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DISCLAIMER

A STUDY OF THE EFFECT OF FLOOR FLEXIBILITY ON BUILDING RESPONSE USING THE KK NPP EXPERIENCE

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ABSTRACT

The 2007 Niigataken Chuetsu-Oki (NCO) earthquake caused strong motions at the Kashiwazaki-Kariwa nuclear power plant (KK NPP) that significantly exceeded the design basis acceleration levels. However, this earthquake did not compromise the safety-related structures, systems, and components (SSCs) at this plant. A large number of strong motions that were recorded at this plant during the 2007 NCO earthquake were utilized in a number of studies that aimed at understanding how NPP structures perform during rare but large earthquakes. Some of these studies indicated that the floor in-plane flexibility (shear deformation and flexural deformation) is one of the important factors that limit the applicability of lumped mass stick models in adequately predicting the building responses. This paper presents a comparative study of shell and lumped mass stick models to determine the significance of the effect of the floor in-plane flexibility on building responses.

INTRODUCTION

The 2007 NCO earthquake occurred off the west coast of Japan at 10:13 am JST (01:13 UTC) on July 16, 2007, with a magnitude of M6.6 and a depth of about 17 km. The epicenter was about 16 km from the KK NPP. The KK NPP is one of the world's largest nuclear power plants with seven reactors and a total output of 8200 Megawatts. Figure 1 shows the plant site of the KK NPP. Safety-related SSCs had no visible damage and performed better than anticipated, although this earthquake caused strong motions at the KK NPP that significantly exceeded the design basis acceleration levels over a wide frequency range.

There are a large number of strong motions recorded at the KK NPP during the 2007 NCO earthquake, including the main shock and aftershocks. These recorded strong motions are very important for assessing seismic safety of NPP structures because data that has been recorded at operating NPPs is rare. Accordingly, this data has been utilized in a number of studies to understand how NPP structures perform during rare but large earthquakes, and this paper presents an investigation of how floor flexibility affects building response during strong ground motions and how floors should be represented adequately in analysis.

This paper first summarizes the issues and insights obtained from previous studies. Many of the insights are found to be applicable to all units of the KK NPP. Some of these studies indicated that single-axis lumped mass beam models, in which floors are represented by individual nodes, could not predict with acceptable accuracy the recorded building responses. This paper aims to isolate the floor flexibility issue from other factors, and discusses how the floor flexibility can be modeled properly so that the structural responses can be predicted with acceptable accuracy. This study uses the data recorded at Unit 1.

The study presented in this paper is part of the collaborative efforts between the United States and Japan on seismic issues, and was performed at Brookhaven National Laboratory under the sponsorship of the U.S. Nuclear Regulatory Commission.

Figure 1 Kashiwazaki-Kariwa Nuclear Power Plant Area [USGS, 2007]

OVERVIEW OF THE PERFORMANCE OF THE KK NPPS

Table 1 shows the recorded peak accelerations and design accelerations for the reactors at the top of the basemats. Except for the case of Unit 5 in the vertical direction, all recorded peak accelerations at the basemat exceeded the target design values. The maximum peak acceleration of 680 gal (cm/s2, ≈ 0.69 g) was recorded in the East-West direction at the top of the basemat of Unit 1. The level of exceedance of some recorded accelerations was significant; for example, the recorded peak acceleration in the East-West direction at Unit 2 was 3.6 times the design value of 167 gal. The maximum acceleration at the ground level was 1,223 gal, which was recorded on the basemat of a small building sitting on the ground.

Based on the experience of this earthquake, a new design-basis maximum acceleration was determined to be 2,300 gal for Units 1-4 and 1,209 gal for Units 5-7. As a comparison, the original design-basis maximum acceleration was 450 gal, which was used for the design of the KK NPP. Both the new and the original design-basis earthquake motions are specified at the bedrock that is about 150 to 290 meters deep at the KK NPP site. The new design-basis ground motions correspond to an annual exceedance probability of 10^{-4} to 10^{-5}. Based on these design-basis ground motions, the seismic motion at the basemat of the reactor buildings were estimated to be 704 to 845 gal for Units 1 to 4 and 606 to 738 gal for Units 5 to 7.

