SEISMIC RESPONSE ANALYSIS FOR RAISED ACCESS FLOOR AND COMPUTER EQUIPMENT SYSTEMS CONSIDERING VERTICAL GROUND MOTIONS

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ABSTRACT

The damage and failure of computer equipment typically supported by raised access floors in critical data processing facilities could have serious safety and economic implications. Current design provisions provide general guidance on how to estimate the seismic demand on non-structural elements within a structure. However, the possible lack of conservatism is of particular concern at locations near active faults where the vertical ground motion components have high amplitudes. Through reduced-order simplified modeling of a frame building and its raised access floors and computer equipment, findings are presented on the insufficiencies of current industrial spectra considering a suite of risk-targeted ground motions with both vertical and horizontal components. Excessive seismic axial force demands are found for both access floors and computer equipment. This investigation concludes that caution should be taken for seismic qualification and design of raised access floor and computer equipment systems considering vertical ground motions.

BACKGROUND

The continuous and proper function of uninterrupted power supply systems, computer servers and other types of data processing equipment that are often supported by raised access floors (RAFs) is undeniably important (Sharpe and Olson,1988; Tajirian, 2009). For example, modern disaster rescue and relief efforts rely heavily on rapid information processing that is performed in data processing equipment mounted on RAFs; in such cases, it is absolutely imperative that both the RAFs and the supported equipment are properly designed to remain functional following an earthquake. Similarly, critical military installations depend on reliable communications to function for the sake of national security. From another perspective, an ever-increasing amount of commerce and finance activities depend on cloud-computing services housed within large data centers around the world. As such, the downtime or failure of computer equipment may lead to catastrophic impact on the aforementioned critical activities.

The current design provisions in ASCE 7-10 outline a general approach for determining the lateral and vertical seismic demands on general non-structural components (NSCs) within a building that depends on a number of factors including the height of attachment within the building (Section 13.3.1) and risk-targeted spectral demands. In addition, ASCE 7 provides limited guidance on designing and installing RAFs by defining a “special access floor” that must meet certain material and anchorage criteria (Section 13.5.7.2). One design advantage of specifying a special access floor is the assumed increase in ductility and subsequent increase in response modification factor (R_p) used for design, from 1.5 to 2.5 (ASHRAE, 2007). Of particular interest is that the magnitude of the vertical demand is assumed to be a 20% of the lateral peak spectral demand at short periods (S_{DS}) applied up or down as shown in ASCE 7-10 Equation 12.14-6.

$$E_v = 0.2\ S_{DS}\ W_p \qquad \textbf{Eq. 1}$$

where S_{DS} is the design spectral demand at the short period and Wp is the operational weight of the NSC.

Several types of required response spectra (RRS) for NSCs have been developed as guidelines for seismic qualification of different categories of NSCs. The widely accepted spectra are found in ICC-ES AC156 (ICC, 2010). The AC156 spectra are developed in accordance with the IBC-2009 design code, which are parametric in that they are a function of S_{DS} and the relative vertical location of the NSC (z / h). Another standard that is widely used for telecommunications equipment is the GR-63-CORE spectra given in the Telecordia Network Equipment Building System (NEBS) Requirements (NEBS, 2006). Different spectra profiles are developed based on the outdated categorization of seismic zones. For computer servers installed in rack frames, IBM has developed a suite of spectra at two seismic or vibration levels (Level 1 and 2). Regarding developing vertical RRS, the general approach is to take the spectral ordinates (Z-direction) as 2/3 of the horizontal ordinates (X or Y-direction). This approach is based on a widely accepted assumption that the ratio of vertical to horizontal peak ground motions (V/H ratio) can be conservatively taken as 2/3, although many studies have shown that the V/H ratio is very sensitive to the spectral period and the distance from the fault (e.g. Bozorgnia and Campbell, 2004).

The following pressing technical and practical reasons are recognized for investigating the effects of combined horizontal and vertical seismic inputs to RAFs and supported computer equipment (CE) and the associated design spectra for such systems. First, as the need of data centers and other telecommunication centers grows immensely, some of these critical facilities will be unavoidably constructed on sites that are relatively close (within 10 miles) to seismic faults (e.g. in the LA basin). These potential near-fault ground motions tend to have much higher vertical components than motions that are farther from the source. Bozorgnia et al. (1995) found that at short periods, the ratio can exceed 2/3 in the near-fault regions and even reach unity or higher, and suggested that these characteristics are universal. As observed in recent earthquakes, (e.g. the Christchurch, NZ earthquakes), the vertical component of near-fault ground motions can often exceed the magnitude of the horizontal components. Compounding the issue is the fact that near-fault ground motions typically have higher frequency content than other motions due to the attenuation characteristics of P-waves (Papazoglou and Elnashai, 1996). Considering the inherent higher modal frequency of most building's vertical systems, it is possible that the resulting in-structure response motions may render even higher V/H ratios as inputs to NSCs after the amplification of horizontal and vertical ground shaking with in buildings.

