Fragility Curve Development of an Electric Cabinet for Isolated Nuclear Power Plants

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1. Introduction

In seismic fragility evaluation of the components in Nuclear Power Plants (NPPs), the fragility curve of each component is produced based on the Floor Response Spectrum (FRS) at which the component places. For general NPPs, the FRS are considered as linear terms to the Peak Ground Acceleration (PGA) of the reference earthquake and the inelastic factor reflecting nonlinear behaviors are considered separately in the seismic fragility evaluation [1]. In case of isolated nuclear power plants, however, the components are subject to non-linearly behaving FRSs relative to the increasing PGA.

In this study, the fragility curve of an electric cabinet in a base-isolated NPP is developed. Numerical models representing the NPP structure and seismic isolators were used to simulate the behavior of the isolated NPP under seismic loads, and the numerical simulation performed using the OpenSees. Different FRSs were obtained as the PGA increases. The battery charger was considered as target electric cabinet and the battery charger test results in our former study [2] were utilized for the seismic fragility evaluation. Fragility parameters are estimated for each PGA level and the fragility curve of the cabinet in the isolated NPP was developed.

2. Numerical Model

The Numerical model of the NPP, initially developed by KEPCO E&C, was converted into OpenSees model in collaboration with the University of California, Berkeley [3]. Lead-Rubber-Bearing (LRB) model was implemented as the isolators of the base-isolated NPP. Total 486 isolators applied to the OpenSees model as shown in Fig. 1.

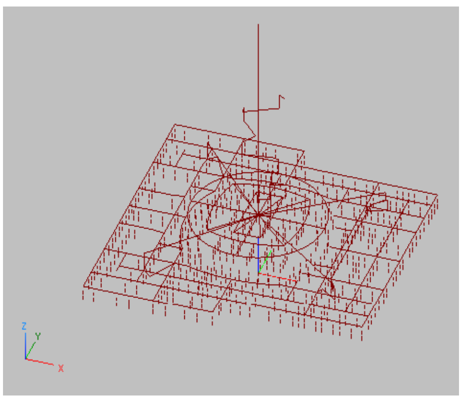

Fig. 1. Numerical model of the isolated NPP

The numerical isolator model presents the LRB isolator in one horizontal direction only, based on the correlation results with full scale test.

Twenty ground motions were used in this study which were scaled spectrally to match a 5% damped USNRC 1.60 target spectrum [4] with the target PGA. The ground motions applied in X direction only for the numerical simulations.

3. Analysis Result

The FRS yielded from the numerical simulations are shown in Fig. 2. The FRSs were produced on the auxiliary building 78 ft. where the battery charger places. The PGA increased 0.1g to 1.0g, and the mean FRS was obtained at each PGA.

The seismically isolated NPP shows nonlinear responses under seismic loads as the LRB isolators have the nonlinear characteristics such as the strength reduction and hardening behaviors [5]. Consequently the FRSs show nonlinear responses as the PGA increases. During the PGA linearly increases from 0.1g to 0.5g, the FRS does not increase linearly and the maximum spectral acceleration near 2 Hz even decreases as the PGA increases 0.2g to 0.5g. Over the PGA of 0.5g, the frequency corresponding to the maximum spectral acceleration moved to the isolation system frequency of about 0.5 Hz, as in the former study [5].

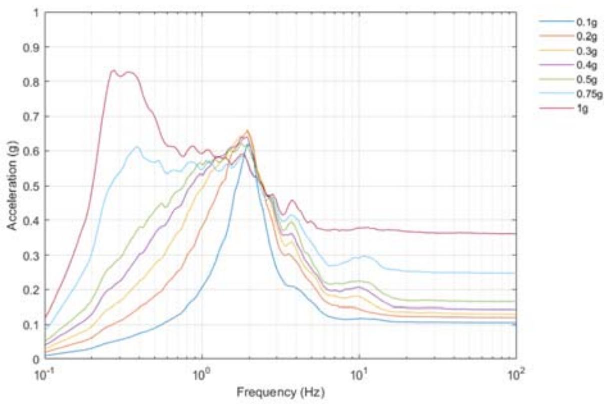

Fig. 2. FRS on auxiliary building 78 ft. in the isolated NPP

4. Evaluation

The Hybrid Method [6] was applied for the seismic fragility evaluation of the battery charger in the isolated

NPP. The hybrid method estimates the High Confidence of Low Probability of Failure (HCLPF) capacity by the Conservative Deterministic Failure Margin (CDFM) method, and approximately estimates the fragility logarithmic standard deviation. The capacity factor at the each PGA was calculated from the FRSs of the isolated NPP and the battery charger test results [2] including the failure mode, and the median capacity factor A_m was obtained at the each PGA as shown in Fig. 3.

