SEISMIC ASSESSMENT AND PERFORMANCE OF NONSTRUCTURAL COMPONENTS AFFECTED BY STRUCTURAL MODELING

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Seismic probabilistic risk assessment (SPRA) requires a large number of simulations to evaluate the seismic vulnerability of structural and nonstructural components in nuclear power plants. The effect of structural modeling and analysis assumptions on dynamic analysis of 3D and simplified 2D stick models of auxiliary buildings and the attached nonstructural components is investigated. Dynamic characteristics and seismic performance of building models are also evaluated, as well as the computational accuracy of the models. The presented results provide better understanding of the dynamic behavior and seismic performance of auxiliary buildings. The results also help to quantify the impact of uncertainties associated with modeling and analysis of simplified numerical models of structural and nonstructural components subjected to seismic shaking on the predicted seismic failure probabilities of these systems.

I. INTRODUCTION

The seismic probabilistic risk assessment (SPRA) integrates all elements such as structures, systems and components (SSCs) in a nuclear power plant (NPP) and evaluates the safety of the entire plant under seismic events. Although the seismic performance of structures and nonstructural components are complicated and diverse, more simplified and effective SSC models are required for the massive computational loads in SPRA.[1] This study presents the quantification of variations induced by simplified and detailed structural models on the seismic performance of nonstructural components. Impacts of structural modeling strategy of auxiliary buildings will be investigated through estimation of epistemic uncertainties for the operational failure of nonstructural components.

In this study, the seismic performance of an auxiliary building is evaluated with simplified 2D and detailed 3D models. The 2D models are generated with simplified sticks, while the 3D models are developed with finite elements. For realistic plans of auxiliary buildings, 3D detailed model includes both asymmetric mass distribution and stiffness of structures. For the simplification of the auxiliary building, a symmetric 3D model is also generated with uniformly distributed mass and symmetric stiffness, and its seismic performance is compared to that of the asymmetric 3D model. Using the modal and time history analyses, the dynamic characteristics of 2D and 3D models are determined, and their seismic responses are estimated. Based on the dynamic analysis results from structural models, the seismic performance of the NSCs are evaluated by considering their operational and physical failure. Effects of modeling and analysis assumptions for each structural model on the performance of NSCs are summarized and analyzed in terms of their seismic failure probabilities, as well as their accuracy, time required for analysis, and modeling simplicity. This study will contribute to the estimation of common mode failures of nonstructural components in different locations of an auxiliary building subjected to seismic shakings.

In this study, Section II describes the auxiliary building and its modeling procedures in 2D and 3D, and Section III presents a set of dynamic analysis results using the modal and time history analyses. The analysis results from different models are compared, and their difference and variations are quantified. In sum, Section IV concludes this study.

