Seismic Fragility Assessment of Base-Isolated Nuclear Power Plant Structures

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ABSTRACT

Base isolators constitute solutions for improving the seismic performance of civil and nuclear engineering structures. This paper evaluates the seismic fragility of based-isolated nuclear power plant structures using the proposed fragility curves. A finite element model of the structures is developed deploying SAP2000, a structural analysis program. For constructing fragility curves, a set of ground motions is employed to perform nonlinear time-history analyses associated with Incremental Dynamic Analyses (IDA). Three Damage States (DS) are defined based on the shear deformation of base isolators. Finally, the maximum likelihood estimation technique generates a set of fragility curves for DS. Additionally, a comparison of fragility curves between IDA and Cloud Analysis (CA) is presented.

Keywords-nuclear power plant; fragility curves; earthquake; base isolator; DS

I. INTRODUCTION

Nuclear Power Plants (NPPs) play an important role in contributing energy to countries, such as the United States, France, Ukraine, South Korea, and Slovakia. The safety design and assessment of such structures are always made considering the effects of earthquakes. Due to the warning risks having emerged from recent earthquakes, seismic fragility assessment of NPP structures is an interesting and endless topic for researchers. Base isolation is a seismic design technique used to protect structures from earthquake forces. It involves separating a building from ground motion, allowing it to move independently of the ground. Some common base isolation techniques have been deployed, including elastomeric bearings, sliding bearings, and pendulum bearings. Among these techniques, lead rubber bearing is one of the most effective solutions for base isolation of infrastructures and nuclear structures. There are several techniques for base isolation of structures, such as using lead and rubber bearings [1-4]. Many researchers have investigated the seismic responses of NPP structures considering the influence of base isolators. Authors in [5] developed a new base isolation model for structures in the OpenSees platform. Authors in [6] presented a systematic review of the history of seismic isolation in nuclear engineering structures and systems during the last 20 years. Additionally, the need for future studies and the development requirements were highlighted. Some studies investigated the influence of base isolator properties on the seismic performance of nuclear engineering structures [3, 7, 8]. A comparison between seismic responses of based- and non-isolated NPP structures was conducted in numerous works [9-12]. However, a fragility evaluation of the base-isolated structures following the probabilistic approach is required. Additionally, the effectiveness of the uncertainty in earthquake ground motions should be considered. This study evaluates the seismic fragility of the base-isolated NPP structures, in which the containment and Auxiliary Buildings (AB) are involved. A set of 40 earthquake ground motion records is employed to perform time-history analyses. Fragility curves are developed using the IDA and CA methods.

II. INPUT EARTHQUAKE MOTIONS

Many ground motion records should be used to perform fragility evaluation. Additionally, the motion sets should cover a wider range of amplitudes, frequency contents, significant durations, and fault distances. In this study, a set of 40 ground motion records is employed to perform nonlinear time-history analyses. It should be stressed that the mean spectrum is compatible with the US NRC 1.60 spectrum [13], which is used to design nuclear power structures. Figure 1 shows all response spectra of input earthquake motions and the NRC design spectrum.

III. STRUCTURAL MODELING

The primary structures in APR-1400 NPPs are selected as the case study in which the Reactor Containment Building (RCB) and AB are analyzed. A Lead Rubber Bearing (LRB) is a type of base isolator used in seismic engineering to protect structures from earthquake effects. It is designed to absorb and dissipate seismic energy, thereby reducing the amount of ground motion transferred to the structures. In this study, LRBs are utilized to improve the seismic performance of NPP structures in which 486 LRBs are installed beneath the base mat. The RCB and AB structures are modeled using simplified beam elements in SAP2000, as evidenced in Figure 2.

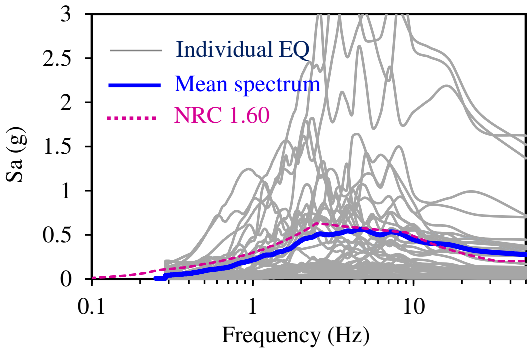


Fig. 1. Response spectra of ground motions.

