FINITE ELEMENT AND LUMPED MASS STRUCTURE MODELLING FOR SPRAs

Greg Hardy¹, Ruben Soto², Steve Short³ and Robert Kassawara⁴

¹ Senior Principal, Simpson Gumpertz & Heger Inc., US
² Project Manager, Simpson Gumpertz & Heger Inc., US
³ Staff Consultant, Simpson Gumpertz & Heger Inc., US
⁴ Project Manager, Electric Power Research Institute, US

ABSTRACT

A critical part of seismic probabilistic risk assessments or seismic margin assessments is the development and use of mathematical models of safety-related structures. From previous design-type analyses, current nuclear power plants (NPPs) typically have lumped mass structural models (LMSMs) to represent safety-related structures. While detailed finite element models (DFEMs) are considered to be more precise, they are complex, time consuming, and expensive to develop and use. While LMSMs are less complex, their accuracy when compared to DFEMs has been brought into question.

The approach taken in a recent Electric Power Research Institute project was to generate LMSMs and DFEMs for typical NPP structures, and compare the structural response to earthquake loadings. This paper will summarize the results of the comparative assessments between the LMSMs and DFEMs used in seismic response analyses. In general, more complicated structures (horizontal, vertical, and torsional irregularities; flexible diaphragms due to significant openings or long spans) that have multiple/varied load paths should use DFEMs in order to adequately assess the seismic response of equipment located in those structures. LMSMs could potentially be enhanced to more closely match the responses generated by the DFEMs, but the effort required to model these enhancements could approach the effort required to generate a DFEM. Structures that are less complex (e.g., axisymmetric) and have simpler load paths give seismic response results from the LMSMs that more closely match the DFEM results. In addition, methods to upgrade the LMSMs to improve on that seismic response match will be discussed.

INTRODUCTION

The current fleet of nuclear power plants (NPPs) in the United States typically have stick models (also referred to as lumped mass structural models (LMSMs)) to represent the safety-related structures, both for the original seismic design basis and for subsequent beyond design basis efforts, such as for the Individual Plant Evaluation for External Events (IPEEE) program. New plant applications typically require that more modern and sophisticated detailed finite element models (DFEMs), available with present-day computing capabilities, be used for structural and seismic design analyses of their safety-related structures. LMSMs have limitations in terms of assumed rigid slabs (in-plane and out-of-plane) and limited degrees of freedom. These different structural modelling approaches used for existing or new NPPs have resulted in the question regarding whether or not the existing stick models are adequate for use in seismic probabilistic risk assessments (SPRAs) and seismic margin assessments (SMAs) despite these limitations.

The existing structural models used in dynamic analyses to develop seismic responses for the design, licensing, and qualification of plant structures, systems, and components (e.g., LMSMs) were reasonably complex for their original intended purpose at the time they were developed. These models were used to capture the overall structural frequencies, mode shapes, and seismic responses. Typically, if model
complexity was increased, the contribution of the modes identified within the simpler model was decreased, as modal mass is shifted to other modes. This often resulted in lower spectral peaks for the significant modes of the structure. However, more recent experience has shown that, for some structures, additional complexity of the numerical model may lead to the identification of higher modes that may be important for some systems and components. In addition, the effect of in-plane and out-of-plane slab response was determined to be important in calculating the horizontal and vertical structural frequencies, respectively.

Electric Power Research Institute (EPRI) 1025287, *Seismic Evaluation Guidance: Screening, Prioritization, and Implementation Details (SPID) for the Resolution of Fukushima Near-Term Task Force Recommendation 2.1: Seismic* (2013) recommends criteria against which structural engineers and peer reviewers should review existing structural models to establish adequacy for SPRAs and SMAs. These SPID criteria are summarized below:

1. The structural models should be capable of capturing the overall structural responses for both the horizontal and vertical components of ground motion.
2. If there is significant coupling between the horizontal and the vertical responses, one combined structural model should be used for analysing all three directions of the earthquake.
3. Structural mass (total structural, major components, and appropriate portion of live load) should be lumped so the total mass, as well as the centre of gravity, is preserved. Rotational inertia should be included if it affects response in the frequency range of interest.
4. The number of nodal or dynamic degrees of freedom should be sufficient to represent significant structural modes. All modes up to structural natural frequencies of about 20 Hz in all directions should be included.
5. Torsional effects resulting from eccentricities between the centre of mass and the centre of rigidity should be included. The centre of mass and the centre of rigidity may not be coincident at all levels, and the torsional rigidity should be computed.
6. The analyst should assess whether a “one-stick” model sufficiently represents the structure. For example, two-stick models could be more appropriate for the analysis of internal and external structures of the containment founded on a common mat.
7. The structural analyst should review whether in-plane floor flexibility (and subsequent amplified seismic response) has been captured appropriately for the purposes of developing accurate seismic response (EPRI (2013) stipulates up to a 15 Hz frequency).

