaviours and vertical responses of the complex structures such as reactor containment buildings or auxiliary buildings. 3D FEM is the most sufficient method for nonlinear seismic response analyses. Nevertheless, this approach is very time-consuming and costly computation. Meanwhile, ESM is only used for linear analyses. Finally, MLSM and BTM are recommended as practical and efficient models for nonlinear analyses of NPP structures.

9. References

[1] KHNP – Korea Hydro and Nuclear Power, https://www.khnp.co.kr/eng/main.do
[2] Nguyen D D, Thusa B, Park H, Azad M S, & Lee T H 2021 Efficiency of various structural modeling schemes on evaluating seismic performance and fragility of APR1400 containment building. *Nuc. Eng. Tech*. DOI: https://doi.org/10.1016/j.net.2021.02.006
[3] Varma V, Reddy G R, Vaze K K, & Kushwaha H S 2002 Simplified approach for seismic analysis of structures. *Int'l J. Struct. Stab. Dyn.*, **2**(02), 207-225.
[4] Choi I K, Choun Y S, Ahn S M, & Seo J M 2008 Probabilistic seismic risk analysis of CANDU containment structure for near-fault earthquakes. *Nuc. Eng. Des.*, **238**(6), 1382-1391.
[5] Ali A, Hayah N A, Kim D, & Cho S G 2014 Probabilistic seismic assessment of base-isolated NPPs subjected to strong ground motions of Tohoku earthquake. *Nuc. Eng. Tech.*, **46**(5), 699-706.
[6] Zentner I 2010. Numerical computation of fragility curves for NPP equipment. *Nuc. Eng. Des.*, **240**(6), 1614-1621.
[7] Zentner I, Humbert N, Ravet S, & Viallet E 2011 Numerical methods for seismic fragility analysis of structures and components in nuclear industry-Application to a reactor coolant system. *Georisk*, **5**(2), 99-109.
[8] Huang Y N, Whittaker A S, & Luco N 2011 A probabilistic seismic risk assessment procedure for nuclear power plants:(I) Methodology. *Nuc. Eng. Des.*, **241**(9), 3996-4003.
[9] Nguyen D D, Thusa B, & Lee T H 2018 Seismic Fragility of Base-Isolated Nuclear Power Plant Considering Effects of Near-Fault Ground Motions. *J. Korean Soc. Hazard Mitig.*, **18**(7), 315-321.
[10] Nguyen D D, Thusa B, & Lee T H 2019 Effects of Significant Duration of Ground Motions on Seismic Responses of Base-Isolated Nuclear Power Plants. *J. Earthq. Eng. Soc. Korea*, **23**(3), 149-157.
[11] Nguyen D D, Thusa B, Han T S, & Lee T H 2020 Identifying significant earthquake intensity measures for evaluating seismic damage and fragility of nuclear power plant structures. *Nuc. Eng. Tech.*, **52**(1), 192-205.
[12] Thusa B, Nguyen D D, & Lee T H 2020 Seismic Response Evaluation of NPP Structures Considering Different Numerical Models and Frequency Contents of Earthquakes. *J. Comp. Struct. Eng. Inst. Korea*, **33**(1), 63-72.
[13] Jung J W, Jang H W, Kim J H, & Hong J W 2017 Effect of second hardening on floor response spectrum of a base-isolated nuclear power plant. *Nuc. Eng. Des.*, **322**, 138-147.
[14] Kim G J, Yang K K, Kim B S, Kim H J, Yun S J, & Song J K 2016 Seismic response evaluation of seismically isolated nuclear power plant structure subjected to Gyeong-Ju earthquake. *J. Earthq. Eng. Soc. Korea*, **20**(7), 453-460.
[15] Lee J H, & Song J K 2015 Seismic fragility analysis of seismically isolated nuclear power plant structures using equivalent linear-and bilinear-lead rubber bearing model. *J. Earthq. Eng. Soc. Korea*, **19**(5), 207-217.
