CONFERENCE 2015 - MANCHESTER
SMiRT23
Structural Mechanics in Reactor Technology

Transactions, SMiRT-23
Manchester, United Kingdom - August 10-14, 2015

Division VII, Paper ID 683

IASMiRT

ON THE COMBINATION OF THE SPATIAL COMPONENTS OF EARTHQUAKES FOR EQUIPMENT FRAGILITY ESTIMATIONS

Cagri Ozgur[1], Yigit Isbiliroglu[2], Siavash Dorvash[3] and Enrique Bazan-Zurita[4]

[1]Project Engineer, Rizzo Associates, USA
[2]Engineering Associate, Rizzo Associates, USA
[3]Project Engineer, Rizzo Associates, USA
[4]Chief Engineer, Structural Engineering, Rizzo Associates, USA

ABSTRACT

One of the procedures accepted in the NRC Regulatory Guide 1.92 (2012) to consider the simultaneous effects of three spatial components of seismic ground motion (X, Y, and Z) consists of conducting the analyses for each component independently and combining the results by the Square-Root-of-the-Sum-of-the-Squares (SRSS) or the 100-40-40 rules for obtaining the representative maximum response of interest. The basis for these approaches is that peak response values do not occur simultaneously.

For the evaluation of equipment attached to large structural models, an in-cascade approach is frequently used. To this end, it is customary to calculate combined In-Structure Response Spectra (ISRS) for each spatial floor direction. The combined ISRS are typically obtained for each direction by combining three co-directional ISRS resulting from the three spatial components of ground motion using the SRSS (or 100-40-40) rule. The combined ISRS (in X, Y and Z directions) are then utilized for fragility calculations of components positioned at the location where the ISRS are obtained.

The final maximum response of interest in the equipment (e.g., seismic anchor forces) is frequently obtained using again either the SRSS or 100-40-40 rules, assuming that they apply for combining the spatial component of local floor motion (i.e., ISRS). However, repeated use of spatial combination rules is not clearly justified. This paper examines this issue by contrasting seismic demands from analyses where supported components are modeled together with the supporting structure to the results of the in-cascade approach. Optional spatial combination rules are evaluated to identify those leading to acceptable results for equipment fragility estimates.

INTRODUCTION

Simultaneous responses to three orthogonal earthquake directions must be considered for seismic fragility evaluation of the Structures, Systems, and Components (SSCs) in Nuclear Power Plants (NPPs). Regulatory Guide 1.92 (2012) accepts that when the response spectra method is used, the maximum response of interest due to earthquake loading in an SSC may be obtained with the SRSS combination of the maximum responses due to ground motion in three orthogonal directions. According to Regulatory Guide 1.92 (2012), the 100-40-40 percent combination rule may be also used.

For equipment seismic fragility calculations, the stiffness and damping of mechanical and electrical equipment (relatively small compared to the building) are usually not included in the building model. Only their masses are lumped at their supporting points. Therefore, frequently three different statistically independent input time-histories are generated matching the foundation input response spectra (FIRS) to be used as inputs in three separate time-history building analyses. Then, for calculating the seismic demand on the equipment, ISRS are developed from the time-history response at a given location in the building. These ISRS serve two purposes. Firstly, they are used in the functionality evaluation of the

equipment item (e.g., test response spectrum (TRS) or generic equipment ruggedness spectra (GERS) versus ISRS comparison). Secondly, they are used as input for anchorage evaluation (e.g., spectral acceleration at the equipment fundamental frequency is applied to the component mass at the equipment center of gravity).

A widely used approach in practice is to generate three ISRS for each ground motion direction at a given location in the building (e.g., X direction ground motion results in three ISRS in the X, Y, and Z directions). In total, this leads to nine different ISRS (three from each ground motion direction). Afterwards, it is customary to obtain a resultant ISRS by combining three co-directional ISRS (typically using the SRSS rule) resulting from the three spatial components of ground motion. These three resultant ISRS are utilized for fragility calculations of equipment positioned at the locations where the ISRS are obtained by calculating the maximum response of interest in the equipment (e.g., seismic anchor forces). It should be noted that the final maximum response of interest in the equipment is estimated using again either the SRSS or the 100-40-40 rules, assuming that the NRC recommended approach applies for combining the responses due to spatial components of floor motion (i.e., ISRS). However, no clear justification is found in literature for the repeated use of spatial combination rules in the in-cascade seismic analyses. This paper addresses this issue by evaluating the accuracy of seismic demands, as compared to results of coupled models of the main building together with the component. For this purpose, a comparative study is performed to evaluate the seismic demands obtained with different spatial combination rules. The results of each evaluated option are compared with those of analyses with coupled building/equipment models which are regarded as the correct solution.

