Canadian Conference - Pacific Conference on Earthquake Engineering 2023

Vancouver, British Columbia

June 25th – June 30th, 2023

Seismic Floor Response Characteristics of a Large Irregular Building

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ABSTRACT

The Auxiliary building (AB) is one of the critical structures in nuclear power plants (NPPs) since it houses all the important safety systems of the nuclear reactor such as radioactive waste system, emergency cooling water system, and chemical control system. The objective of this study is to evaluate the seismic responses at every critical location of the AB structure in the advanced power reactor 1400 (APR-1400) NPPs. The multi-layer shell model (MLSM) was developed to simulate the seismic behaviors of the AB. A set of 40 input ground motions records is selected from historic earthquakes to perform linear time-history analyses. Floor response spectra (FRS)are studied at 12 distinct locations of every floor of the structure. The floor responses are evaluated as an average of the responses to the input motions. The results show an incredibly significant difference in seismic responses at various locations on the same floor of AB. For the case of AB in APR1400, the X-component of earthquake motion is more sensitive than Y-components. It suggests that the current modeling techniques, which are frequently used in design practice, can underestimate or overestimate floor responses of such structures. Additionally, this study also suggests to virtually divide a floor into several groups based on their seismic response characteristics for an efficient evaluation of seismic performance of AB. Additionally, the free vibration sensitivity analysis conducted based on Pearson's correlation coefficient illustrated a positive linear relationship between material properties and major vibration modes of the structure.

Keywords: Auxiliary building; multi-layer shell model; floor response spectrum; time-history analysis.

INTRODUCTION

Auxiliary building is the largest structure associated with NPP structures. Auxiliary building houses of most of the NPP equipment's and safety systems of the reactor such as radioactive waste system, emergency cooling water system, chemical and volume control system, heat exchangers generators. As NPP is one the most hazardous structures concerning thousands of lives and environment which we have experienced after the Chernobyl (Ukraine,1986) and Fukushima Daiichi (Japan 2011). Moreover, the uncertainties due to earthquakes are always huge concerns for the safety of NPP structures which knock the researchers for the necessity of study of seismic performance evaluation of NPP structures and components.

For seismic performance evaluations, NPP structures are normally modeled in terms of the lumped-mass stick model (LMSM) or three-dimensional finite element model using solid elements (3D FEM). LMSM simplifies the real structures to linear-elastic beam elements with concentrated masses at nodes. This modeling approach has been widely applied for seismic response analyses and vulnerability assessments of NPP structures [1][2] and equipment [3].

In addition to LMSM and 3D FEM, the shell element model can be used for structural response analyses of nuclear engineering structures. Some studies utilized a linear shell model [4] to facilitate numerical simulations. Besides, a multi-layer shell model (MLSM) considering nonlinearity of materials was also applied to perform the behaviors of the NPP structures under internal pressures [5] and earthquakes [6]. The Auxiliary building is simple but massive critical shear wall structure in NPP structures. A full scale [7] and scaled model of RC NPP model with both containment and auxiliary building [8] was previously studied for safety and damage assessment under aircraft impact loading. However, the studies for Auxiliary building of NPP structures are hardly any. While, in almost every study of floor response spectrum of any structures, the floor responses are recorded on specific node and are considered with rigid diaphragm hence represent the response of the whole floor area but for large floor areas and having large openings can have variation in the floor responses at various location, which has not been mentioned earlier. Furthermore, seismic performance evaluation studies of a full-scale structure of Auxiliary building are still limited. Due to computational limitations proper studies have not been carried out so far.

The aim of this study is to investigate the seismic performance of a full-scale model of Auxiliary building as well as perform a free vibration sensitivity analysis of AB with several 100 random samples of compressive strength of concrete and yielding strength of rebars. A set of 40 input ground motions such that the mean response spectra matched to the US Nuclear Regulatory Commission (NRC) 1.60 design spectrum is selected from PEER center database to perform linear time-history analyses. Seismic responses of the AB are measured in terms of floor response spectra which is concerning outputs in the seismic evaluation of NPPs. The main goal of this investigation is to perform a benchmark study for seismic performance of NPP AB structures.

NUMERICAL MODELING

Structural configuration of Auxiliary building

The Auxiliary building structure of APR-1400 Nuclear power plant developed by Korea Electric Power Corporation and Korea Hydro & Nuclear Power (Figure 1) was adopted for the numerical analysis of this study. The Auxiliary Building of APR-1400 NPP is the largest structure of NPP having around 104.85m length along longitudinal axis and 102.4m on the transverse axis. AB is a simple shear wall building consisting of nine floors with variable floor height according to the installed NPP control systems. Each storey height of AB is listed in table no.1. Structurally, AB is entirely a shear wall structure having various thicknesses with thickest section as the external wall. For clarity, we have categorized the shear walls of AB into various groups according to thickness and purpose of the wall. The section details and reinforcement details of several wall sections adopted in AB of APR-1400 are listed in Table 2.

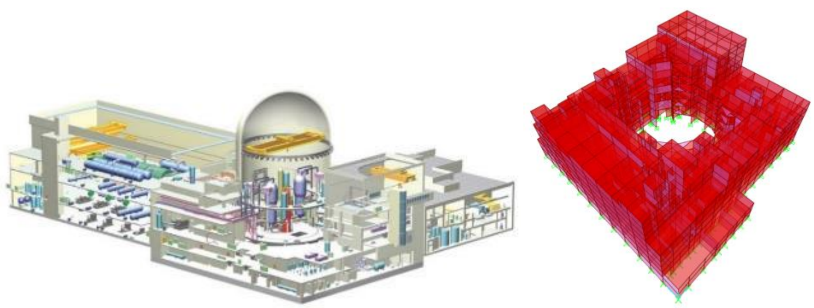


Figure 1. General view (left) and Auxiliary Building (right) of APR-1400 NPP

Table 1. Floor details.

Floor	Floor height	Floor elevation
Ground floor(B2)	7.0104	0
First floor(B1)	6.7056	7.0104
Second floor	6.096	13.716
Third floor	5.334	19.812
Fourth floor	5.6388	25.146
Fifth floor	4.8768	30.7848
Sixth floor	5.4864	35.6616
Seventh floor	2.4384	41.148
Eighth floor	7.1628	43.5864
Ninth floor		50.7492

Numerical modeling

For MLSM, the numerical model of containment building is developed in SAP2000 [9] using smeared multi-layer shell elements. The shell element is divided into several layers with different thicknesses. Each layer represents a specific material in which reinforcement and concrete layers are set up together, as shown in Figure 2. Material properties are assigned to corresponding layers, in which the nonlinearity is considered in material models, as shown in Figure 3. The floor load of 11.97KN/m2 is applied to the floors having NPP equipment and control systems. The multi-layer shell element is theoretically derived from the principles of composite material mechanics. This kind of element can simulate the interaction between in-plane and out-of-plane responses and the in-plane flexural-shear behaviors of RC walls [10-12].