Existing structural models (i.e., those used for design basis, USIA-46, or IPEEE studies) could potentially be used in structural dynamic analyses that are performed to support SPRAs or SMAs. However, as noted in the SPID (EPRI, 2013), their seismic adequacy should be demonstrated for this purpose. This requires that a review of the existing models be performed by an experienced structural engineer (and a peer reviewer) to determine the adequacy of the models for dynamic analysis for application in seismic risk assessments. The purpose of this project, sponsored by EPRI, is to provide these experienced structural engineers with some direct model seismic response comparisons, which will assist them in calibrating their judgments (EPRI, 2014).

EPRI has conducted a set of research tasks to address this question related to the structural model fidelity as it pertains to seismic response requirements. To address this topic in a generic manner, seismic response characterization studies have been conducted, which include variation in two key elements in the seismic response:

- Structural model complexity
- Site response characteristics
Two nuclear structures were selected for this study: a representative control building was selected for a complex structure case study, and a representative diesel generator building (DGB) was selected for a compact structure case study. For each of these cases, a fixed-base analysis was performed to represent a rock site response. Seismic response incorporating soil-structure interaction (SSI) was conducted to represent a soil site response.

**COMPLEX STRUCTURE MODEL RESULTS**

The complex structure for this research study was a control building from a U.S. NPP. The control building is a six-story concrete shear wall structure; two of its lower floors are embedded into the soil on three sides. The control building’s walls, slabs, and columns are all reinforced concrete. Steel beams are also part of the vertical load-resisting system. A single set of input acceleration histories (X, Y, and Z components) were used to perform the fixed-base and SSI analyses. Both the LMSM and the DFEM were developed using the computer program SAP2000 (CSI, 2010; SGH, 2011).

The control building LMSM is a re-creation of the design basis lumped mass model. It consists of multiple beam elements per floor (multi-stick) used to represent the full-height reinforced concrete walls. The nodes at the ends of these beam elements are each rigidly connected to a single floor mass node with high stiffness elements representing a rigid slab (in-plane and out-of-plane). The foundation slab, treated as a rigid foundation in the design basis analysis, is also represented with a rigid connection to a control point at the bottom of the foundation. The control building DFEM was developed using shell and beam elements to explicitly represent the structural geometry. Figure 1 depicts the DFEM of the control building and shows the complex nature of the structure and the variety of load paths that exist in resisting the seismic loads.

![Figure 1: Detailed Finite Element Model of the Control Building](image-url)
The total mass from the two models were very comparable, but the stiffnesses were found to be different in the simple stick model vs. the DFEM. The deflection due to a 1g static load is compared in Figure 2 for three locations in the DFEM compared to the LMSM. These kinds of stiffness differences will typically result in corresponding differences in the modal properties and the in-structure response spectra (ISRS).

The in-structure responses for the fixed-base models were compared at numerous locations throughout the structure. The responses for the LMSM were often larger than the DFEM (Figure 3a), while there were also locations where the results of the DFEM exceeded the LMSM (Figure 3b). The differences in acceleration, combined with the frequency shifts that were exhibited, were judged to be larger than would be typically deemed acceptable within SPRA response analyses. The differences were also significant when SSI analyses were conducted for the soil site case.

Figure 2: Static Analysis 1g Deflection Comparison in the Horizontal X-Direction – Control Building

Figure 3a: LMSM exceeds the DFEM Response   Figure 3b: DFEM Response exceeds the LMSM
SIMPLIFIED STRUCTURE MODEL RESULTS

A nuclear plant DGB was selected to represent a compact, symmetric structure for purposes of this study. The DGB is a single-story concrete shear wall structure that is founded at the ground surface. Both the LMSM and the DFEM were developed using the computer program SAP2000 (CSI, 2010; SGH, 2011).

The DGB LMSM consists of rigid beam elements at each slab level, which includes the roof slab and slabs at the roofs of the exhaust shafts. These rigid links serve to connect the nodes at the centre of rigidity of the walls below the slab, the centre of rigidity of the walls above the slab, and the centre of mass of the slab in question. The foundation slab is represented with a rigid connection to a control point for seismic input at the bottom of the foundation.

