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EFFECTS OF HIGH FREQUENCY GROUND MOTION ON THE LOCAL SEISMIC RESPONSES OF SAFETY-RELATED NUCLEAR STRUCTURES

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ABSTRACT

Recent regulations and industry concerns about the high frequency (HF) content of ground motions at the Central and Eastern United States (CEUS) hard rock sites have resulted in consideration of HF ground motion for potential new construction of nuclear power plants. To this end, the Nuclear Regulatory Commission (NRC) has issued Interim Staff Guidance DC/COL-ISG-01 that provides acceptable technical approaches for addressing HF ground motion effects for new reactor seismic designs. Specifically, Section 3.1.1 of ISG-01 states that the analytical models should be adequately refined to sufficiently capture the HF content up to at least 50 Hz, and that subsequent in-structure response spectra (ISRS) should contain spectral responses up to 100 Hz.

These regulatory requirements have forced the industry to evolve from using traditional lumped-mass-stick (LMS) models that provide good characterization of the overall or global dynamic behavior of safety related buildings into implementing more refined 3D finite element (FE) models that are better able to predict not only the global but also local seismic responses within the required HF range. Such refined 3D FE models also allows the analysts to generate seismic response at any desired location within the building, though careful judgment has to be exercised to differentiate the high responses that may arise from local effects induced by the HF content of the seismic input motion from those responses that reflect the global behavior of the structure. In particular, high acceleration peaks observed in the ISRS curves within the HF range present a concern for the potential impact on sensitive equipment and non-ductile components attached at a given location.

The purpose of this paper is to investigate the effects of high frequency ground motion on the local seismic responses of safety-related nuclear structures. Numerical results are presented to illustrate the concepts and to provide guidance to the practitioners on the dynamic coupling considerations that may be needed to mitigate the local responses effects.

INTRODUCTION

In the U.S.A., safety related equipment in nuclear power plants are required to be designed such that their intended safety function will not be compromised during and after a postulated earthquake event. Because of the large scale of nuclear facility structures and the number of electrical and mechanical equipment housed in these structures, seismic performance of most equipment is evaluated in a two-step method. First, in-structure response spectra (ISRS) in two horizontal and one vertical direction are developed at various equipment-support locations from a dynamic model, including the supporting structure as well as the soil or rock on which the structure is situated. Second, the in-structure response spectra are considered as an input to the subsequent analyses of the supported equipment using dynamic analysis method or equivalent static load method (SRP Chapter 3.9.2, 2007) for the evaluation of their structural integrity and functionality.

As noted above, the first step requires the development of dynamic models that are able to capture and transmit the input ground motion so that the filtered out structural responses at the desired equipment locations could be accurately predicted. In particular, at CEUS hard rock sites the latest regulatory requirements (DC/COL-ISG-1, 2008) have impose additional criteria for developing dynamic models that need to be able to transmit the high-frequency (HF) content of the input ground motion up to at least 50 Hz and capture ISRS up to 100 Hz. Figure 1 presents an example of typical ground motion response spectrum (GMRS) with HF content at CEUS rock site, as opposed to a RG 1.60 (1973) design spectral shape. The maximum acceleration values in the HF GMRS tend to be reached in the 20-40 Hz range while the design ground spectrum shape prescribed by RG 1.60 has dominant spectral amplification in the low frequency (LF) range of 2-10 Hz.

These regulatory requirements have forced the industry to evolve from using traditional lumped-mass-stick (LMS) models to more refined three-dimensional (3D) finite element (FE) models. In contrast to LMS models, the much more refined 3D FE models are not only able to provide good characterization of the overall or global dynamic behavior, but also to predict local seismic responses that better reflect floor/wall flexibility effects. Since the frequencies associated with the out-of-plane vibrations of the floor slabs or wall panels tend to fall within the frequency range of the HF ground motion spectra, significant amplifications of seismic acceleration may be expected in the HF range which may impose additional demand on vibration sensitive electrical and/or control system components installed at these locations.