Table 1 Recorded Peak Accelerations and Design Accelerations at the Basemat [NISA 2009]

(Unit: Gal)

	North-south component	East-west component	Vertical component
Unit 1	311 (274)	680 (273)	408 (235)
Unit 2	304 (167)	606 (167)	282 (235)
Unit 3	308 (192)	384 (193)	311 (235)
Unit 4	310 (193)	492 (194)	337 (235)
Unit 5	277 (249)	442 (254)	205 (235)
Unit 6	271 (263)	322 (263)	488 (235)
Unit 7	267 (263)	356 (263)	355 (235)

The figures in brackets indicate respective design-basis acceleration.

OVERVIEW OF ISSUES FOUND IN OTHER STUDIES

It was demonstrated that single-axis lumped mass stick models, in which floors are represented by individual nodes and are inherently assumed to be rigid, could not predict the horizontal building responses at Units 4 & 6 with a reasonable level of accuracy (Inoue et al. 2011a). The in-plane floor flexibility (both shear deformation and flexural deformation) was found to play a significant role in accurately estimating the horizontal building responses, especially when there are large openings in the floors. The frequency at which the floor flexibility had the most significant impact on building response appeared to be associated with the floor in-plane mode. The multiple-axis lumped mass stick models, which utilized floor springs to represent the floor in-plane flexural and shear deformations, appeared to be capable of predicting the measured response with reasonable accuracy (Inoue et al. 2011b). As expected, the detailed 3D shell element models were able to estimate the building responses. The floor in-plane flexibility effect was also found at the intermediate floors at KK Unit 6 reactor building during the Mid Niigata Prefectrue Earthquake that occurred in 2004 (M6.8). More recently, this effect also was found in the response spectra at the intermediate floors at the reactor buildings of the Onagawa NPP during the 2011 Great East Japan Earthquake/Tsunami.

Besides the floor flexibility issue, the studies by Inoue, et al., found that the soil surrounding the foundation walls, including the backfill and the soil layer above the top-of-the-basemat elevation, should be disconnected from the models in order for them to be able to estimate the building responses more accurately. This modeling strategy was supported by a site observation that the surrounding soil was sunken after the earthquake possibly due to exfoliation and/or nonlinear degradation. This issue is considered to be very significant because soil-structure interaction effects significantly change the system dynamic characteristics as compared to fixed base models. Similarly, ASCE 4-98 [2000] states for the embedment effects that “the potential for reduced lateral soil support of the structure should be considered when accounting for embedment effects. One method to address this concern is to assume no connectivity between structure and lateral soil over the upper half of the embedment or 20 ft (6 m), whichever is less."

Structure-structure (reactor building-turbine building) interaction was shown to be important in the analysis. The nearby turbine building had to be modeled, even with a coarse model, in the analysis of the reactor building. For the KK NPP, the structure-structure effect is believed to be significant because (1) the gaps between the reactor building and the turbine building are filled with shock-absorbing material, (2) the vicinity of the basemats of these two buildings are constrained by concrete, and (3) the KK site is a soft rock site that enlarges the interaction effect.

Other issues found in these studies that do not affect the evaluation of the floor flexibility issue can be found in a NUREG/CR (Nie et al. to be published in 2013).

STUDY OF FLOOR FLEXIBILITY EFFECT

The issues identified above in other studies all affect the level of accuracy in predicting the building responses. However, to assess more effectively the floor in-plane flexibility issue, it is prudent to isolate other factors from the effect of the floor flexibility in the finite element analysis. To this end, both the single-axis lumped mass stick models and the 3D shell models analyzed in this study were assumed to be fixed at the top of the basemat where the seismic input motion was placed. Because of the dissimilarity between the finite element models and the real KK Unit 1 reactor building, the comparisons were made between predicted motions of these models rather than to the recorded motions.