To develop numerical results, two simple but representative models with different eccentricities are selected to represent one symmetric and one asymmetric structure. As input, two sets of three statistically independent time-histories are used. In addition, two equipment models with different dynamic characteristics are examined. A total of four different spatial combination options are considered for the in-cascade approach. The representative maximum response of interest (e.g., combined tension and shear interaction on anchor bolts to calculate seismic anchor forces) from the in-cascade approach for each different spatial combination option is compared with the maximum response from the coupled analysis of structure and equipment.

The subsequent sections describe the different options evaluated for combining responses due to three directional earthquake loadings for equipment fragility estimations. The analytical structure and equipment models are described in detail. Finally, results and the conclusions of the comparative study are provided.

OPTIONS FOR COMBINING SPATIAL COMPONENTS OF SEISMIC INPUT AND SEISMIC RESPONSE

Four different options using in-cascade methodology for obtaining the seismic anchor forces of the equipment are examined herein and their results are compared to those of the time-history response of the coupled system. In each of these four options, the anchor forces are calculated using the same nine ISRS obtained at the component mounting location, but different combination options are applied to calculate the combined ISRS and anchor forces. The representative response of interest for anchorage evaluation is usually obtained from the interaction of tensile and shears forces on anchor bolts based on ACI 349 (2001). Table 1 describes the different options considered in the comparative study including the correct solution. It should be noted that, for symmetric structures, each applied input motion creates response only in the direction of the motion. Therefore, different combination methods to calculate the resultant ISRS (e.g., absolute sum or SRSS) essentially give the same resultant ISRS.

In Option 1, the anchor forces are obtained with the time-history analyses of the coupled system (i.e., structure and equipment are modeled together). This response is regarded as the exact solution. Figure 1 provides the summary of Option 1. Note that all possible directional combinations are considered for obtaining the critical anchor force (+X+Y+Z, +X+Y-Z, +X-Y+Z, +X-Y-Z, +X+Y+Z, +X+Y-Z, +X-Y+Z, +X-Y-Z). The interaction ratio shown in Figure 1 is calculated for each time step and the most critical value is taken as the exact solution. Options 2 through 5, on the other hand, use the in-cascade methodology to estimate the seismic anchor forces on the equipment which different spatial combination options are considered to obtain the combined ISRS and to calculate the anchor forces. The details of Options 2 through 5 are summarized in Figure 2.

Option 2 obtains the resultant ISRS in each direction as the absolute sum of three co-directional ISRS from the three spatial components of ground motion. Anchor forces are estimated independently from each resultant ISRS (X, Y & Z) and then the similar responses (tension or shear anchor forces) combined with the 100-40-40 rule. In Option 3, three resultant ISRS are obtained by the SRSS method. Anchor forces are then estimated by absolute summation of responses resulting from each resultant ISRS. Option 4 is the same as Option 3 except that anchor forces are obtained by the 100-40-40 rule. It should be noted that spatial combination rules are repetitively used for Option 4.

The representative response of interest for anchorage evaluation is usually obtained from the interaction of tensile and shears forces on anchor bolts based on ACI 349 (2001), as shown in Figure 1 and Figure 2. When the 100-40-40 rule is used in Options 2 and 4, the most critical shear and tension interaction is identified from three separate combinations (100-40-40, 40-100-40, and 40-40-100). However, the 100-40-40 rule is sometimes used by taking the maximums of each demand parameter (such as shear and tension) from the three factored combinations. This case is also considered in this study as Option 5. Except for the slightly different implementation of the100-40-40 rule, Option 5 is the same as Option 4.

Table 1. Description of different spatial combination options considered in the comparative study

Spatial Combination Option No	Description
1	**Time-history** response; obtain the critical response considering each time step (correct solution)
2	Combine 9 ISRS to obtain **3** ISRS by **absolute sum**; obtain forces by **100-40-40** rule
3	Combine 9 ISRS to obtain **3** ISRS by **SRSS; obtain forces by absolute sum**
4	Combine 9 ISRS to obtain **3** ISRS by **SRSS; obtain forces by 100-40-40** rule
5	Combine 9 ISRS to obtain **3** ISRS by **SRSS; obtain forces by max. of 100-40-40** rule

ANALYTICAL MODELS

Torsional effects become more significant as the distance between the centers of rigidity and of mass (i.e., eccentricity) of the structure increases. This eccentricity couples the seismic response; for instance, the earthquake in the X direction generates responses in the X, Y, and Z directions at the floors in the presence of eccentricity perpendicular to X. In such cases, even if the ground motion components are not correlated, the resultant ISRS will exhibit some degree of correlation. Therefore, to assess torsional coupling effects, two building models—one symmetric and one asymmetric—are considered in this study as illustrated in Figure 3. The building in Figure 3-(i) has no torsional eccentricity whereas the building in Figure 3-(ii) is eccentric in both directions, similar to most buildings of NPPs. Representative equipment pieces are included in both models, to allow calculation of anchor forces that are regarded as the exact solution.

