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

ASSESSMENT OF RESULTANT EARTHQUAKE IN-STRUCTURE RESPONSE SPECTRA

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ABSTRACT

Seismic probabilistic risk assessments for nuclear facilities frequently use In-Structure Response Spectra (ISRS) in the calculation of fragilities of systems and components. Typically, horizontal ISRS are calculated along the main directions of seismic analysis, defined as Cartesian axes X and Y. Appreciable differences in these ISRS could arise when the direction of X and Y changes either for the seismic input or the local ISRS. It is impractical to repeat the analyses for all anticipated directions of ground motion and of equipment orientation. Thus, aiming to reduce the impact of a particular selection of X-Y axes, the authors have proposed the calculation of resultant horizontal In-Structure Response Spectra. These spectra are practically insensitive to the choice of X-Y axes. This paper describes confirmatory analyses of the “invariance” property of resultant ISRS. In addition, we contrast conventional and resultant ISRS calculated with stick and with finite element models of the same structure. It is found that the agreement between resultant ISRS from the two models is significantly more favourable than for ISRS oriented along X and Y. Therefore, resultant ISRS provide more robust estimates of seismic demand when somewhat less refined models are used in the analyses.

INTRODUCTION

In the so-called in-cascade approach, the seismic demand on systems and equipment supported in the main structures of nuclear power plants is mostly based on In-Structure Response Spectra (ISRS). In this approach, it is assumed that excluding the stiffness of the secondary systems in model of the primary building has no significant effects on the overall seismic response. Thus, only the masses of components are lumped at their supporting locations on the model of the host structure. An elastic analysis of the primary model is performed in time domain furnishing seismic stresses in the main structures and acceleration time-histories at the locations where relevant secondary systems are placed. The time-histories are used to develop ISRS which then serve as input for the seismic analyses of the secondary components.

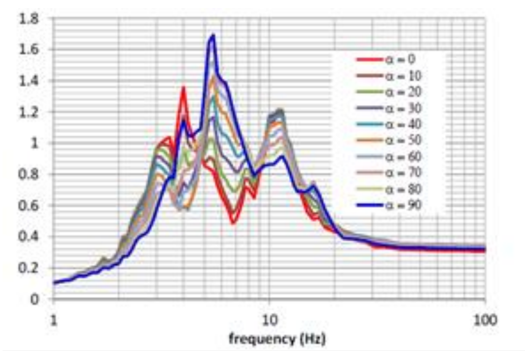
The input for the dynamic analyses of the main building consists of three components of ground motion. Usually, engineers apply the horizontal seismic input along X-Y Cartesian axes which coincide with the “principal” axes of the building. In practice, the horizontal directions of analyses are open to the preferences of the analyst and the calculated ISRS can be appreciably affected by the selected orientation.

A seismic probabilistic risk assessment (SPRA) requires the development of median and unbiased estimates of the ISRS. In a previous study, the authors have introduced the concept of “resultant” ISRS as an option to direct use of the ISRS in the X and Y directions Jarernprasert et al. (2014). It was found that the use of “resultant horizontal ISRS” would offset the effects of directional uncertainties, and that the equal orthogonal components (resultant divided by square root of 2) provide a very close estimate of arithmetic or geometric average of the X-Y ISRS.

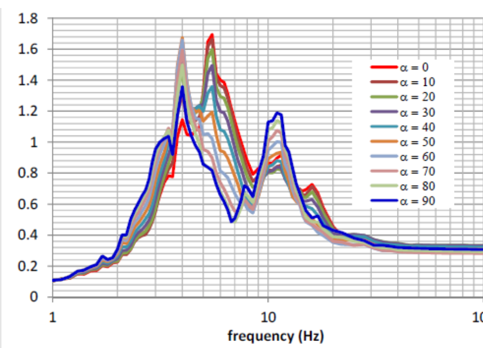
This paper begins with a brief review of our previous work on resultant ISRS. Then, we provide additional numerical verification that resultant ISRS are insensitive to the orientation of the horizontal Cartesian axes. To this end, we examine samples of ISRS obtained via time-history analyses of finite element models of representative nuclear power structures. Finally, we assess ISRS calculated with two appreciably different structural models of the same structure, namely, a finite element model and a stick model. While differences between the results of the two models are still observed, resultant ISRS compare more favourable than axes oriented ISRS, showing that resultant ISRS, being less sensitive to the refinement of the structural model, provide more robust and reliable estimates of seismic demand.