Second, FEMA E-74 (Section 6.5.3.1) summarizes the typical causes of seismic damage to RAFs and supported equipment including, i) access floors may collapse due to insufficient bracing or weak anchorage, and ii) supported equipment may slide due to insufficient anchorage. It can be seen that the potential damage to RAFs and supported equipment is directly linked to the anchorage design and construction at the interface of RAFs to building floors and RAFs to computer equipment. This requires a thorough investigation of the force demands at these interfaces, including axial forces, shear forces and moments induced by both vertical and horizontal response accelerations.

In summary, as building codes and performance-based design methodologies advance in practice, buildings are being engineered to resist earthquakes at specific risk levels with due consideration of either near-fault or ordinary ground motions. However, there exists a significant discrepancy between the developments in the seismic design of buildings compared to their enveloped NSCs. The intent of this investigation is to highlight the importance of properly considering vertical earthquake motions for the analysis of a generic RAF-CE system. Through numerical modeling of a building system and a coupled RAF-CE system, the resulting in-structure response spectra are examined and correlated to seismic intensities and key RAF-CE demands. Design recommendations and future research needs are suggested.

RELATED WORK

Although the Building Seismic Safety Council has identified raised floors as a critical level research priority (NIST, 2003) stating the significance of developing consequence functions, preliminary investigation indicates that manufacturers of access floors have not yet invested in the research to fully characterize the dynamic behavior of their products under typical loading situations. Perhaps a lack of demand from the engineering and design community has played a role in this information gap. A survey of relevant research literature indicates that relatively little has been done to investigate the dynamic behavior of RAF-CE systems, and even less has specifically focused on the effects of vertical ground motions on either RAFs or CEs. Wong & Tso (1991) examined spectra and compared the GR-63-CORE spectra with response from an analytical model subjected to synthetic time histories, and concluded that the NEBS floor response spectra criteria must be extended to include the amplification effects due to access floors. Pekcan et al. (2003) studied vertical and horizontal floor responses resulting from two numerical concrete building models and compared to the GR-63-CORE spectra, concluding that especially for the vertical spectra at higher frequency ranges (> 10 Hz), the GR-63-CORE spectra are not conservative. However, this paper did not focus on modeling RAF-CE systems but with a general interest in rigid or flexible NSCs and their rocking behavior.

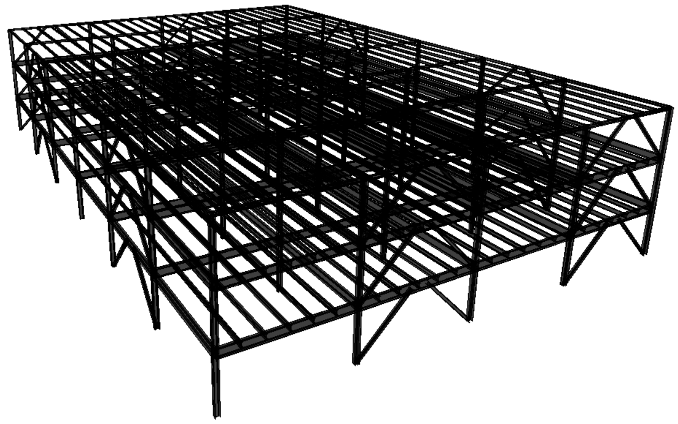
Lambrou and Constantinou (1994) described the testing of an RAF-CE system on a tri-axial shake table. The test results separate out the effects of the vertical component for comparison, but the marginal effects of considering vertical motions appear to be limited. Closer examination of the test arrangement reveals that it was not necessarily intended to accurately capture the vertical dynamic characteristics of an RAF-CE system installed in a building. Specifically, the maximum span length of the supporting beams is 10 feet, and only a single server rack is included. Additional weight to account for other servers is lumped at the column locations. As a result, further investigation into the vertical behavior of a typical installed AF-CE system is merited. Nonetheless, this report provided insightful information on dynamic parameters of both the RAFs and the CE including horizontal modal frequencies, damping ratios, and the observed nonlinearities within rack frames and computers.

