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EVALUATION OF SEISMIC PERFORMANCE OF REACTOR CONTAINMENT BUILDING USING BEAM-TRUSS ELEMENT MODEL

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Abstract

The reactor containment building (RCB) is one of the most extremely critical structures in nuclear power plants. In numerical seismic performance analyses, this structure is normally modeled in terms of the lumped-mass stick model (LMSM) or full three-dimensional finite element model (3D FEM). However, the LMSM simplifies the real structures to linear-elastic beam elements with concentrated masses, hence, it is not able to capture the typical failure modes of the structure such as shear or flexure-shear behavior. Moreover, the 3D FEM, which is considered as the most accurate and reliable model for the numerical approach, obviously requires an expensive computation, especially in nonlinear time-history analyses, and thus it may not be suitable for practical analyses and assessments. Additionally, a study on the application of an efficient numerical model for seismic response simulations of nuclear power plant structures has not been conducted yet. The purpose of this study is to investigate seismic performances of a reactor containment building using a so-called beam-truss element model (BTM), which is expected to surmount the drawbacks of both the LMSM and 3D FEM.

The proposed model comprises of the vertical and horizontal beam and diagonal truss elements. The vertical and horizontal beams consider the integration of concrete and reinforcements. Meanwhile, the diagonal truss elements represent the behavior of pure concrete. The proposed model is verified with the LMSM and 3D FEM in modal and time-history analyses. It is shown that the modal analysis result of BTM is highly comparable with that of the 3D FEM in both values and modal shapes. The BTM can reflect the complex vibration modes of the 3D FEM, while the LMSM is not able to capture these behaviors. Furthermore, the comparison results of time-history analyses highlight that BTM is capable of modeling seismic performances of nuclear power plant structures. It is important to emphasize that the proposed BTM can reduce the computational effort significantly, specifically in nonlinear dynamic analyses.

Keywords: reactor containment building; beam-truss element model; floor response spectra; time-history analysis

1. Introduction

The reactor containment building in nuclear power plants (NPPs) plays an extremely important role in preventing radioactive leakage to outside. This structure requires to be designed to robustly resist against the external influences such as impact loads or earthquakes. However, some recent accidents related to NPPs due to earthquakes such as the 1999 Chi-Chi (Taiwan) earthquake, the 2011 Tohoku (Japan) earthquake, or the 2016 Gyeongju (Korea) earthquake have raised a concern about the seismic evaluation and safety assessment of NPP structures and components.

To evaluate seismic performance of NPP structures, two kinds of numerical models, which are lumped-mass stick model (LMSM) [1-6] and three-dimensional finite element model (3D FEM) [7-11], are popularly used. However, each model contains advantages and disadvantages. LMSM simplifies the real structure to a beam stick model with nodal masses. This model limits in linear analyses and requires a less computational effort. Whereas, 3D FEM is the most accurate model in simulating seismic performance of structures. The challenge of 3D FEM is time-consuming in calculation, especially in nonlinear time-history analyses.

Several studies developed simplified numerical models for conventional reinforced concrete shear walls such as multi-vertical-line element model [12-13], truss element model [14-15], beam-truss element model [16]. However, an application of these numerical models for seismic performance evaluation of the reactor containment building (RCB) in NPPs is not conducted yet.

The purpose of this study is to evaluate seismic performances of a reactor containment building using a so-called beam-truss element model (BTM), which is expected to surmount the limitations of both the LMSM and 3D FEM.

2. Numerical modeling

2.1 Description of RCB structure

The containment building of the advanced power reactor 1400 (APR1400), which was developed by Korea Electric Power Corporation (KEPCO) and Korea Hydro & Nuclear Power (KHNP), was employed for numerical analyses. The reactor containment cylinder has 23.5 m radius, 54 m height and 1.22 m thickness. The radius of the dome is 23.2 m, the average thickness is 1.07 m. Fig. 1 shows the general and cutting view of APR1400, in which the RCB is located at the center of the plant.

Fig. 1 - General view (left) and cutting view of APR1400 (right)

2.3 Finite element model of RCB using BTM

In this study, the numerical model of RCB is developed in OpenSees, an open source platform for earthquake engineering simulation [17]. The structure is modeled in terms of beam and truss elements, namely beam-truss model (BTM). Fig. 2 shows the finite element BTM of RCB in OpenSees. This model is comprised of horizontal and vertical beam elements and diagonal truss elements, as shown in Fig. 3.

