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STATE OF THE ART IN SEISMIC FRAGILITY ASSESSMENT

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ABSTRACT

Seismic fragilities have been an integral tool to the Seismic Probabilistic Risk Assessment (SPRA) since the inception of SPRAs 35+ years ago. The earthquake/tsunami that damaged the Fukushima nuclear power plant increased the use of the SPRA and at the same time was a motivator for increased research into improved fragility methods. Seismic fragility assessment is becoming a more common tool, expanding to non-nuclear industries, as risk-informed approaches are becoming the normal for new design and for evaluation.

Documents that form the backbone of the seismic fragility methodology include the following Electric Power Research Institute (EPRI) reports:

- EPRI NP-6041, *A Methodology for Assessment of Nuclear Power Plant Seismic Margin (Revision 1)*, August 1991
- EPRI TR-103959, *Methodology for Developing Seismic Fragilities*, June 1994
- EPRI 1002988, *Seismic Fragility Applications Guide*, December 2002
- EPRI 1019200, *Seismic Fragility Applications Guide Update*, December 2009
- EPRI 30020000709, *SPRA Implementation Guide*, December 2013
- EPRI 1025287, Seismic Evaluation Guidance: Screening, Prioritization and Implementation Details, 2013

EPRI is developing a new seismic fragility guide to combine appropriate fragility related elements from these documents and from other references (including the EPRI high frequency report and EPRI documents related to the U.S. industry response to the Fukushima accident) and to develop new criteria to address current areas needing improvement. This new EPRI seismic fragility guide will represent the state-of-the-art with respect to seismic fragility when it is published in 2018. This paper summarizes several of these recent improvements and state-of-the-art seismic fragility methods.

INTRODUCTION

Seismic fragility methods were developed almost forty years ago as part of the first seismic probabilistic risk assessments (SPRAs) for the nuclear power industry. Seismic fragility methodology has evolved tremendously over that time period, as the earthquake effects were better understood and as computational techniques improved. Most recently, utilization of seismic fragility methods within the nuclear power community has increased dramatically as a result of the 2011 Tohoku earthquake/tsunami in Japan that damaged the Fukushima nuclear power plant (NPP). Seismic fragility is becoming a more common tool in the engineering community and has expanded to non-nuclear industries, as risk-informed approaches are becoming the norm for new seismic design and for evaluation.

Seismic fragilities are expressed as sets of conditional failure probabilities and are graphically depicted as fragility curves. A point on a fragility curve quantifies the probability that a structure, system, or component (SSC) will fail given the occurrence of an earthquake of some specified size, typically measured in terms of ground acceleration.

Fragilities are typically represented by a continuum (set) of fragility curves that collectively describe the uncertainty in the assessed structure or component fragility; the curves are identified by the cumulative probability of being the correct or at least a conservative curve (e.g., 95% curve).

Figure 1 depicts the typical seismic family of fragility curves. For this example, the median fragility is shown to be 0.87g peak ground acceleration, and the high confidence of a low probability of failure (HCLPF) is 0.32g.