Only the recorded motion in the North-South direction on the top of the basemat was considered as the input motion in the analyses. In addition, the mass distribution and the stiffness distribution of these two types of models were made as equivalent as possible, in order to minimize the modeling discrepancy.

Description of Models

Instead of creating a reactor building model based on the actual structure of the KK NPP Unit 1, a simplified model (referred herein as the QF model) was developed based on a similar model used by Inoue, et al. [2011b]. Minor changes were made to that model in order to match the dimensions of the KK Unit 1 Reactor Building and to introduce openings of different sizes. Figure 2 shows a sketch of a quarter model developed in ANSYS (2011) for the simplified reactor building.

Modal analyses of this model were performed with fixed base condition and varying symmetry and anti-symmetry conditions at the X=0 and Y=0 surfaces in order to determine all the major modes. The frequency of the first mode in the X direction was found to be 4.77 Hz, and the frequency of the first mode in the Y direction was found to be 4.73 Hz. Both frequencies are close to the fundamental frequency reported in other studies.

Another 3D shell model (referred herein as the QR model) was created by converting the floors of the quarter model into rigid floors. However, because symmetry and anti-symmetry plans contradict the constraint equations for the rigid floors, an approach that was not readily available in ANSYS was developed to achieve the rigid floors. A modal analysis of this model showed that the fundamental frequency increases to 5.71 Hz, from 4.73 Hz for the case of flexible floors.

To validate the approach developed above for creating rigid floors in the quarter model, a full model was developed by mirroring the quarter model twice in ANSYS. Figure 3 shows the full model meshed with shell elements. Modal analyses of this model were performed for two cases: (1) flexible floors, and (2) rigid floors. The fundamental frequencies in the X direction and in the Y direction for the flexible-floor model were found to be 4.77 Hz and 4.73 Hz, respectively, which are the same as those for the quarter model with flexible floors. The fundamental frequency for the model of rigid floors (referred herein as the FR model) is about 5.73 Hz, very close to that of the quarter model with rigid floors.