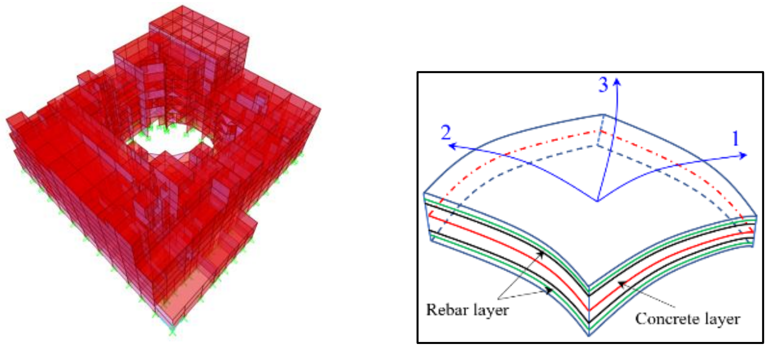


Figure 2. Illustration of MLSM

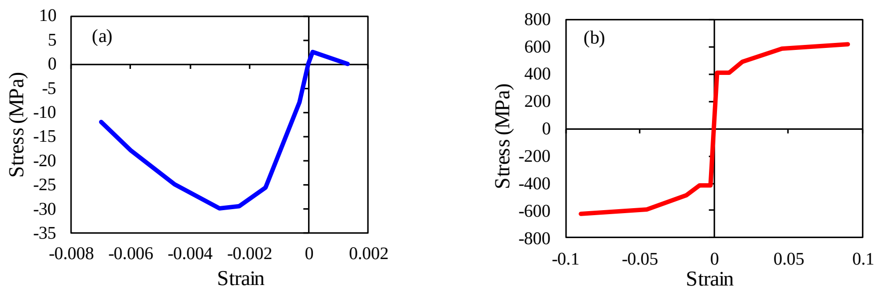


Figure 3. Nonlinear material models for MLSM: (a) concrete and (b) reinforcing bars.

The details of reinforcing bars and concrete and material properties need to be pre-defined to generate MLSM, in which nonlinear characteristics of materials are considered. Based on these input parameters, we expect that MLSM can approximate the nonlinear behaviors of the structure accurately. This MLSM can be a promising approach in terms of computation for analyzing larger structures like Auxiliary building as this numerical model significantly reduces the number of degrees of freedom compared to the Solid FEM approach.

Mesh Sensitivity analysis

We conducted a series of Eigen value analyses till the convergence to perform mesh sensitivity. Four mesh sizes of 8m, 4m, 2m, and 1m were adopted to investigate the mesh sensitivity of the AB. Figure 4. shows the mesh convergence test plot for mode one of eigen value analysis. From Figure 4, the 2m mesh containing 39381 no. of shell elements is the best mesh size for accurate numerical results. Table.3. gives the eigen values analysis results for various mesh sizes.

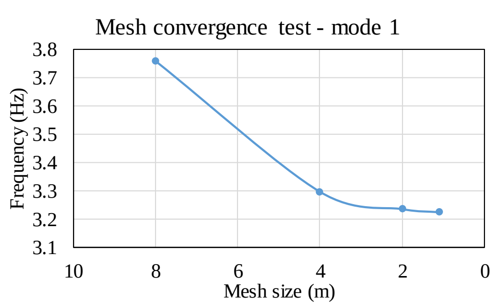


Figure 4. Mesh convergence test

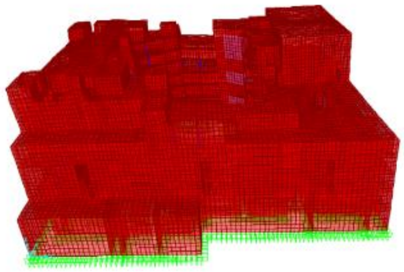
Table 3. Eigen value analysis results of AB with various mesh size

Mode of vibrations	Frequency (Hz)			
	Mesh 8m	Mesh 4m	Mesh 2m	Mesh 1.1m
Mode 1	3.75726	3.29568	3.23436	3.22338
Mode 2	4.76612	4.45749	4.42502	4.47213

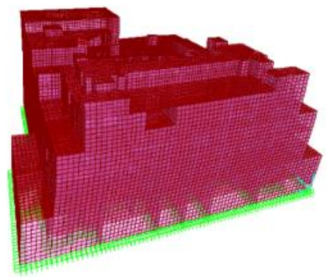
Mode 3	7.22812*	6.8600*	6.11532*	5.97756*
Mode 4	8.41796**	7.81289**	6.73033**	7.0156**
Mode 5	10.21359***	9.53424***	9.65419***	9.38777***
Note: *: translation X, **: translation Y, ***: torsional mode				

Eigenvalue analysis

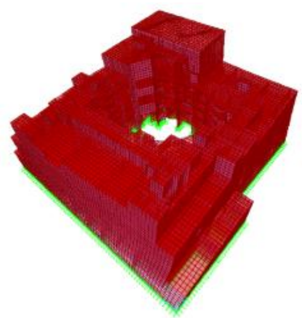
Eigenvalue analysis was conducted to study the mode shapes and modal vibration frequency of the AB. In this study, three main modes shapes (translation x, translation y and torsional mode) were studied. Figure 5 shows the three main critical vibrational modes of the numerical model. Table 3 presents the natural frequencies of the first five vibration modes of the investigated numerical model for the optimum mesh size of 2m. The result of eigenvalue analyses reveals that AB is a lot stiffer structure.