Such concerns are primarily built upon the use of the aforementioned two-step evaluation method for the secondary systems, which is based on a decoupled analysis assuming that any interaction between the primary structure and the secondary system is negligible. According to NRC SRP Chapter 3.7.2 (2007), dynamic decoupling is allowed when the total mass of the supported subsystem is less than 1% of the total mass of the supporting system. Similar statement can also be found in ASCE 4-98 (1998), i.e., dynamic coupling is not required if the total mass of the secondary system is 1% or less of the mass of the supporting primary system and if a coupled analysis will not increase the responses of the primary system over that of a decoupled analysis by more than 10%. When applying this general requirement to nuclear safety related structures, the two common problems that the engineers are facing are: (1) what is the definition of the mass of the supporting primary system? Does it denote the total or partial mass of the supporting floor/wall panel where the secondary system is situated or the total mass of the entire floor or wall, or entire primary system? (2) While the criteria allow decoupled analysis as long as the difference in the responses of the primary system between a decoupled and coupled analysis is less than 10%, what is the impact on the response of the secondary system?

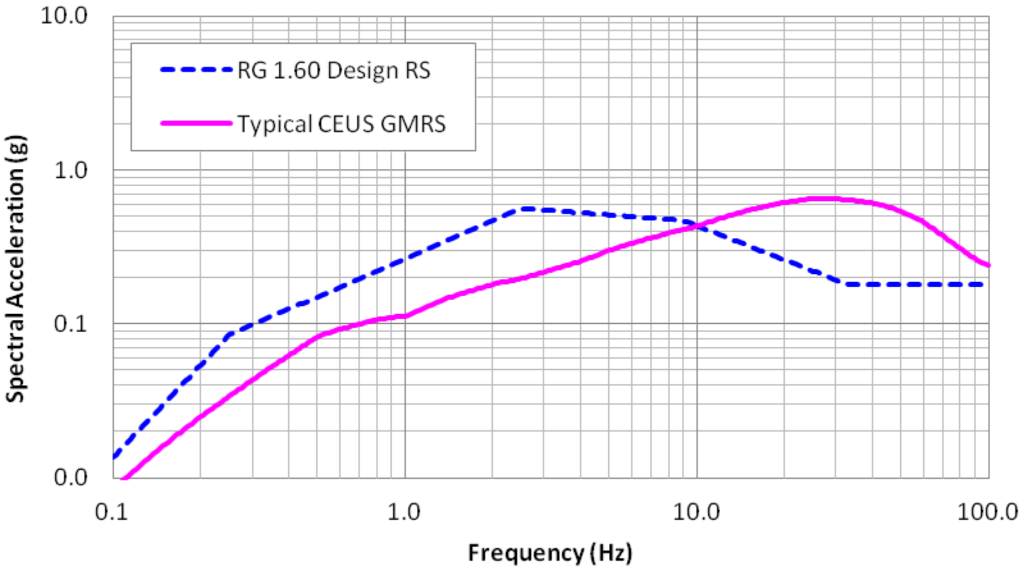


Figure 1: Typical CEUS site specific GMRS vs. RG 1.60 design spectral shape