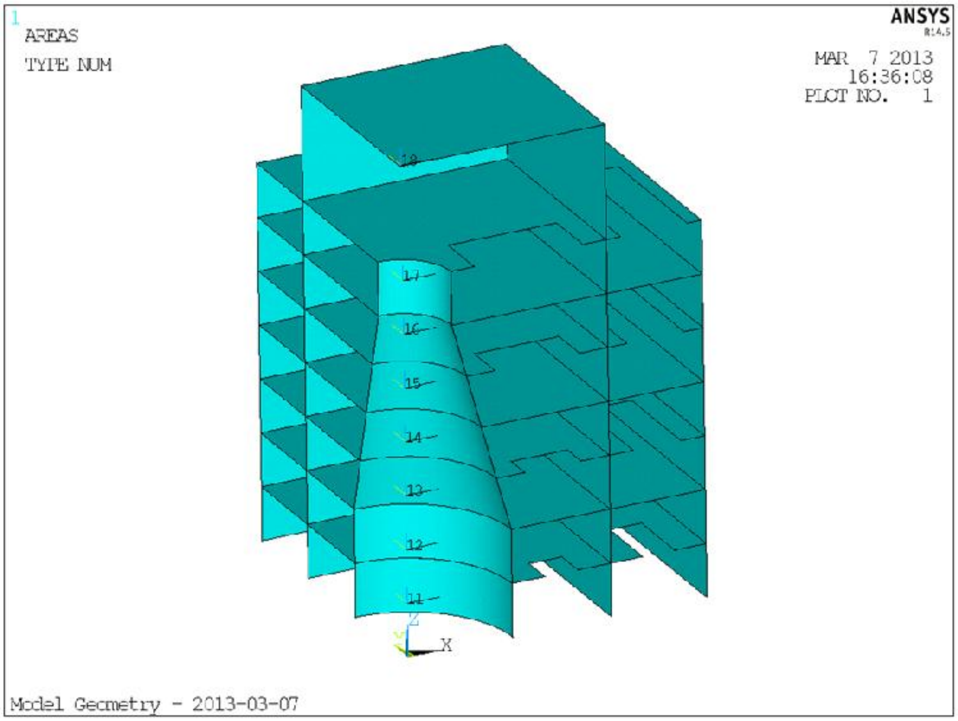

Figure 2 The Quarter Model for the Simplified Reactor Building

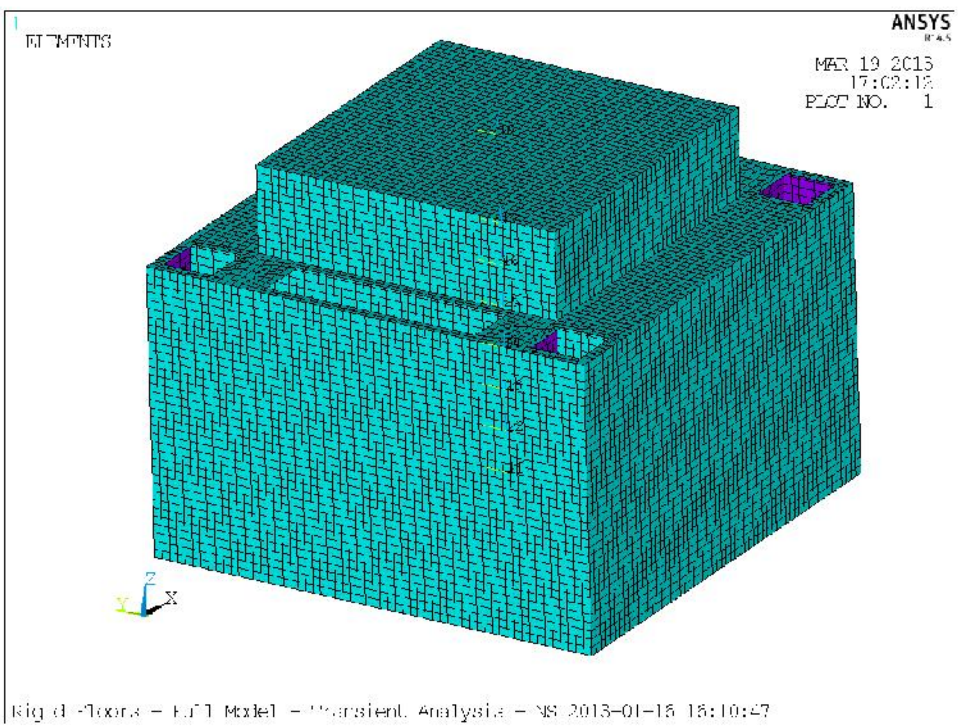

Figure 3 The Mesh of the Full Model

A single-axis lumped mass stick model was developed for the simplified reactor building based on the properties of the shell models. As shown in Figure 4, each story is represented by one beam element, and one concentrated mass element is placed at each floor elevation to represent the masses of the floor and half of the walls above and below the floor elevation. The shear area for each story includes two outer walls, two inner walls, and half of the cylindrical shells, all in parallel to the input motion direction. In particular, the entire length of an outer/inner wall is considered as shear area due to the presence of flanges. The moment of inertia for the beam elements consists of the contributions of: (1) the cylindrical shell, (2) the outer and inner walls in parallel to the input motion direction, and (3) flanges of the outer and inner walls with an effective flange width of 1/3 of the story height (due to shear lag effects). The fundamental frequency was found to be 4.91 Hz, which is closer to the shell models with flexible floors than those with rigid floors. This approach to develop the structural stick models has been used in practice, and this model is referred herein as the B1 model.