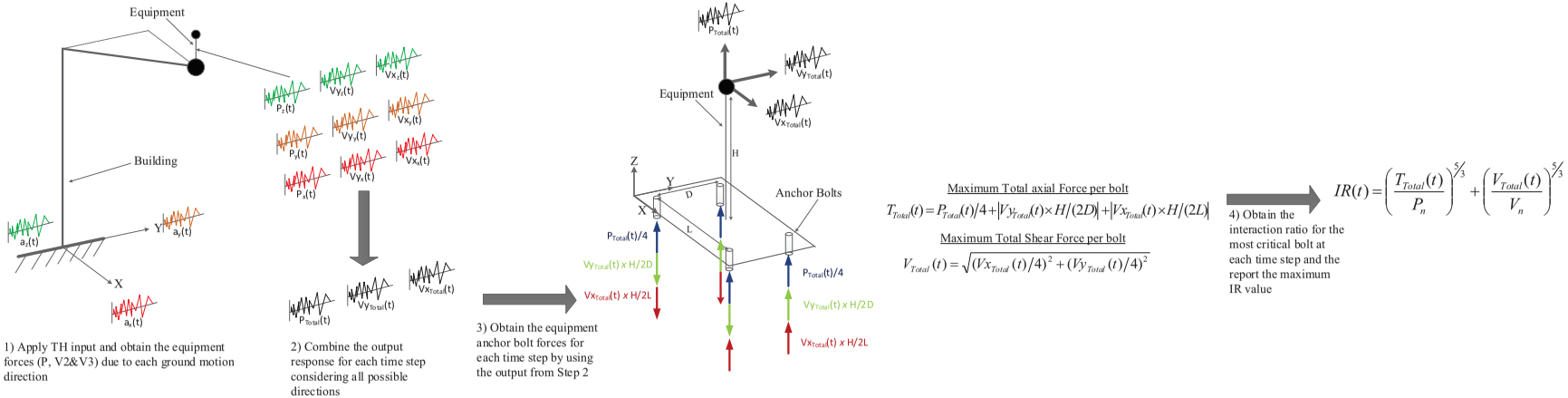


Figure 1. Summary of Option 1.

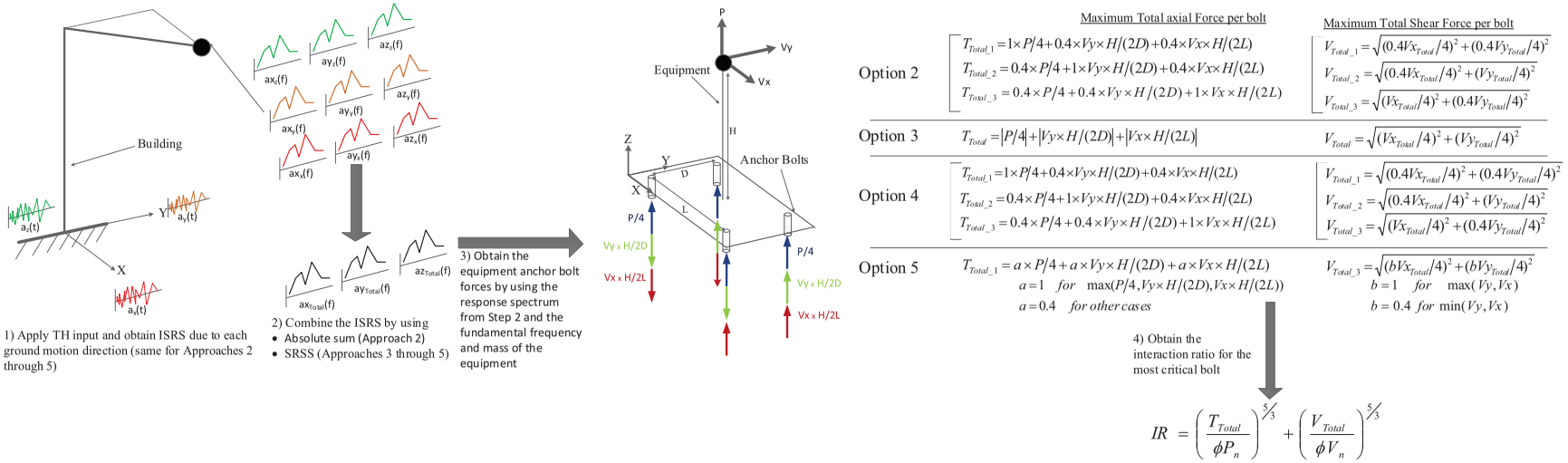


Figure 2. Summary of Options 2 through 5.