ANALYTICAL MODELING

Prototype Building

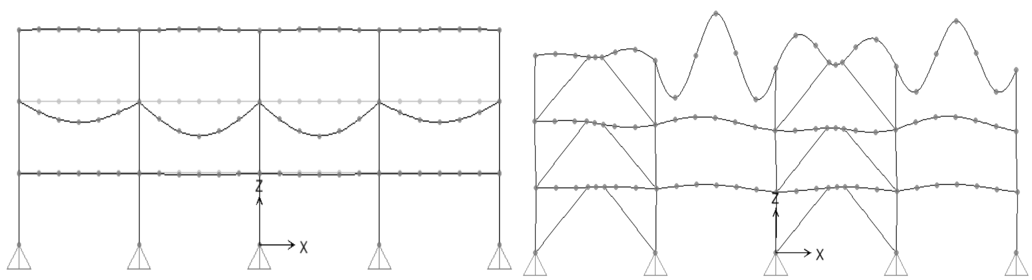
A three story eccentrically braced frame (EBF) steel building similar to that described in Gupta & Krawinkler (1999) was selected to represent a typical building in which an RAF-CE system might be installed. For this study, the RAF-CE system was assumed to be located on the second floor of the building. Ganuza (2006) re-designed this building system based on a newer seismic standard (NEHRP's Recommended Provisions; BSSC, 2004). SAP2000 was used to create a 3-D model of the structure, and Figure 1 shows an isometric view of the 3-D SAP model. Although key dynamic and ductility parameters are provided, it is recognized that evaluating the seismic performance of RAF-CE systems requires critical information that is lacking, namely (1) the vertical stiffness and modal frequency of the building under consideration, and (2) the potential spatial variability of the vertical component of the floor level response. Technical difficulties exist in achieving these two modeling objectives, so certain modeling assumptions were made. Liberty was taken to provide stiffened beams to account for composite beam-slab action in order to more accurately characterize the building's vertical stiffness.

Figure 1 - Isometric view of the SAP2000 model for the 3-story EBF building



A modal analysis was performed to determine its fundamental lateral and vertical periods. Rather than lumping seismic mass at beam-column intersections as is commonly done in dynamic analysis of buildings, a uniform dead load of 97 psf was applied over the entire floor area and distributed to each floor beam based on tributary area, which further serves as distributed seismic mass for the model. This dead load results in modal results that closely match those reported in Ganuza (2006). Non-linear hinges were placed at the EBF links and a push-over analysis was conducted on the SAP2000 model to determine the non-linear performance characteristics of the structure. The fundamental horizontal period of the building as determined from a modal analysis is T_1 = 0.73 seconds. Since out-of-plane floor behavior varies greatly as a function of loading, span length, boundary conditions, construction materials, beam/slab depth, etc., a reasonable approximation is deemed appropriate for this study. Two mode shapes from the 3-D modal analysis are shown below in Figure 2(a) and (b). Figure 2(a) illustrates an example of local floor behavior, which is relatively flexible at about 3 Hz, and Figure 2(b) represents a more global vertical behavior of the entire structure, which is more rigid at about 11 Hz. It is noted that both modes have significant mass participation in the vertical direction, implying that at the 2nd story floor, one expects to see spatial variability of floor-level vertical response.

Figure 2 - (a) Vertical local mode, 3 Hz; (b) vertical global mode, 11 Hz.