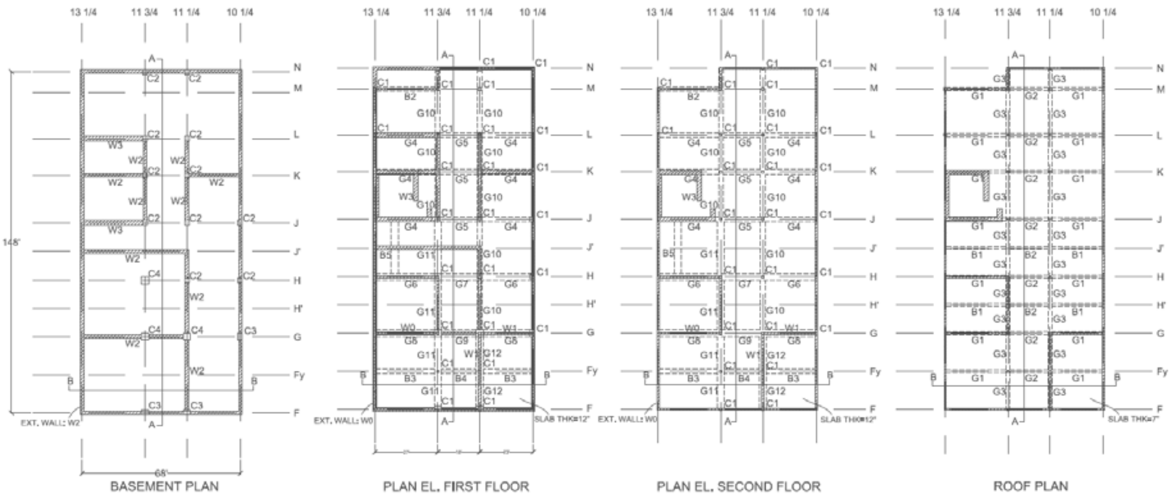
II. MODEL DESCRIPTION

II.A. Auxiliary Building

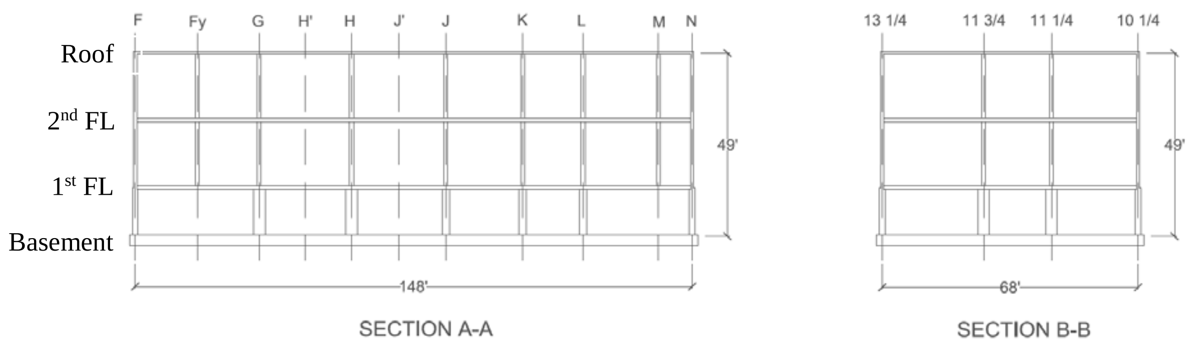
I.A.1. General Description of a Realistic Auxiliary Building

Due to obvious security risks, structural plans for nuclear power plants are not readily available. In that respect, a partial plan set of the decommissioned Connecticut Yankee NPP in Haddam, CT was obtained from the library of congress [http://www.loc.gov/pictures/item/ct0714.sheet.00003a/]. From this partial plan set, a set of modified structural plans was created to represent a typical NPP auxiliary building as shown in Fig. 1.

The Connecticut Yankee NPP auxiliary building was a reinforced concrete building with two stories above ground level and a partial basement. As with most buildings, the structural components, such as walls, slabs, beams, and columns, of this auxiliary building had diverse dimensional and structural properties varying throughout its footprint. As it is likely to have some heavy equipment in typical NPP auxiliary buildings, the structural plan set created for this paper was very asymmetric as illustrated in Fig. 1. The structural beams, columns, and walls are not symmetrically placed, and therefore, the stiffness distribution in this building is not symmetric, as well as the mass distribution of the building as shown in Fig.1(c).



(a)

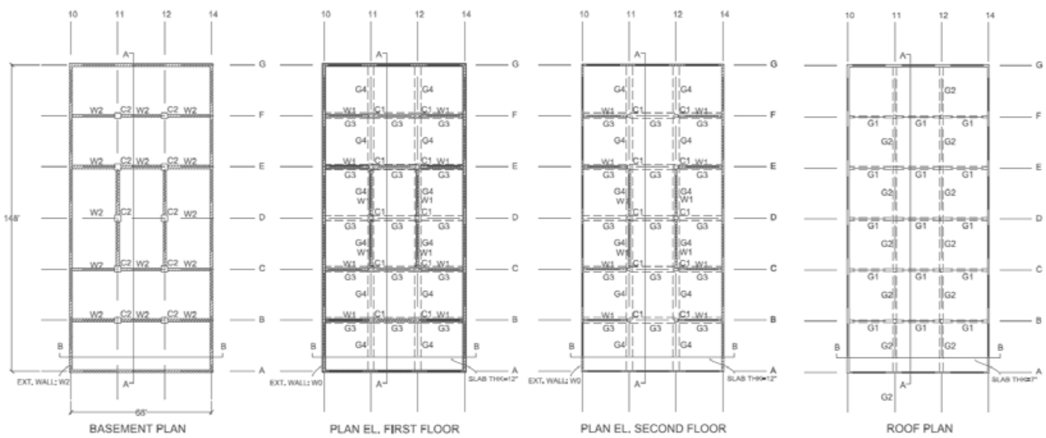


(b)