The DGB DFEM was developed using shell and beam elements to explicitly represent the structural geometry. In order to yield an objective comparison between the two types of structural models (LMSM and DFEM), certain modelling parameters remained constant. This includes consistency in material properties, uncracked concrete sections, rigid foundation assumption, foundation input motion, and the equipment and live load mass. (Note: These same consistency assumptions were also made for the complex model comparisons.) It must be noted that certain parameters (i.e., rigid foundation and uncracked sections) should be validated through sensitivity studies, such that recommendations for structural model refinement (LMSM or DFEM) can be made prior to an actual SPRA seismic response analysis. The DGB DFEM is shown in Figure 4.

Similar to the complex structure evaluation, a comparison study of the example DGB LMSM and DFEM was performed to evaluate the effects of the inherent LMSM modelling simplifications. The study is based on the seismic responses to the recorded time history of an actual seismic event. The input motion
record was taken from the Pacific Earthquake Engineering Research Next Generation Attenuation database (2012) and consists of a single set of acceleration histories (X, Y, Z components). The purpose of this assessment was to determine whether an LMSM is adequate to develop sufficiently accurate structural response of a compact symmetric building compared to a DFEM. Static 1g analysis results, model properties, and ISRS are used to compare the similarities and differences between the two structural models. The masses of the two models matched exactly, but the 1g static displacement showed differences (Figure 5). These differences are similar to the complex model results which show that the LMSM is stiffer than the DFEM, which will result in a higher fundamental frequency than results from the LMSM. Figure 5 also plots a case where the diaphragm was constrained to represent a rigid slab in the DFEM and shows much closer match in the static displacement.

ISRS were calculated for both models for both the fixed-base case (representing the rock site response) and the soil site case. Both of these cases resulted in some differences in the responses at certain locations in the model. The differences ranged from higher responses in the LMSM to lower responses in the LMSM, and many locations where the responses were similar. Figure 6 depicts a nodal location where the response in one horizontal direction differed significantly between the two models, while in the other horizontal direction, the responses were very comparable. This difference is related to the structure having a flexible diaphragm in the X-direction and a more rigid diaphragm in the Y-direction due to the rectangular shape of the building and the presence of a centre wall. The X-direction responses showed a considerable frequency shift, as well as an increase in amplitude for the LMSM. But at frequencies below approximately 13 Hz, it would be unconservative to use the LMSM results for the SPRA or SMA.
RESULTS AND CONCLUSIONS

The results of the comparative assessments between the LMSMs and DFEMs used in seismic response analyses were documented in EPRI 3002002804 (2014). In general, it is recommended that more complicated structures with multiple/varied load paths use DFEMs in order to adequately assess the seismic response of equipment located in those structures. LMSMs could potentially be enhanced to more closely match the responses generated by the DFEMs. However, the effort required to model these enhancements could approach the effort required to generate a DFEM for these complex structures. Structures that are less complex (e.g., axisymmetric) and have simpler load paths give seismic response results from the LMSMs that more closely match the DFEM results.

Specific conclusions from this recent research (EPRI, 2014) include the following:

- DFEMs provide the most accurate characterization of seismic response for equipment located within the structure.
LMSMs can approximate the seismic response, and may exhibit sufficient accuracy depending on the structural configuration and on the intended SPRA/SMA application.

Differences in seismic response between LMSMs and DFEMs generally result from differences in the natural frequencies of the equivalent structures, the mass participation ratios at equivalent modes, the spectral shape of the input motion, the shifting in natural frequencies due to the coupling of the structure with the soil, and the inability of the LMSM to capture the slab’s out-of-plane and in-plane behaviour.

Structural modelling of the floor slabs (both in-plane and out-of-plane) is typically shown to be the most important element in determining the accuracy of the LMSM seismic response. In-plane and out-of-plane slab flexibility and the resulting amplified seismic response have to be carefully considered by a structural analyst in order to ensure that accurate seismic response is captured up to the frequency range required by the SPRA.

LMSMs that assume rigid floor slabs (in-plane and out-of-plane) result in increased stiffness (relative to the DFEM results) in all three directions because the flexible behaviour of slabs is constrained. The increased stiffness of the LMSM was observed in a comparison of the natural frequencies of important structural modes and in the resulting shifting of the fixed-base ISRS peaks. The increase in stiffness was observed for both the compact and complex structures reviewed as part of this study.

Modelling methods were studied to effectively upgrade the simplified compact structure LMSM to more closely match the results for the corresponding DFEM. These methods consist of adding simple oscillators to capture the flexibility in floor slabs (both in-plane and out-of-plane).

Conclusions from this study were based on a limited review of structure types, structure configurations, and input motions. Experience and judgment need to be carefully applied to project these results to other structures. While additional research to expand the breadth of the structures, configurations, and seismic input would undoubtedly enrich/extend the conclusions from this study, the basic conclusions are judged to be robust and will prove valuable as a guide for structural engineers participating in the seismic response portion of an SPRA.

REFERENCES