Seismic Fragility Curve Calculation of Equipment in NPP Using Sampling Approach

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1. Introduction

Seismic fragility analysis of structures, system and components of nuclear power plant structures (NPPs) are conducted based on the log-normal assumption of the fragility curves for its simplicity. To calculate the fragility curves, the safety factor method considers uncertainties from various sources using safety factors with their medians and logarithmic standard deviations. The log-normal assumption makes it possible to represent the fragility curve in log-normal distribution using the composite value of safety factors. However, it remains questionable if the assumption is always valid under any circumstances.

For example, highly nonlinear behavior of the structure could has different effect on the fragility value with different ground motion intensities. In other word, the effect of nonlinearity cannot be considered using a single factor. The nonlinearity could has no effect under a ground motion intensity, but has significant effect under another intensity. In this case, the fragility curve cannot be calculated with the safety factor method but the seismic analyses on each ground motion should be conducted to generate the fragility.

In this paper, seismic fragility curves of equipment mounted on the floor of a NPP structure is calculated using sampling-based approach. Probabilistic seismic analysis of a representative NPP structure is implemented. For efficient analysis, advanced Latin Hypercube sampling method is used to extend the sample size until the convergence of the probabilistic response. Uncertainties in material properties of the structure, input ground motions and equipment are considered in the sampling process. The probabilistic distribution of the structural response computed from the probabilistic analysis results are used for the calculation of fragility curve. The fragility curves are represented in parametric (lognormal) and non-parametric form, and the results are discussed.

2. Numerical model

A numerical model of auxilliary building of a NPP structure is constructed with an open source software OpenSees. A lumped mass model is used to reduce the computing time for the numerous number of analysis. Seismic behavior of the structure is dominated with the shear wall behavior, and the nonlinear behavior of the shear wall is idealized using *HystereticMaterial* provided in OpenSees. Shear wall behavior including strength deterioration and pinching effect can be represented using the material model.

3. Probabilistic analysis

For the probabilistic analysis, three cases are considered. Case 1 considers uncertainty from ground input motions. 30 ground motions are used. Case 2 includes uncertainty from ground motions and nonlinear behavior of the structure. Backbone curves of the shear walls are sampled to represent the uncertainties of the structural behavior. Case 3 adds the uncertainty of equipment frequency. The equipment frequency is assumed to have lognormal standard deviation of 0.1. Each uncertainty sources are considered using the advanced Latin Hypercube sampling, and the analysis continues extending the sample size until the probabilistic distribution of the response converges.

The figure 1 and 2 represents the cumulative distribution function of the 480V MCC response in spectral acceleration. The figure 1 compares the probabilistic response of case 1 and 2, and the figure 2 compare the case 2 and 3.
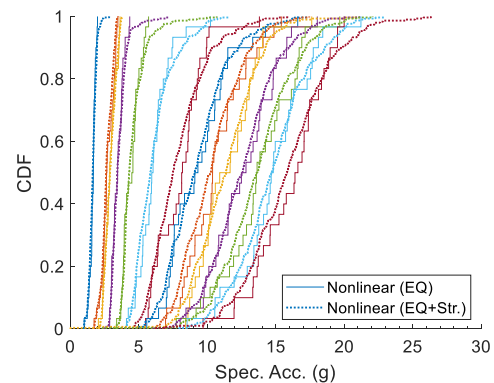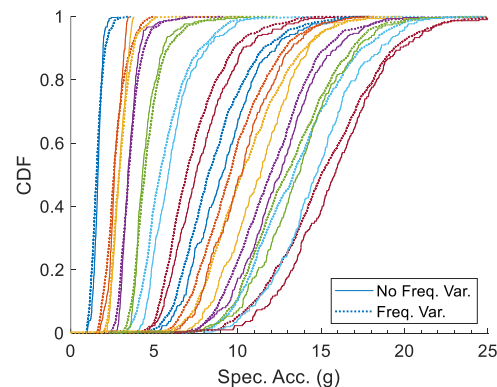

Fig. 1. CDF of response: case 1 and 2 (0.25-3.5 g)

Fig. 2. CDF of response: case 2 and 3 (0.25-3.5 g)

4. Fragility curve

Fragility curve of 480V MCC is calculated using the equation (1).

$$P_f(\alpha) = P(DM > Ds | IM = \alpha) \qquad (1)$$

Where DM is damage measure, which is the probability distribution of the response here and represented in spectral acceleration. Ds is a threshold, which is the capacity of the equipment in spectral acceleration. IM is intensity measure of ground motion, which is PGA here.