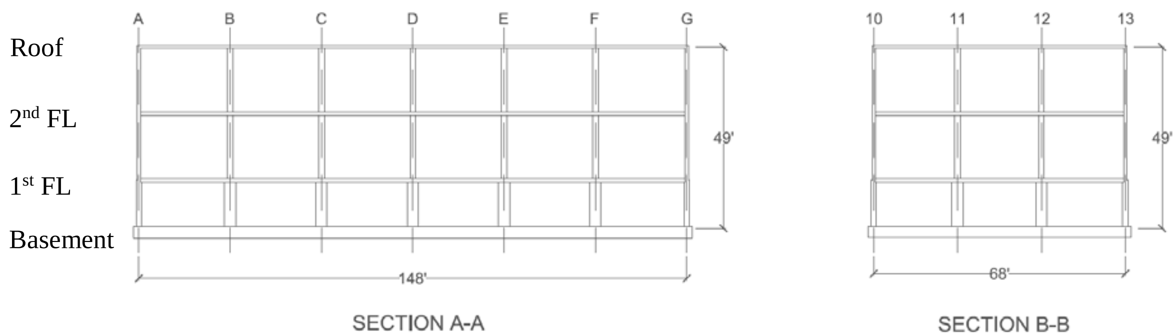
Fig. 1. Modified Structural Plans of Connecticut Yankee NPP Auxiliary Building:
(a) Plan Drawing of Each Level (b) Elevation Drawing of Each Side

I.A.2. Symmetric Auxiliary Building

For the simplified 2D, or stick models, the plans shown in Fig.1 were modified to create a symmetric building. In order to do this, the sum of the volume of all columns, beams, walls, and slabs was determined, and then distributed uniformly throughout the building footprint so the building is symmetric in terms of both geometry and structural properties. The details of the symmetric building can be seen in Fig. 2. This symmetric building has the same total mass at each floor level as those of the asymmetric case.



(a)



(b)

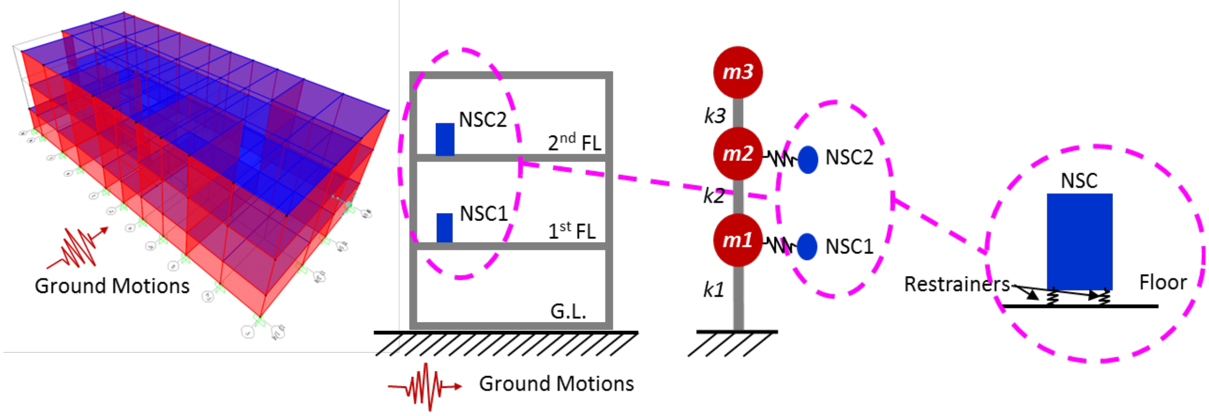
Fig. 2. Modified Symmetrical Structural Plans of Connecticut Yankee NPP Auxiliary Building:
(a) Plan Drawing of Each Level (b) Elevation Drawing of Each Face

II.B. Auxiliary Building Models

II.B.1. 3D and 2D Models

For the asymmetric and symmetric models described in Section II.A, 3D finite element (FE) models are generated in SAP2000 [2]. After analyzing the dynamic characteristics of the 3D models, simplified 2D stick models are generated in MATLAB [3] using the total or lumped mass and stiffness of each floor. Fig. 3 presents the simplification of models of the auxiliary building from the asymmetric 3D model to simplified 2D model and the attached NSCs. The NSCs are restrained on the first and second floors, whose dynamic responses are directly affected by the absolute acceleration response of each floor under seismic loading. In this study, it is assumed that the NCSs are stiff enough to have high fundamental frequencies such as heavy mechanical equipment. Since rigid components are typically restrained well on a floor, their seismic response is very close to the floor response under seismic shaking. However, if the nonstructural components are relatively flexible, say with a fundamental frequency less than 36 Hz, their seismic response needs to be re-computed considering their flexibilities with respect to the building floors.