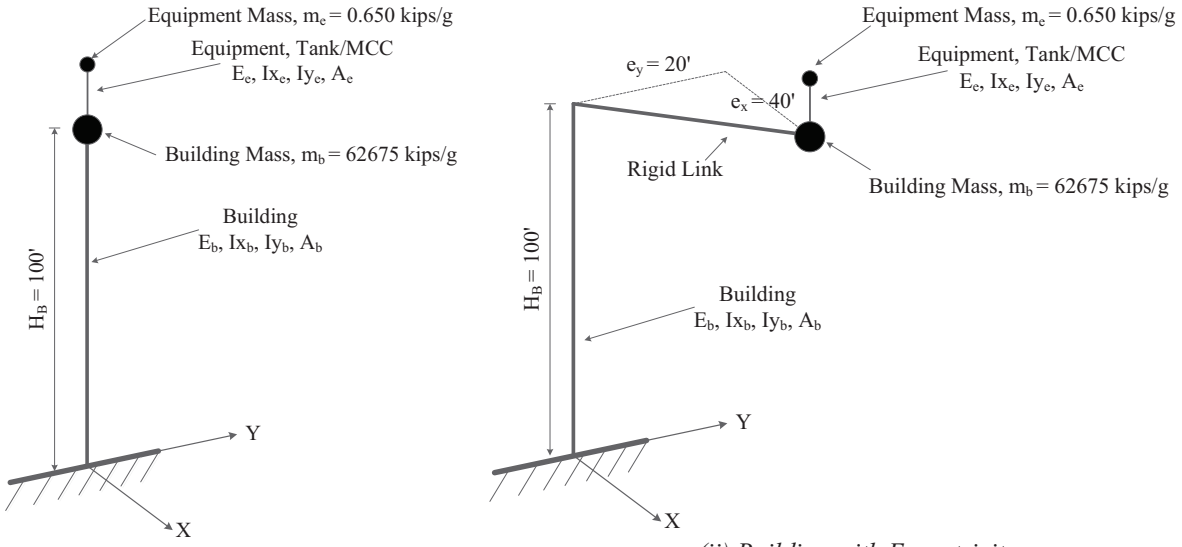


Figure 3. Different structure geometries considered in the analyses.

Modal properties of the equipment (front-back, side-to-side, and vertical dimensions) can also impact the combined response to the spatial seismic components. As mentioned above, if the building has significant torsional coupling effects, resultant ISRS will be somewhat correlated even if the components of the seismic input ground motion are statically independent. In addition, if the fundamental frequencies of the equipment are similar in any two directions, it is likely that final responses in the equipment (such as axial anchor force) that result from three resultant ISRS will be correlated as they may share common frequency contents. In such cases, repeated combination rules such as SRSS or 100-40-40 could result in un-conservative estimates of the maximum response of interest. Therefore, two types of equipment are studied: 1) the first one has the same modal properties in two horizontal directions as in the case of vertical tanks, 2) equipment having different modal properties in horizontal directions such as Motor Control Centers (MCCs). The equipment geometries representing a tank and an MCC are shown in Figure 4. 5% damping is used both for the equipment and the building. The equipment is anchored with four anchor bolts and 3/8" diameter expansion bolts are assumed. The pullout capacity and shear capacities of the anchor bolts are taken as 3 kips and 4 kips, respectively, from EPRI NP-5228-SLR1 (1998).

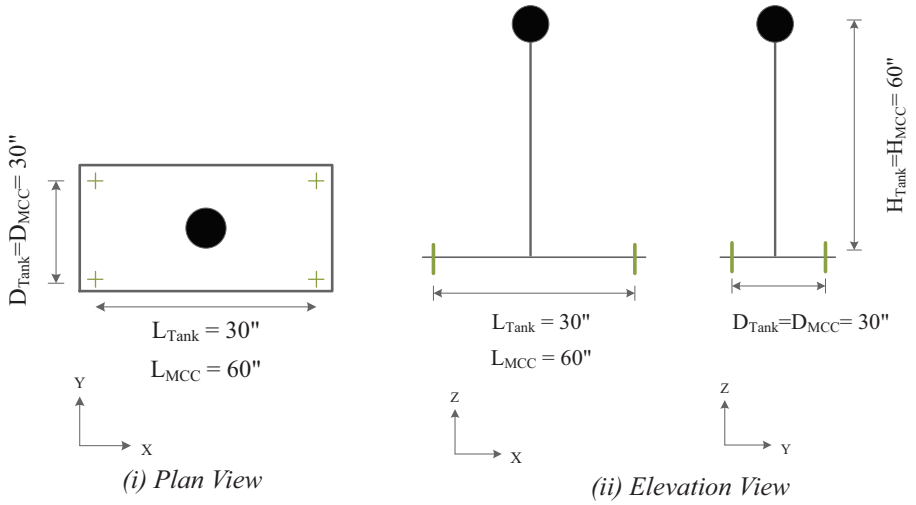


Figure 4. Equipment geometry used in the analyses.