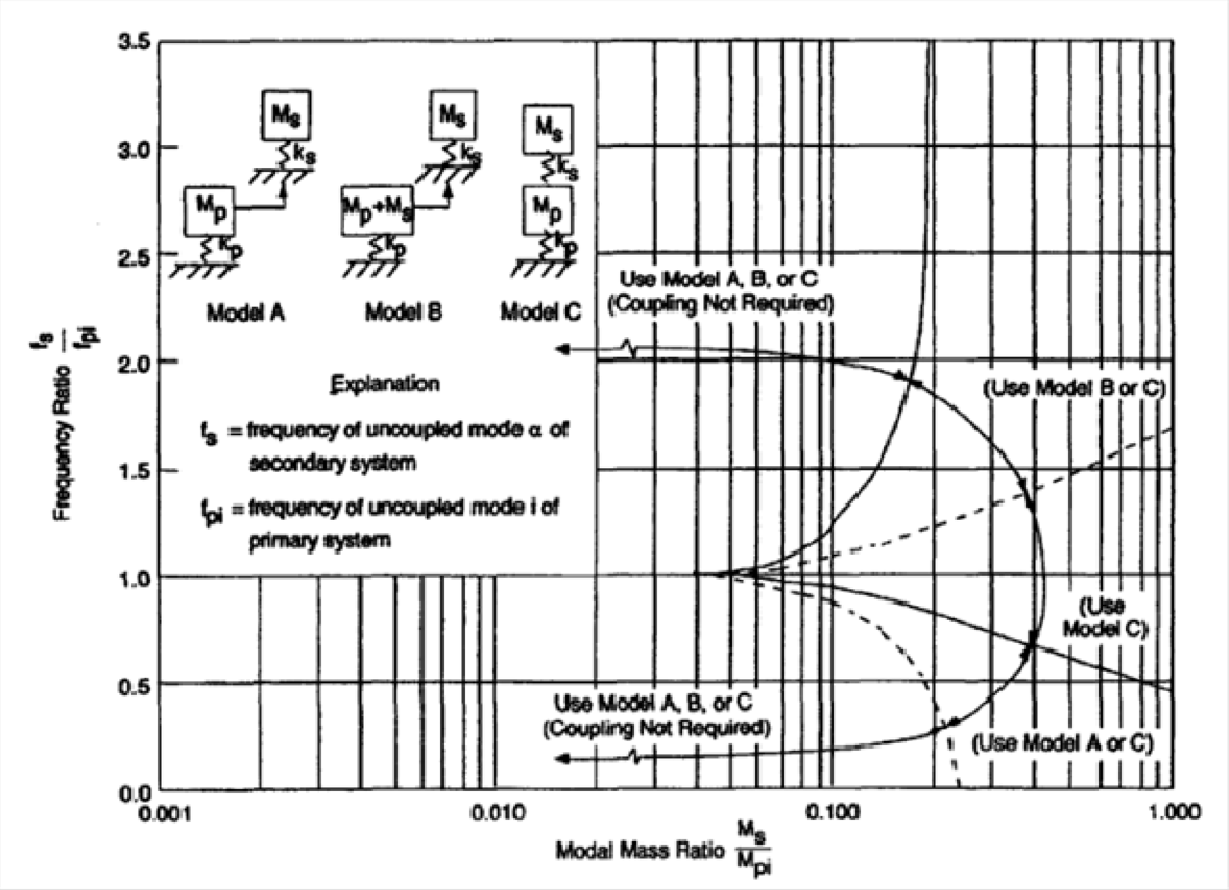


Figure 2: Decoupling criteria for secondary systems with single-point attachment to the primary system (excerpted from ASCE 4-98 Figure 3.1-2)

For the secondary systems with single-point attachment to the supporting structure, ASCE 4-98 (1998) provides some guidance for addressing the questions above. As shown in Figure 2 (excerpted from ASCE 4-98 Figure 3.1-2), dynamic interaction between the primary structure and the secondary system is closely related to the ratios between modal masses and frequencies. The modal mass ratio denotes the ratio of the total mass M_s of the secondary system and the modal mass M_{pi} of the primary structure mode *i* and the frequency ratio denotes the ratio of the uncoupled modal frequencies of the secondary system f_s and the *i* mode of the primary systems f_{pi}, respectively.

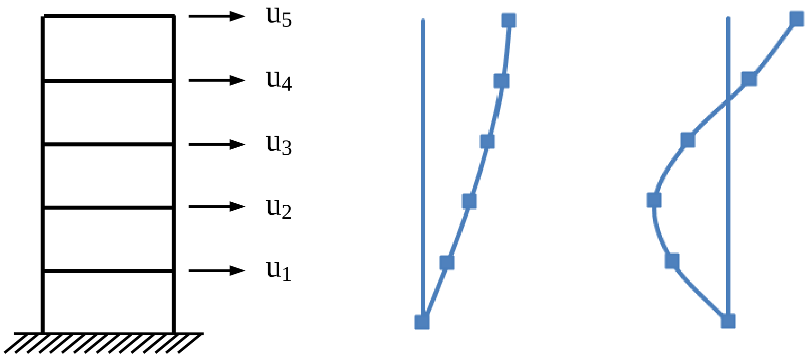
Since the ISRS peaks within HF range usually correspond to local vibrations of slab and/or wall panels in the supporting structure, the modal mass associated with these modes is often relatively small. Therefore, it is expected that any interaction between the primary and secondary systems would be very sensitive to the existence of equipment with even small self-weight. Consequently, decoupled analysis may lead to a considerable overestimation of the estimated demand for the secondary system in the subsequent seismic evaluation.