In this study, all asymmetric and symmetric 3D models and 2D models share the same total mass values at each floor level. The variables *m1, m2, and m3* represents the lumped mass value at the first, second and roof levels, respectively, for all models. The only difference between the asymmetric and symmetric 3D models is the mass distribution and variation in lateral stiffness. The asymmetry of the 3D model comes from irregular gravity loading and irregular locations of lateral load-resisting structural components such as walls and columns as shown in Figs. 1 and 2. Therefore, it is expected that the torsional response of the asymmetric model will significantly influence its lateral response when the earthquake loading is applied in the two orthogonal directions. The 2D models are developed based on the dynamic characteristics of 3D models in the weak, or transverse, direction. Table I presents the lumped mass and stiffness of each floor as shown in Fig. 3(c). These constant values of total lumped mass are applied to all models, and the lateral stiffness is slightly different for asymmetric and symmetric cases as well as 2D and 3D models.



(a) (b) (c) (d)

Fig. 3. Simplification of Auxiliary Building Models: (a) 3D Finite Element Model, (b) Conceptual 2D Model of Auxiliary Building, (c) 2D Stick Model, and (d) Nonstructural Component Restrained to Floor

TABLE I. Mass and Stiffness of 2D Models

Mass (kip-s^2/inch)			**Stiffness (kip/inch)**					
m_1	m_2	m_3	k_1		k_2		k_3	
			Asymmetric	Symmetric	Asymmetric	Symmetric	Asymmetric	Symmetric
12.71	12.71	3.66	0.8277 x10^6	0.9560 x10^6	0.2882x10^6	0.2937x10^6	0.2923 x10^6	0.2937 x10^6

II.B.2. Dynamic Analysis Procedures

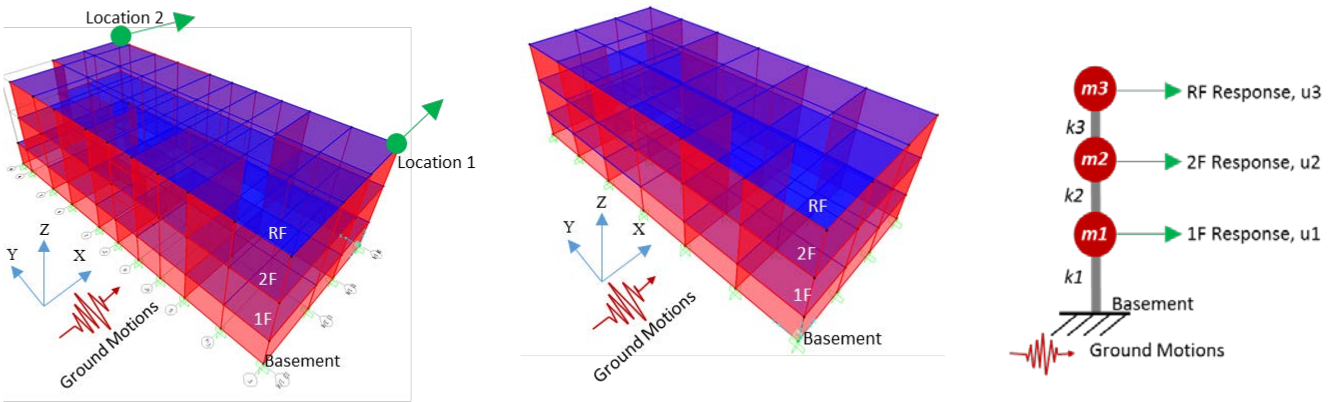
The mass and stiffness values and damping properties of auxiliary buildings are used in the analytical equation of motion shown in Eq. (1). For the damping effects of the reinforced concrete buildings, it is assumed that the damping ratio (ζ) is 0.05. For the modal analyses, the fundamental frequencies of each model are evaluated, while the seismic responses of each floor are estimated using the time history analysis through

$$M\begin{Bmatrix}\ddot{u_1}\\ \ddot{u_2}\\ \ddot{u_3}\end{Bmatrix}+C\begin{Bmatrix}\dot{u_1}\\ \dot{u_2}\\ \dot{u_3}\end{Bmatrix}+K\begin{Bmatrix}u_1\\ u_2\\ u_3\end{Bmatrix}=-Ml\ddot{u_g} \tag{1}$$

where $M=\begin{bmatrix}m1 & 0 & 0\\ 0 & m2 & 0\\ 0 & 0 & m3\end{bmatrix}$ is the mass matrix, $K=\begin{bmatrix}k1+k2 & -k2 & 0\\ -k2 & k2+k3 & -k3\\ 0 & -k3 & k3\end{bmatrix}$ is the stiffness matrix, $C=a_0M+a_0K$ is the damping matrix with $a_0=\frac{2\zeta\omega_1\omega_2}{\omega_1+\omega_2}$ and $a_1=\frac{2\zeta}{\omega_1+\omega_2}$. ω_1 and ω_2 are the first two fundamental frequencies of the structure. u_1, u_2, and u_3 represent the displacement response of each floor as shown in Fig. 4.