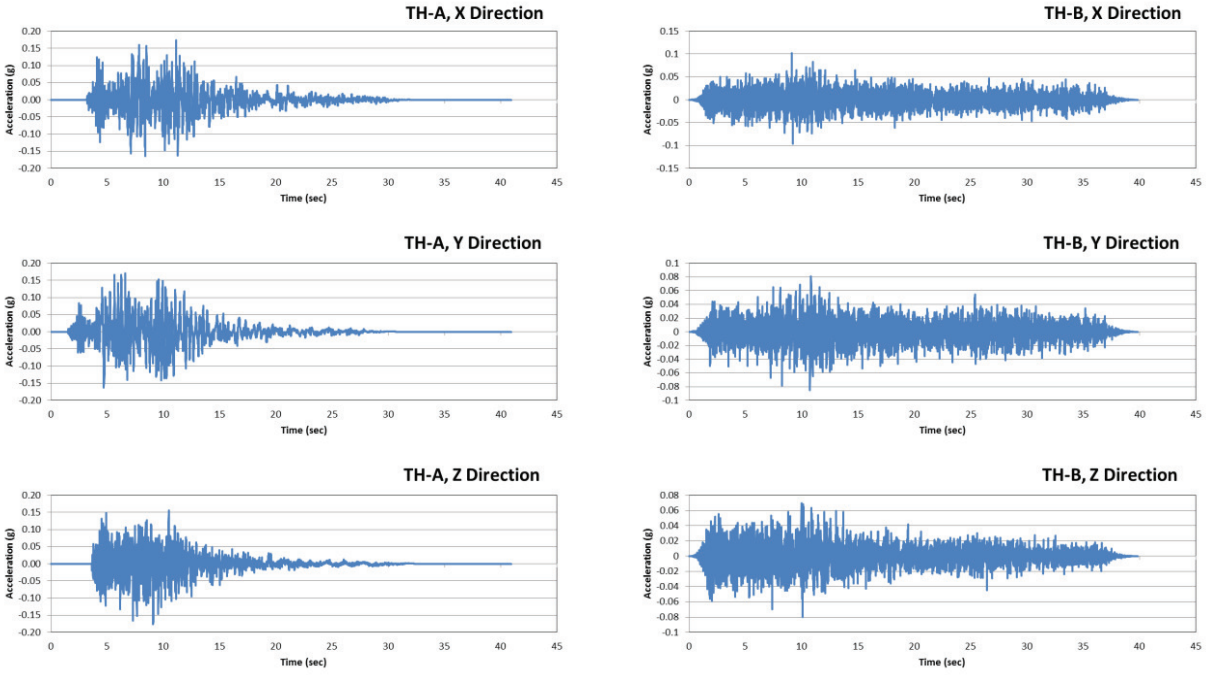
Table 2 provides the material and section properties used in the analyses. The modal information of the building and the equipment are tabulated in Table 3. Two different sets of time-histories (TH-A and TH-B) are considered for the analyses which are shown in Figure 5. Each time-history input set is composed of two horizontal and one vertical ground motion time histories. The associated response spectra of each time-history match the site-specific FIRS which are developed for two different sites. These input time-histories were developed meeting the criteria stated in Appendix F of Regulatory Guide 1.208 (2007) for Design Time Histories in Standard Review Plan (SRP, NUREG-0800 (2014), section 3.7.1).

Table 2. Material and section properties used in the analyses.

Component	E (ksi)	Ix (ft^4)	Iy (ft^4)	A (ft^2)	H (ft)
Building (Symmetrical)	3000	3390612	7009579.8	97608774	100
Building (Asymmetric)	3000	5929160.5	11621154.6	64568557.8	100
Tank	30000	4.919E-04	4.919E-04	1.004E-03	5
MCC	30000	4.919E-04	3.075E-03	1.004E-03	5

Table 3. Fundamental frequencies of the building and equipment.

Component	f_x (Hz)	f_y (Hz)	f_z (Hz)
Building (Symmetric & Asymmetric)	7.56	10.87	40.57
Tank	8.00	8.00	33.00
MCC	8.00	20.00	33.00



(i) TH A *(ii) TH B*

Figure 5. Input Motions used in the TH analyses.

RESULTS

As mentioned in previous sections, a comparative study is performed in order to examine seismic demands obtained with different options for combining results of spatial components of ground motion. The representative maximum response of interest in the equipment is the combined tension and shear interaction of anchor bolts (i.e., interaction ratio, IR) based on ACI 349 (2001). Table 4 presents the spectral accelerations corresponding to the natural frequencies of the equipment listed in Table 3 for each building and TH. The spectral accelerations that are provided in Table 4 are extracted from nine ISRS at the equipment mounting location resulting from three spatial components of seismic ground motion. These ISRS are obtained from the analyses where both the structure and the equipment are included in the model. Different in-cascade options that utilize these spectral accelerations (by applying to the component mass at the equipment center of gravity) for calculating the seismic anchor IR are presented Figure 2. Figure 1, on the other hand, provides the summary of Option 1, which is considered here as the exact solution.