(a) Translation mode X



(b) Translation mode Y

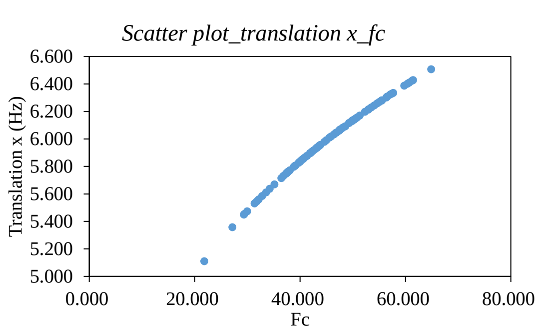


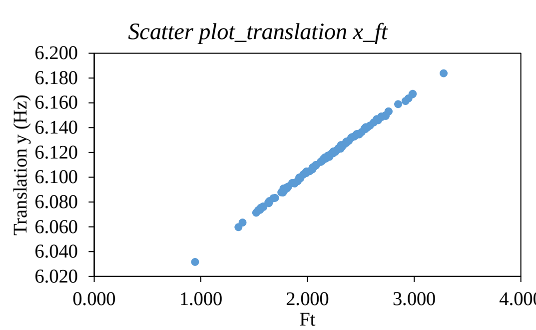
(c) Torsional mode

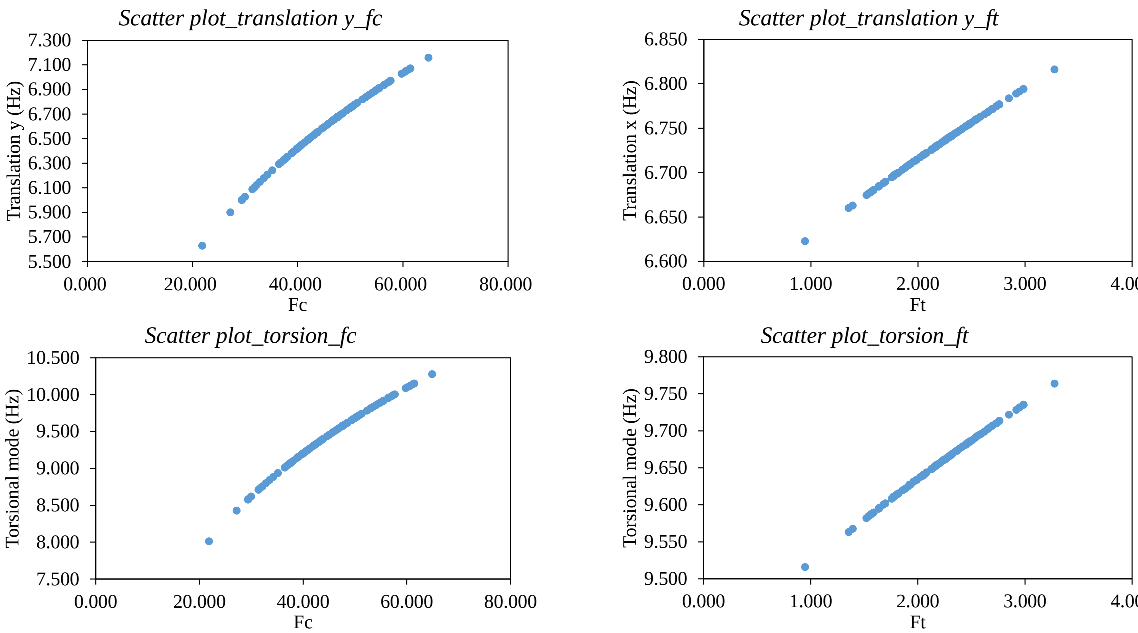
Figure 5. Modes shapes

Sensitivity analysis of Auxiliary Building using free vibration analysis

Sensitivity analysis based on Pearson's correlation coefficient was applied to study the influence of major uncertainty parameter of concrete i.e., the compressive strength (fc) and tensile strength (ft). Latin hypercubic sampling was adopted to generate 100 random input parameters for fc and ft. Free vibration analysis was conducted for each input parameter combination varying one at a time. The 3 major critical vibration modes (i.e., Translation x, y, and Torsion) were recorded as output in each analysis. Figure 6 represents the scatter plot for each input parameter versus the critical vibration modes. Table 6 represents the Pearson's correlation test results between the input and output parameters.







(a) 100 Fc samples (b) 100 Ft samples

Figure 6. Scatter plots of three vibration modes with fc and ft samples

Table 4. Pearson's correlation test

Parameter		Correlation coefficient (r)	N	T stat.	df	p value
Input fc	Trans. X	0.99500	100	98.63788	98	0.00000
	Trans. Y	0.99502	100	98.81564	98	0.00000
	Torsion	0.99433	100	92.55462	98	0.00000
Input ft	Trans. X	0.99936	100	275.55806	98	0.00000
	Trans. Y	0.99963	100	365.58277	98	0.00000
	Torsion	0.99955	100	328.37254	98	0.00000

The Pearson's correlation coefficient test results from Table 4 shows that all the three critical vibration modes (Translation x, translation y and torsional mode) are linearly correlated with the fc and ft of concrete with all statistically positively significant with p=0.000($p<0.05$). Hence the increase in fc and ft leads to increased frequency of vibration modes.

Input ground motions

The APR-1400 NPP structures have been seismically designed using the US NRC 1.60 spectrum [13] with a PGA of 0.3g at the safe shutdown earthquake level. This study uses a set of 40 natural ground motions with mean response spectra as the NRC 1.60 design spectrum to conduct time-history analyses, as shown in Figure 7. The ground motion records are selected from worldwide historical earthquakes, which are provided in the PEER center database [14].

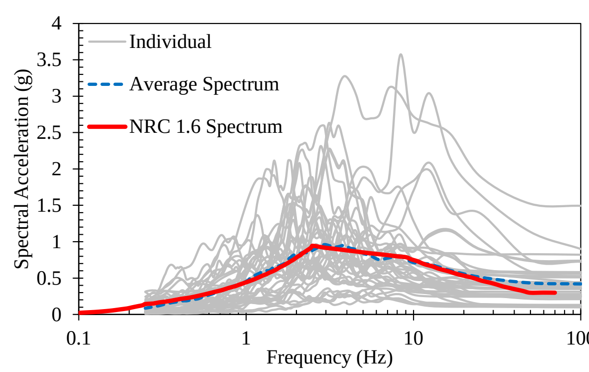


Figure 7. Input ground motions

Seismic performance evaluation

Linear dynamic analyses in the Auxiliary building were carried out by imposing ground motion on both X and Y- direction, one at a time. The Auxiliary building is symmetric in at least one axis along the x axis. We performed a series of linear time-history analyses in both the horizontal X and Y-direction to obtain the seismic responses of the AB. It is noted that we apply the Newmark method with $\gamma = 0.5$ and $\beta = 0.25$, which yields the constant average acceleration method (i.e., middle point rule) for solving the equation of motion in dynamic analyses.