In this paper, a parametric study is performed to investigate the effect of mass perturbation on the interaction effects between the primary and secondary system, with a focus on the response of the secondary systems. A case study on a cellular box-type reinforced concrete structure, which is typical in nuclear power plants, is also discussed.

PARAMETRIC STUDY ON A 5-DOF SYSTEM

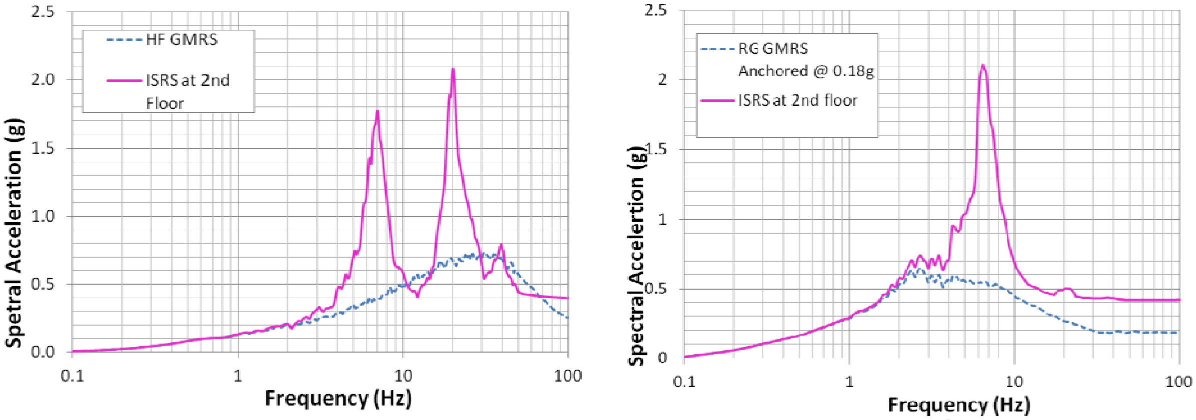
A five-story uniform shear building is used in the parametric study, as depicted in Figure 3. The weight of each floor is 315 kip with the total mass of the system equal to 1,575 kip (=315 kip x 5). The modal frequencies and associated mass participation are listed in Table 1 and the mode shapes of the first two modes are shown in Figure 3.

The system is subject to both the HF (hard rock site) and LF (RG 1.60) input ground motions of Figure 1, with the ISRS responses reported at the second floor in Figure 4. One major peak is present in the ISRS curve corresponding to the LF input motion of Figure 4b. In contrast, two peaks with significant amplifications are observed in the ISRS curve from the HF ground motion of Figure 4a, with the higher peak corresponding to the second mode of the system. Although the modal mass associated with the second mode is far less than that of the first mode, the spectral acceleration at the frequency of the second mode have higher amplification, due to the fact that the second frequency falls within the dominant frequency range of the input HF ground motion.



5- DOF System Mode 1 Mode 2

Figure 3: 5-DOF system with the first two mode shapes



(a) (b)

Figure 4: ISRS at the 2nd floor when the system is subject to (a) HF GMRS (b) LF GMRS

Table 1: Frequencies and mass participation

Mode No.	**Frequency (Hz)**	**Mass Participation (%)**
1	6.852	87.95
2	20.000	8.72
3	31.528	2.42
4	40.502	0.75
5	46.195	0.16

In the following parametric study, the sensitivity of the spectral acceleration to the modal mass ratio between the secondary and primary systems is investigated using the 5 degree-of-freedom (DOF) system. The study assumes that safety related equipment is located at the second floor with single attachment and that the system is subject to a ground motion with HF content. To investigate the effects of dynamic interaction on the ISRS response, the secondary system is located at the 2nd floor and tuned to the first and second modes of the primary system, respectively. Specifically, five cases are considered as follows:

(1) Case 1: The equipment has a mass equal to 10% of the modal mass of the 1st mode of the primary system, i.e., 138.6 kip.