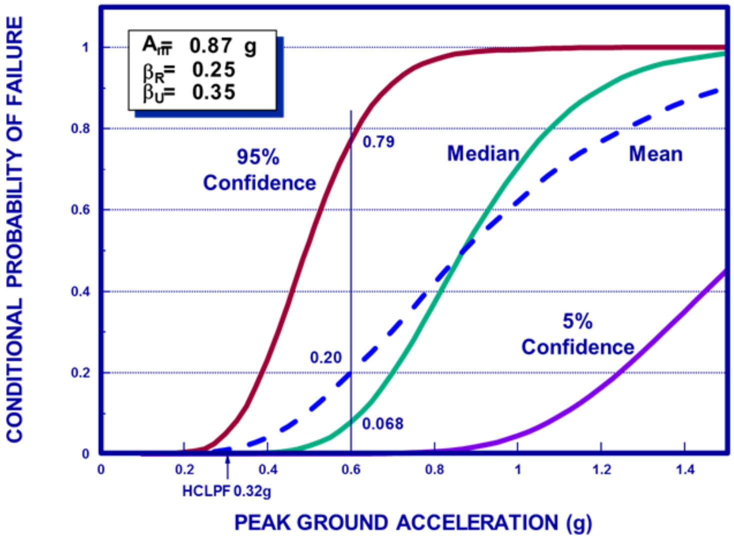

Figure 1: Family of Seismic Fragility Curves

The underlying concepts and definitions necessary for developing fragility curves are discussed in detail in EPRI TR-103959 (1994) and EPRI 3002000709 (2013b). In an SPRA, the fragility curves will ultimately be convolved with the seismic hazard curves to determine unconditional failure probability distributions for use in the systems analysis plant logic model.

RECENT ADVANCES IN SEISMIC FRAGILITIES

Seismic fragilities are developed based on realistic estimates of the seismic capacity of the SSC divided by the seismic response at the location of that SSC. The state of the art has advanced in both the determination of the seismic capacity and the seismic response. Several of these advances are summarized in this paper:

- Seismic Response Analysis Improvements
  - Structure Modeling Fidelity – use of finite element and stick models
  - Development of structure response using equipment/structure interaction methods

- Seismic Capacity Analysis Improvements
  - High Frequency Ductility Methods
  - Embedded Anchor Capacity
  - High Frequency Capacity of Chatter-Sensitive Components
  - Fragility Development Based on Earthquake Experience Data

Structure Modelling Fidelity – Use of Finite Element and Stick Models

A critical part of SPRAs or seismic margin assessments (SMAs) is the development and use of mathematical models of safety-related structures. From previous design-type analyses, current NPPs typically have existing 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 for SPRA applications when compared to DFEMs has been brought into question.

EPRI conducted a research project to assess the quality of LMSM and DFEM models for the purposes of supporting SPRA and SMA studies (EPRI, 2014a). LMSMs and DFEMs were developed for typical NPP structures, and the structural responses to a variety of earthquake loadings were compared. The EPRI study (2014a) demonstrated that, in general, more complicated structures such as the Control Building shown in Figure 2 should be modeled using a DFEM in order to accurately capture the seismic response. These more complicated structures typically have one or more of the following:

- Horizontal, vertical, and torsional irregularities.
- Flexible diaphragms due to significant openings or long spans.
- Multiple/varied load paths.

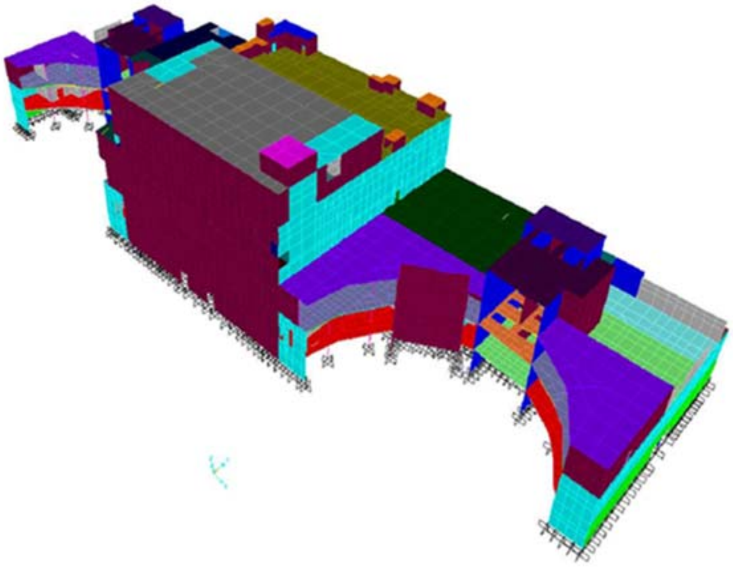

Figure 2: Detailed Finite Element Model of the Control Building

However, EPRI 3002002804 (2014a) also provided a methodology that would enhance the existing LMSMs such that they would more closely match the responses generated by the DFEMs. This approach to enhance the LMSM is technically valid, but for some applications the effort required to model these enhancements could approach the effort required to generate a new 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. The results of this EPRI study are instrumental in identifying the types of structure models that are appropriate for use in realistic beyond design basis studies.