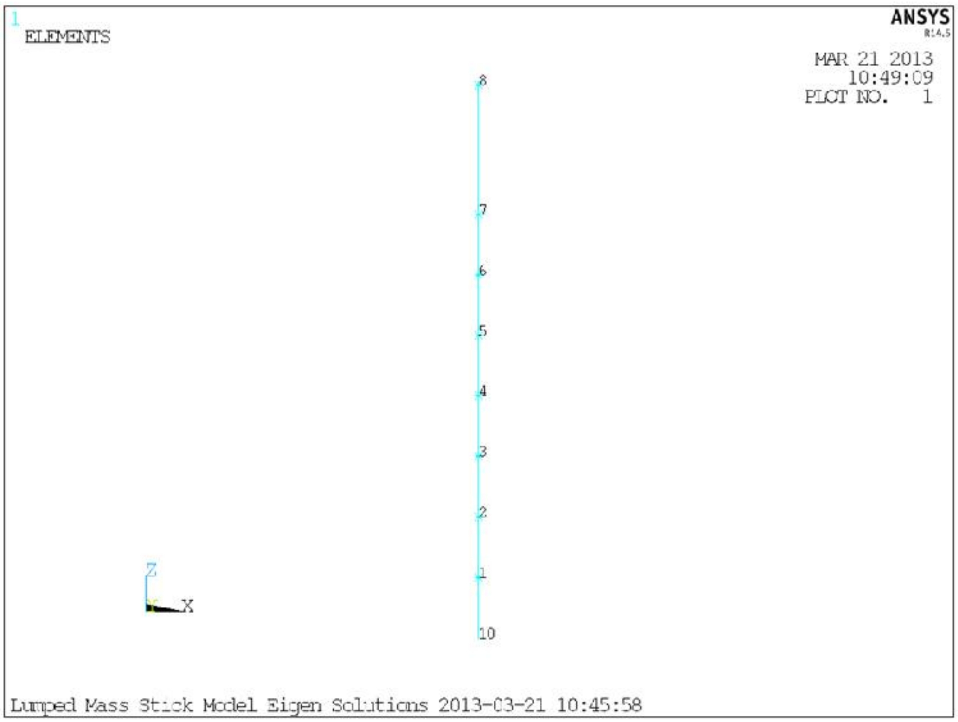

Figure 4 Lumped Mass Stick Model for the Simplified Reactor Building Model

Although single-axis lumped mass stick models imply that the floors are rigid, the parameters developed above for the definition of shear areas and moments of inertia are actually not fully compatible with the rigid floor assumption. Completely rigid floors make the entire lateral force bearing walls work in unison as a solid section does. To simulate the condition of true rigid floors as in the rigid-floor shell models, another stick model was created by including the entire area of the cylindrical shell as shear area and the entire perpendicular outer and inner walls in calculating the moment of inertia. The fundamental frequency of this model is 5.75 Hz, very close to those of the shell models with rigid floors. It should be pointed out that the use of the entire cylindrical wall as shear area is not appropriate in a real design situation because the steel reinforcement is not normally oriented to resist out-of-plane shear force. However, the material in this study is assumed homogeneous and the rigid floor assumption makes the entire cylindrical wall, being at the center of the building, work as shear area. This model is referred herein as the B2 model.

Result Assessment

The five analytical cases to be compared are summarized below, with each case indicated by a two-letter code in bold and the color used in the figures for comparison:

QF (blue): the quarter model with flexible floors,
QR (red): the quarter model with rigid floors,
FR (red): the full model with rigid floors,
B1 (black): the lumped mass stick model B1, and
B2 (magenta): the lumped mass stick model B2 developed assuming rigid floors.