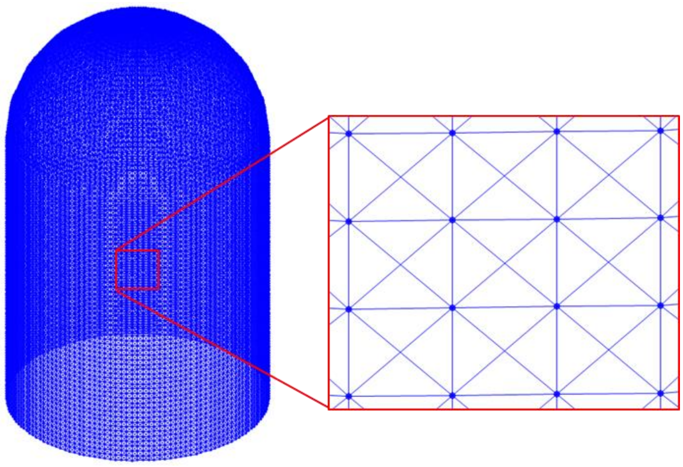


Fig. 2 - Finite element model of RCB using BTM in OpenSees

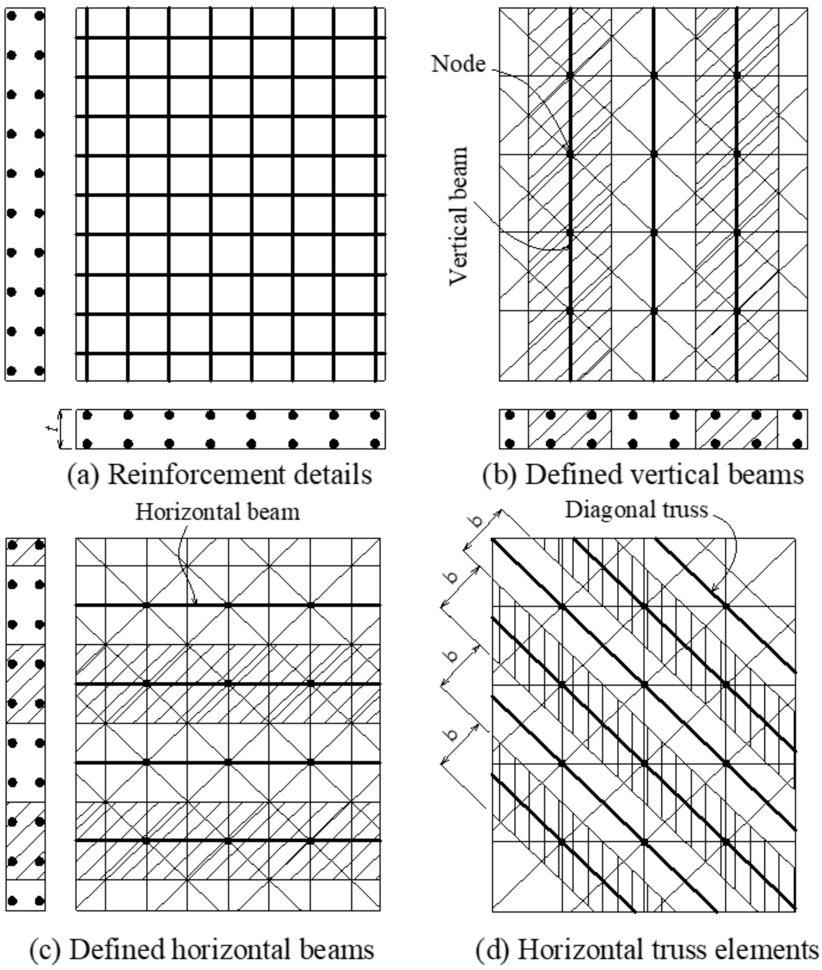


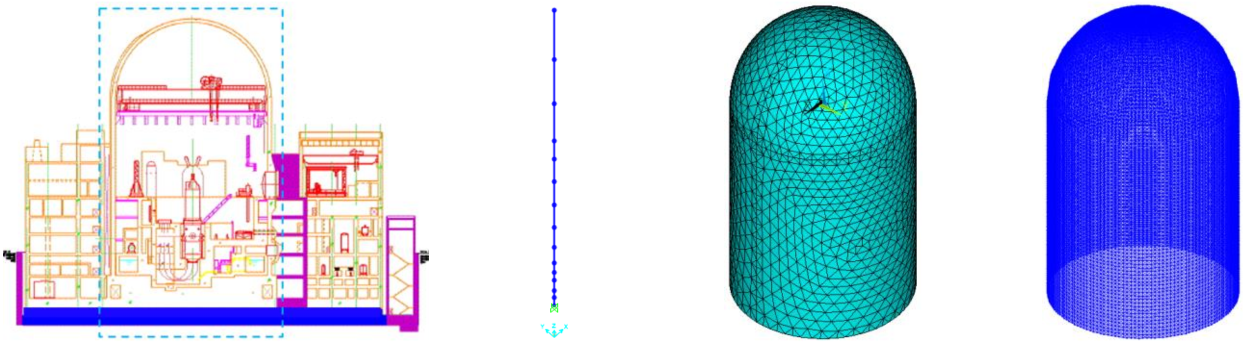
Fig. 3 - Schematic numerical modelling of RCB using BTM

For horizontal and vertical beam elements, both concrete and reinforcements are considered in fiber section model. Meanwhile, pure concrete material is accounting for diagonal truss elements. In OpenSees, various uniaxial material models for concrete and steel materials have been developed. For this study, the *concrete02* model, which adopted the Kent-Park model [18], is applied for modeling concrete of the beam and truss elements. The *steel02* model, which adopted the Menegotto-Pinto model [19], is used for modelling reinforcing bars of the beam elements. These two models have taken into account the nonlinear characteristics of materials.