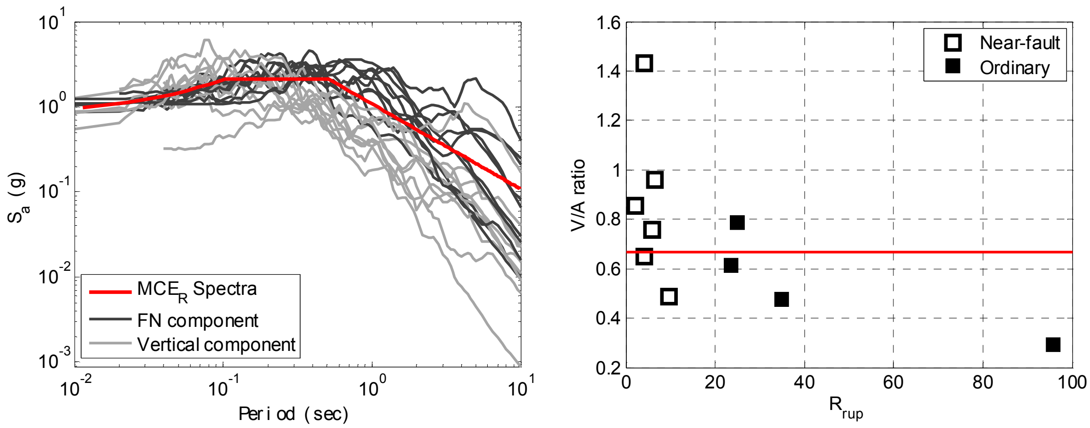
Design Spectra and Ground Motions

Site conditions for the prototype building match those described in Ganuza, which follows the 2003 NEHRP Recommended Provisions for a Site Class "D" location in Los Angeles (high seismicity). The mapped spectral parameters for the risk-targeted maximum considered earthquake (MCE_R) level event are S_{MS} = 2.11g and S_{M1} = 1.08g. Ten of the twelve MCE_R-level ground motion records listed in Ganuza's thesis were selected from the PEER Strong Ground Motion Database and scaled to match the design spectrum (Table 1). Six of these events are considered near fault ground motions, and four are 'ordinary' motions. In lieu of scaling at T_1 only, the horizontal ground motions were scaled to match the MCE_R spectra in the period range of 0.2 T_1 to 1.5 T_1, following the new guidance in ASCE 7-10. The vertical ground motions were scaled using the same factor. Figure 3(a) shows a graphical comparison of the scaled time history records with the MCE_R spectra, confirming that they are scaled properly in the period range specified. Figure 3(b) offers another characterization in which the V/H ratios are plotted against the recording locations to the ruptures. This confirms the observation that for near-fault motions, the V/H ratio is usually larger 2/3.

Table 1 - Information for the selected ground motions

NGA #	Event	Year	Recording Station	Mag.	R_{rup} (km)	Scale Factor	PGA-X (g)	PGA-Z (g)	S_a-X (g) T_1=0.73 s	S_a-Z (g) T_1=0.09 s
143	Tabas- Iran	1978	Tabas	7.35	2.0	1.19	0.81	0.69	1.48	1.17
180	Imperial Valley-06	1979	El Centro Array #5	6.53	4.0	2.28	0.38	0.54	1.48	3.28
529	N. Palm Springs	1986	North Palm Springs	6.06	4.0	1.83	0.67	0.43	1.48	2.36
765	Loma Prieta	1989	Gilroy Array #1	6.93	9.6	2.46	0.43	0.21	1.48	1.63
838	Landers	1992	Barstow	7.28	34.9	9.80	0.14	0.07	1.48	0.93
900	Landers	1992	Yermo Fire Station	7.28	23.6	5.02	0.22	0.14	1.48	1.01
1044	Northridge-01	1994	Newhall Fire Station	6.69	5.9	1.57	0.72	0.55	1.48	0.81
1063	Northridge-01	1994	Rinaldi Receiving Sta	6.69	6.5	1.65	0.87	0.83	1.48	1.52
1105	Kobe- Japan	1995	HIK	6.9	95.7	7.90	0.13	0.04	1.48	0.23
1180	Chi-Chi-Taiwan	1999	CHY002	7.62	25.0	9.20	0.12	0.09	1.48	2.75

Figure 3 - (a) Spectral plots of MCE_R spectrum and spectra of scaled ground motions; (b) plots of V/H ratios against the distance to the rupture surface (R_{rup})