SUMMARY OF PREVIOUS WORK

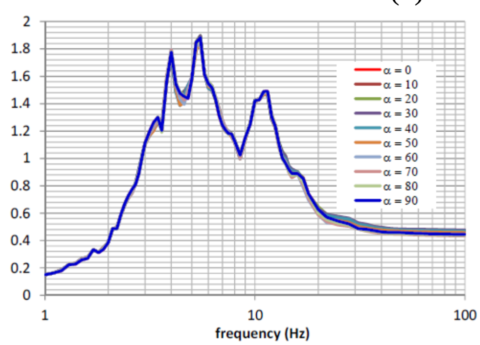
The authors have recently presented a study on five percent damped horizontal ISRS obtained via dynamic analyses finite element models Jarernprasert et al. (2014). The same time history was used separately as seismic input in two conventional X and Y horizontal directions. Resulting floor time histories in the X and Y horizontal axes were used to obtain ISRS at representative points on the structure. Co-directional ISRS (one from each direction of ground motion) were combined by the SRSS rule. Maintaining the orientation of X and Y for the seismic input, ISRS were also calculated along axes rotated by an angle α with respect to X and Y. Figure 1 reproduces the comparison of the ISRS for α between zero and 90 degrees, showing a strong dependence on the orientation of the ISRS.



(a) ISRS for α respect to Y



(b) ISRS for α respect to X



c) Resultant ISRS

Figure 1. ISRS along axes at an angle α, a) with respect to the original Y axis ($ISRS_{Y\alpha}$), b) with respect to the original X axis ($ISRS_{X\alpha}$), and c) resultant spectra.

Figure 1 also reproduces the comparison of the resultant ISRS, equal to $\sqrt{(ISRS_{X\alpha}^2 + ISRS_{Y\alpha}^2)}$, for all values of α. Even though the ISRS are not strictly vectors, the remarkable invariance of the resultant spectra probably reflects the vectorial nature of the in-structure accelerations used in calculating the ISRS.

CONFIRMATORY RESULTS

For this study we used several models of NPP buildings for additional comparative analyses of ISRS. The finite element model of the first Building 1 is displayed in ***Figure 2***. This is a concrete shear wall building with seven floors and it was prepared following industry-accepted guidelines ASCE (2013). Time history analyses were carried out with the seismic input in two X−Y horizontal axes. Resulting floor accelerations were used to calculate five percent damped ISRS at selected points in the X and Y directions. Co-directional spectra were combined by the SRSS rule.

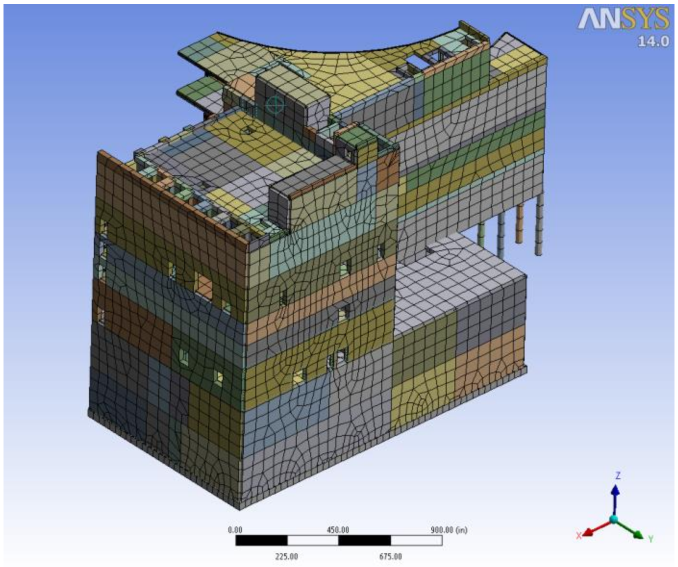


Figure 2. Finite element model of a typical NPP building.

New axes X′ and Y′ were defined by rotating the original X and Y by 45 degrees. The seismic analyses were repeated and ISRS were obtained along X′ and Y′. Figure 3 compares the ISRS along the original and the rotated axes, at a corner point on the sixth floor of the building in Figure 2. Similarly, Figure 4 compares ISRS at an eccentric point at the top floor of another building (Building 2) analysed with a finite element model. Building 2 is more irregular than Building 1 and has a lower height to base dimension ratio. Both figures are evidence that changing the orientation of horizontal axes leads to noticeable differences on the ISRS shapes and peaks.

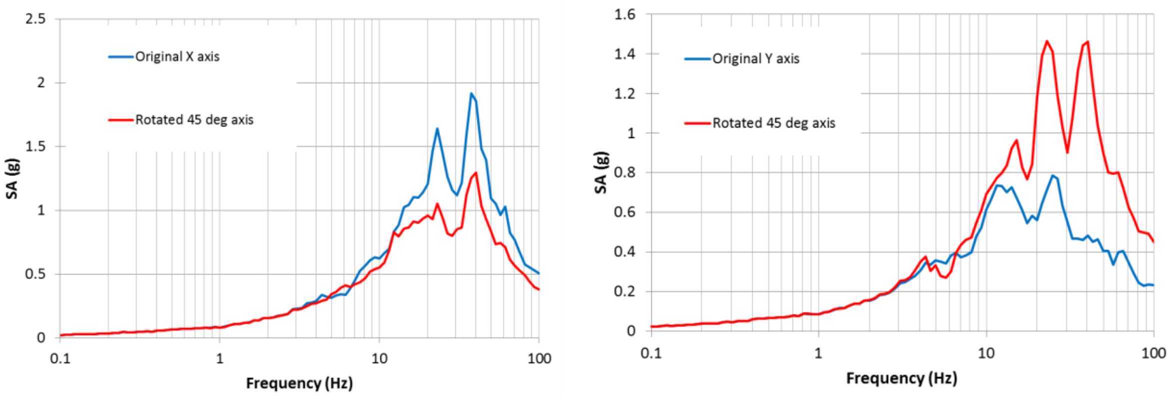


Figure 3. ISRS along Original (blue) and Rotated (red) Axes at an Intermediate Elevation of Building 1.