Case 1A: Decoupled analysis is conducted by having the self-weight of the secondary system lumped at the 2nd floor without consideration of the equipment stiffness;

Case 1B: Coupled analysis is conducted with the fundamental frequency of the secondary system tuned to the frequency of the 1st mode for the building;

(2) Case 2: The equipment has a mass equal to 10% of the modal mass of the 2nd mode of the primary system, i.e., 13.7 kip.

Case 2A: Decoupled analysis is conducted by having the self-weight of the secondary system lumped at the 2nd floor without consideration of the equipment stiffness;

Case 2B: Coupled analysis is conducted with the fundamental frequency of the secondary system tuned to the frequency of the 1st mode for the building;

Case 2C: Coupled analysis is conducted with the fundamental frequency of the secondary system tuned to the frequency of the 2nd mode for the building;

Table 2 lists the modal frequencies of all five test cases considered in the parametric study with the benchmark case representing the modal frequencies of the decoupled primary system (with no equipment attached). The maximum acceleration in the secondary system as well as the 2nd floor ISRS curves are summarized in Table 3 and Figures 5 & 6, respectively. Note that the maximum acceleration from the decoupled analysis is measured from the ISRS curve at the 2nd floor at the uncoupled modal frequency of the secondary system. The maximum acceleration from the coupled analysis is measured directly at the secondary system from the coupled analysis.

For Case 1, the dynamic characteristics of the primary-secondary system are affected due to the relatively heavy weight of the equipment attached to the 2nd floor. Significant frequency shift is observed for Case 1B as shown in Column 4 of Table 2. It is also observed that the maximum acceleration measured from the coupled analysis (Case 1B) is reduced by 53% of the estimated value from the decoupled analysis (Case 1A).

For Case 2 in which the weight of the equipment attached to the 2nd floor is 10% of the modal mass associated with the 2nd mode of the uncoupled primary system, it is observed that the frequency shift between decoupled and coupled systems is less pronounced (see Column 5 through 7 in Table 2). The comparison of the maximum acceleration of the secondary system shows that the decoupled analysis (Case 2A) is able to provide reasonable prediction on the responses of the coupled system even after having the secondary system tuned to the 1st mode of the primary system, since the mass ratio between the modal mass of secondary system and of primary system mode 1 is small (less than 1%). However, when the frequency of the equipment is tuned to the 2nd frequency of the supporting structure, significant reduction in the maximum acceleration of the equipment can be obtained from the coupled analysis (Case 2C), with a reduction of 35% from the decoupled analysis value (Case 2A).

The parametric study above shows that higher frequencies of the structure could be excited by the HF content of the input ground motions. As a result, high peaks are present in the ISRS curves within the HF range. Due to the typically low modal mass associated with these higher modes, the dynamic interaction between the primary structure and secondary system may become more important even for relatively lighter equipment. Therefore, a coupled analysis could lead to a significant reduction in the amplitude of ISRS responses in the HF range and remove some of the overestimation from the decoupled analysis results.

Table 2: Frequencies for cases considered in the parametric study

Mode No.	Benchmark	Case 1A	Case 1B	Case 2A	Case 2B	Case 2C
1	6.852	6.693	6.114	6.836	6.618	6.834
2	20.000	18.593	7.576	19.847	7.084	18.791
3	31.528	31.342	20.206	31.509	20.021	21.271
4	40.502	38.746	31.538	40.318	31.529	31.542
5	46.195	44.579	40.557	45.914	40.508	40.561
6			46.265		46.202	46.266

Table 3: Maximum acceleration of the secondary system

Case No.	Decoupled (g)	Coupled (g)	Reduction
1A & 1B	1.8	0.8	53%
2A & 2B	1.7	1.5	14%
2A & 2C	2.1	1.3	35%