Floor response spectrum (FRS) is one of the most critical outputs for evaluating the seismic performance of NPP structures. Numerous safety systems of the reactor like radioactive waste system, emergency cooling water system, chemical control system, as well as several devices and relays, including electrical, electronic, and mechanical components, are attached to this structure at various levels and locations. The seismic responses of all the safety systems and their equipment's along with devices are generally evaluated by using FRS. Seismic responses at twelve distinct locations as shown in Figure 8 on each floor were investigated in this study.

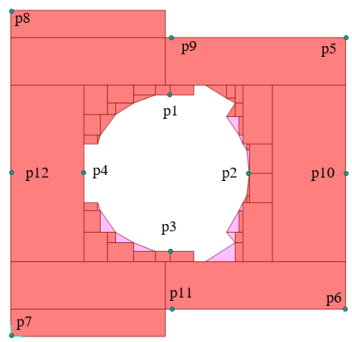
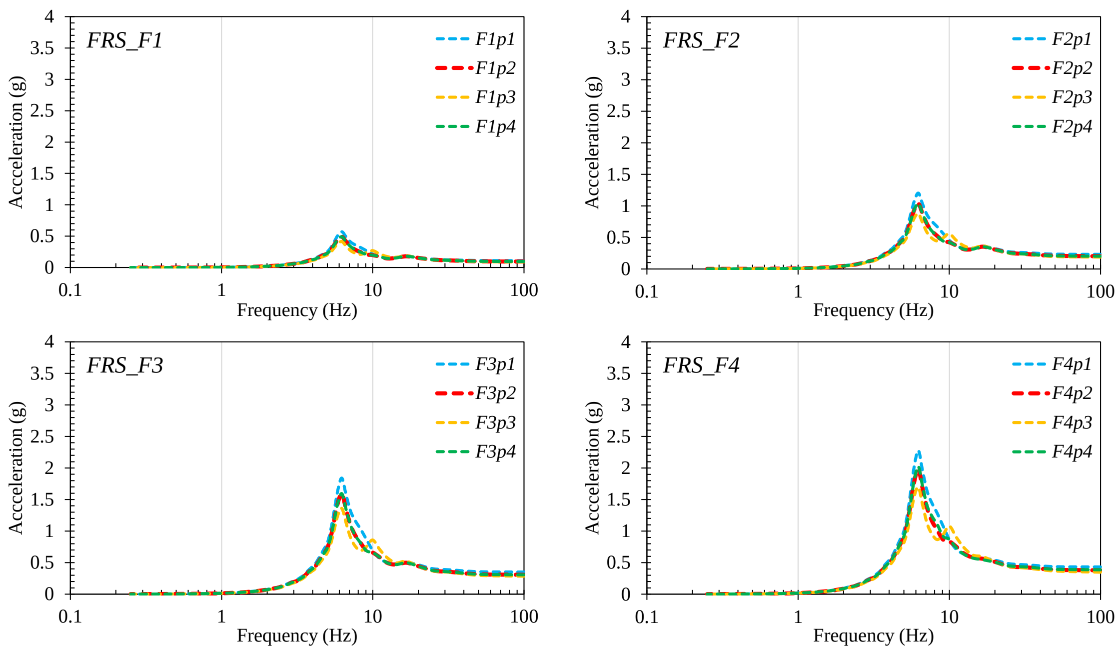


Figure 8. Twelve seismic response recorder locations

In the first set of study, FRS of four extremities (p1, p2, p3 and p4) of RCB which have close contact with the AB were investigated when the earthquake is applied along X-direction. The mean seismic response spectrum of the first set of locations (p1-4) in each floor of the AB is presented in Figure 9. It is observed that the results are consistent and there are a significant number of discrepancies between seismic response of each location of four extremities. Location p3 has the lowest seismic response on all the floors whereas location p1 has highest peak response among these four locations which is around 33% higher response than that of p3. While the response at p2 and p4 are around 16-18% higher than that of p3 respectively in all floors. This shows that there are significant fluctuations in the in the floor response of AB although the floors are assumed to be rigid.



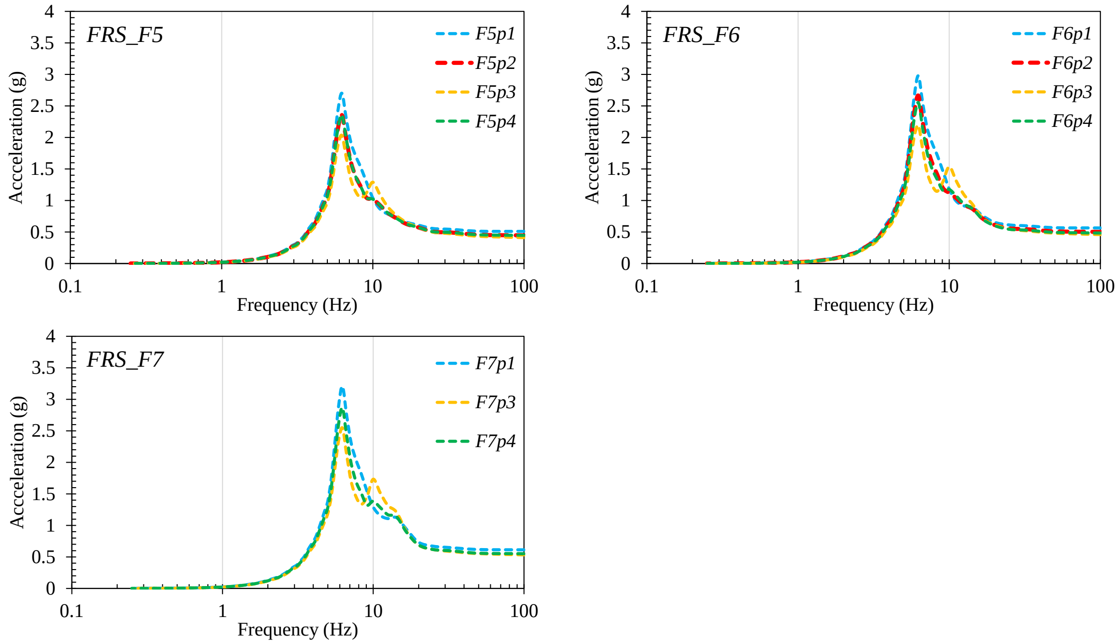
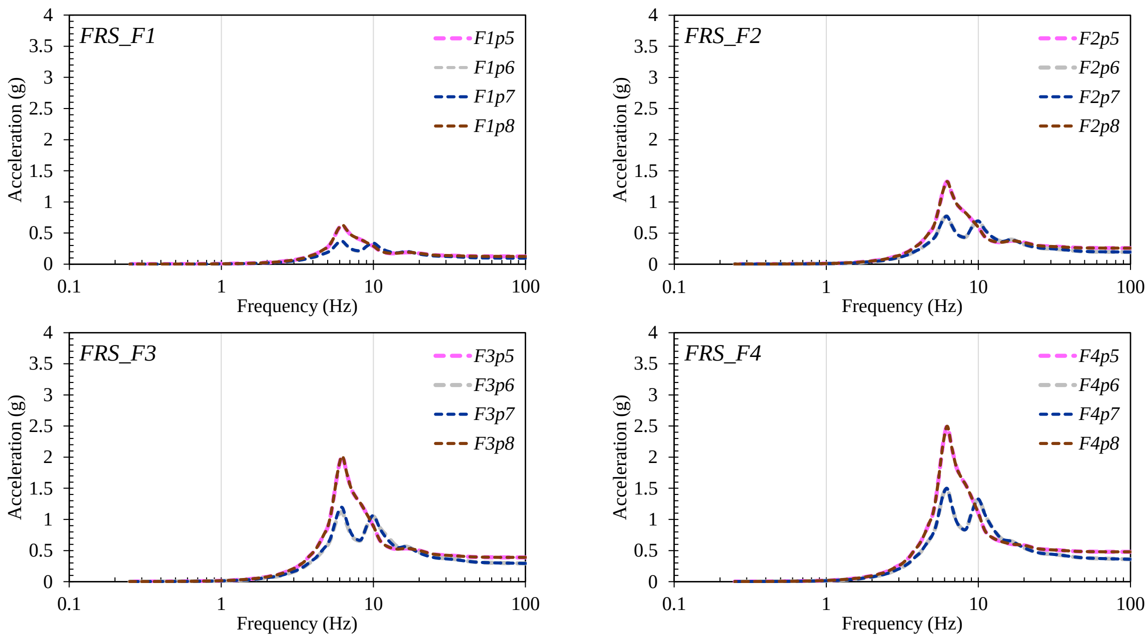