On the other hand, the resultant ISRS shown in Figure 5, related to the conventional ISRS in Figures 3 and 4, are insensitive to the orientation of the Cartesian axes. This observation holds for all comparisons that we have performed, and it is a desirable feature in probabilistic evaluations because it provides a seismic response essentially independent of the orientation of the "principal" directions of equipment with respect to X and Y. For brevity, only representative ISRS are presented in Figures 3, 4 and 5 but confirmed our conclusions by examining ISRS at other buildings and with different input.

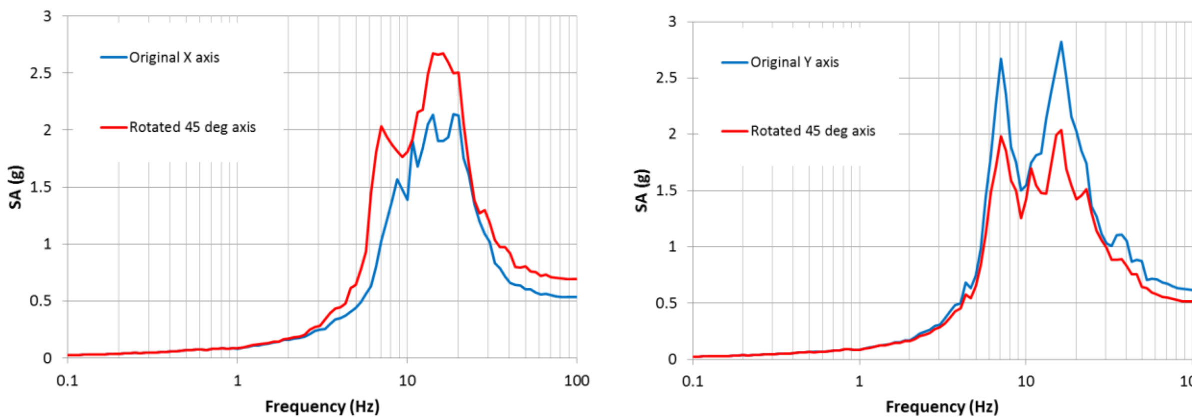
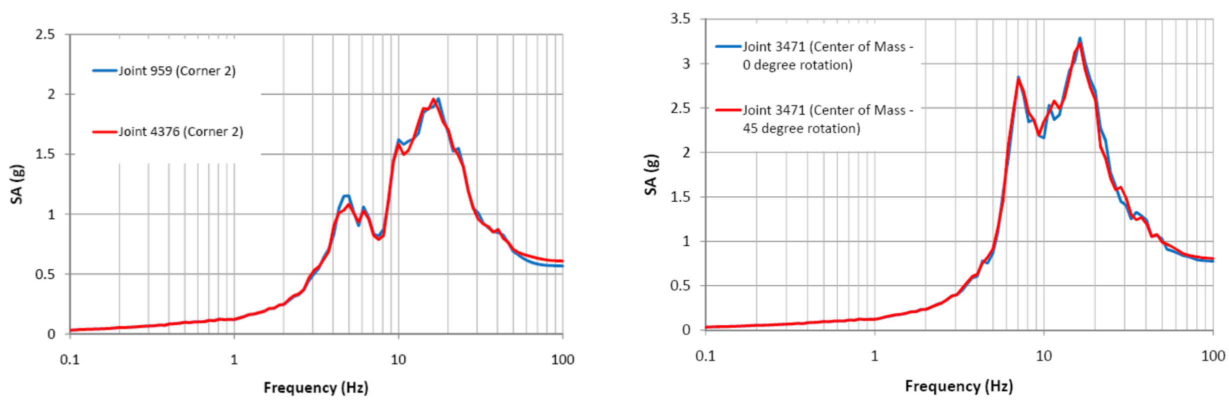


Figure 4. ISRS along original (blue) and rotated (red) Axes at a High Elevation of Building 2.



a) For Building 1 (Fig. 2) b) For Building 2 (Fig. 4)

Figure 5. Resultant ISRS along Original (blue) and Rotated (red) Axes.