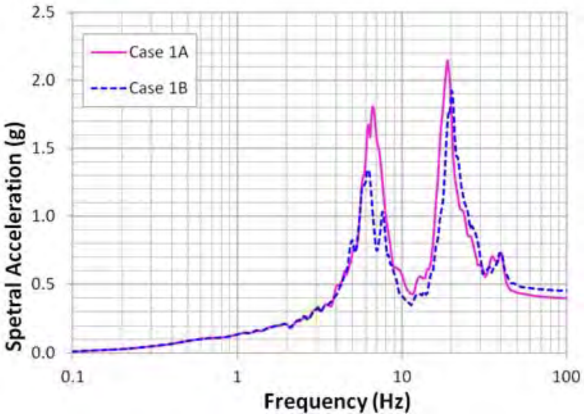
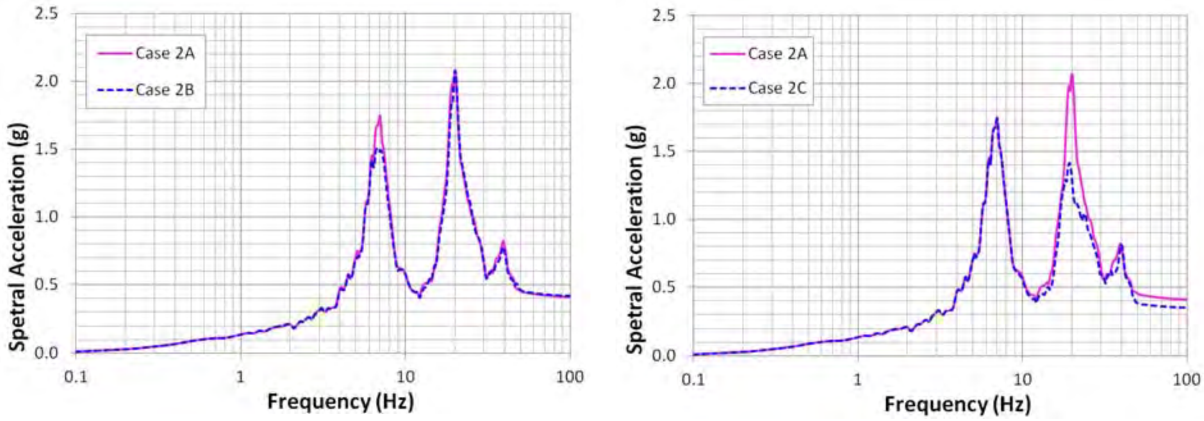


Figure 5: ISRS measured at the 2nd floor for Case 1A & 1B



(a) Case 2A & 2B

(b) Case 2A & 2C

Figure 6: ISRS measured at the 2nd floor

CASE STUDY

This section presents a case study which utilizes a full size model of a representative nuclear power plant structure subject to HF input ground motion. The subject structure is a cellular box-type reinforced concrete structure founded on bedrock at a CEUS hard rock site, with thicknesses of slab and/or wall panels ranging from 1 to 3 feet. A detailed 3D FE model is constructed (see Figure 7) and time history analyses are performed using software package ANSYS version 13.0 (ANSYS, 2010). The time history records match the HF GMRS shown in Figure 1 with a time step of 0.001 sec per guidelines presented in Moreschi et al. (2012). The concrete floor slabs and walls are modeled using ANSYS element type SHELL181, which has both bending and membrane capabilities and are suitable for analyzing thin to moderately-thick shell structures. Beams and columns are modeled with element type BEAM188. Fixed-base boundary condition is assumed, resulting in fundamental (global) frequencies in the 6 to 8 Hz range along the horizontal directions and above 15 Hz in the vertical direction.

The parametric study on an idealized MDOF system presented in the previous section indicated that the interaction between the secondary system and supporting structure at higher frequencies could be more sensitive even to small mass perturbations. The purpose of this case study is to investigate the impact of relatively light equipment on the seismic responses of the primary and secondary systems in the HF range on a nuclear structure.