The 3D finite element (FE) models are analyzed using the SAP2000 software. For time history analyses of the 2D models in MATLAB, Eq. (1) is solved using the Bogachi-Shampine method [4] which is implemented in the function, *ode 23*, in MATLAB. This is a Runge–Kutta method of order three with four stages with the First Same As Last (FSAL) property, so that it uses approximately three function evaluations per time step. The solution of Eq. (1) provides: (1) the absolute acceleration responses of each floor, and (2) floor displacement responses of each floor (u_1, u_2, and u_3).

In this study, the weak axis of the building is considered for the seismic performance assessment, which is the *x*-direction of the 3D models as shown in Fig. 4. The 3D FE models of the asymmetric and symmetric buildings are shown in Fig. 4(a) and 4(b), respectively.



(a) (b) (c)

Fig. 4. Simulation Models (a) 3D Asymmetric Model (b) 3D Symmetric Model and (c) 2D Stick Models

III. DYNAMIC ANALYSIS

III.A. Modal Analysis

For the evaluation of dynamic characteristics of each model, modal analyses are conducted, and the results are summarized in Table II. Since 2D models have three horizontal degrees-of-freedom (DOFs) only, three modes and associated frequencies are determined. For the 3D models, significant frequencies in *x*-direction are selected and presented in the table and compared to the 2D results, where *SumUX* is the unitless value of cumulative modal participation factor. This variable provides the information of significant mode shapes and frequencies and their contribution to the total response. By comparing the fundamental frequencies in Table II, it is observed that the stiffness of 2D models for both asymmetric and symmetric buildings is slightly larger than that of 3D models.

TABLE II. Results of Modal Analyses

Asymmetric					Symmetric				
3D			2D		3D			2D	
Mode	SumUX	Frequency (Hz)	Mode	Frequency (Hz)	Mode	SumUX	Frequency (Hz)	Mode	Frequency (Hz)
1	0.77	16.04	1	17.35	1	0.76	16.58	1	17.85
5	0.92	41.77	2	46.64	5	0.88	43.13	2	48.52
7	0.99	49.49	3	54.11	7	1.00	51.49	3	54.96

III.B. Time History Analysis

III.B.1 Applied Ground Motion History

For the time history analysis (THA), an acceleration record of the El Centro earthquake is applied. Shown in Fig. 5, this ground motion (GM) was recorded at USGS STATION 117 during the 1940 Imperial Valley earthquake. The duration of this GM history is around 40 sec, and positive and negative peak accelerations are 0.271 g (at 2.5 sec) and -0.313 g (at 2.2 sec), respectively.