The structure may perform beyond elastic behavior under a strong earthquake. In order to achieve an accurate representation of nonlinear behavior, the *nonlinearBeamColumn* element in OpenSees with the fiber section modelling scheme is used. The *concrete02* and *steel02* constitutive models are assigned to concrete and steel fibers, respectively.

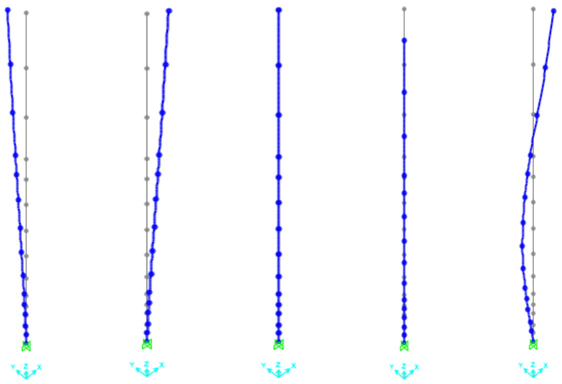
2.4 Modal analysis

In this study, we performed the modal analysis and compared the natural frequencies and mode shapes between LMSM, 3D FEM, and BTM. Figs. 5-7 show the vibrational mode shapes of LMSM, 3D FEM, and BTM, respectively. It is observed that for the fundamental modes (i.e. translations and torsion), the results of these models are highly comparable. The torsional vibration of LMSM is in mode 3, whereas it is fallen to mode 9 for 3D FEM and BTM. Additionally, LMSM was not able to characterize the complex deformed vibration modes (e.g. distortion of the cylinder), which can be occurred in 3D FEM and BTM. In other words, BTM is capable of representing the complex behavior of RCB as 3D FEM.



Reactor containment building in APR1400 NPP | LMSM (42 DOFs) | 3D FEM (166,980 DOFs) | BTM (81,006 DOFs)