Jarernprasert et al. (2014) have also studied the effects of directionality on other central measures of a variable ISRS such as the arithmetic average or geometric mean. Considering an average ISRS to be applied in any two horizontal directions is consistent with the accepted understanding that the horizontal ground spectrum represents the geometric mean to be input in any two orthogonal directions. Thus, we have compared average spectra at several locations of representative buildings. In Figure 6, the arithmetic average of the spectra for the original axes (blue line) is compared to the average spectrum when the horizontal axes were rotated by 45 degrees (red line). The average spectrum practically remains unchanged under the rotation of horizontal axes, and identical conclusion is extracted from comparing geometric means. Figure 6 also displays in black line the resultant spectrum divided by $\sqrt{2}$, i.e., one of two equal orthogonal components of the spectrum. The black line overlaps the blue and red ones, indicating that the component of the resultant spectra constitutes an excellent proxy of the average spectra.

ISRS FROM DIFFERENT MODELS OF THE SAME BUILDING

Before the widespread availability of computer codes, the seismic analyses of nuclear facilities were conducted using simplified stick models. In such models, building masses are lumped at the floor elevations and are connected by beam representations of inter-story stiffness attributed to walls and columns. A stick model (SM) assumes that floor slabs are sufficiently stiff in-plane to be represented as horizontal rigid diaphragms, and that under overall bending moments, horizontal planar sections remain plane. Because the development of three-dimensional finite element models (FEMs) may still be expensive and time consuming, improved three-dimensional stick models are still a viable option for analyses in support re-evaluations of plant structures and supported mechanical and electrical equipment.

In this section we assess the ability of SMs to estimate the seismic response of more accurate FEMs of the same building. The focus of our assessment is placed on ISRS calculated with the two analytical representations with the same total mass and under identical seismic ground motion. Figure 7 shows the stick model for Building 1, modeled with finite elements as presented in Figure 2.

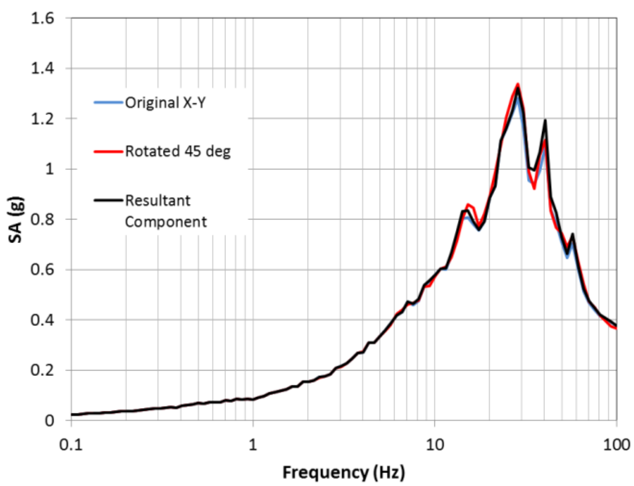


Figure 6. Horizontal Average ISRS of Building 1and Component of Resultant Spectrum.

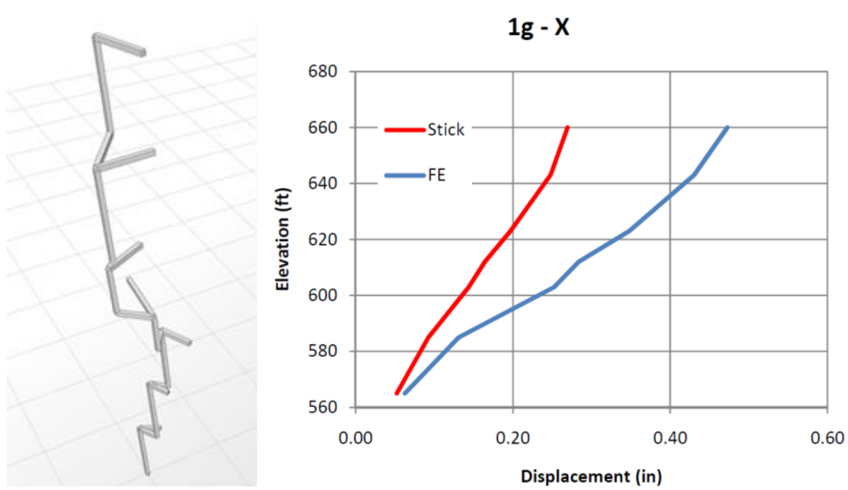


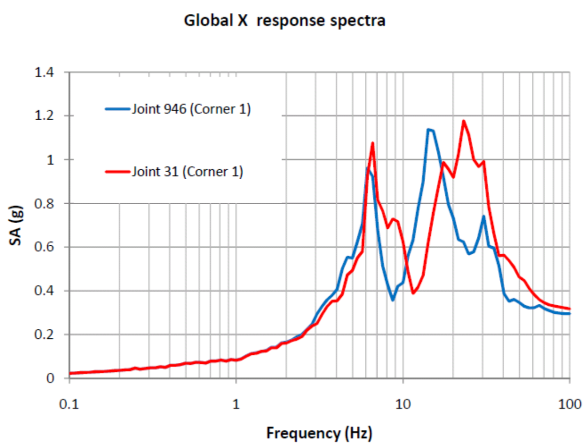
Figure 7. Sick Model and X-Displacements of Building 1 due to 1-g Forces.