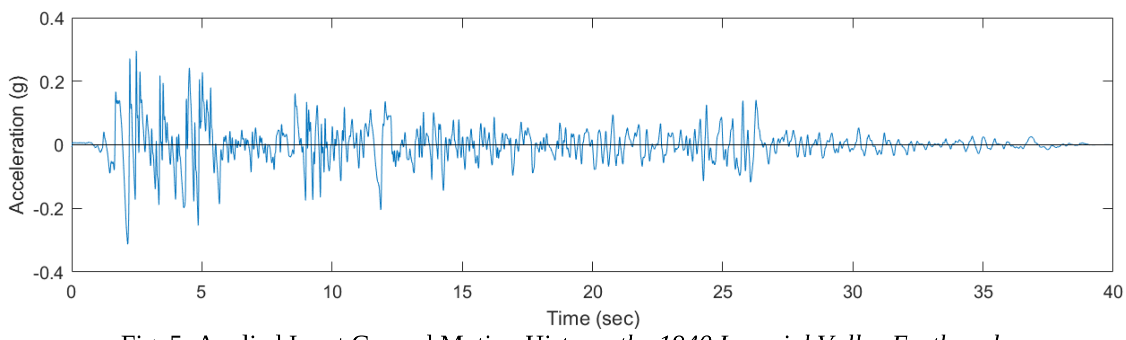
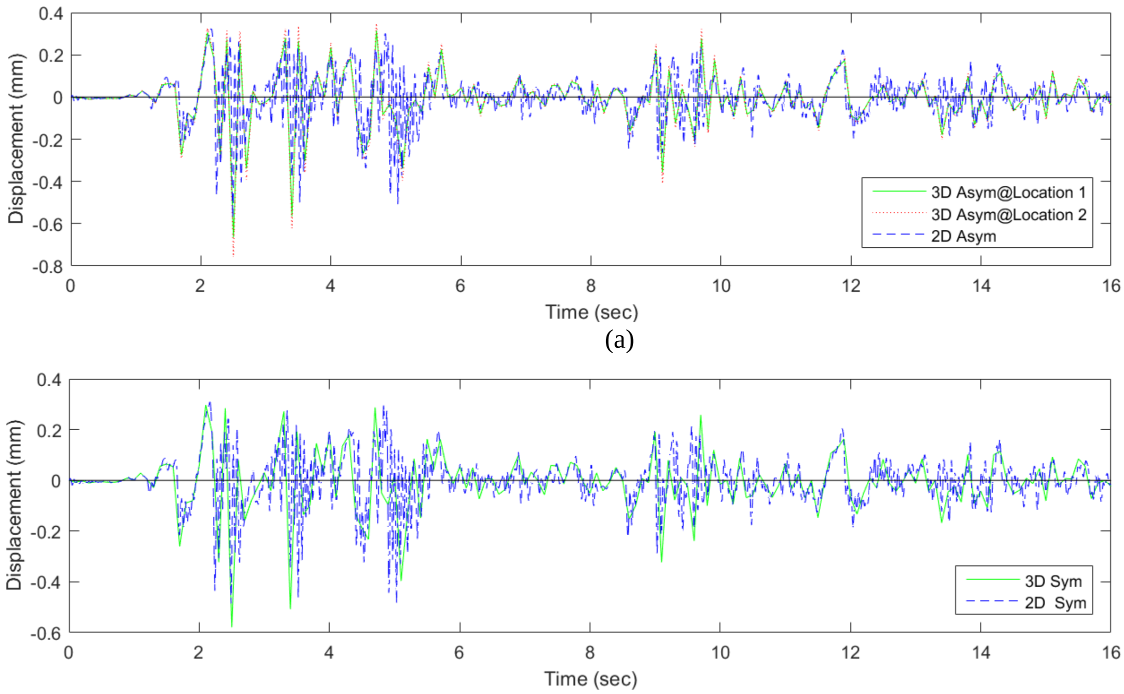


Fig. 5. Applied Input Ground Motion History: *the 1940 Imperial Valley Earthquake*

III.B.2 Displacement Responses of 3D and 2D models

Fig. 6 presents the displacement responses calculated at the roof floor of 3D and 2D models subjected to the GM history, which is presented in Fig 5. In order to capture and evaluate the response discrepancy on the same floor induced by the asymmetry, both responses at Location 1 and Location 2 on the roof of 3D model (see Fig. 4) are compared for the asymmetric 3D model. The response of the asymmetric 2D model is also added in Fig. 6. As shown in Fig. 6(a), all three responses show very close peaks at the same time (at around 2.5 sec). However, as previously discussed, the slightly lower stiffness of the 2D model generally caused a bit smaller response of the 2D model compared to 3D models. Comparison of the responses at Locations 1 and 2 shows that the displacement response at Location 2 is slightly larger than that at Location 1. This is expected due to lower lateral stiffness of the structure near Location 2 compared to Location 1.

For the symmetric 3D and 2D models, overall, the calculated displacement histories and the values of peak displacements are very close, but most peak values of the 2D model are slightly smaller than those of the 3D model during the entire time history.



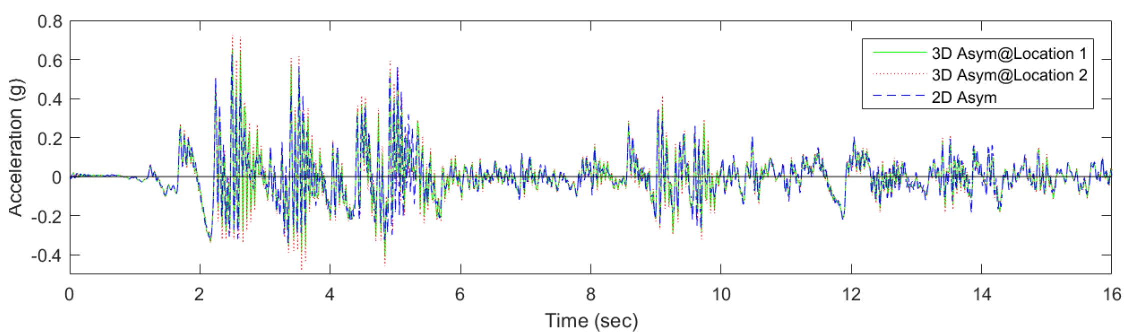
(a)