Fig. 4 - Numerical models of RCB



Mode 1 | Mode 2 | Mode 3 | Mode 4 | Mode 5

Fig. 5 - Modal shapes of LMSM

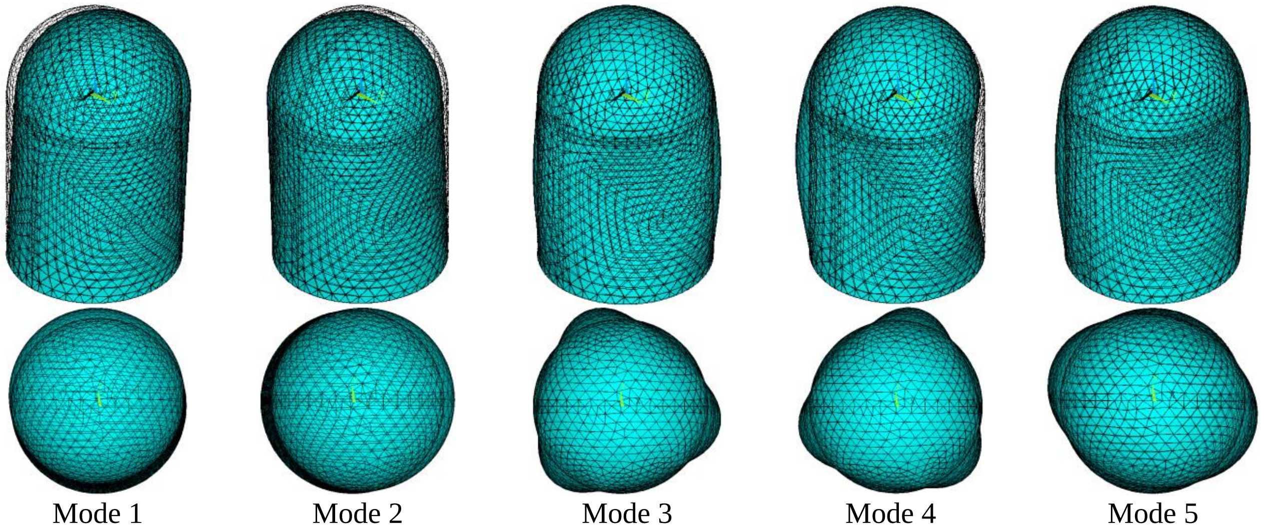


Fig. 6 - Modal shapes of 3D FEM

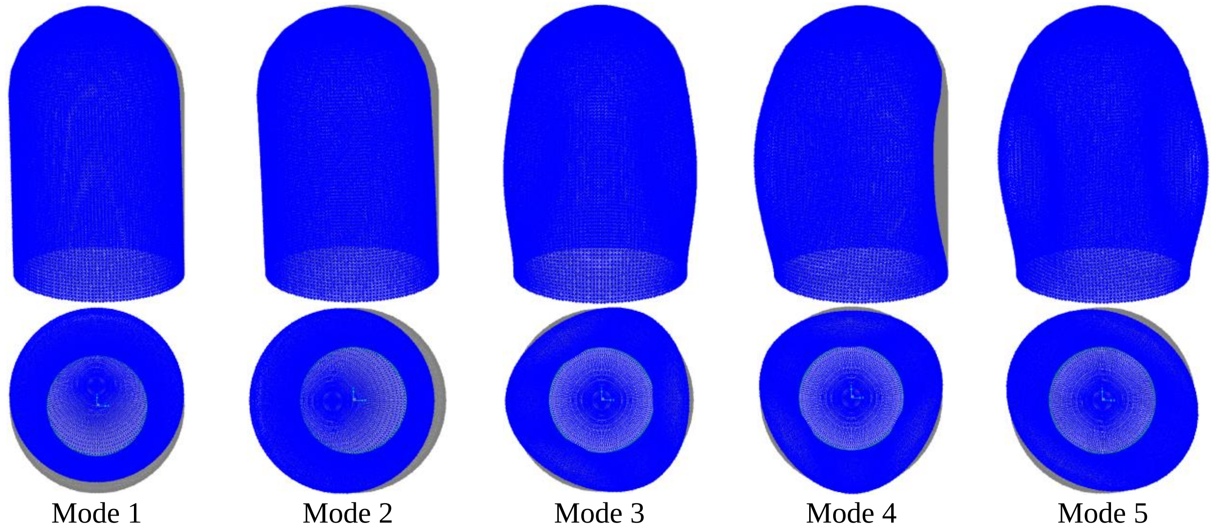


Fig. 7 - Modal shapes of BTM

Table 1 - Natural frequencies (Hz) of LMSM, 3D FEM, Shell model, and BTM

Mode	**LMSM (linear elastic)**	**3D FEM (linear elastic)**	**BTM (fiber section)**
1	3.85	3.97	3.99
2	3.85	3.97	3.99
3	8.37	5.39	5.90
4	11.60	5.39	5.90
5	11.63	6.35	6.16
6	11.63	6.35	6.16
7	21.96	6.82	7.58
8	21.96	6.82	7.58
9	24.20	8.50	8.81
10	24.20	9.90	9.86

Table 1 presents the natural frequencies of the first 10 vibration modes of the three models. The frequency values of the fundamental modes obtained from LMSM, 3D FEM, and BTM were shown to be in good agreement. However, the 3D FEM and BTM contained complex vibration modes that obviously could not be captured in the simplified LMSM, the frequency values at higher modes in those models are apparently different.