Table 1: Modal Frequencies and Mass Participations from the Models of Building 1.

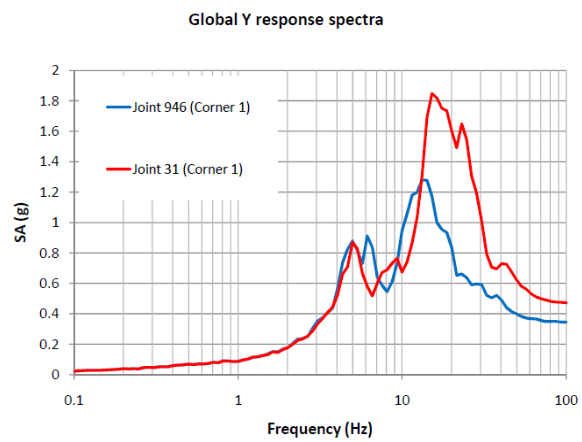
Stick Model (SM)			
Mode	Freq. (Hz)	X-mass (%)	Y-mass (%)
1	5.1	0.0	63.2
2	6.8	64.3	0.0
3	9.0	6.1	0.1

Finite Element Model (FEM)			
Mode	Freq. (Hz)	X-mass (%)	Y-mass (%)
1	3.6	6.7	31.7
2	4.7	24.6	21.3
3	6.3	27.8	1.3

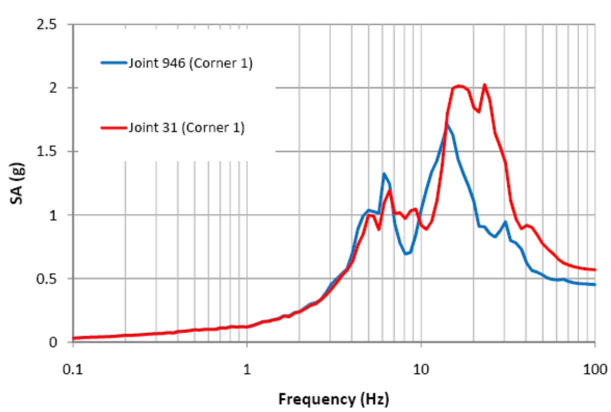
The stick model in Figure 7 includes sufficient beam elements to represent the distribution of mass with height and mass eccentricities. Figure 7 also compares the lateral displacements of the centers of masses in the X axis due to 1-g forces applied to the two models of Building 1. The displacements from the SM (red line) are appreciably smaller than those from the FEM (blue line) indicating that the SM is stiffer than the FEM. This also explains the higher lateral natural frequencies and mass participations produced by the SM as listed in the comparative Table 1. The reason is that the FEM captures numerous local deformations in walls and floors. The SM could be improved to be closer to the FEM EPRI (2014), but this was not attempted to compare resultant ISRS from a SM developed independently of a FEM.



a) ISRS along X



b) ISRS along Y

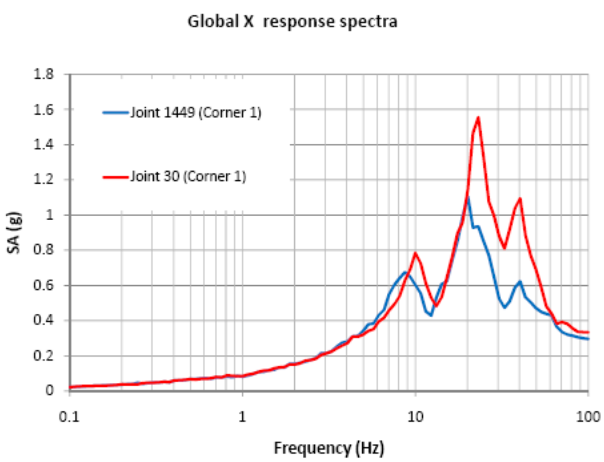


c) Resultant ISRS

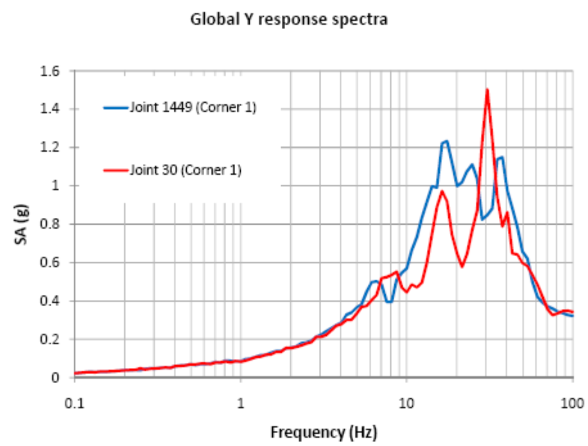
Figure 9. ISRS at a Corner Point 1 at a High Elevation of Building 1.