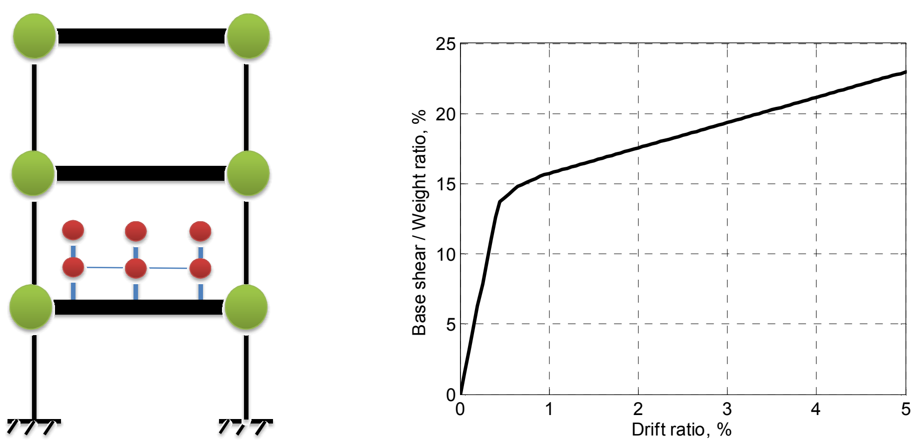


Reduced-Order Modeling

After determining the building's generalized mass and non-linear stiffness properties from the SAP2000 model, a 2-D reduced-order model was developed using OpenSees (http://opensees.berkeley.edu). The benefits of using a reduced order model include rapid simulation, easy parametric tuning and efficiency in summarizing in-structure response and nonstructural demands. The fundamental lateral period of the building was taken as T_{1H} = 0.73 seconds. The vertical fundamental period was assessed at two locations on the second floor level representing the upper and lower bounds of possible responses; T_{1V} = 0.09 seconds at a column and T_{2V} = 0.30 seconds at mid-span of a secondary floor beam.

Figure 4a illustrates this model, which is treated a single bay of the original four-bay frame, and the height of stories are identical to the original stories. Three arrays of RAF-CEs are shown as three lumped mass 2-DOF systems. The building system is modeled as a shear building system, in which the floor is assumed to be infinitely rigid and no rotational displacement at the floor level is allowed. Non-linearity is considered by using force-based inelastic beam elements for the columns. The lateral yield drift ratio at the roof level is 0.5% with a base shear-weight ratio of 14% (Figure 4b). The building is expected to yield under both design basis earthquake (DBE) and MCE level ground motions. Eigenvalue analysis indicates that the post-yield fundamental lateral period is 1.52 seconds.

Figure 4 - Reduced-order model: (a) buidling and RAF-CE system, and (b) building push-over curve.



(a) (b)

The following items impose significant challenges in characterizing the dynamic behavior of an RAF-CE system. (1) RAFs are multi-support systems with large degrees of spatial variability and consequently are subject to variable floor response input motions. (2) Although it is appropriate to assume linear elastic behavior of the computer equipment rack frames, the complex dynamic interaction between the servers themselves and the frames is not well documented. The dynamic mass participation of a CE system (which can weigh up to 3000 lbs, whereas the rack frame is around 500 lbs) is unknown. (3) There is no documented information of the vertical stiffness of a typical RAF-CE system. (4) There are no verified models on the inelastic behavior of anchorage of the RAF to the building floor or connections at AF-CE interfaces. (5) Little is known about the stiffness of the diaphragm created by attached RAF panels and stringers. (6) Little is known about the post-yield behavior of RAF systems, although some reports suggest a possible lack of ductility (FIMS, 1987).

In light of these challenges, a number of modeling assumptions were made. First, since it is extremely difficulty to model the dynamics and coupling effects between the rack frame and the computer servers within the cabinets, the weight of the servers was considered to be payload only, and the servers within the frame were considered to weigh 1500 pounds. Second, the lateral stiffness of the rack frame was taken as 5 kips/inch, and the weight was taken as 500 pounds, resulting in a lateral frequency of 10 Hz. The RAF was modeled as only a 'slice' in the primary shaking direction (X-direction) of the rack frame and computers, with a centered mass of 140 pounds and a lateral frequency of 31 Hz. Finally, it is assumed that there are three arrays of CE systems in the out-of-plane direction (Y-direction). The RAF-CE array system was modeled with a weak diaphragm at the RAF panel level. The resulting RAF-CE array has the following lateral periods: T_1 = 0.33 seconds, T_2 = 0.164 seconds and T_3 = 0.0158 seconds. In the vertical direction, the RAF-CE is modeled as infinitely rigid, which implies that there is no response amplification in the vertical direction.