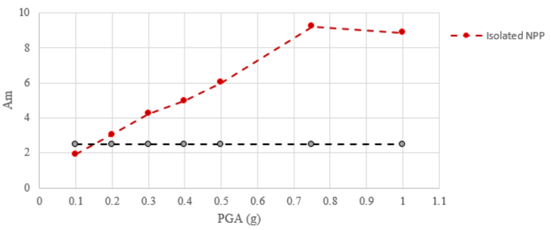

Fig. 3. Median capacity factor of the battery charger in the isolated NPP (red points)

For non-isolated NPPs, general NPPs, the median capacity factor is a constant independent from the change of the PGA as shown in the gray points in Fig. 3. So the fragility curve of the component can be obtained by the hybrid method.

The median capacity factor of the battery charger in the isolated NPP varies dependent on the PGA as the red points in Fig. 3. As the median capacity factor is not a constant, the fragility curve of the battery charger cannot be produced by the established seismic fragility evaluation methodology. To develop the fragility curve of the component in the isolated NPP, the conditional probability of failure was calculated at the each PGA level. The conditional probability of failure was obtained from Test Response Spectral Acceleration Capacity (TRSc) and Reference Response Spectral Acceleration Demand (RRSc). The TRSc derived from the battery charger test results which is independent from the PGA. The RRSc was obtained from the FRS of the isolated NPP so dependent on the PGA level. The conditional probability of failure can be calculated by below equation.

$$P_f(a) = \int_0^{\infty} f_D(x,a)\left(\int_0^{x} f_C(y)dy\right)dx \qquad (1)$$

a : PGA level
$P_f(a)$: Probability of failure
f_C, f_D : Probability density function of capacity/demand

By utilizing the derived conditional probability of failure corresponding to the each PGA level, the fragility curve of the battery charger can be develop. As the hybrid method approximates the logarithmic standard deviation of the fragility curve and the composite logarithmic standard deviation of 0.3 was recommended by EPRI [1] in this case, the fragility curve of the battery charger can be develop by fitting it into the derived conditional probability of failure. From this procedure, the fragility curve of the battery charger in the isolated NPP was obtained as shown in Fig. 4. The red dot line in Fig. 4 is the conditional probability of failure calculated by the TRSc, RRSc, and equation (1). And the black CDF line is the best fitting result to the red dot line. The developed fragility curve has the median capacity factor A_m of 7.3155.

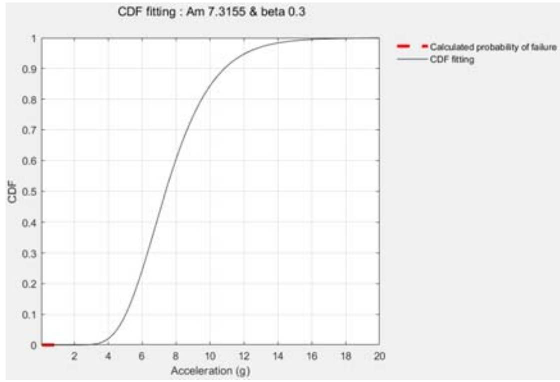

Fig. 4. Developed fragility curve of the battery charger in the isolated NPP (black line)

4. Conclusions

The components in isolated nuclear power plants experience the FRSs which behave nonlinearly relative to the change of the PGA. The median capacity factor of the battery charger in the isolated NPP varies dependent on the PGA. As the median capacity factor is not a constant, the fragility curve of the battery charger cannot be produced by the established seismic fragility evaluation methodology. In this study, we developed the fragility curve of the battery charger in the isolated NPP by applying the hybrid method and yielding the probability of failure at the PGA directly. And numerical models representing the NPP structure and seismic isolators were used to simulate the behavior of the isolated NPP and obtain the FRSs under seismic loads. The conditional probability of failure was calculated based on the FRSs and the battery charger test results. Then the fragility curve of the battery charger was developed by fitting it into the derived conditional probability of failure. This study could provide a methodology for the seismic fragility evaluation of the components in isolated nuclear power plants.

Acknowledgement

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REFERENCES

[1] Electric Power Research Institute (EPRI), Methodology for Developing Seismic Fragilities, TR-103959, 1994
[2] S. Lee, I.K. Choi, and D.U. Park, In-Cabinet Response of a Battery Charger for Nuclear Power Plants and Chattering during Shaking Table Tests, Trans. of the Korean Nuclear Society Autumn Meeting, 2020.
[3] Schellenberg, A.H., Sarebanha, A., Schoettler, M.J., Mosqueda, G., Benzoni, and G., Mahin, S.A., Hybrid Simulation of Seismic Isolation Systems Applied to an APR-1400 Nuclear Power Plant, Pacific Earthquake Engineering Research Center: Berkeley, CA, 2015.
[4] U.S. Nuclear Regulatory Commission, Reg. Guide 1.60 - Design Response Spectra for Seismic Design of Nuclear Power Plants, Rev. 2, 2014.
[5] G. An, M. Kim, J. Jung, G. Mosqueda, and J. Fabian Marquez, Evaluation of Clearance to Stop Requirements in A Seismically Isolated Nuclear Power Plant, Energies, 13, 6156, 2020.
[6] R.P. Kennedy, Overview of Methods for Seismic PRA and Margin Analysis Including Recent Innovations, Proceedings of the OECD-NEA Workshop on seismic Risk, 1999.