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Development of Probabilistic Performance Evaluation Procedure for Umbilical Lines of Seismically Isolated NPPs

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1. Introduction

Recently, to design the nuclear power plants (NPPs) more efficiently and safely against the strong seismic load, many researchers focus on the seismic isolation system. For the adoption of seismic isolation system to the NPPs, the seismic performance of isolation devices, structures, and components should be guaranteed firstly. Hence, some researches were performed to determine the seismic performance of such items [1,2]. For the interface piping system between isolated structure and non-isolated structure, the seismic capacity should be carefully estimated since that the required displacement absorption capacity will be increased significantly by the adoption of the seismic isolation system. Nowadays, in NUREG report, the probabilistic performance criteria for isolated NPP structures & components are proposed. Hence, in this study, we developed the probabilistic performance evaluation method & procedure for interface piping system, and applied the method to an example pipe. The detailed procedure and main results are summarized in next section.

2. Methods and Results

2.1 Evaluation of Clearance to Hard Stop

According to NUREG report, the clearance to hard stop (CHS) displacement must be equal to or greater than the 90th percentile isolation system displacement under extended design basis (EDB) loading. To performing the seismic analysis and estimate the displacement response, we modeled the target NPP, APR1400, and isolation system. The target design frequency of isolated nuclear island is determined to 0.5 Hz. Fig. 1 depicts the auxiliary building structure model of APR1400 NPP.

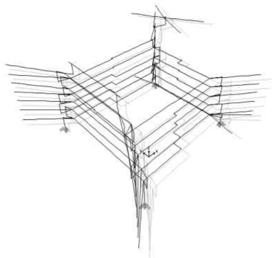

Fig. 1. Modeling of auxiliary building structure.

To evaluate the CHS displacement, firstly, we selected 30 sets of earthquakes which modified to match the target EDB response spectrum. Then, the seismic analyses were performed to compose the probability density function (PDF) of displacement responses (Fig. 2). From the probabilistic information of response, we calculated the mean & standard deviation and determined the CHS displacement to 109.65 cm which of 90^{th} percentile of displacement response.

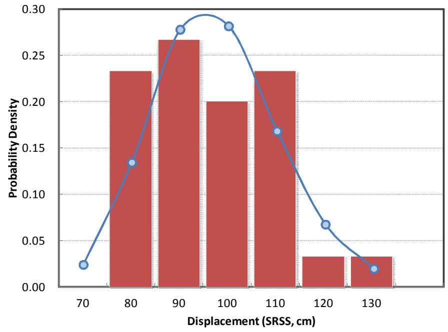

Fig. 2. PDF of displacement responses.

2.2 Probabilistic Performance Evaluation Method

The target performance goal of umbilical lines under EDB loading is greater than 90% confidence that each type of safety-related umbilical line remains functional for the CHS displacement. Also, qualification of the reliability of umbilical lines by numerical analysis will require development of fragility functions that plot probability of failure against an appropriate seismic demand (e.g., lateral displacement for displacement-sensitive umbilical lines). For the probabilistic performance evaluation of umbilical lines under EDB loading, we proposed the appropriate procedure which was demonstrated in in Fig. 3.

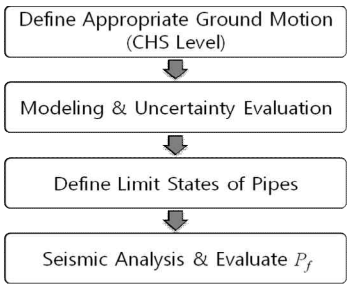

Fig. 3. Procedure to evaluate the probabilistic performance.

To apply and verify the proposed method, we selected the example piping system which was demonstrated in Fig. 4. We assumed that one end of it is attached at the non-isolated turbine building, and another end of it is fixed at the isolated auxiliary building.

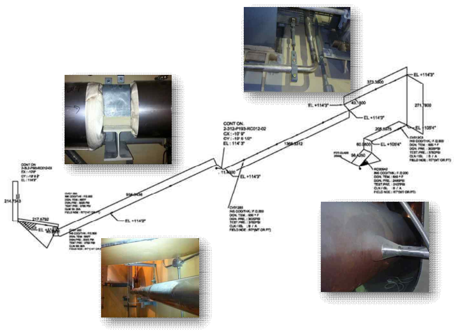

Fig. 4. Iso-drawing and pictures of the example piping system.

The limit state of piping system is determined to strain level of 0.31 based on the test results by Chitoshi et al.. They carried out the opening & closing bending tests for 21 specimens and reported the critical strains for each failure mode. To perform the uncertainty analysis, we assumed that the probabilistic distribution of response will follow the lognormal distribution, and its lognormal standard distribution will be 0.10. With this assumption, we can illustrate the PDF w.r.t the strain level (Fig. 5). From this PDF, we could figure out that the confidence of the example umbilical line is 56.5%, which is smaller than the performance goal, 90%.

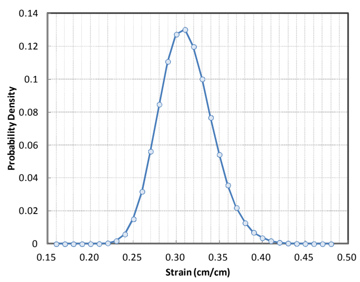

Fig. 5. PDF of strain response under CHS displacement level.

On the other hand, some assumed factors exist in the procedure of the evaluation of the confidence level. We also performed parametric studies on the assumed factors, i.e., lognormal standard deviation of response distribution, and limit state strain level. Fig. 6 depict the confidence level w.r.t the variation of assumed standard deviation & limit strain. We can find that the target confidence level can be achieved if the standard deviation becomes smaller than 0.02 or the limit strain is larger than 0.347.

We also evaluated the fragility curves to qualify the reliability of umbilical lines by numerical analysis method. In Fig. 7, the fragility curves were plotted with respect to the assumed lognormal standard deviation value, 0.10, 0.05, and 0.03, respectively.

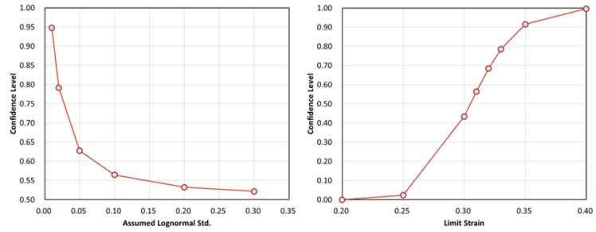

Fig. 6. Confidence w.r.t variations of assumed values.

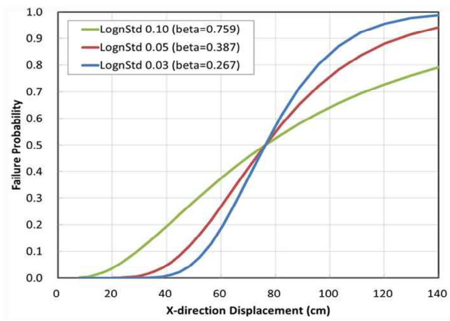

Fig. 7. Fragility curves w.r.t. assumed distributions.

3. Conclusions

For the interface piping system, the seismic capacity should be carefully estimated since that the required displacement absorption capacity will be increased significantly by the adoption of the seismic isolation system. In this study, we proposed a procedure to perform the probabilistic performance evaluation of interface piping system for seismically isolated NPPs, and carried out the preliminary performance evaluation of the target example umbilical line. For EDB level earthquakes, the target performance goal cannot be fulfilled, but we also find out that the result can be changed with respect to the variation of the assumed values, i.e., the distribution of response, and the limit state of piping system.

Acknowledgement

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