IN-STRUCTURE RESPONSE RESULTS

Linear Elastic 3D Modeling

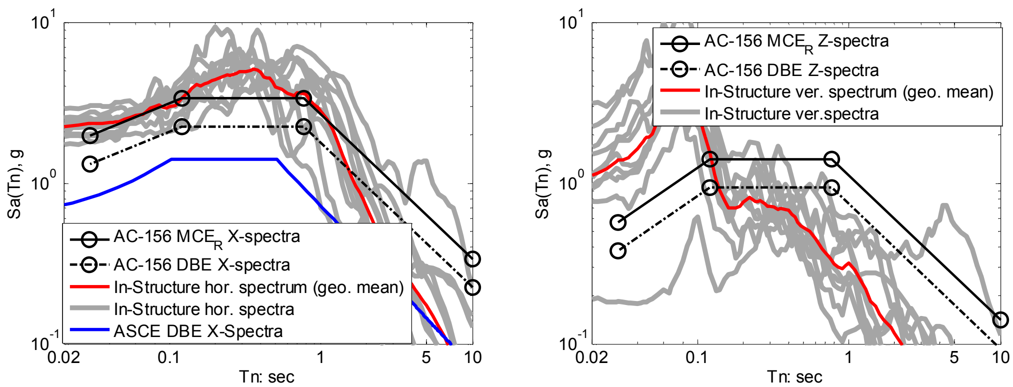
The ten scaled time history records at the DBE level were applied to the 3-D SAP model and maximum joint accelerations were recorded at four locations at the 2nd story floor: (1) the base of a column, (2) an interior column at the second floor level, (3) mid-span of an interior primary girder and (4) mid-span of a middle floor beam. Table 2 summarizes the maximum joint acceleration amplifications of the three elevated points observed from the linear elastic time history analysis. The averages of the 10 records are shown.

Table 2 - Average response amplifications over free-field at 2nd floor level

Location	**X +**	**Y +**	**Z +**	**X -**	**Y -**	**Z -**
Base of Column	1.9	1.7	1.7	2.0	1.8	1.7
Mid-span of Girder	1.9	1.7	1.9	2.0	1.8	2.2
Mid-span of Beam	1.9	1.7	4.2	2.0	1.8	5.0

Vertical response amplifications of up to five times the peak ground motion levels observed in the linear analytical model are consistent with those reported in Pekcan, et al. (2003) who also cites consistency with field observations following the 1994 Northridge earthquake. This result clearly confirms that vertical response amplification depends on spatial location, as the two dominants modes, 3 Hz and 11 Hz, reflect the local floor plan stiffness and the global frame stiffness, respectively, where the flexible local stiffness (3 Hz) results in higher vertical amplification. In turn, this implies that an RAF-CE system must be treated as a multi-support input system. In the reduced-order model, this can be achieved simply by tuning the model to exhibit a specific vertical mode; however, in this paper, a conservative treatment is adopted by only considering the global vertical mode at 11 Hz.

Figure 5 - Horizontal and vertical in-structure spectra generated at the second floor compared with AC-156 Spectra, (a) horizontal and (b) vertical.

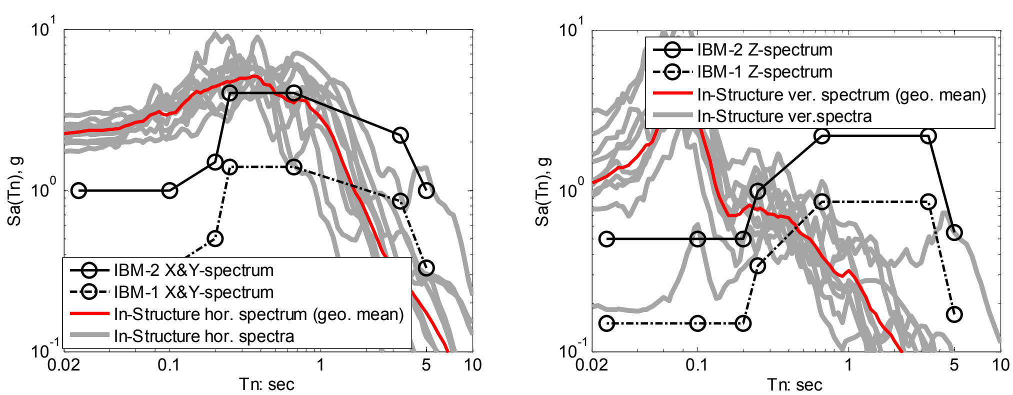


(a) (b)

Non-Linear Inelastic Reduced-order Modeling

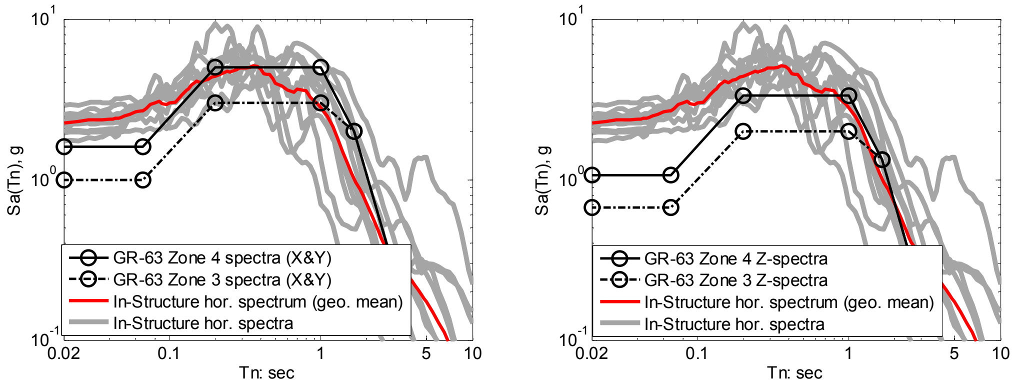
Figures 5 through 7 below compare the in-structure response results of the non-linear inelastic analysis of the reduced-order model to three widely used industry standard design spectra mentioned previously (AC-156, GR-63 Zone 3 & 4 and IBM-1/2).