(b)

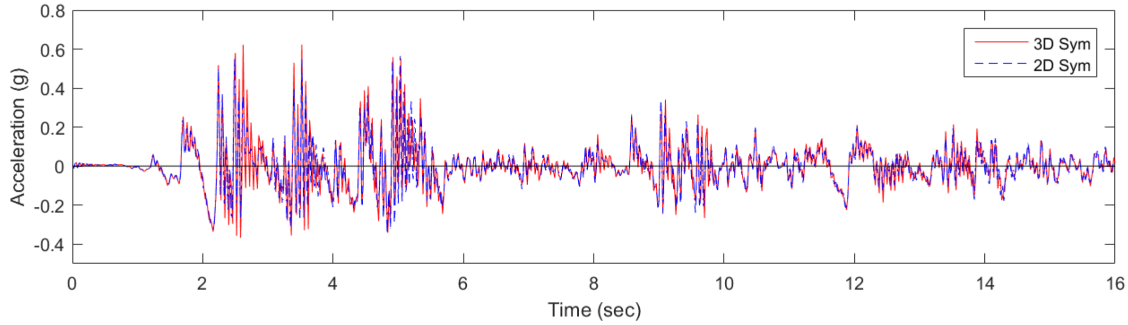
Fig. 6. Displacement Response at Roof Level: (a) Asymmetric Building, and (b) Symmetric Building

III.B.3 Absolute Acceleration Response of 3D and 2D models

Acceleration responses of structures during the time history analysis are sensitive to time steps. In this study, the same time step of 0.02 sec is applied to all 3D and 2D models. Fig. 7 presents the absolute acceleration responses at the roof level of the models. As expected, maximum values of the absolute acceleration responses are observed at Location 2 of the 3D asymmetric model. The acceleration response of the 2D model is slightly smaller than those of both asymmetric and symmetric 3D models.



(a)



(b)

Fig. 7. Absolute Acceleration Response at Roof FL: (a) Asymmetric Building, and (b) Symmetric Building

III.B.3 Comparison of the Results of all Models

Figs. 8 and 9 present the difference in calculated absolute acceleration response of the asymmetric and symmetric models. In order to show larger peaks, the response histories between 2 to 6 seconds are zoomed in. As shown in the zoomed plots, the absolute acceleration response of the symmetric model is slightly smaller than that of asymmetric model. Based on the fundamental frequencies of models, it is expected that the stiffness of symmetric models are marginally larger than that of asymmetric models.

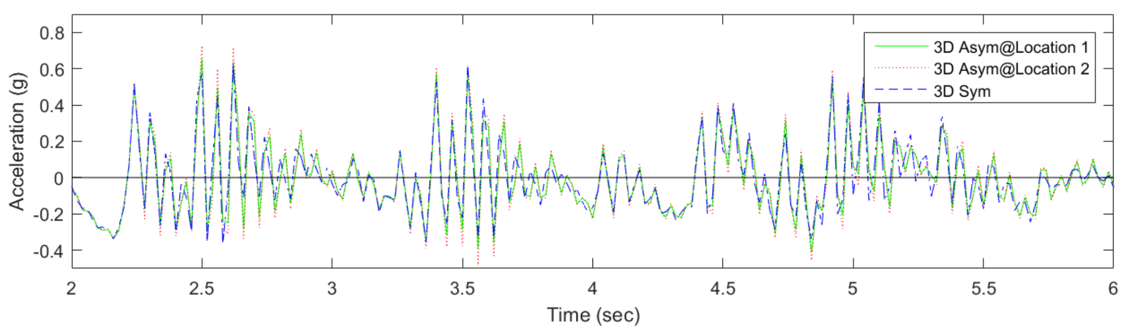


Fig. 8. Absolute Acceleration Response at Roof FL of 3D model (X-direction)