Table 5 and Table 6 present the normalized interaction ratios (N_{IR}) for the cases considered for tank and MCC, respectively. For all the three cases, normalization is performed separately by dividing each calculated IR by the IR considered to be the exact one (from Option 1). Thus, values lower than unity indicate un-conservative estimation of the IR and vice versa. Ratios closer to 1 reveal higher accuracy. Figure 6 and Figure 7 illustrate the results presented in Table 5 and Table 6, respectively.

Table 4. Input spectral accelerations to equipment (tank and MCC) for different cases.

EQ direction	ISRS direction	Spectral Accelerations for Tank (g)			Spectral Accelerations for MCC (g)		
		Case 1 – symm. TH-A	Case 2 – unsymm. TH-A	Case 3 – unsymm. TH-B	Case 1 – symm. TH-A	Case 2 – unsymm. TH-A	Case 3 – unsymm. TH-B
X	X	2.729	2.516	1.108	2.729	2.516	1.108
	Y	0.000	0.687	0.315	0.000	0.147	0.071
	Z	0.000	0.406	0.187	0.000	0.120	0.131
Y	X	0.000	0.588	0.144	0.000	0.588	0.144
	Y	1.116	0.874	0.277	0.720	0.429	0.182
	Z	0.000	0.375	0.127	0.000	0.479	0.253
Z	X	0.000	0.341	0.135	0.000	0.341	0.135
	Y	0.000	0.362	0.107	0.000	0.392	0.153
	Z	0.398	0.542	0.223	0.256	0.476	0.187

Table 5. Normalized interaction ratios (N_{IR}) obtained in the comparative study for tank.

App ID	Case 1 - Symmetric structure - Input TH A				Case 2 - Asymmetric structure - Input TH A				Case 3 - Asymmetric structure - Input TH B			
	T_{Tot}[3] (kip)	$V_{x.Tot}$[2] (kip)	$V_{y.Tot}$[2] (kip)	N_{IR}[1]	T_{Tot}[3] (kip)	$V_{x.Tot}$[2] (kip)	$V_{y.Tot}$[2] (kip)	N_{IR}[1]	T_{Tot}[3] (kip)	$V_{x.Tot}$[2] (kip)	$V_{y.Tot}$[2] (kip)	N_{IR}[1]
1	2.10	0.46	0.06	**1.00**	2.48	0.44	0.18	**1.00**	1.09	0.21	0.06	**1.00**
2	2.09	0.44	0.07	**0.99**	2.82	0.56	0.12	**1.25**	1.12	0.23	0.05	**1.05**
3	2.56	0.44	0.18	**1.38**	2.58	0.42	0.19	**1.06**	1.06	0.18	0.07	**0.96**
4	2.09	0.44	0.07	**0.99**	2.05	0.42	0.08	**0.73**	0.86	0.18	0.03	**0.68**
5	2.09	0.44	0.07	**0.99**	2.05	0.42	0.08	**0.73**	0.86	0.18	0.03	**0.68**

Notes: [1] All interaction ratios are normalized by the IR of the Option 1.
[2] $V_{x.Tot}$ and $V_{y.Tot}$ are the total anchor bolt shear forces in X and Y directions, respectively.
[3] T_{Tot} is the total anchor bolt tensile force obtained from the P, V_x and V_y as shown in Figure 1 and Figure 2.

Table 6. Normalized interaction ratios (N_{IR}) obtained in the comparative study for MCC

App ID	Case 1 - Symmetric structure - Input TH A				Case 2 - Asymmetric structure - Input TH A				Case 3 - Asymmetric structure - Input TH B			
	T_{Tot}[3] (kip)	$V_{x.Tot}$[2] (kip)	$V_{y.Tot}$[2] (kip)	N_{IR}[1]	T_{Tot}[3] (kip)	$V_{x.Tot}$[2] (kip)	$V_{y.Tot}$[2] (kip)	N_{IR}[1]	T_{Tot}[3] (kip)	$V_{x.Tot}$[2] (kip)	$V_{y.Tot}$[2] (kip)	N_{IR}[1]
1	1.07	0.45	0.04	**1.00**	1.14	0.42	0.06	**1.00**	0.47	0.20	0.01	**1.00**
2	1.09	0.44	0.05	**1.02**	1.44	0.56	0.06	**1.49**	0.59	0.23	0.03	**1.45**
3	1.40	0.44	0.12	**1.48**	1.35	0.42	0.10	**1.29**	0.58	0.18	0.04	**1.37**
4	1.09	0.44	0.05	**1.02**	1.05	0.42	0.04	**0.88**	0.45	0.18	0.02	**0.93**
5	1.09	0.44	0.05	**1.02**	1.05	0.42	0.04	**0.88**	0.45	0.18	0.02	**0.93**

Notes: [1] All interaction ratios are normalized by the IR of the Option 1.
[2] $V_{x.Tot}$ and $V_{y.Tot}$ are the total anchor bolt shear forces in X and Y directions, respectively.
[3] T_{Tot} is the total anchor bolt tensile force obtained from the P, V_x and V_y as shown in Figure 1 and Figure 2.