3. Input ground motions

To evaluate the seismic performance of RCB structure, 10 ground motions with their response spectra are scaled matching to the NRC 1.60 design spectrum [20]. Fig. 8 shows response spectra of motions used in this study. Noting that all used motions were generated by using SeismoSignal program [21].

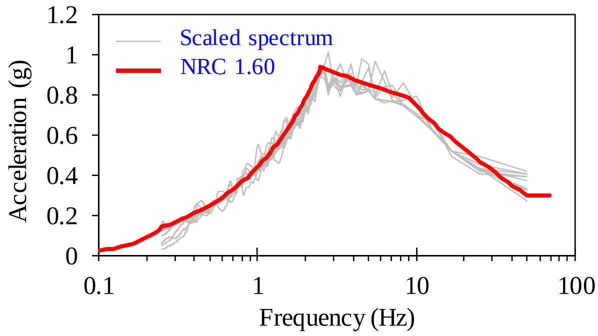


Fig. 8 - Response spectra of input ground motions

4. Response of RCB structure

We performed a series of linear time-history analyses in the horizontal X-direction to obtain the seismic responses of the RCB. Floor response spectra (FRS) is one of the most important outputs to evaluate the seismic performance of NPP structures in various natural frequencies. FRS of the 3D FEM and BTM was computed at the intersection of the XZ plane and the containment at the same height as LMSM.

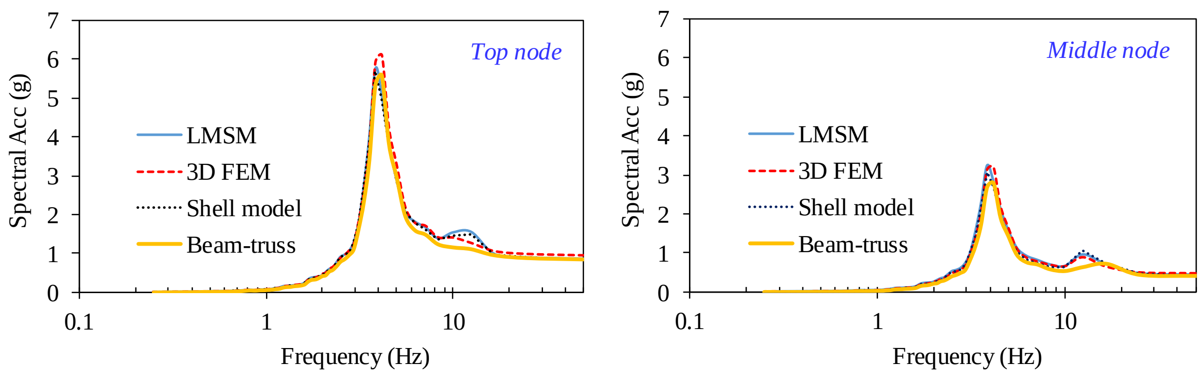


Fig. 9 - Comparison of FRS of RCB under the 1940 El-Centro earthquake

Fig. 9 shows a comparison of FRS of RCB between LMSM, 3D FEM, and BTM under the 1940 El-Centro earthquake. It can be observed that the results of three models are in good agreement. Table 2 also describes the computational elapsed time for a linear time-history analysis between three models. It implies that the 3D FEM is the most time-consuming model followed by BTM, and LMSM. Considering the accuracy of numerical model and computational effort, BTM shows to be a good option for time-history analysis of RCB.

Fig. 10 shows FRS at the different elevations of RCB under the input motions, in which the solid curves represent the mean response spectra. The FRS were primarily amplified at the fundamental frequency of RCB (i.e. approximately 3.9 Hz). Fig. 11 shows the comparison of mean FRS between BTM and 3D FEM for linear time-history analyses. It is found that results of FRS are highly comparable, highlighting the capability of BTM in seismic performance evaluation of RCB structure.