In-Structure Response Spectrum Based on Equipment/Structure Interaction

Floor response spectra for dynamic response of equipment mounted in structures have traditionally been generated without considering dynamic interaction between the structure and the equipment. The seismic structural response typically exhibits a narrow-banded shape. As a result, the floor response spectra usually have high spectral peak amplitudes in the narrow frequency bands corresponding to the natural frequencies of the structural system. The use of such spectra in SPRAs for the development of fragilities can lead to excessive conservatisms, especially when the equipment frequency and structure frequency are in resonance. This situation has been documented in past technical papers, such as Tseng (1989) and Lee and Yoo (2005).

Tseng (1989) proposed an analytical method for developing equipment response spectra using mass ratio in the frequency domain. This method is analytically rigorous and has been validated. It is based on the dynamic sub structuring method as applied to the dynamic soil-structure interaction (SSI) analysis. More recently, EPRI investigated this topic with the goal of validating the usefulness of this method both for new nuclear plant design applications as well as for SPRA applications (EPRI, 2017). The recent EPRI report shows that very limited reductions in the floor spectra are realized for the typical horizontal nuclear structure response, but that more substantial reductions in the vertical response are realized if the structure and equipment have frequencies in the same range. Figure 3 depicts the maximum reductions that can occur (center of the slab condition) for an example vertical floor response spectrum at different mass ratios (MR) between the structure and the equipment.

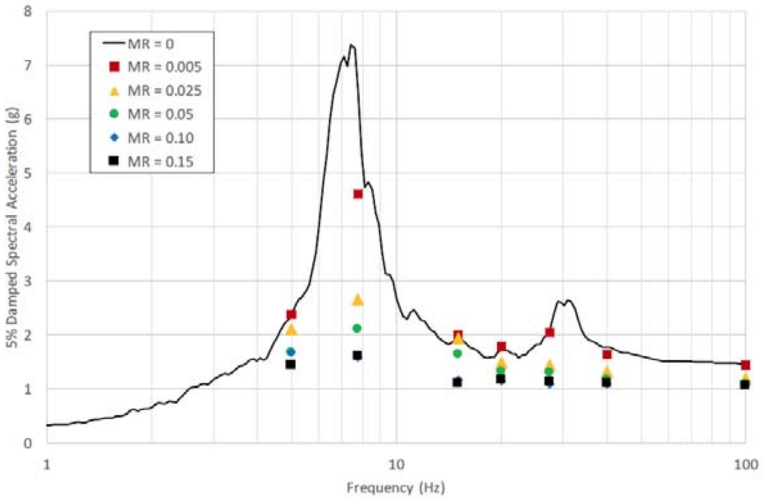

Figure 3. Figure 5-33 from EPRI (2017) Comparison of Vertical ISRS for the Slab Center

High Frequency Ductility Methods

EPRI is currently sponsoring a research project to develop a method for computing inelastic energy absorption factors for use in seismic fragility evaluations of equipment anchorage. Traditionally, the ductility for equipment anchorage has been assumed to be negligible in seismic fragility analyses. This assumption is valid for low frequency components subjected to low frequency seismic input but is not the case for equipment subjected to high frequency input. The anchorage ductility method being developed is based on the Effective Frequency/ Effective Damping approach described in EPRI TR-103959 (1994) for computing inelastic energy absorption factors for shear wall structures. Modifications to the above approach are made for application to equipment anchorage. The developed method can be used to account for the increase in seismic strength of equipment anchorage due to higher ductility levels that are achieved under high frequency seismic excitations. These methods can be used for a variety of anchorage types, and they account for both horizontal and vertical seismic inputs. The inelastic energy absorption factor ($F\mu$) is based on the input floor response spectrum. The computed $F\mu$ is then multiplied with the anchorage elastic strength factor (Fs) to compute the total capacity factor for the anchorage.

The basis for these newly derived high frequency ductility recommendations are a large number of non-linear time history analyses on a simplified model (one for horizontal response and one for vertical response) and incorporating the empirical deflection failure levels for the different anchor types. Figure 4 depicts the simplified model used in the analyses for the horizontal response case.