Parts a) and b) of Figure 9 display the ISRS along X and Y, respectively, obtained with the SM (red line) and with the FEM (blue line). In general, the Y–ISRS from the SM envelops the ISRS from the FEM except for frequencies between and 17 Hz where the SM produces lower values. The peaks of the ISRS reflect differences in the natural frequencies of their corresponding models and the Y–peak from the SM overestimates the FEM peak by about 43%. The comparison of resultant ISRS in Figure 9 Part c) is more favorable not only for exhibiting closer values but because the SM–ISRS envelops the FEM–ISRS in practically all frequencies. Further, the peak of the resultant ISRS yielded by the SM overestimates the peak from the FEM by a reduced amount of 27%.

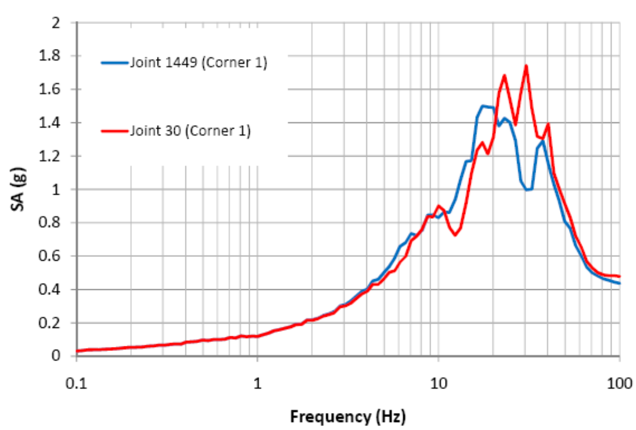
SMs and FEMs were also developed for a second building with more irregular distributions of masses and stiffness than Building 1, and with a smaller height to base dimension ratio. None of the natural modes of Building 2 engages more than about 50 percent of the total mass, and lower natural frequencies are not as dominant as in Building 1. The comparison of ISRS is presented in Figure 10, confirming that resultant ISRS from the SM furnish a better match with the resultant counterpart from FEM than conventional ISRS, both in spectral shape and in peak values.



a) ISRS along X



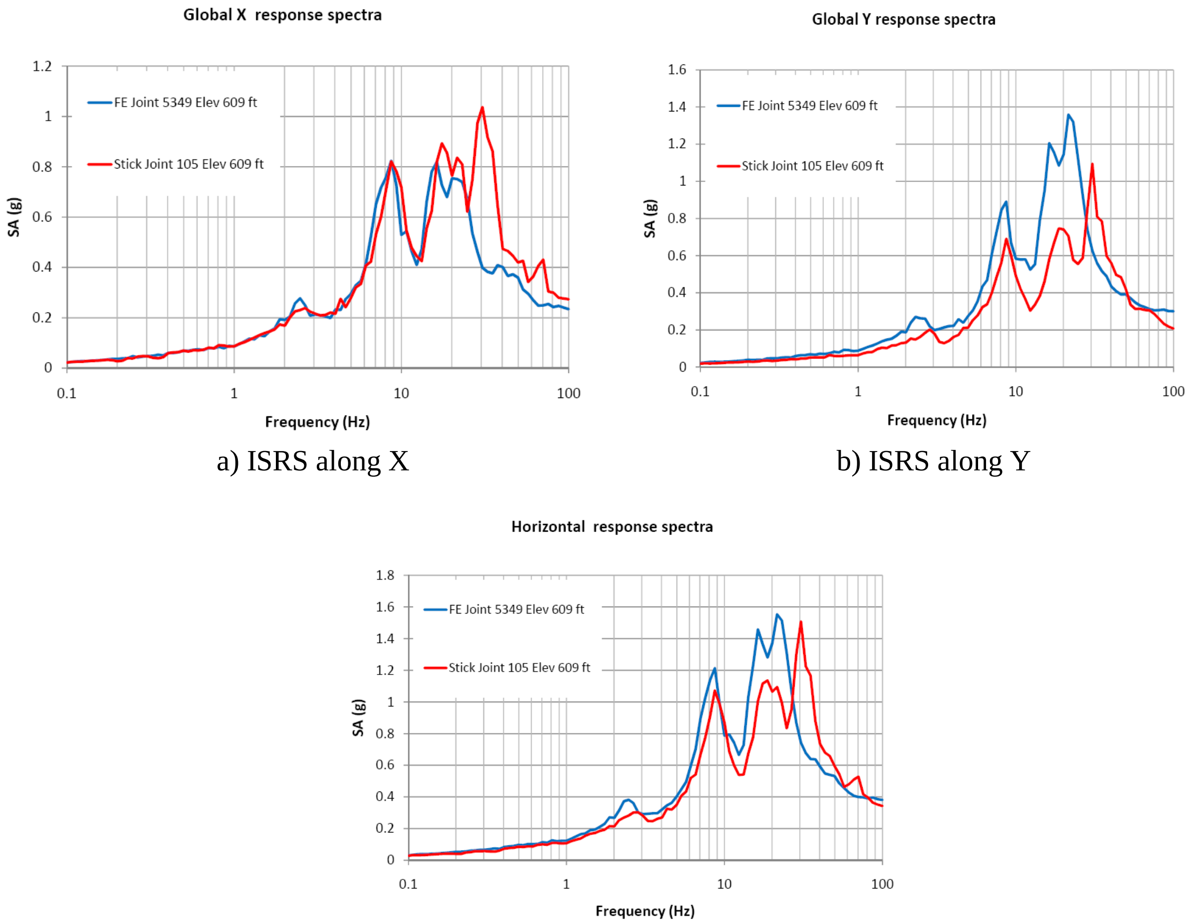
b) ISRS along Y



c) Resultant ISRS

Figure 10. ISRS at an Eccentric Point of Building 2.