The response acceleration time histories and the corresponding response spectra were compared at locations through the models. Figure 5 shows a comparison of acceleration time histories and response spectra at a node along the center line of the shell model at the 3rd floor and in the input motion direction. The B1 model can reflect well the fundamental frequency of the QF model around 4.73 Hz, although it does not predict well the spectral magnitude. At this location, the response spectrum of the QF model shows two peaks of similar magnitudes: the first one is the fundamental building mode and the second one is the floor in-plane mode. The B1 model cannot predict the floor in-plane mode, and the small peak around 9 Hz is the second mode of the B1 model. This finding is similar to what was found in the JNES study of the KK NPP Unit 4.

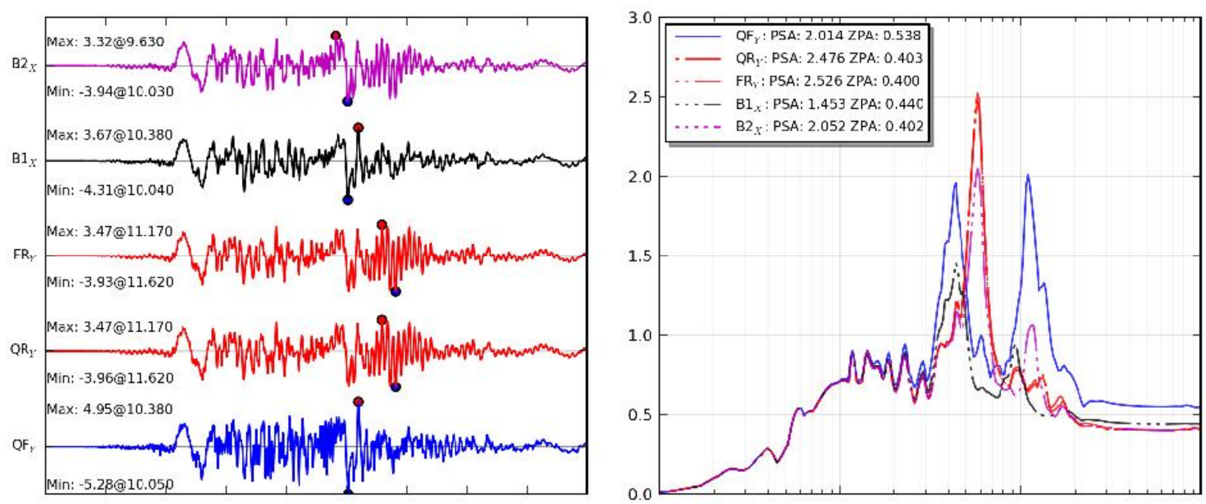

Figure 5 Comparison of Acceleration Time Histories and Response Spectra – 3rd Floor

The peak spectral accelerations (PSAs) and the zero-period accelerations (ZPAs) were also compared at these locations throughout the models, as shown in Figure 6 for the 7th floor. In this figure, the value at the top of each box shows the relative difference between B1 and QF for PSA while the one at the bottom shows the relative difference for ZPA. A positive value indicates that the B1 model is unconservative. Along the outer wall (the main shear wall), the maximum relative difference for PSA is 12% and that for ZPA is 18.5%. However, for locations farther away from the outer wall (closer to the center line of the building), the B1 model becomes less accurate and more unconservative. The largest relative difference is 58% in PSA and 35.1% in ZPA, which occurred at node 85 located at the seventh floor. This level of accuracy is not considered acceptable in practice and demonstrates that the floor in-plane flexibility (both shear deformation and flexural deformation) should be considered for generating floor response spectra for equipment qualification, and potentially for design of floors and other structural components.