[16] Eem S H, Jung H J, Kim M K, & Choi I K 2013 Seismic fragility evaluation of isolated NPP containment structure considering soil-structure interaction effect. *J. Earthq. Eng. Soc. Korea*, **17**(2), 53-59.

[17] Lee E H, Kim J M, Joo K H, & Kim H U 2016 Evaluation of the soil-structure interaction effect on seismically isolated nuclear power plant structures. *J. Earthq. Eng. Soc. Korea*, **20**(6), 379-389.
[18] Cho S G, Kim D, & Chaudhary S 2011 A simplified model for nonlinear seismic response analysis of equipment cabinets in nuclear power plants. *Nuc. Eng. Des.*, **241**(8), 2750-2757.
[19] Eem S H, & Choi I K 2018 Seismic Response Analysis of Nuclear Power Plant Structures and Equipment due to the Pohang Earthquake. *J. Earthq. Eng. Soc. Korea*, **22**(3), 113-119.
[20] Park J B, Park N C, Lee S J, Park Y P, & Choi Y 2017 Seismic analysis of the APR1400 nuclear reactor system using a verified beam element model. *Nuc. Eng. Des.*, **313**, 108-117.
[21] Lee H, Ou Y C, Roh H, & Lee J S 2015 Simplified model and seismic response of integrated nuclear containment system based on frequency adaptive lumped-mass stick modeling approach. *KSCE J. Civ. Eng.*, **19**(6), 1757-1766.
[22] Roh H, Lee H, & Lee J S 2013 New lumped-mass-stick model based on modal characteristics of structures: development and application to a nuclear containment building. *Earthq. Eng. Eng. Vibr.*, **12**(2), 307-317.
[23] Ou Y C, Hashlamon I, Kim W, & Roh H 2019 Development of basic technique to improve seismic response accuracy of tributary area-based lumped-mass stick models. *Earthq. Eng. Eng. Vibr.*, **18**(1), 113-127.
[24] Uwizerimana S 2015 *Structural Modeling and Dynamic Analysis of Nuclear Power Plant Structures.* Master dissertation, The Ohio State University, USA.
[25] Nour A, Cherfaoui A, Gocevski V, & Léger P 2016 Probabilistic seismic safety assessment of a CANDU 6 nuclear power plant including ambient vibration tests: Case study. *Nuc. Eng. Des.*, **304**, 125-138.
[26] Sextos A G, Manolis G D, Athanasiou A, & Ioannidis N 2017 Seismically induced uplift effects on nuclear power plants. Part 1: Containment building rocking spectra. *Nuc. Eng. Des.*, **318**, 276-287.
[27] Zhai C H, Bao X, Zheng Z, & Wang X Y 2018 Impact of aftershocks on a post-mainshock damaged containment structure considering duration. *Soil Dyn. Earthq. Eng.*, **115**, 129-141.
[28] Huang X, Kwon O S, Bentz E, & Tcherner J 2018 Method for evaluation of concrete containment structure subjected to earthquake excitation and internal pressure increase. *Earthq. Eng. Struct. Dyn.*, **47**(6), 1544-1565.
[29] Bao X, Zhang M H, & Zhai C H 2019 Fragility analysis of a containment structure under far-fault and near-fault seismic sequences considering post-mainshock damage states. *Eng. Struct.*, **198**, 109511.
[30] Wang D, Wu C, Zhang Y, Ding Z, & Chen W 2019 Elastic-plastic behavior of AP1000 nuclear island structure under mainshock-aftershock sequences. *Annals Nuc. Energy*, **123**, 1-17.
[31] Saouma V E, & Hariri-Ardebili M A 2019 Seismic capacity and fragility analysis of an ASR-affected nuclear containment vessel structure. *Nuc. Eng. Des.*, **346**, 140-156.
[32] De Grandis S, Domaneschi M, & Perotti F 2009 A numerical procedure for computing the fragility of NPP components under random seismic excitation. *Nuc. Eng. Des.*, **239**(11), 2491-2499.