Figure 9. Mean FRS for each floor at location p1, p2, p3 and p4

Furthermore, the 2nd set of locations consisted of all the four edge corners of the floor represented by p5, p6, p7 and p8 as shown in Figure 10. From the mean FRS of each 4 nodes of this set of locations, there are two specific groups of response along the direction of application of earthquake load. The response of p5 and p8 have almost the same response, while p6 and p7 showed the same behavior. This means the response of each corner which is aligned with the direction of application of earthquake load shows same response. The response in p5 and p8 is around 56.74% higher than that of p6 and p7. This is because p5 and p8 extend up to the 9th floor increasing mass along this area.



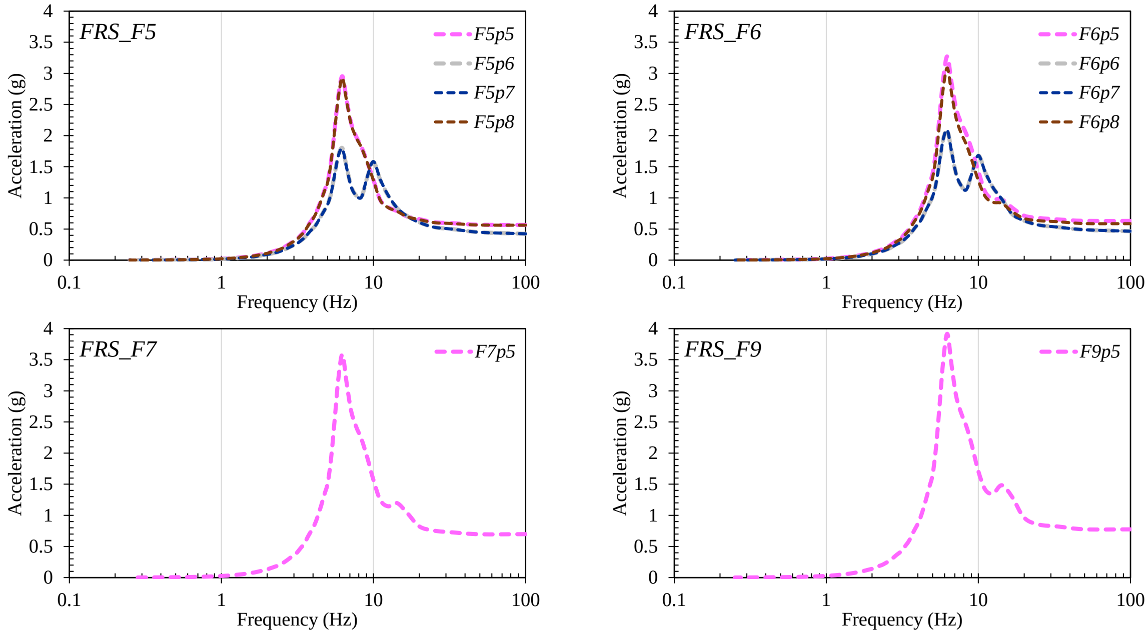
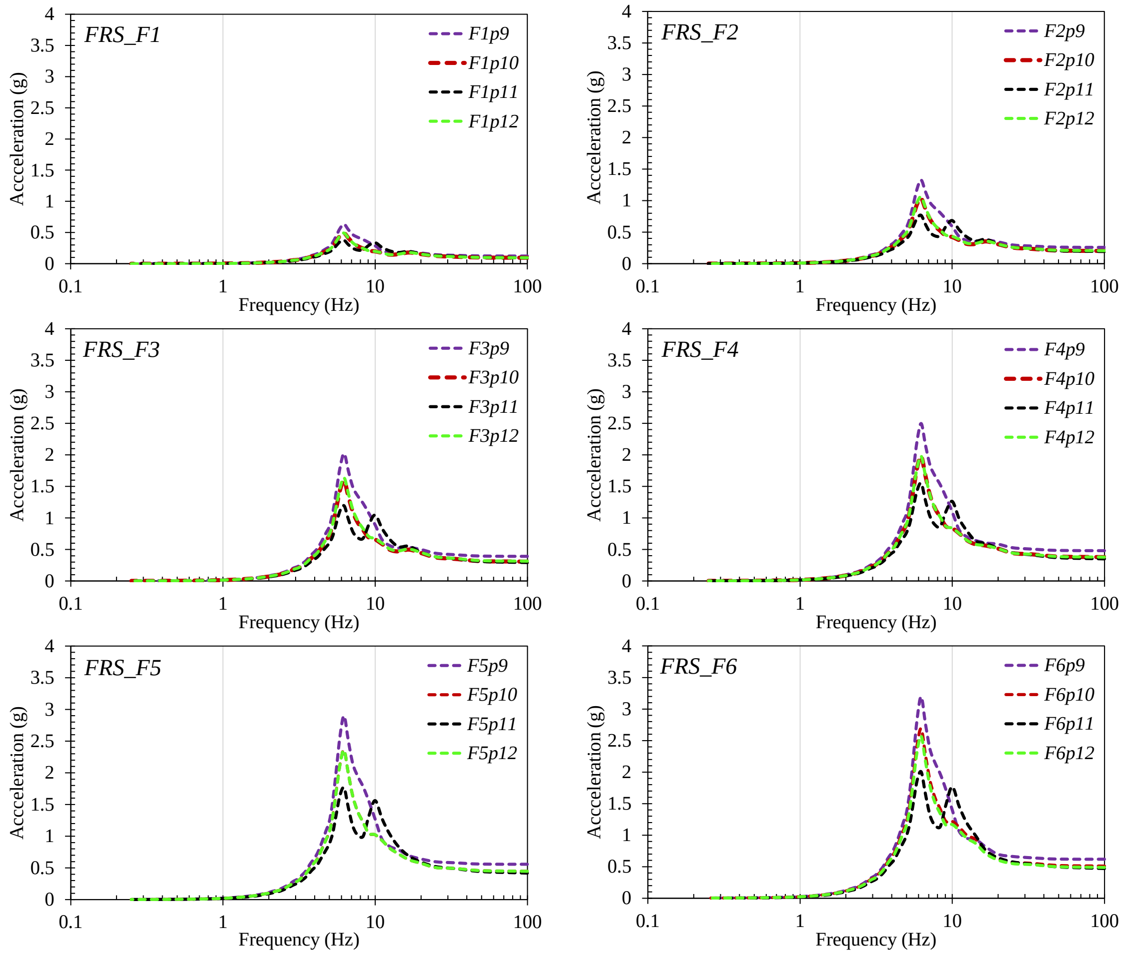