ISRS with FEM and SM were additionally developed for a cylindrical Building 3, representing a concrete shield structure. Due to the symmetry of the building, the SM provides an overall closer approximation to the FEM than Buildings 1 and 2. Also, the fundamental lateral frequency of 2.9 hertz (Hz) according to the SM is very close to 2.7 Hz yielded by FEM. ISRS were calculated where several components are attached to the cylindrical wall of the structure. Figure 11 compares ISRS at an intermediate elevation showing that results from the SM envelope those of the FEM in the X direction but not in Y. The differences are mostly attributed to out of roundness deflections not represented in the SM. However, Figure 11 c) shows again that an enhanced comparison is attained by contrasting resultant ISRS. Differences due to ovalling are still evident, but the resultant SM-ISRS and FEM-ISRS are appreciably closer than the X and Y ISRS. In particular the spectral peaks exhibit much closer values.



a) ISRS along X

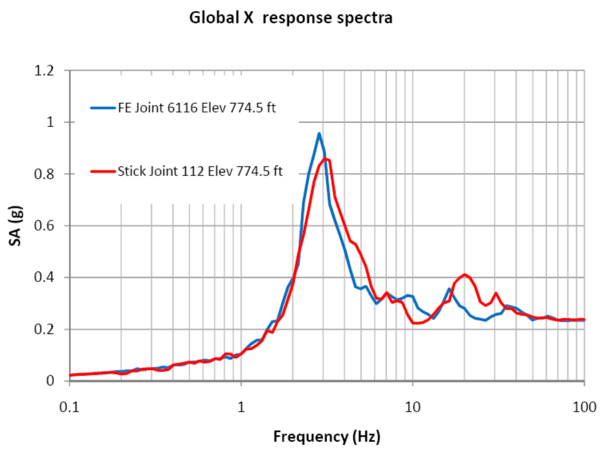
b) ISRS along Y

c) Resultant ISRS

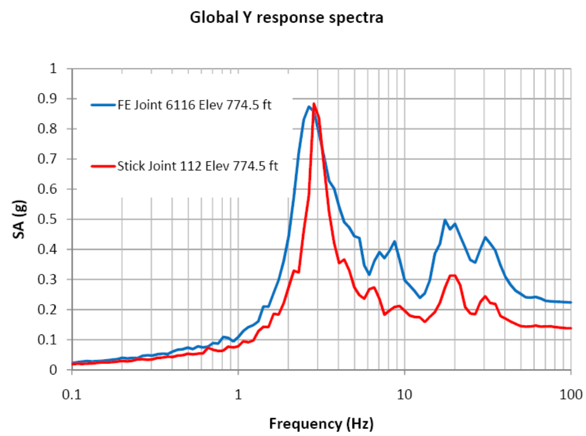
Figure 11. ISRS in the X-Direction at an Intermediate Elevation of Building 3.

Similar comparisons of ISRS are depicted in Figure 12 a) through c), also for Building 3, but now at an elevation in the vicinity of the building cap. The agreement between ISRS from the SM and the FEM are all better than at the lower elevation. The reason is that the horizontal cap minimizes out of roundness distortions. The closeness between the resultant ISRS from both models (Figure 12 c) is still appreciably more evident than for conventional ISRS.

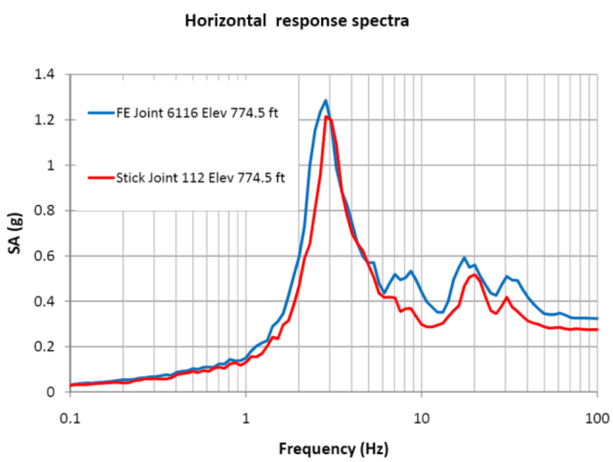
From the comparative study between ISRS from FEM and SM by Hardy et al. EPRI (2014) we selected results in Chapter 3 for a compact symmetric structure, where constraints were imposed on the FEM that are implicit in the stick model. Parts a and b of Figure 13 reproduce the X and Y ISRS at the main slab of the building from both models. Fair agreement is observed between the ISRS in Y, but in X, the peak of the ISRS from the SM (blue line) is about 30 percent higher and shifted to the right when compared to the FEM result (red line). Part c of Figure 13 displays the enveloped ISRS (maximum of X and Y values), which is frequently used in calculation of component fragilities. Part d) of this figure plots the two equal components of the ISRS (resultant divided by 2). While comparisons of shapes in the last two plots are similar, the component of the resultant is not conservatively biased.