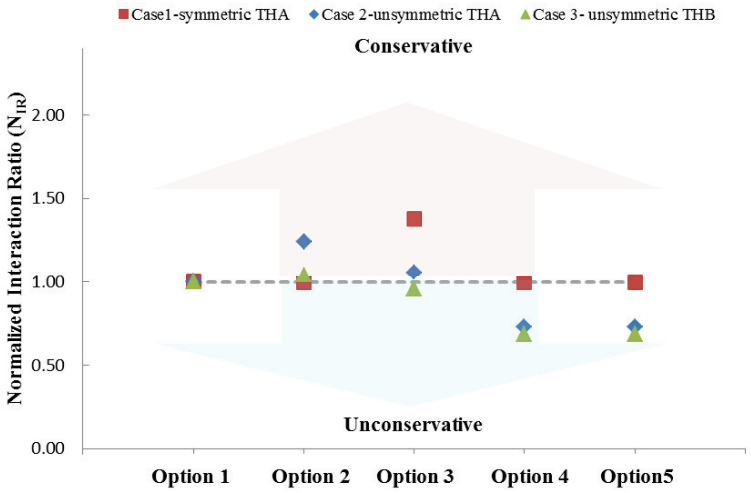


Figure 6. Normalized interaction ratios (N_{IR}) evaluated in the comparative study for tank.

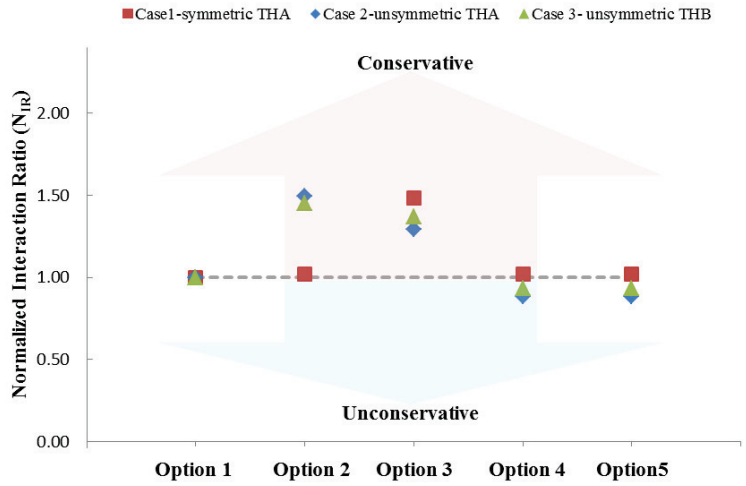


Figure 7. Normalized interaction ratios (N_{IR}) evaluated in the comparative study for MCC.

Different options yield varied levels of accuracy as can be seen from Figure 6 and Figure 7 (or from Table 5 and Table 6). For Options 3, 4, and 5, a higher level of conservatism is attained in the N_{IR} for the symmetric cases as compared to the N_{IR} for the asymmetric cases. For instance, N_{IR} obtained for the tank by using Option 4 is 0.99 for the symmetric structure case 1, whereas N_{IR} is only 0.68 for the asymmetrical structure case 3. For Option 2, the level of conservatism increases for the asymmetric case since the resulting ISRS are obtained from the absolute sum of three co-directional ISRS from the three spatial components of ground motion and the spatial combination rules (100-40-40 rule in this case) is applied only once.

It should be noted from Figure 6 and Figure 7 (or from Table 5 and Table 6) that all the in-cascade options (Options 2 through 5) tend to result in higher N_{IR}s for MCC than the N_{IR}s obtained for the tank, especially for the asymmetrical structure cases (e.g., Option 4 – case 3 N_{IR} is 0.93 for MCC, which is higher than the N_{IR} obtained for the tank for the same case, 0.68). The decreases in the N_{IR}s are mainly due to the fact that combination rules (SRSS or 100-40-40) inherently assume a substantial amount of statistical independence in the responses resulting from three directional seismic input motions. However, responses in each direction at the equipment mounting location (e.g., ISRS) become statistically correlated because torsional coupling effects are significant for asymmetric structures. Similarly, when the equipment has close modal frequencies in both horizontal directions (in the case of the tank), responses in the equipment due to three resultant ISRS, such as anchor bolt axial force, become correlated. Therefore, the level of conservatism decreases as the torsional coupling effects increase in the main structure, and also as the modal frequencies of the equipment in any two directions get closer.

Options 2 and 3 generally result in conservative N_{IR} estimates compared to other options. For the studied cases, the highest conservatism for Options 2 and 3 is about 50%.