The capacity of 480V MCC is estimated with the fragility results based on the linear analysis. The median capacity of the 480V MCC based on the linear analysis is 1.62 g (in PGA), so the seismic analysis with 30 input motions with 1.62 g of PGA are conducted as in the figure 3. As the natural frequency of the 480V MCC is 8.4 hz, the spectral acceleration value the frequency becomes the response of the 480V MCC. Median spectral acceleration value are assumed to be the median capacity of 480V MCC, which is 10.83 g.
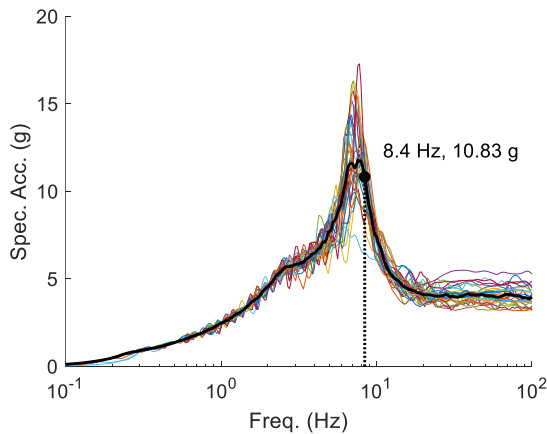

Fig. 3. Calculation of capacity of 480V MCC

With the probability distribution and the median capacity obtained from section 3 and 4, fragilities are calculated. The fragility curves are represented in point-fitted form and the lognormal form as in the figure 4. The lognormal form of the fragility curves are calculated based on the following equation (2) and (3). The equation (2) shows the lognormal representation of fragility curves, and the parameters of the fragility curves are obtained by maximizing the likelihood function of equation (3).

$$P_f = \Phi\left(\frac{\ln \alpha - \ln A_m}{\beta}\right) \qquad (2)$$

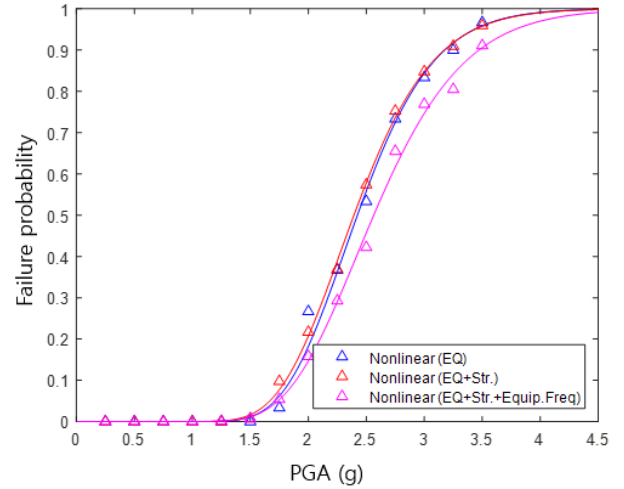$$L(A_m, \beta) = \prod_{i=1}^{n} P_f(\alpha_i)^{x_i}(1 - P_f(\alpha_i))^{(1-x_i)} \qquad (3)$$

Fig. 4. Fragility curve of 480V MCC

The calculated failure probability values are represented in triangles, and the lognormally fitted fragility curves are represented in the solid lines. It can be seen that the lognormal representation of the fragility curves are appropriate in most cases. The effect of input motion is remarkable compared to the effect of structural variation. Also, variation in the component frequency makes quite a difference in the fragility curve.

5. Conclusion

The safety factor method for calculating the seismic fragility curve can be inappropriate when the structural response exhibits high nonlinearity. In this case, the fragility curve can be calculated using the sampling approach which would be more realistic way of considering the seismic response. In this research, the probabilistic seismic response was obtained using efficient sampling method and used in calculating the seismic fragility curves of the representative component in NPP structure. It was concluded that the effect of input motion has the most significant effect on the fragility results, so the selection of the input motion should be made carefully. Also, the equipment frequency has non-negligible effect on the results. The lognormal representation of fragility curves are appropriate for the case in this research, but the future work should be done for presence of the exceptional case.

REFERENCES

[1] ASCE, Seismic Analysis of Safety-Related Nuclear Structures. ASCE 4-16, 2007.
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