[33] Jussila V, Li Y, & Fülöp L 2016 Statistical analysis of the variation of floor vibrations in nuclear power plants subject to seismic loads. *Nuc. Eng. Des.*, **309**, 84-96.
[34] Hur J, Althoff E, Sezen H, Denning R, & Aldemir T 2017 Seismic assessment and performance of nonstructural components affected by structural modeling. *Nuc. Eng. Tech.*, **49**(2), 387-394.
[35] Dundulis G, Kačianauskas R, Markauskas D, Stupak E, Stupak S, & Šliaupa S 2017 Reanalysis of the floor response spectra of the Ignalina Nuclear Power Plant Reactor Building. *Nuc. Eng. Des.*, **324**, 260-268.
[36] Lee H P 2011 Shell finite element of reinforced concrete for internal pressure analysis of nuclear containment building. *Nuc. Eng. Des.*, **241**(2), 515-525.
[37] Nakamura N, Yabushita N, Suzuki T, Yamada J, Tsunashima N, & Nakano T 2008 Analyses of reactor building by 3D nonlinear FEM models considering basemat uplift for simultaneous horizontal and vertical ground motions. *Nuc. Eng. Des.*, **238**(12), 3551-3560.

[38] Nakamura N, Akita S, Suzuki T, Koba M, Nakamura S, & Nakano T 2010 Study of ultimate seismic response and fragility evaluation of nuclear power building using nonlinear three-dimensional finite element model. *Nuc. Eng. Des.*, **240**(1), 166-180.
[39] Van Nguyen D, Kim D, & Nguyen D D 2020 Nonlinear seismic soil-structure interaction analysis of nuclear reactor building considering the effect of earthquake frequency content. *Struct.,* **26**, 901-914.
[40] Nguyen D D, & Nguyen C N 2020 Seismic Responses of NPP Structures Considering the Effects of Lead Rubber Bearing. *Eng. Tech. App. Sci. Res.*, **10**(6), 6500-6503.
[41] Nguyen D D, Thusa B, Park H, Lee H, & Lee T H 2019 Effects of mechanical properties of LRB on seismic performance of base-isolated NPP structures. *Transactions of the 25th Structural Mechanics in Reactor Technology (SMiRT-25*), Charlotte, NC, USA.
[42] Park Y J, Hofmayer C H 1994 Technical Guidelines for Aseismic Design of Nuclear Power Plants. Translation of JEAG 4601-1987, NUREG/CR-6241.
[43] Miao Z W, Lu X Z, Jiang J J, & Ye L P 2006 Nonlinear FE model for RC shear walls based on multi-layer shell element and microplane constitutive model. *Comp. Meth. Eng. Sc.*, 21-23.
[44] Fahjan Y M, Kubin J, & Tan M T 2010 Nonlinear analysis methods for reinforced concrete buildings with shear walls. In *14th European Conference on Earthquake Engineering*.
[45] Lu X, Xie L, Guan H, Huang Y, & Lu X 2015 A shear wall element for nonlinear seismic analysis of super-tall buildings using OpenSees. *Finite Elem. Anal. Des.*, **98**, 14-25.
[46] Lu Y, & Panagiotou M 2014 Three-dimensional cyclic beam-truss model for nonplanar reinforced concrete walls. *J. Struct. Eng.*, **140**(3), 04013071.
[47] Lu Y, Panagiotou M, & Koutromanos I 2016 Three-dimensional beam-truss model for reinforced concrete walls and slabs–part 1: modeling approach, validation, and parametric study for individual reinforced concrete walls. *Earthq. Eng. Struct. Dyn.*, **45**(9), 1495-1513.
[48] Lu Y, & Panagiotou M 2016 Three-dimensional beam–truss model for reinforced concrete walls and slabs–part 2: modeling approach and validation for slabs and coupled walls. *Earthq. Eng. Struct. Dyn.*, **45**(11), 1707-1724.