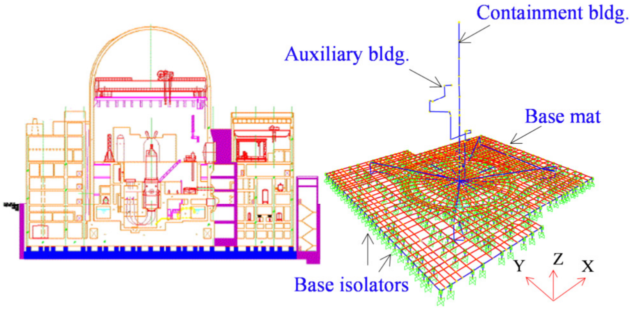
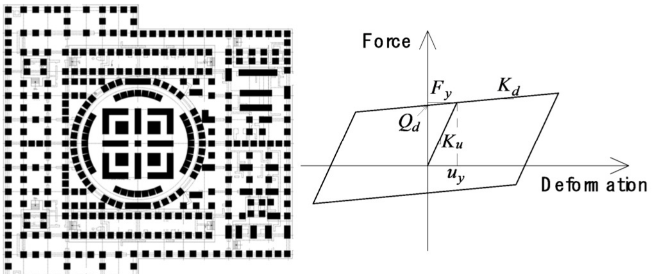


Fig. 2. Schematic NPP structures and finite element modeling.

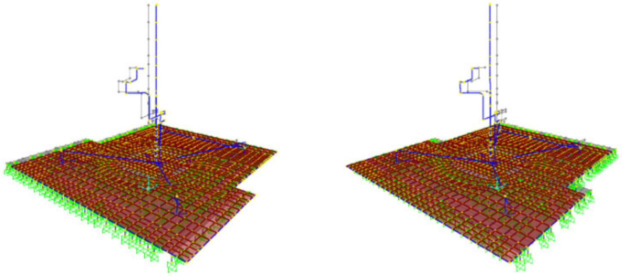


Base isolator properties:

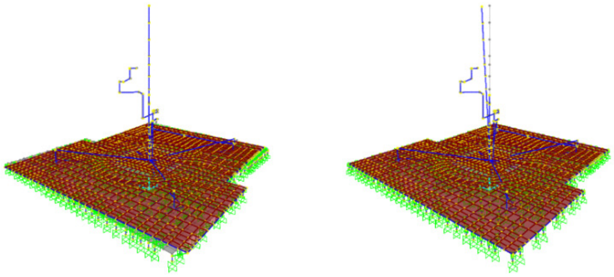
- Elastic stiffness, Ku = 537.703e+03 KN/m
- Post yield stiffness ratio: 0.00782
- Yield strength, Fy = 1009.6574 KN
- Effective stiffness, Ke = 8973.9376 KN/m

Fig. 3. Base isolator layout and its mechanical properties.

The calculated masses of structures are assigned to the element nodes. Elastic shell elements are assigned for the base-mat foundation of the structures, which share a mutual base-mat foundation. Figure 3 depicts the layout of 486 LRBs and their mechanical properties. The shear behavior of LRB is assumed as a hysteretic bi-linear model. The modal analysis result is portrayed in Figure 4. It can be observed that the fundamental modes, Mode 1 and Mode 2, are in translational vibrations (in X- and Y-direction) of base isolators. In other words, the primary vibration modes are governed by the LRBs. Therefore, the shear deformation of LRB is the most critical Engineering Demand Parameter (EDP) for based-isolated structures subjected to earthquakes.



Mode 1, $f_1 = 2.1$ Hz Mode 2, $f_2 = 2.09$ Hz



Mode 3, $f_3 = 1.41$ Hz Mode 4, $f_4 = 0.24$ Hz

Fig. 4. Modal analysis results of base-isolated NPP.

IV. SEISMIC PERFORMANCE

To evaluate the fragility of the base-isolated NPP structures, nonlinear time-history analyses are performed. It should be noted that only horizontal earthquake motions in the X-direction are considered, and the effects of bi-directional and vertical motions are ignored. For non-isolated NPP structures, floor accelerations and displacements should be monitored during performing dynamic analyses. The shear deformation of LRBs is quantified as the key EDP for based-isolated NPP structures. Figure 5 illustrates the time-history displacement and acceleration responses at the top of RCB and concerning cases without base isolators. It is found that LRBs enlarge the horizontal displacement of the structure due to their deformation. LRB reduces the floor acceleration significantly compared to the case without base isolators. Figure 6 displays the hysteretic behavior of the base isolators during an earthquake. This shape follows the bilinear model of LRB defined in Figure 3. The current study focuses on the shear deformation of LRB to evaluate the seismic fragility of the structures. Figure 7 presents the result of IDA on the based-isolated structures for 40 ground motion records. The lateral deformation of LBR increases with an increment of ground motion intensity (i.e., PGA). All imposed motions are scaled up to a PGA of 1.5 g. Figure 8 shows the result of CA for 40 ground motions. It is suggested that the EDP used in IDA and CA is the shear deformation of LRBs.

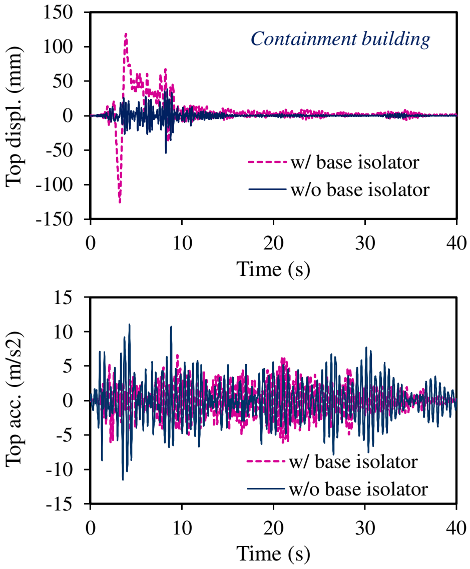


Fig. 5. Time-history responses of RCB with and without isolators.