Figure 6 - Horizontal and vertical in-structure spectra generated at the second floor compared with IBM-1/2 Spectra, (a) horizontal and (b) vertical.



(a) (b)

Figure 7 - Horizontal and vertical in-structure spectra generated at the second floor compared with GR-63 (Zone 3 & 4) Spectra, (a) horizontal and (b) vertical.



(a) (b)

AC-156 spectra were constructed based on the risk-targeted DBE level spectra. Figure 6(a) indicates that the spectrum reflects the possible spectral amplification; however, it underestimates the magnitude when T_n is less than 1.3 sec. The vertical spectral demands in AC-156 can envelope the resulting vertical response spectra; however, at the vertical resonance of the building (0.09 sec or 11 Hz), the AC-156 significantly underestimates the amplification for this scenario.

For the other two RRS spectra, there exists a lack of interoperability between their spectral ordinates and the risk-targeted ones in ASCE 7. Nonetheless, the overall trends in all their spectral dimensions are observed. For lateral seismic spectra, when T_n is greater than 0.7 sec, the IBM-2 spectra envelope the geometric mean of the in-structure spectra at the DBE level except when T_n is less than 0.7 sec. Similarly, GR-63 Zone 4 spectral ordinates envelope the response spectra when T_n is greater than 0.3 sec,

The observations above suggest that the AC-156 and the IBM-2 spectra fail to adequately characterize the in-structure horizontal response for high-frequency systems. For computer servers, it is understood that high-frequency seismic input and response would not typically cause performance degradation for the server rack or the mounted servers (Notohardjono et al. 2006). However, the high spectral in-structure response at high frequencies may result in very large base shear force demands in the side-to-side direction of a CE array (i.e. server cabinet array in a data center) or the interface of the RAF to the building floor. Given that the lateral period of the AF-CE array system in this study is 0.3 sec, this concern is warranted, and the effects may be exacerbated for systems in for which $T_n < 0.3$ sec.

For vertical seismic spectra, the AC-156 does not capture the potential response amplification of at or near the fundamental vertical period of the building; nonetheless, the overall trend is acceptable in terms of enveloping the response spectra when $T_n > 0.1$ sec. The IBM-2 Z-spectra severely overestimate vertical spectral demands for $T_n > 0.2$ sec, and more severely underestimate when $T_n < 0.2$ sec. The GR-63 Zone 4 Z-spectra underestimate the vertical spectral demands for $T_n < 1.0$ sec, and envelope relatively well for $T_n > 1.0$ sec. In the reduced-order simulation, it was assumed that the RAF-CE system was infinitely rigid in the vertical direction. Realistically, the vertical system frequency may be less than 50 Hz (period > 0.02 seconds). This implies that if these three industrial spectra are used to estimate the vertical demands on RAF-CE systems or used for seismic qualification, significant underestimation may be expected, which introduces unexpected seismic risk to the system design and operation. When combined with the high lateral force demand, more severe risk may arise for the anchorage design of both the RAF and the CE system.

RAF-CE Response Demands

Figures 8 and 9 show the RAF-CE response demands in terms of lateral acceleration amplification drift ratio, and base forces when subject to the DBE level ground motions. Figure 8(a) illustrates the continuous amplification of acceleration response through the RAF-CE system, which by average can reach about 3 times the input PGA at the top of the RAF and 3.6 times at the CE (center of gravity). The lateral drift ratios are plotted in Figure 8(b). It can be seen that the total drift can approach 7% at the top of the RAF-CE and 3% at the top of RAF.

Figure 8 - Lateral acceleration amplification and drift ratios at the RAF top and the CE level, (a) Horizontal acceleration amplification; (b) lateral drift ratios.