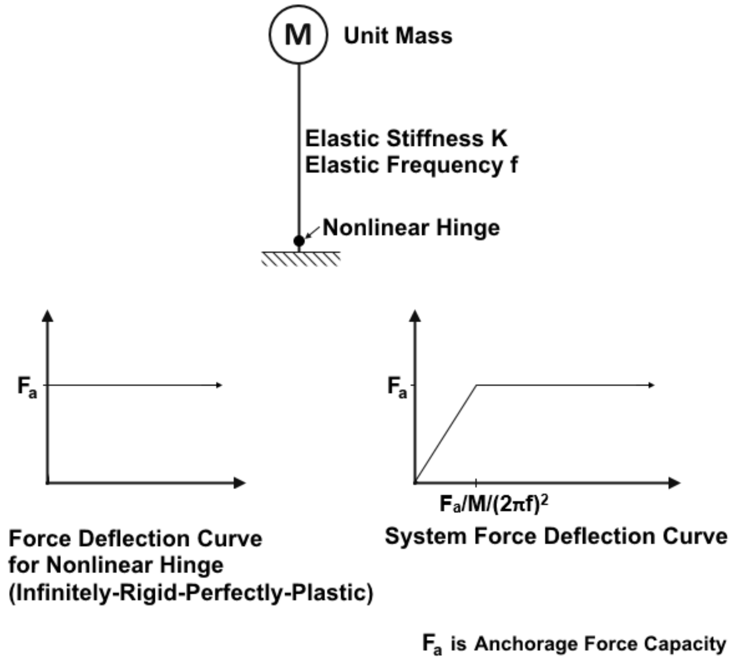

Figure 4: Horizontal Model

The EPRI report is scheduled to be issued in the fall of 2017. The results are showing capacity increase factors that range between 1.0 for very brittle anchorage configurations subjected to primarily low frequency input motions, to a capacity increase in excess of 1.5 for more ductile anchorage configurations subjected to higher frequency input motions. These high frequency ductility values will greatly assist in the generation of more realistic fragility values, particularly for rock site nuclear plants.

Embedded Anchor Capacity

The governing failure modes for many nuclear plant SSCs are their anchorage. Larger and heavier components are typically anchored by embedded anchors (three types are shown in Figure 5). The current versions of ACI 349 and ACI 318 contain methods to develop the capacity for these cast-in-place bolts/embedded anchors, some of which result in significantly reduced capacities when compared to earlier versions of these codes, particularly for larger embedment lengths. These reduced seismic capacities are judged to be overly conservative for SMA and SPRA applications and could potentially lead to modifications to those plants currently conducting seismic assessments. EPRI conducted a research project to ascertain the validity of using existing code strength equations as part of SPRA and SMA applications (EPRI, 2016).

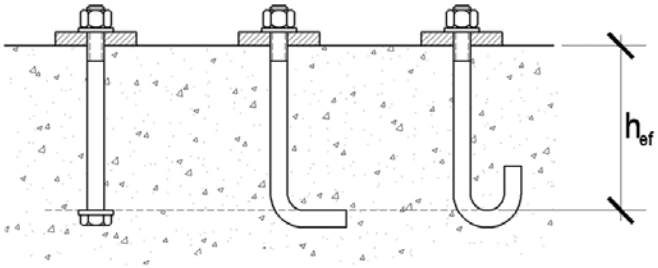

Figure 5: Embedded Anchor Types: (a) Headed Bolt; (b) L-Bolt; (c) J-Bolt.

The approach undertaken for the EPRI 2016 study was to research the available test data for embedded bolts and to use that test data to develop strength characterizations for embedded bolt failures due to tensile loading for use in SPRAs and SMAs. The emphasis of this EPRI project was to study the strength of the deeply embedded bolts since their code strengths were based on a limited set of data that was available at that time. Additional data was found as a part of the EPRI project and regression analyses were conducted using the embedded bolt strength test data. Best fit assessments were then conducted to identify the optimum characterizations for the identification of both the best estimate strengths, as well as the HCLPF strengths.