Table 2 - Comparison of computational time for a linear time history analysis between LMSM, 3D FEM, and BTM under the 1940 El-Centro earthquake

Numerical model	**LMSM**	**3D FEM**	**BTM**
Computational time (Computer: CPU Intel Core i5-7600 @3.50 GHz, RAM 16 GB)	~ 0.5 min	~ 4 hours	~ 3 mins

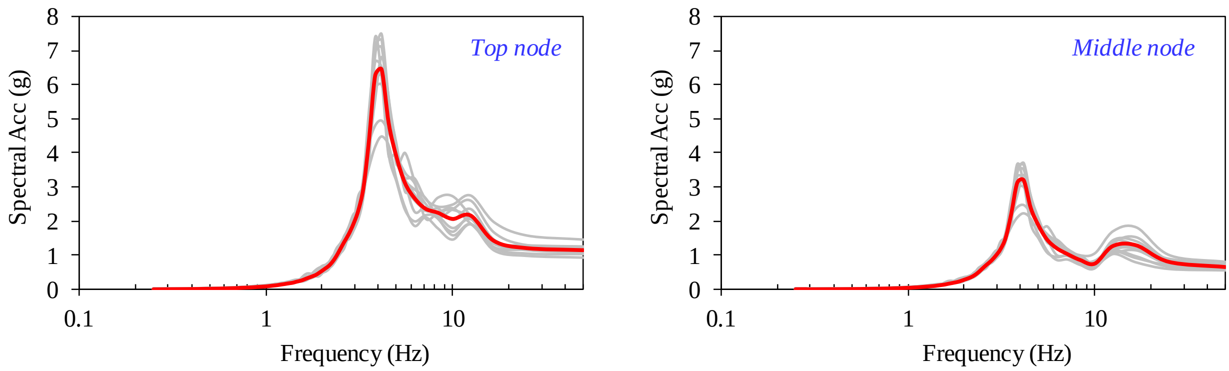


Fig. 10 - FRS of RCB in linear time-history analyses using BTM

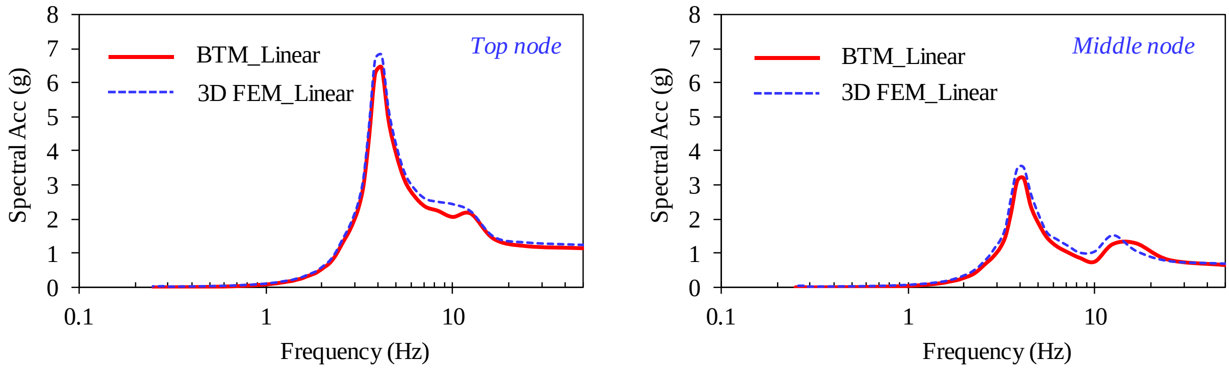


Fig. 11 - Comparison of FRS of RCB between BTM and 3D FEM

In this study, a series of nonlinear time-history analyses of RCB using BTM were also performed. Fig. 12 shows FRS of the structure at the top and middle nodes, in which the solid curves are the mean spectra. Similar to the linear analyses, the FRS at the top were sorely amplified at the fundamental frequency of RCB. However, at the middle elevation, FRS is not only amplified at the fundamental frequency but also magnified at a higher frequency (i.e. approximately 7.5 Hz). Fig. 13 shows the comparison of mean FRS between linear and nonlinear time-history analyses using 3D FEM and BTM. It should be noted that only linear analysis is applied for 3D FEM, meanwhile both linear and nonlinear analyses are performed for

BTM. It is probably due to inelastic behaviors, there is a gap between FRS of the structure in linear and nonlinear time-history analyses, especially at the middle node with frequency larger than 6.0 Hz.