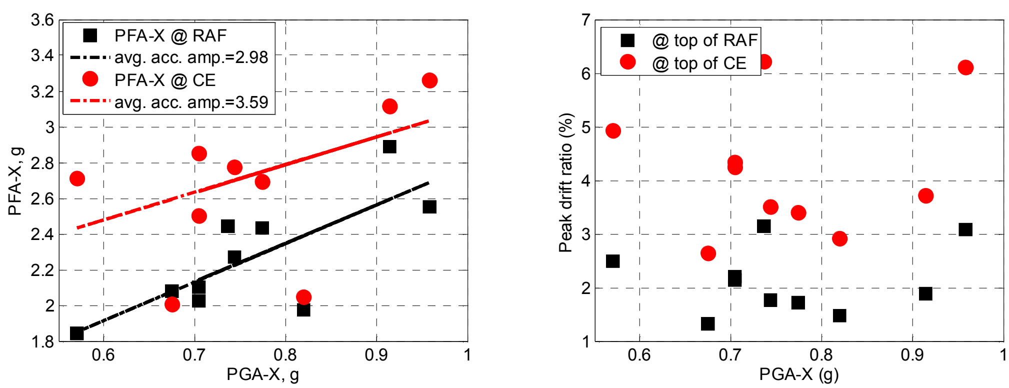


Figure 9 - (a) Maximum/minimum base axial force to the weight ratio at the RAF base (circled makers indicate non near-fault ground motion input); and (b) the normalized base moment at the RAF base.

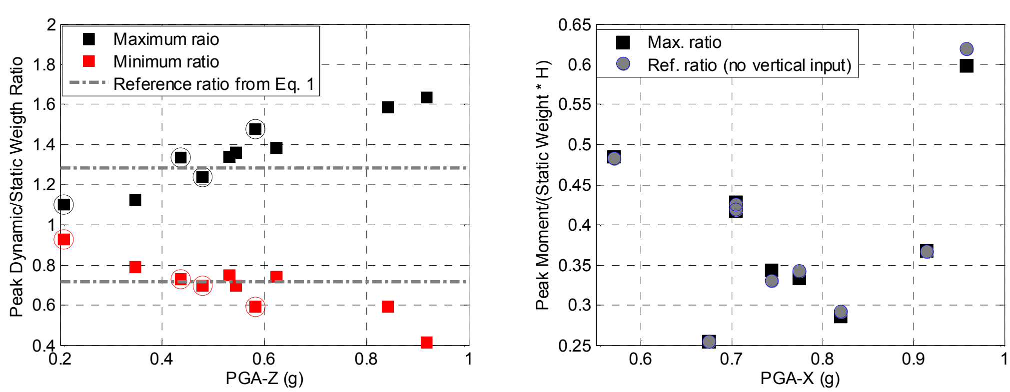


Figure 9(a) provides the comparison of axial force demands between introducing vertical input and without vertical input. At high PGA-Z levels, the maximum ratio is about 1.6, and the minimum is 0.4. As the vertical PGA increases, the difference between the maximum and minimum weight ratios increases as well. It is worthy to note that near-fault ground motions tend to generate larger axial force demands. Additionally, the majority of data points do not fall within the reference ratio from Eq. 1, although all the motions are scaled to the same DBE levels. Figure 9(b) plots the resulting moment at the RAF base against the input lateral demands. It can be seen that the effect of including vertical ground motions on this metric is marginal. However, one can expect the risk in designing the anchorage system considering both axial forces and base moment if the axial demands are not properly considered.

CONCLUSION

This study presents a numerical evaluation of the current Required Response Spectra (RRS) for designing and seismic qualification of raised access floor and supported equipment at a specified ASCE-7 compatible risk level. The widely used AC-156, GR-63-CORE Zone 3 & 4, and IBM-1/2 spectra are included, and 3-D building modeling and reduced-order simplified modeling are employed. The numerical study shows that based on a three-story frame building, all three RRSs underestimate the vertical response to varying degrees at higher frequencies. Only the AC-156 spectra exhibits a clear link to the ASCE risk-target based approach for in-structure response. The resulting seismic demands in this specific case-based study also confirm the significance of vertical inputs that may result in higher-than-expected axial force demands at the base of the access floors and computer equipment. Caution needs to be taken to consider the combined axial forces, base shear and base moment demands when designing the anchorage systems for these components. It is noted that highly nonlinear dynamics resulting from the connection interfaces of the access floors, rack frames and the computers are not included in this study. There is a strong need for experimental research to validate computational models and develop the next generation ASCE 7 code-compatible design spectra for the raised access floor systems and supported equipment.

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