Figure 10. Mean FRS for each floor at location p5, p6, p7 and p8

Finally, the 3rd set of locations were the middle locations of each side of AB represented as p9, p10, p11 and p12 are presented in Figure 11.



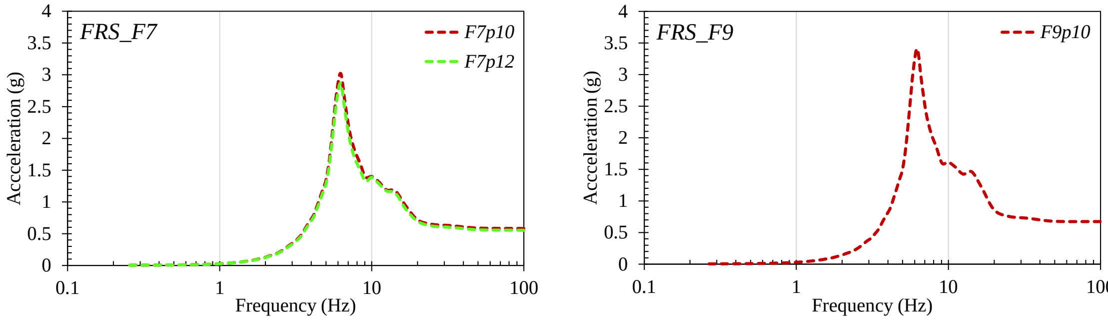
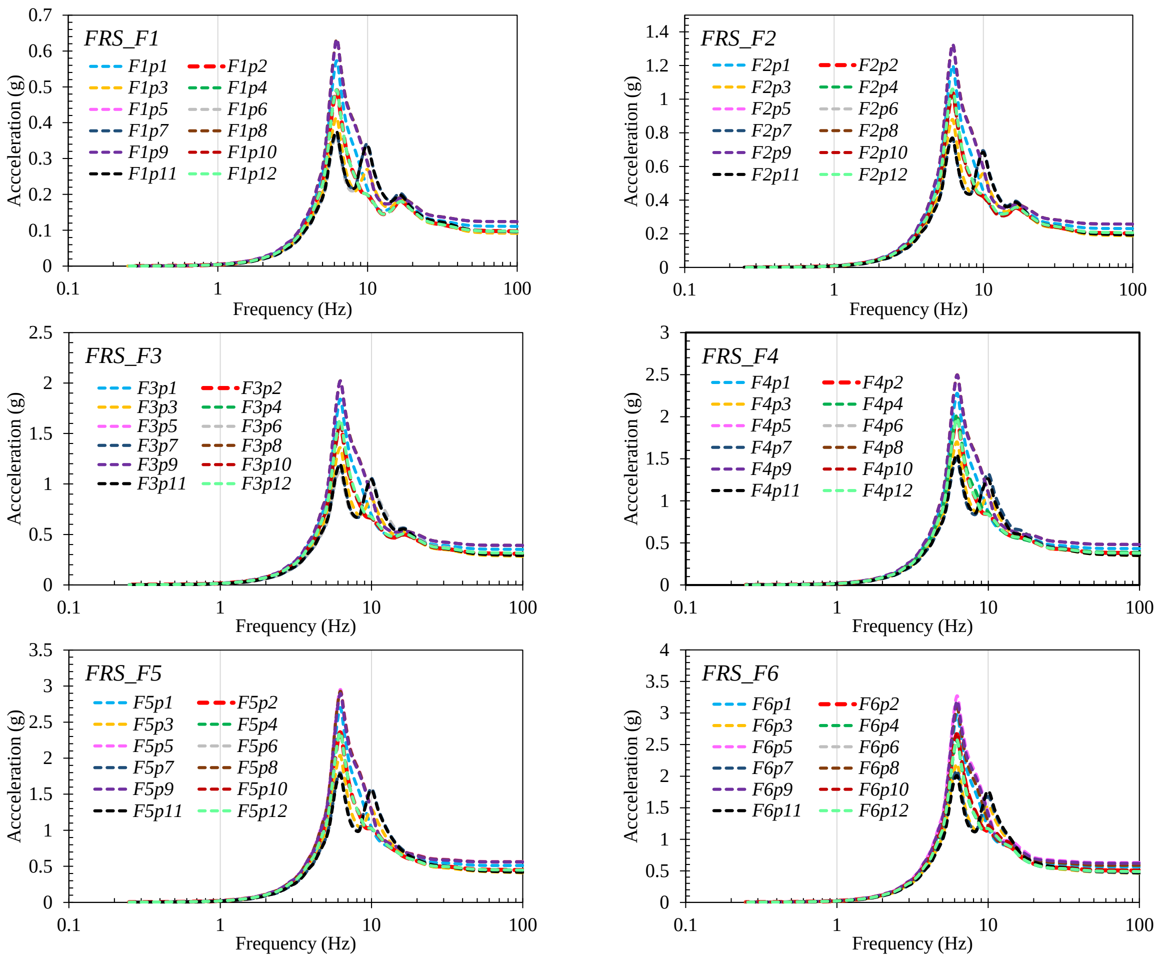