The results of the EPRI study demonstrate that current American Concrete Institute tensile code equations for design of deeply embedded anchors should be updated for use in deriving the HCLPF for fragility calculations. The newly developed strength relationships more accurately reflect the median and high confidence strengths for embedded anchors and are recommended for use in all SPRAs and SMAs. EPRI is currently conducting a follow-on 2017 study exclusively for the concrete breakout capacity for J-bolts. The goal of this current project is to assess the available test data on J-bolts to see if additional capacity can be demonstrated.

High Frequency Capacity of Chatter-Sensitive Components

Updated seismic hazards in parts of the world that have hard rock characteristics will contain significant amounts of high-frequency vibratory motion. Previous studies concluded that high-frequency motions were, in general, non-damaging to components and structures that have strain- or stress-based potential failures modes. The studies also concluded that components, such as relays and other devices subject to electrical functionality failure modes, have unknown acceleration sensitivity for frequencies greater than 16 Hz.

The ability of some potentially sensitive power plant components to properly function during these high-frequency motions has been considered in prior studies but only in a limited manner. EPRI conducted shake table testing of a diverse set of common NPP safety system components considered to be potentially high-frequency-sensitive. These components are typically relays and other control devices with intermittent states, which are subject to change of state, contact chatter, signal change/drift, and other intermittent electrical functionality failure modes. Testing was conducted using a common test protocol for three-axis high-frequency input motion and monitoring of the component functional performance. The results of this test program were documented in EPRI 3002002997 (EPRI, 2014b). An example of the results of this EPRI test program for selected contactors and motor starters is shown in Figure 6. These tested capacities in the high-frequency part of the spectrum are directly useful for seismic fragilities for situations where the high frequency response is significant.

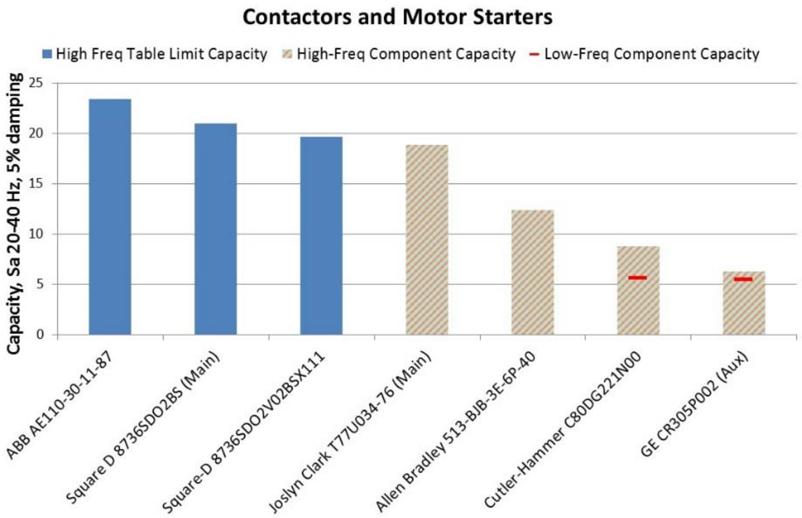

Figure 5: Capacity Test Spectral Acceleration Values Achieved for Selected Contactors and Motor Starters (5% Damping, 20 to 40 Hz).

EPRI 3002004396 (2015) provides guidance on the use of these high frequency test results as part of the seismic fragility or seismic margin process. For plants performing SPRAs, supplemental guidance is provided for applying the seismic fragility methodology provided in EPRI TR-103959 (1994) to account for high-frequency input motions, given the median in-structure response spectra (ISRS) for the cabinet location. Guidance is also provided on the use of (1) low-frequency and high-frequency test capacities and (2) recommendations provided for the application of broad frequency input device capacity factors to cover both the low- and high-frequency regions.