a) ISRS along X



b) ISRS along Y

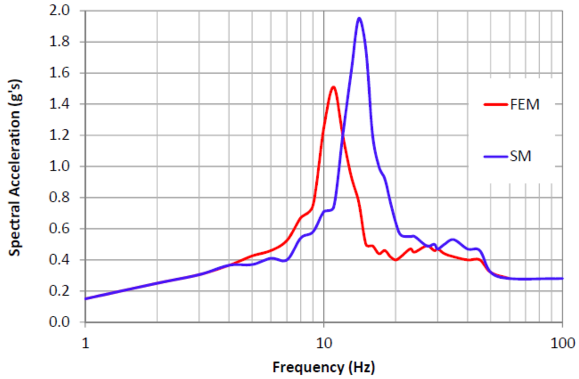


c) Resultant ISRS

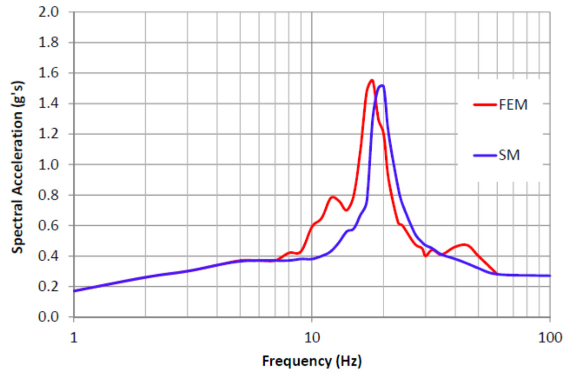
Figure 12. ISRS at a High Elevation of Building 3.

CONCLUSIONS

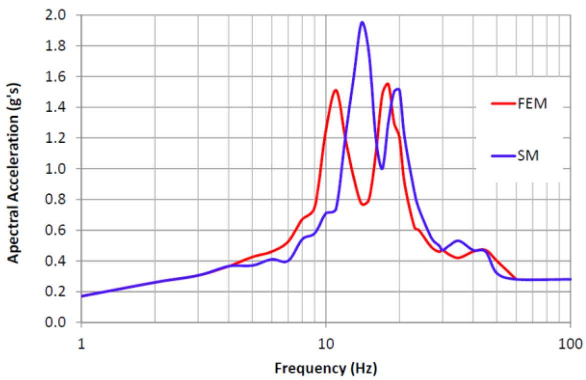
The study reported in this paper confirms that "resultant horizontal ISRS" appreciably offsets the effects of directional uncertainties. This suggests the convenience of using the practically invariant resultant ISRS or, equivalently, its equal orthogonal components (resultant divided by square root of 2) in the calculation of component fragilities. We trust that these are not merely accidental findings and will be substantiated by further analyses conducted in other projects. Additionally, the orthogonal components of the resultant ISRS provide a very close estimate of the arithmetic or geometric average horizontal ISRS. The use of geometric mean ISRS would be consistent with using ground motion spectra as the geometric mean of two orthogonal components. In addition of being practically indistinguishable in the cases examined in this paper, the components of the resultant spectra leads to the correct results in the limiting condition where one horizontal ISRS is zero, unlike the arithmetic or geometric means.



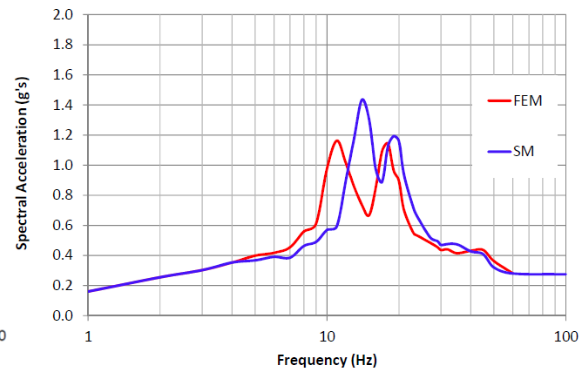
a) ISRS along X



b) ISRS along Y



c) Envelope ISRS



d) Component of the Resultant ISRS

Figure 13. ISRS at a High Elevation of Building 3.

Our comparisons of ISRS from stick models and from finite element models indicate that resultant ISRS are a more stable estimate of the seismic demand, being less sensitive to the degree of refinement of the structural model. This conclusion applies when local deformations, which stick models are unable to represent, do not affect significantly the motion where the ISRS are calculated. Resultant ISRS should be even more robust in comparisons between results from relatively coarse finite elements models with those of more refined models.

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