Figure 11. Mean FRS for each floor at location p9, p10, p11 and p12

Figure 11 shows the mean FRS plot for 3rd set of locations (i.e., p9, p10, p11, p12). Three different peaks are observed in Figure 11 for each floor. The largest peak is from response of location p9 which is around 57% higher than that of p11. While the responses of p10 and p12 are having almost similar responses on every floor. The peak response at p10 and p12 is around 28.41% higher than the peak response of p11.

The comparison of mean FRS for all the 12 locations is shown in Figure 12. It can be observed that all the locations are amplified at the fundamental frequency of AB (i.e., 6.115 Hz). Five distinct groups of peak responses are observed in all locations of each floor. The first peak is the highest peak which are responses of p5, p8 and p9 which are around 56% to 58% higher than the lowest peak response attributed by lowest response group of p6, p7 and p11. Secondly, p1 gives the second highest peak which is around 32% to 35% higher than that of lowest response group (i.e., p6, p7, and p11). The third response group is the responses of p2, p4, p10 and p12. The third response group shows a 16% to 18% rise in seismic response in comparison to the response of lowest response group. The fourth response group consists of responses of p3 which are around 8% to 13% higher response than that of the lowest response group. All these five-response groups lie in five different alignment groups along the direction of application of earthquake load in each floor of AB as shown in Figure 13.



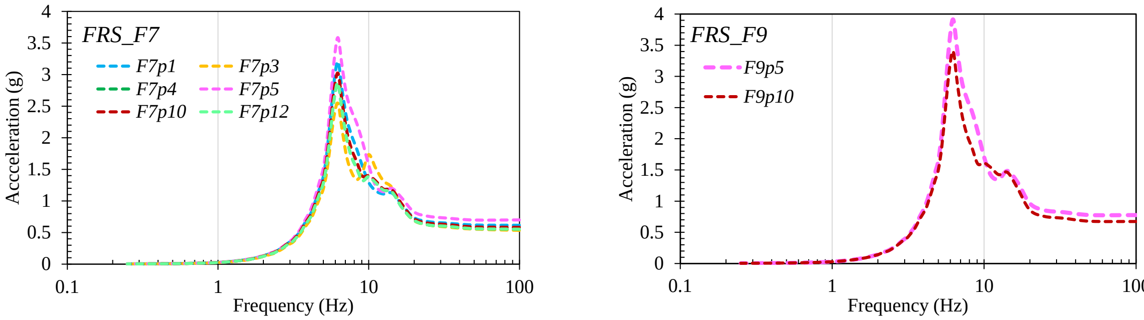


Figure 12. Mean FRS for each floor at all the locations p1- p12.

Figure 13 presents the five alignment groups categorized according to the alignment of twelve nodes along the X-direction earthquake load. From Figure 12, the observed five different peaks lie along each alignment from X1 to X5. It is observed that the locations along X1 showed the highest peak floor response while it decreases as we move from X1 to X5. X1 consists of 3 locations i.e., p5, p8, and p9. Similarly, X2, X3, X4, and X5 consist of locations as shown in Figure 13. The nodes located on alignment X5 have lowest peak floor responses. The floor response along the alignments corresponds to the response of nodes along each alignment which is floor responses presented in Figure 12. The lowest peak floor response shown by X5 can be due to the floor load as well condition of continuity in floors above it i.e., X5 lasts till floor level 6. While the variation of floor responses is due to the torsional behavior of the AB.

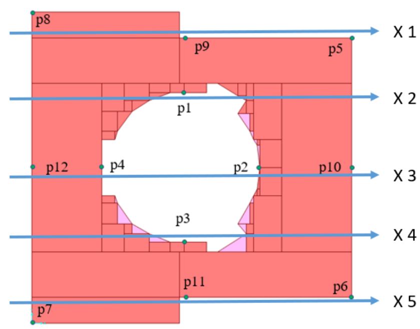
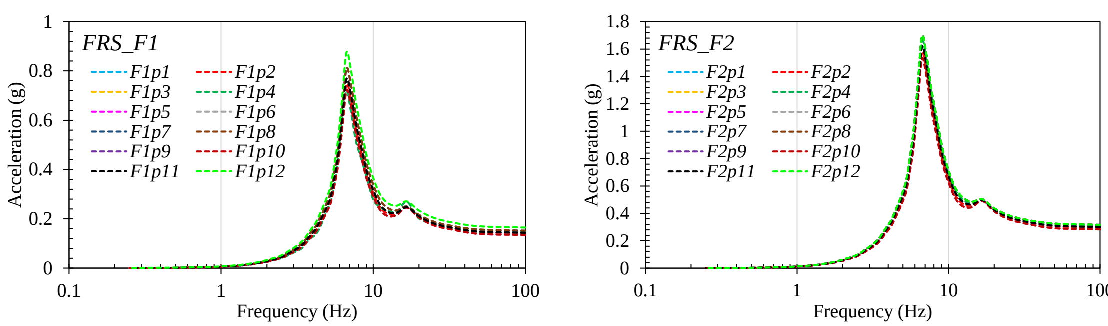


Figure 13. Five alignment lines of AB along the X-direction earthquake

In the second phase of the study, the earthquake load is applied along the Y- direction. The FRS for all the three sets of locations i.e. extremities of RCB (p1, p2, p3 and p4), four edge corners (p5, p6, p7 and p8), and middle location of each face of AB (p9, p10, p11 and p12) were investigated. The mean seismic floor response spectrum of all the locations is presented in Figure 14. It is observed that the results are consistent and behave in a similar pattern as discussed earlier when the earthquake load is on X-direction. However, the variation of floor response is lesser in magnitude in comparison to X direction motions significant groups of response. The FRS peaks on the locations p5, p10 and p6 are lowest seismic response on all the floors whereas location p8, p7 and p12 has highest peak response among all the locations which is around 10 to 20% higher response than that of lowest response. The response at location p2 is 2 to 3% higher, while the response at p1, p3, p9, and p11 are around 5-10% higher than the lowest response respectively in all floors. Similarly, response at p4 ranges from 10 to 13% higher than the minimum value. This results from Y-direction motion also validates that there are significant fluctuations in the floor response of AB although the floors are assumed to be rigid.