Fragility Development Based on Earthquake Experience Data

Earthquake experience data has been used for many years to perform both deterministic seismic evaluation/qualification studies, as well as to provide the basis for seismic fragility analysis (EPRI, 2009). Probabilistic applications for a seismic fragility involve developing a distribution of seismic capacity based on the observed successful performance of similar equipment in past earthquakes. A recent EPRI research project has documented a more detailed approach for developing fragilities from experience data based on a Bayesian methodology (EPRI, 2014c). In addition, the EPRI study incorporated a more complete characterization of all of the earthquake experience data in the EPRI eSQUG earthquake experience database (EPRI, 2014c). The seismic capacities developed for the four example equipment classes (motor control centers, fans, inverters/battery chargers and horizontal pumps) using the recommended Bayesian approach exceed the capacities developed from EPRI 1019200 (2009) by approximately 23% to 49%. The Bayesian results are considered to represent a best estimate, whereas the previously used frequentist approach is considered to produce a conservative lower bound.

The seismic capacities and experience-based methodology evaluated in EPRI 30020002933 (2014c) can be used to support the development of seismic fragilities in current and future SPRAs. The increased seismic capacities will assist in screening out high capacity equipment from further review, which will improve the realism of SPRA results and focus efforts on the most risk significant systems and components. EPRI is currently completing a follow on project which provides the results for a second group of four classes of equipment which will be published in the fall of 2017 and will provide experience-based seismic capacities for motor-operated valves, control panels, medium voltage switchgear, and engine generators.

CONCLUSION

There has been a steady stream of improvements to the seismic fragility methodology and data since its inception over thirty-five years ago. The recent accident at Fukushima caused by the 2011 large earthquake and the subsequent tsunami has accelerated the need for these fragility enhancements. Several of the more recent advancements are highlighted in this paper, all of which should be taken advantage of in a modern SPRA. A more thorough detailing of both the fragility methodology and these recent advancements will be documented in a new EPRI report on seismic fragilities.

REFERENCES

EPRI (1991). “A Methodology for Assessment of Nuclear Plant Seismic Margin, Revision 1,” Palo Alto, California. EPRI NP-6041-SL.

EPRI (1994). “Methodology for Developing Seismic Fragilities,” Palo Alto, California. EPRI TR-103959.

EPRI (2002). “Seismic Fragility Applications Guide,” Palo Alto, California, EPRI 1002988.

EPRI (2009). “Seismic Fragility Applications Guide Update,” Palo Alto, California, EPRI 1019200.

EPRI (2013a). “Seismic Evaluation Guidance: Screening, Prioritization and Implementation Details (SPID) for the Resolution of Fukushima Near-Term Task Force Recommendation 2.1: Seismic,” EPRI 1025287, Palo Alto, California.

EPRI (2013b). “Seismic Probabilistic Risk Assessment Implementation Guide”, Palo Alto, California. EPRI 3002000709.

EPRI (2014a). “Assessment of Lumped Mass and Finite Element Structural Models for Seismic Analysis Applications,” Palo Alto, California, EPRI 3002002804.

EPRI (2014b). “High Frequency Testing Summary,” Palo Alto, California. EPRI 3002002997.

EPRI (2014c). “Assessment of the Use of Experience Data to Develop Seismic Fragilities,” Palo Alto, California. EPRI 30020002933.

EPRI (2015). “High Frequency Program: Application Guidance for Functional Confirmation and Fragility Evaluation,” Palo Alto, California. EPRI 3002004396.

EPRI (2016). “Seismic Fragility Strength Equation Recommendations for Embedded Anchors,” Palo Alto, California. EPRI 3002008099.

EPRI (2017), “Advanced Nuclear Technology: High-Frequency Seismic Loading Evaluation for Standard Nuclear Power Plants,” Palo Alto, California. EPRI 3002009429.

Lee, S.H.; Yoo, K.H. (2005). “Generation of Equipment Response Spectrum Considering Equipment-Structure Interaction,” Proceedings of the KNS Spring Meeting.

Tseng, W.S. (1989). "Equipment Response Spectra including Equipment-Structure Interaction Effects," Proceedings of the 1989 ASME Pressure Vessels and Piping Conference, Honolulu, Hawaii, ASME, PVP - Vol. 155, pp. 21-29.