To this end, consider a piece of equipment that is located at the center of a slab weighting 250 kips (as shown in Figure 7) and tuned to the local first frequency of the slab of about 20 Hz. First, a decoupled analysis denoted as Case 1 is performed for the primary structure without consideration of the mass and stiffness contribution of the equipment. Second, coupled analyses are performed in which the equipment is explicitly modeled as a mass-spring system and three sub-cases are considered for varying weights of the equipment:

1. Case 2A: 10% of the self-weight of the supporting floor slab of the room, i.e., 25 kip;
2. Case 2B: 5% of the self-weight of the supporting floor slab of the room, i.e., 12.5 kip;
3. Case 2C: 1% of the self-weight of the supporting floor slab of the room, i.e., 2.5 kip.

The maximum vertical acceleration in the secondary system from all three test cases is summarized in Table 4. The ISRS results due to vertical input ground motion only (i.e., vertical response due to vertical input motion) are reported at the center as well as one corner of the supporting slab. The response at the center represents the local vibration of the slab, while the response at the corner, which is at the intersection of major shear walls and floor slab, represents the global behavior of the structure.

As indicated in Table 4, significant overestimation in the seismic response of the secondary equipment is observed in all three cases. When the equipment is about 10% of the self-weight of the room slab (Case 2A), the maximum acceleration from the coupled analysis is reduced by 71% of the result predicted by the decoupled analysis. Even in the presence of relatively light equipment (Case 2C), the coupled analysis leads to a 31% reduction in the seismic demand of the equipment.

In addition, comparison of the ISRS curves (Figure 8) shows that seismic responses at the center of the slab are dominated by the out-of-plane vibrations of the floor and therefore are sensitive to the mass perturbation of the supported equipment. Coupled analysis tends to reduce the spectral responses at this location since the coupled model seems to behave as a tuned mass-damper system. On the other hand, the ISRS at the corner of the slab mainly reflect the global dynamic behaviors of the primary system and thus remain almost unchanged for all the test cases.

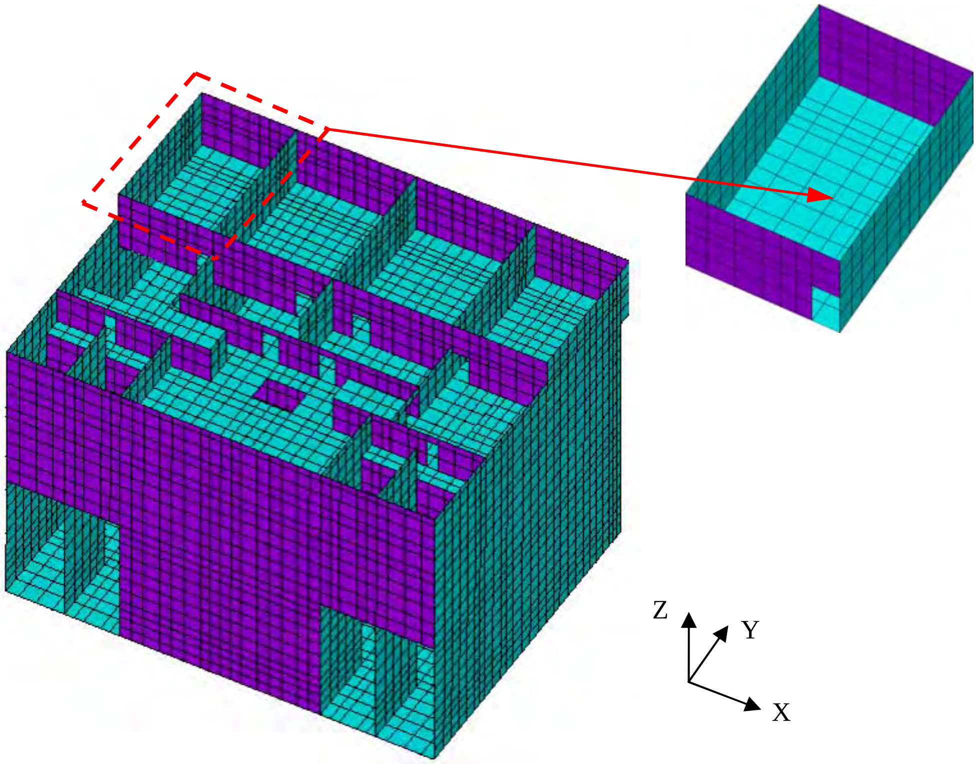
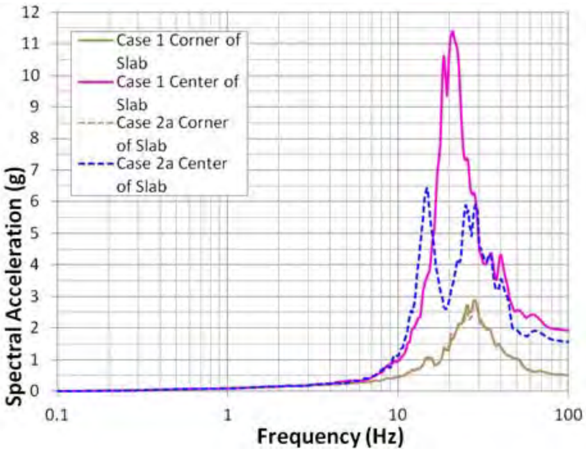