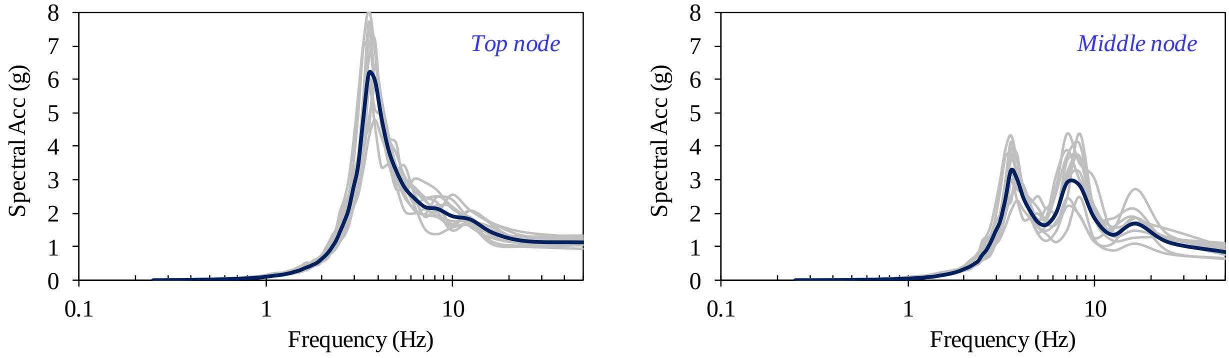


Fig. 12 - FRS of RCB in nonlinear time-history analyses using BTM

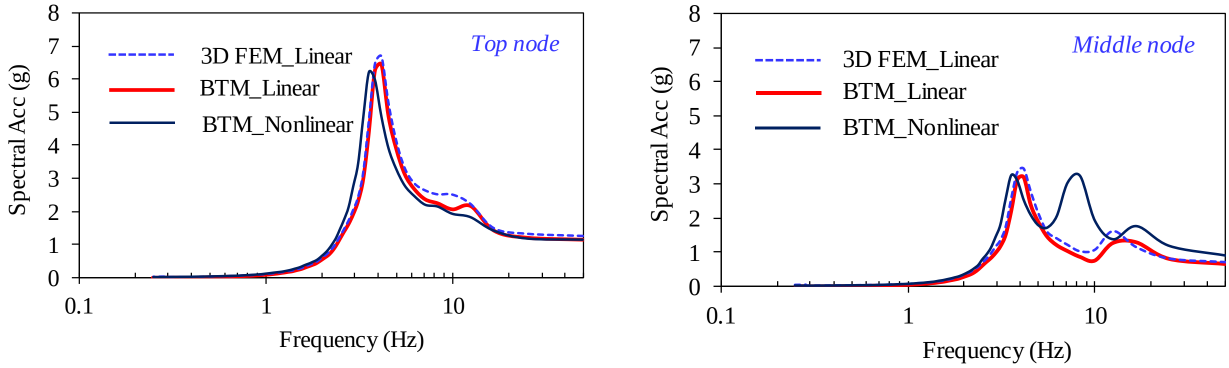


Fig. 13 - Comparison of FRS of RCB between BTM and 3D FEM

5. Parametric study

We also performed parametric studies on the variation of compressive strength of concrete (f_c') and concrete material models. The compressive strength of concrete varied from 45, 55, 65, 75, 85, to 95 MPa were considered in the numerical modelling. Fig. 14 shows the results of FRS with different strengths of concrete. It can be observed that the higher strength of concrete, the lower FRS of the structure. However, the variation of FRS is insignificant.