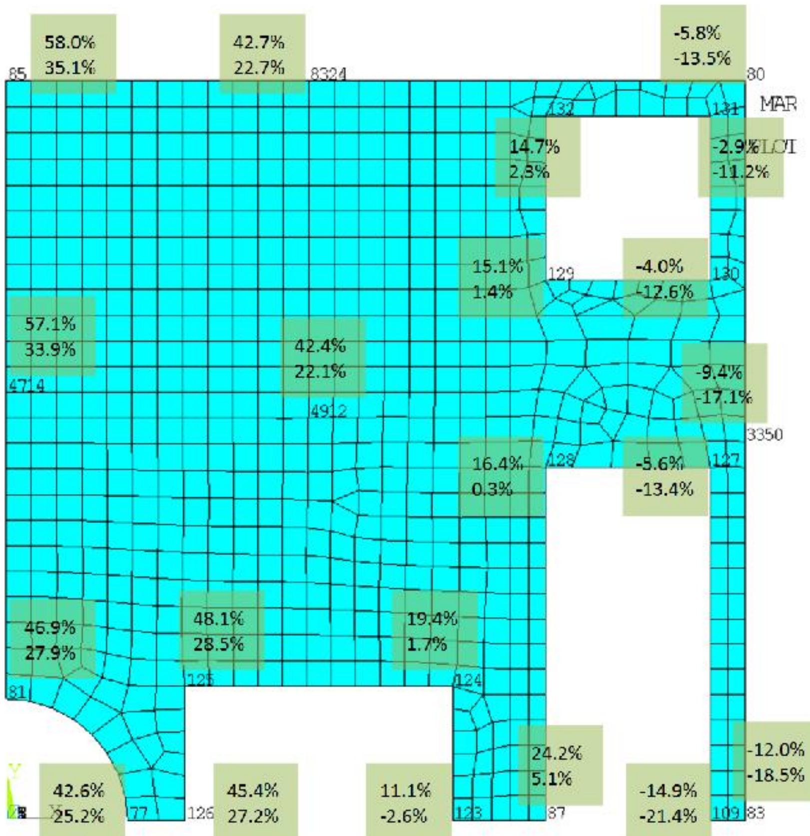

Figure 6 Relative Differences of PSA/ZPA between QF and B1 – 7th Floor (%)

Figure 7 and Figure 8 show the variation of the relative difference in PSA and the relative difference in ZPA as a function of elevation, respectively, at three common plan locations as also shown in these figures. These figures also include a plan diagram in the middle of the figures to indicate these locations and the input motion direction by a short double arrowed line as well. In a clearer fashion, Figure 7 shows that the B1 model is very accurate and mostly conservative in predicting PSA and is relatively accurate and always conservative in predicting ZPA along the outer wall at all floor elevations. At location (0 m, 42.5 m) where the B1 model performs the least accurately, the relative differences in PSA and ZPA are relatively small at the 1st floor because at this elevation, the building mostly follows the input motion and the effect of amplification of the input motion is small. The relative difference in PSA reaches a plateau of about 37% between the second floor and the sixth floor, and shows a sudden increase at the seventh floor. As shown in Figure 8, the relative difference in ZPA does not exhibit the behavior of a plateau but has a similar large increase at the seventh floor. The large increases in the differences in PSA and ZPA at the seventh floor suggests that the B1 model cannot represent well buildings with dramatic floor-to-floor stiffness change.

More detailed description of the analysis and comparison of results can be found in a NUREG/CR (Nie et al. to be published in 2013).

