The Influence of Near- and Far-field Earthquakes on the Seismic Performance of Base-Isolated Nuclear Power Plant Structures

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Seismic analyses and fragility evaluations of NPP structures were implemented in [8-16]. Among that, remarkably, authors in [9-10] developed the seismic fragility curves of a non-isolated CANDU type NPP containment building for near-field ground motions based on the displacements obtained from the nonlinear time history analyses. Authors in [17] assessed the safety implication of near-field earthquakes on NPP structures designed according to the North American codes. They concluded that the near-field motion effects were not so damaging to the containment which is a relatively stiff structure. However, the effects of near-field forward-directivity, fling-step, and far-field motions on seismic fragility curves of base-isolated NPP structure were not evaluated.

The purpose of this study is to develop seismic fragility curves of a base-isolated APR-1400 NPP structure considering the influence of near- and far-field ground motions. For near-field earthquakes, two typical characteristics, forward-directivity and fling-step are accounted for in fragility analyses. The limit states are defined based on the shear strain capacity of Lead Rubber Bearings (LRBs). A set of fragility curves for limit states are generated using the maximum likelihood estimation. The influence of earthquake groups on fragility curves is also examined.

II. INPUT GROUND MOTIONS

Near-field earthquakes contain a large portion of fault energy in the form of pulses [2]. Pulses can normally be recognized through acceleration, velocity, and displacement time histories. Two typical effects in near-field ground motions are forward-directivity and fling-step phenomena. Forward directivity occurs where the fault rupture propagates with a velocity close to the shear-wave velocity. This is accompanied...
by generating long-period, short-duration, and large-amplitude pulses in the velocity time histories. Displacement associated with such a shear-wave velocity is largest in the fault-normal direction for strike-slip faults [1, 3]. On the other hand, fling step effect produces the evolution of residual ground displacement due to the tectonic deformation associated with the rupture mechanism. This is generally characterized by a unidirectional high amplitude velocity pulse and a monotonic step in the displacement time history [2]. Figure 1 illustrates the time-history traces of near- and far-field earthquakes. A high-velocity pulse can be seen in the 1979 Imperial Valley earthquake. For the 1971 San Fernando earthquake, i.e. a far-field motion, no high pulses existed in the time histories. It should be noted that if a motion record has an epicentral distance less than 12km, it is considered as a near-field earthquake, otherwise it is considered a far-field motion [18].

In this study, two different groups of ground motions classified into near-field and ordinary far-field types were considered. For each group, 20 motion records were involved for fragility analysis. All used records were adopted from the PEER center database. Figure 2 shows the response spectra of ground motions in three groups. The thick curve indicates the mean spectrum.

In this study, the advanced power reactor 1400 (APR-1400) developed by Korea Electric Power Corporation, was employed for numerical analysis. We focused our modeling on the Reactor Containment Building (RCB), the Internal Structure (IS), and the Auxiliary Building (AB). The Finite Element Model (FEM) of the base-isolated NPP structure was developed using the Lumped-Mass Stick Model (LMSM) in SAP2000 [19]. The masses and equivalent section properties were calculated based on the designed cross sections of the structures. The structures were modeled in terms of elastic beam elements. Furthermore, elastic shell elements were applied for the base-mat. The lumped masses were assigned to the associated element nodes. Figure 3(a) shows the FEM of the base-isolated NPP structures and the mechanical properties of LRBs. For the base isolation system, 486 LRBs were installed under the base-mat to enhance the seismic performance of the NPP structures. Figure 3(b) illustrates the bilinear shear force-deformation model of LRBs due to shear forces. The bilinear model of LRB was assumed to be a parallelogram. Therefore, the values of \( Q_d \), \( F_y \), \( K_u \) and \( K_d \) in the negative direction are equal to those in the positive. The mechanical properties of LRBs are also described in Figure 3(b). The results of eigenvalue analysis are presented in Figure 4. The result is consistent with the findings in [20-21].
Among several methods to develop seismic fragility curves, the Maximum Likelihood Estimation (MLE) approach [25] was used in this study. In this approach, the fragility function is assumed as a log-normal Cumulative Distribution Function (CDF) expressed by:

$$F_k(\alpha) = \Phi \left[ \ln(\alpha/c_k) / \zeta_k \right]$$

(1)

where $\alpha$ is the earthquake intensity, namely PGA in this study, $c_k$ and $\zeta_k$ are the median and the log-standard deviations of the log-normal CDF, and $\Phi(\cdot)$ is the standard normal CDF. In (1), the subscript $k$ indicates the $k$-th limit state when more than one limit state is considered. In the MLE, $c_k$ and $\zeta_k$ are determined by maximizing the likelihood function. This function is defined by:

$$L = \prod_{i=1}^{N} F_k(\alpha_i)^y_k[1 - F_k(\alpha_i)]^{(1-y_k)}$$

(2)

where $F_k(\alpha)$ increases when damage occurs and $1 - F_k(\alpha)$, the probability of not experiencing a damage, increases when damage does not occur for an earthquake intensity $\alpha_i$. $N$ is the number of ground motions considered and $x_i$ is a Bernoulli random variable that indicates whether the structure is damaged or not where $0$ indicates no damage and $1$ indicates damage. $c_k$ and $\zeta_k$ are determined so that (2) is maximized with respect to $c_k$ and $\zeta_k$ as follows:

$$\frac{\partial L}{\partial c_k} = \frac{\partial L}{\partial \zeta_k} = 0, \quad k = 1, \ldots, N_{\text{state}}$$

(3)

where $N_{\text{state}}$ is the number of limit states.

Fragility curves of base-isolated NPP structures were developed for the 3 limit states considering the three groups of ground motions. Figure 7 shows the fragility curves for the 3 limit states with different earthquake groups. It can be observed that the base-isolated NPP structure might behave as without damage if the level of PGA is less than 0.6g, which is significantly higher than the operational basis earthquake design level of APR-1400 NPP structures. Additionally, the isolated structure suffered no damage within PGA 0.8g of far-field earthquakes.

Figure 8 shows the comparison of fragility curves for the three groups of earthquakes. It can be observed that the structural model under near-field motions is more vulnerable than that due to far-field earthquakes. This can be attributed to the obvious reason that the deformation of LRBs produced by near-field motions is higher than that under far-field motions.
V. CONCLUSIONS

In this study, seismic fragility curves of the base-isolated APR1400 NPP structures were derived for different limit states based on the maximum likelihood estimation. The influence of near-field and far-field ground motions was considered. Based on the numerical results, the following conclusions are drawn:

- The maximum deformations of LRBs were shown to be smaller for far-field earthquakes than for near-field ground motions. This is due to the high-amplitude pulse effect of near-field motions.
- The probability of failure of base-isolated NPP structures is significantly higher for near-field ground motions compared to that for far-field earthquakes.
- The NPP model has not suffered any damage within PGA 0.6g, which is higher than the safe shutdown earthquake design level of APR-1400 NPP structures.
- It is crucial to select earthquake ground motions with both near- and far-field motions for the seismic evaluation of NPP structures.

REFERENCES