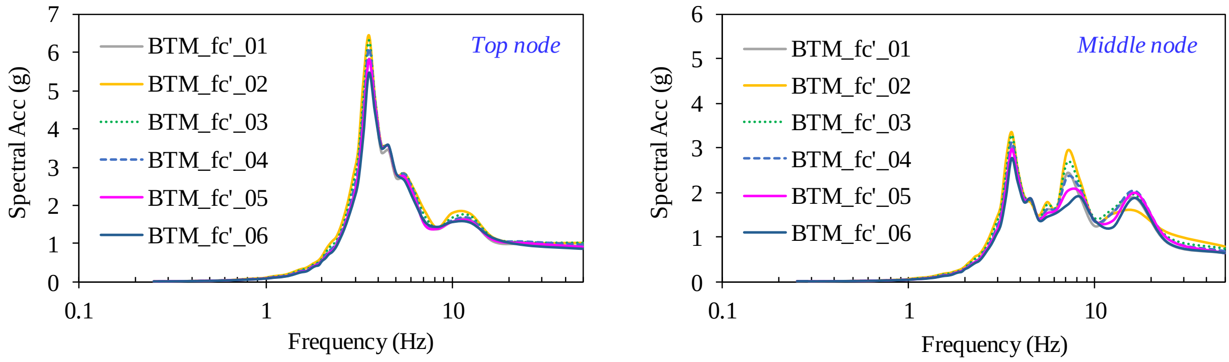


Fig. 14 - Comparison of FRS with different compressive strengths of concrete

In this study, an investigation of different models of concrete is also conducted, in which *concrete02* and *concrete04* [17] models are used. Fig. 15 shows a comparison of FRS at different elevations of RCB considering between concrete models. A same value of compressive strength of concrete was applied for both models but the difference of FRS between them are relatively high. This gap may be due to the discrepancy of material model shapes.

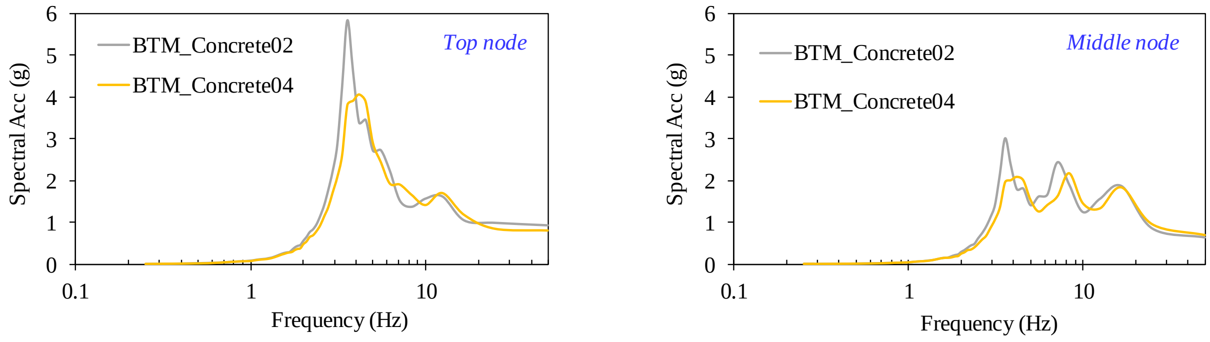


Fig. 15 - Comparison of FRS with different compressive strength of concrete

6. Conclusions

A series of time-history analyses are performed to highlight the capability of BTM for seismic evaluation of reactor containment building. The numerical results of BTM are compared with those of other developed models such as LMSM, Shell model and 3D FEM. Following conclusions are drawn.

- Fundamental frequencies of numerical models are in good agreement. Modal shapes of BTM are highly comparable to those of 3D FEM and Shell model.
- For performing time-history analyses, 3D FEM (solid) is the most time-consuming model, followed by Shell model, BTM, and LMSM. Among those models, BTM may be an optimal model to perform seismic responses of RCB, in which the computational effort and accuracy of result are satisfied.
- Linear time-history analyses of LMSM, 3D FEM, Shell model, & BTM are in good agreement. FRS of the structure is amplified at the fundamental frequency (~ 4.0 Hz).
- Different grades of compressive strength of concrete (fc' = 45, 55, 65, 75, 85, 95 MPa) are considered to investigate its influence on FRS of the structure. It reveals that the higher compressive strength of concrete the lower FRS at the peak value.
- Different concrete material models in OpenSees, in which *concrete02* and *concrete04* are considered. Even though we used a same value of compressive strength of concrete but the difference of FRS between two models are relatively high. This gap may be due to the discrepancy of material model shapes.

7. Acknowledgement

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