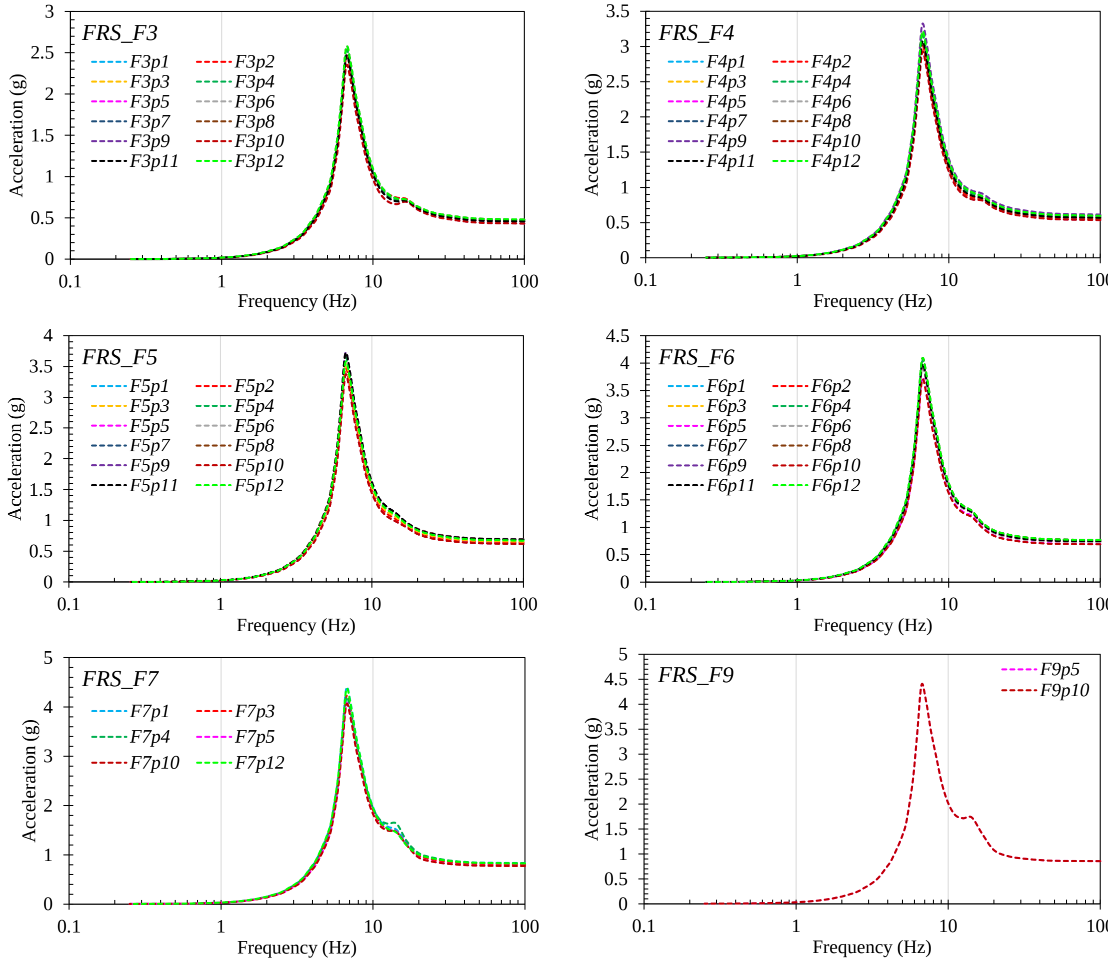


Figure 14. Mean FRS to Y-direction motion for each floor at all the locations p1- p12.

Figure 15 presents the alignments along the Y- axis of AB, where Y1, Y2, Y3, Y4, and Y5 are the groups categorized according to the FRS response alignment of twelve nodes along the Y-direction. The locations along Y1 showed highest peak response, while locations along Y5 showed lowest response.

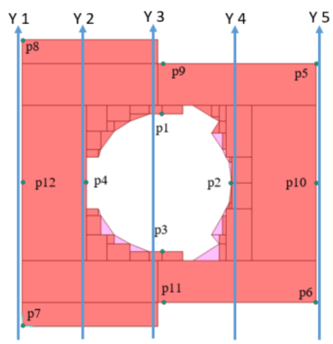


Figure 15. Three alignment lines of AB along the Y-direction earthquake

CONCLUSIONS

This study investigates the floor response spectrum of Auxiliary building of APR1400 NPP. The nonlinear FEM model of Auxiliary building is developed by applying multi-layer shell model using commercial software SAP2000v15. A series of linear time series are performed for all the input ground motions. The seismic floor response is studied for the various critical locations along various alignment on each floor. In addition, a series of free vibration analysis is conducted in this study. Free vibration sensitivity study was performed for the two important parameters of concrete i.e., fc and ft. The following conclusions can be drawn based on the output of numerical analyses.

- The three critical vibration modes are significantly correlated with the compressive strength (fc) and tensile strength(ft) of the concrete material model. The critical vibration modes are linearly positively correlated to fc and ft.
- For massive structures like Auxiliary building of NPP torsion can be the most critical mode of vibration that must be considered.
- There is significant variation in floor response spectrum of various locations in same floor though the floor is designed to behave rigid. This is due to the massive floor area and torsional behavior of the structure.
- The peak floor response varies from 16% to 58% of lowest response on various locations of same floor.

ACKNOWLEDGMENTS

This research is supported by the Korea Institute of Energy Technology Evaluation and Planning (KETEP) and the Ministry of Trade, Industry & Energy (MOTIE) of the Republic of Korea (No. 20201510100020).

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