Options 4 and 5 provide the same N_{IR} for the cases considered here, since, in these cases, both the maximum shear and axial forces in the anchor bolts result from the same 100-40-40 permutation. However, this behavior is not general and Option 5 usually is more conservative compared to Option 4. For Options 4 and 5, slightly un-conservative N_{IR} estimations are observed for MCC (maximum 12% un-conservative), whereas the level of error becomes larger for the tank (up to 32% un-conservatism). As mentioned in the preceding paragraphs, the level of correlation response is larger when the equipment exhibits similar dynamic characteristics in both horizontal directions. This observation seems also to explain the un-conservative N_{IR} estimations for the tank (32%) by Options 4 and 5. For the MCC, on the other hand, although the fundamental frequencies in each direction are well separated from each other (8-20-33 Hz), up to 12% un-conservative estimations are yielded by Options 4 and 5. In this case, it is believed that the narrow banded shape of ISRS due to the filtering effect of the structure leads to N_{IR} estimates on the un-conservative side.

CONCLUSIONS

A comparative study is conducted to examine the seismic demands on secondary systems obtained with different spatial combination rules. Two simplified building models are considered: one representing symmetric structures and the other modelling asymmetric structures, along with two sets of statistically independent time-histories. In addition, two equipment models with different dynamic characteristics are examined. Four different spatial combination options are considered for the in-cascade option, whereas another option considers the coupled model, which is regarded to yield the exact solution. A representative maximum response of interest (e.g., combined tension and shear interaction of anchor bolts) obtained from the in-cascade option for each different spatial combination case is contrasted with the maximum response obtained from the coupled structure/equipment analysis. Un-conservative cases are particularly observed when Option 4 or Option 5 are used to calculate the seismic anchor forces for

equipment with similar fundamental frequencies in each direction, and when the equipment is mounted on an asymmetric structure.

The results shown in the paper highlight the complexities associated with obtaining the representative maximum response of interest combining the responses due to spatial components of floor motion (i.e., ISRS). The in-cascade options can underestimate the seismic demand when 1) ISRS are correlated due to torsional coupling effects in the structure, and 2) equipment has similar fundamental frequencies in two horizontal directions, as in the case of vertical tanks, and 3) narrow banded ISRS are used. In general, Options 2 and 3 provide highly conservative estimations of N_{IR}s for asymmetric buildings and for the equipment having different modal properties in horizontal directions, which is not desired for fragility estimations of the equipment. On the other hand, Options 4 and 5 provide conservative estimations if the above listed cases are not observed. In addition, the IR estimations from Options 4 and 5 are less conservative compared to the estimations from Options 2 and 3 if the above listed cases are not observed. It should be noted that the results presented in this paper correspond to the extreme case scenarios where the equipment is located far away from the center of stiffness. Typically torsional effects become less significant when the equipment is located close to the rotation center.

The results presented in this paper correspond to the single-degree-of-freedom secondary components with a small mass compared to the primary mass. It is well known that the in-cascade approach is usually conservative compared to structure/component analyses even for a single component of ground motion, where the spatial combination rule is not an issue. While the use of the in-cascade approach still provides a practical means for estimating the response of secondary components, the optimistic repeated use of spatial combination rules can provide un-conservative estimates for certain conditions listed above. Options 2 and 3 provide conservative results for all the cases in the limited analyses performed herein. However, the level of conservatism can be large if the building is asymmetric and the equipment has different modal properties in horizontal directions (which is common for most of the equipment). When reduction of conservatism is desirable (as in the case of seismic fragility calculations) either 1) coupled analyses can be performed, or 2) Options 4 and 5 be used with caution for obtaining response of interest in any type of equipment mounted on symmetric buildings or for obtaining responses in equipment having different modal properties in horizontal directions (e.g., MCC) mounted on asymmetric buildings. Based on the findings of this study, more comprehensive statistical studies should be performed in order to derive more conclusive recommendations. Also note that structural models with multi-degree-of freedom secondary systems that could exhibit torsional eccentricity are not considered in this study.

REFERENCES

Regulatory Guide 1.92. (2012). “Combining Modal Responses and Spatial Components in Seismic Response Analysis”, Rev. 3, U.S. Nuclear Regulatory Commission, Washington, DC.

ACI 349. (2001), “Code Requirements for Nuclear Safety-Related Concrete Structures,” and Commentary, ACI 349-01/349-R01, American Concrete Institute, Inc.

EPRI NP-5228-SLR1. (1991). “Seismic Verification of Nuclear Plant Equipment Anchorage”, Rev. 1, Palo Alto, CA, USA.

Regulatory Guide 1.208. (2007), “A Performance-Based Approach to Define the Site-Specific Earthquake Ground Motion,” U.S. Nuclear Regulatory Commission, Washington, DC.

NUREG-0800, Standard Review Plan 3.7.1. (2014), “Seismic Design Parameters,” Rev. 4, U.S. Nuclear Regulatory Commission, Washington, DC.