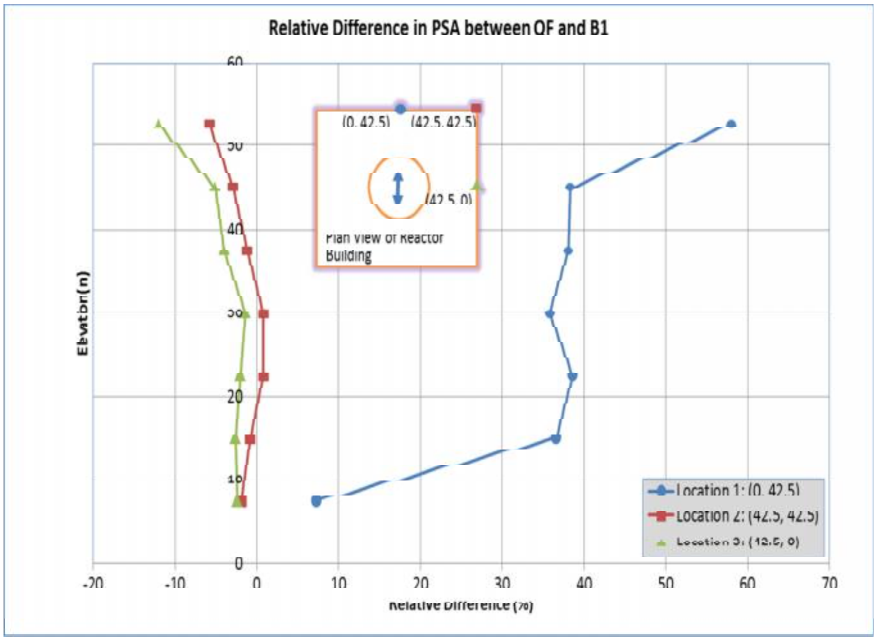

Figure 7 Vertical Variation of Relative Difference of PSA between QF and B1

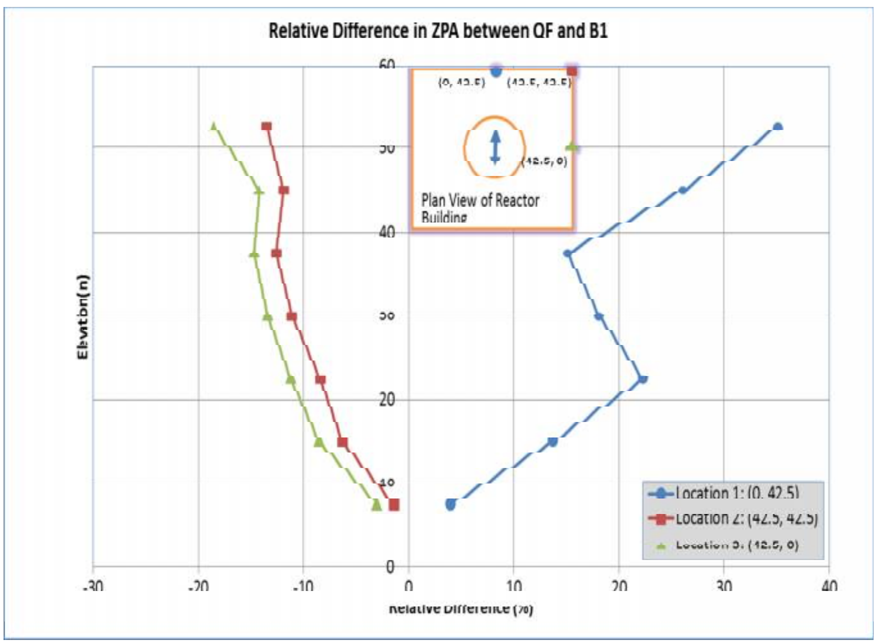

Figure 8 Vertical Variation of Relative Difference of ZPA between QF and B1

CONCLUSION

It is concluded that the effect of floor in-plane flexibility can be important in predicting building responses, in particular at locations close to the centerline of the building. For locations farther away from the outer walls (or closer to the centerline of the model), the lumped mass stick model becomes less accurate and more unconservative. The largest relative difference for the models in this study was found to be 58% in PSA and 35.1% in ZPA. This level of accuracy is not considered acceptable in practice. It was also shown that the lumped mass stick model cannot represent well buildings with dramatic floor-to-floor stiffness change.

The effect of floor in-plane flexibility should be considered for generating floor response spectra for equipment qualification. It may also need to be included for generating acceleration profiles that are used in the design of the lateral force resisting members placed closer to the center of the reactor building (e.g., inner walls and the cylindrical shell). Since reactor buildings consist of mostly floors, shear walls and other plate components, shell models are more convenient to generate and are adequate in modeling the floors properly. In cases where computational demand is large, a coarser shell model may be used if justified.

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