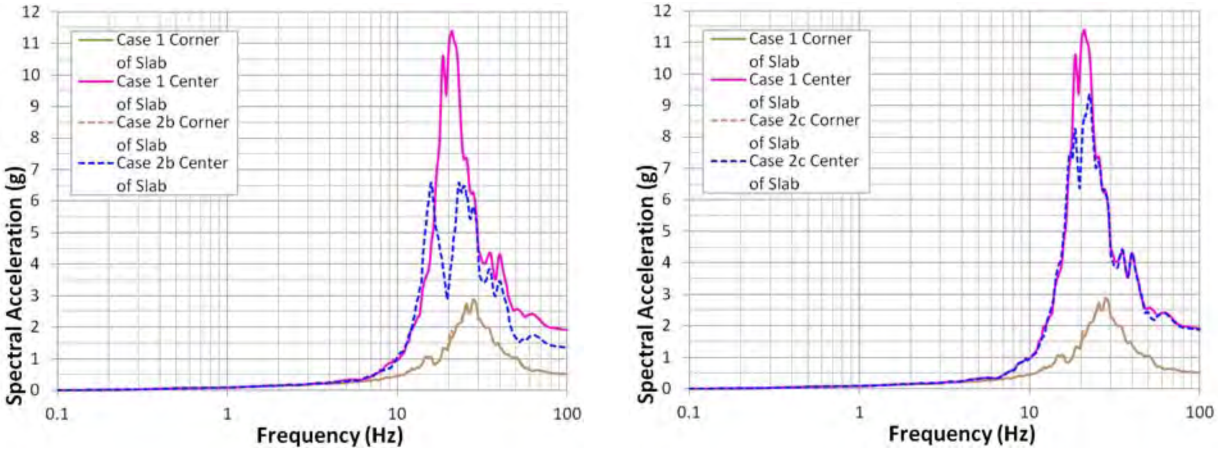
Figure 7: FE model of a representative structure with the slab of interest highlighted

Table 4: Maximum acceleration of the secondary system

Case No.	Decoupled (g)	Coupled (g)	Reduction
2A	10.7	3.1	71%
2B	10.7	3.4	68%
2C	10.7	7.4	31%



(a) Case 1 & 2A



(b) Case 1 & 2B

(c) Case 1 & 2C

Figure 8: ISRS measured at one corner and the center of the floor slab in the room of interest

CONCLUSION

High spectral acceleration peaks in the HF range are observed in the ISRS curves of the structures considered in this paper when subject to input ground motion with HF content. These peaks are usually associated with local responses of the structure, such as the out-of-plane vibration of floor slabs and/or wall panels. Inspection of results from a parametric study of an idealized MDOF system indicates that the dynamic coupling between the primary and secondary systems can be very sensitive at high frequencies even to a small mass perturbation. Therefore the dynamic coupling consideration can lead to significant reduction in the estimation of the accelerations of the secondary system, even for relatively lighter equipment. The same concepts are then examined for a representative nuclear structure in the case study. It is concluded that the dynamic coupling consideration may play an important role in the mitigation of the observed high local responses in the HF range.

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