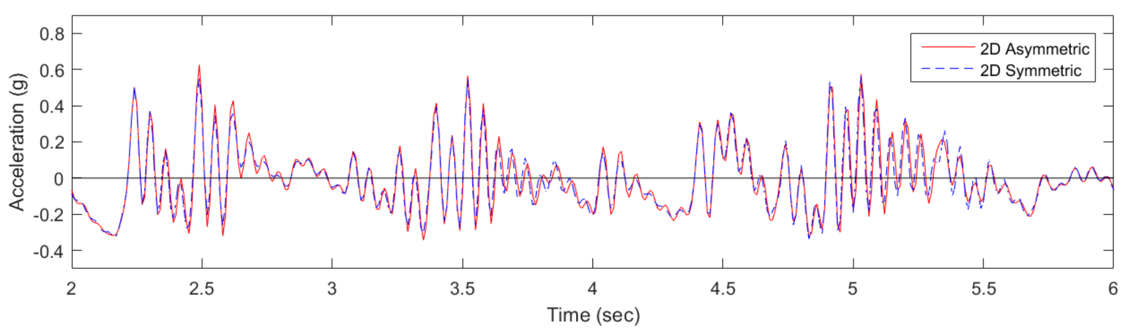


Fig. 9. Absolute Acceleration Response at Roof FL of 2D model

For the comparison of all models, the maximum values of all responses at each floor level are summarized in Tables III and IV. As asymmetric buildings easily twist under one direction (*x*-direction) of seismic loading as shown in Fig. 4, different locations on a floor have slightly different responses in the same direction. During the time history analysis, it was observed that the asymmetric model in Fig. 4(a) is slightly rotating counterclockwise under x-direction loading. Therefore, the displacement and absolute acceleration responses in Locations 1 and 2 in Fig. 4(a) are marginally different in Figs. 7 and 8. For the asymmetric 3D model, peak responses from all locations of each floor are analyzed in terms of mean, standard deviation (SD), and their coefficient of variation (c.o.v.). In addition, the differences between the maximum peaks of symmetric 2D and 3D models are computed in Tables III and IV. In Table III, the displacement response of all buildings are relatively small since the selected ground motion history is not a strong one and has a peak ground acceleration (PGA) of approximately 0.3 g.

TABLE III. Maximum Displacement in x-Direction

Displacement	Asymmetric					Symmetric		
	3D			2D	Difference (ratio)	3D	2D	Difference (ratio)
	Mean (mm)	SD (mm)	c.o.v.	(mm)	= $(3D_{Avg}-2D)/3D$	(mm)	(mm)	= (3D-2D)/3D
Roof	0.736	0.028	0.038	0.576	0.22	0.610	0.485	0.20
2nd floor	0.595	0.028	0.047	0.499	0.16	0.493	0.418	0.15
1st floor	0.191	0.019	0.100	0.170	0.11	0.149	0.133	0.11

TABLE IV. Maximum Absolute Acceleration in x-Direction

Acceleration	Asymmetric					Symmetric		
	3D			2D	Difference (ratio)	3D	2D	Difference (ratio)
	Mean (g)	SD (g)	c.o.v.	(g)	= $(3D_{Avg}-2D)/3D$	(g)	(g)	=(3D-2D)/3D
Roof	0.689	0.022	0.032	0.626	0.09	0.623	0.564	0.09
2nd floor	0.589	0.022	0.037	0.576	0.02	0.542	0.510	0.06
1st floor	0.337	0.013	0.039	0.370	-0.10	0.327	0.343	-0.05

IV. CONCLUSIONS

For the computational efficiency of SPRA, simplified structural models are necessary. This study investigates the seismic performance of an auxiliary building and attached nonstructural components using a realistic 3D, modified symmetric 3D, and simplified 2D stick models in order to capture the impacts of the simplification process of structural modeling and analysis, and hence, the uncertainty associated with the simplified models. It was observed that the seismic response of 2D models can be less conservative than the detailed 3D models. Unlike symmetric buildings, asymmetric buildings can have larger variations in their seismic response of each floor. Both displacement and absolute acceleration responses at all locations of each floor of asymmetric 3D model were found to be within 3-10% of the coefficient of variation (c.o.v.). The differences of maximum displacement responses between 3D and 2D models are around 10-20%, and those for absolute acceleration responses are around 2-10%. Therefore, the discrepancy of displacement response is larger than that of absolute acceleration response. These analyses provide better understandings of the dynamic behavior and seismic performance of auxiliary buildings using models with varying complexities. The results also help quantify the uncertainties related to simplified numerical models of structural and nonstructural components subjected to seismic shaking, and their effects on the seismic failure probabilities of these systems.

ACKNOWLEDGMENTS

This research is being performed with funding from the DOE Office of Nuclear Energy's Nuclear Energy University Programs. The support provided for the project NEUP 13-5132 is greatly acknowledged.

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