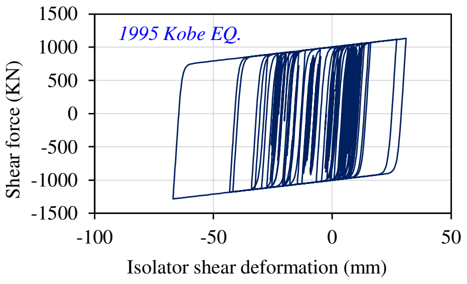


Fig. 6. Seismic hysteretic behavior of base isolators.

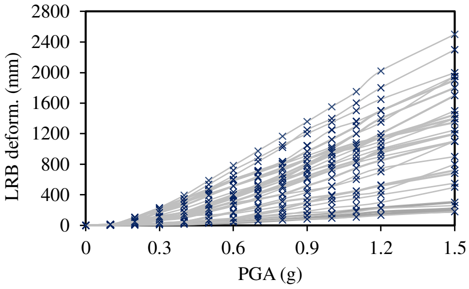


Fig. 7. Incremental deformation of LRB under earthquakes.

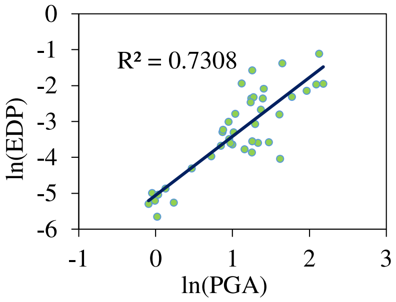


Fig. 8. CA result.

V. FRAGILITY EVALUATION

In fragility evaluation, a wide range of ground motion intensities should be considered to observe the possible behavior/damage levels of structures. There are some typical methods to develop fragility curves, such as CA, Multiple Strip Analysis (MSA), and IDA. In the present study, CA and IDA were employed to evaluate the seismic fragility of the NPP structures.

To develop seismic fragility curves, different DS are specified. DS describe the damage to the structures for different earthquake intensity levels. This study defined three DS, slight, moderate, and extensive, based on the shear strain of LRB. The shear strain is expressed by the ratio of the maximum lateral deformation (Δ) and the height of LRB (H). Based on previous studies [1, 14, 15], LRB may be broken around a 500% shear strain. Therefore, these results were adopted to define the three DS. If the shear strain exceeds 100% (i.e., Δ ≥ 224 mm), a slight DS1 is established. Similarly, if the shear strain reaches 250% (i.e., Δ ≥ 560 mm) and 400% (i.e., Δ ≥ 896 mm), the moderate DS2 and extensive DS3 are specified, respectively. This approach was also applied in [2, 16-18]. A fragility function expresses the conditional probability according to which a structural system reaches or exceeds a DS when subjected to a specific ground motion intensity. The fragility function is expressed as a log-normal cumulative distribution function, given by:

$$P[DS|IM] = \Phi\left[\frac{\ln(IM)-\mu}{\beta}\right] \qquad (1)$$

where P[DS|IM] is the probability of exceeding the DS at a given ground motion Intensity Measure (IM).

IM is the Peak Ground Acceleration (PGA). Φ[-] is a standard normal cumulative distribution function. The parameters μ and β are the median and standard deviation of ln(IM), respectively. These parameters are calculated using the maximum likelihood estimation [19, 20]. Figure 9 portrays the fragility curves for various DS of based-isolated structures. It can be observed that the base-isolated NPP structures have no damage within a PGA of 0.5 g. The structures also have a very small probability of extensive DS3 with a PGA of up to 1.0 g. Even if PGA increases up to 1.5 g, the probability of serious damage is less than 20%. This implies that base isolators and LRBs play a crucial role in significantly reducing the damage to the structures.

Figure 10 demonstrates a comparison of the fragility curves developed by IDA and CA methods. The CA approach was proposed in [21] for developing a Probabilistic Seismic Demand Model (PSDM). This model represents the relationship between a specific earthquake intensity measure and EDP. Based on the defined damage index and corresponding DS, the mean and standard deviation values are determined using regression on the PSDM. As a result, fragility curves are generated. The fragility curves obtained from IDA are overall compatible with those of CA for the three DS.

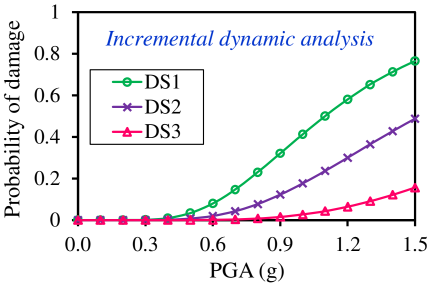


Fig. 9. Fragility curves of base-isolated NPP structures.

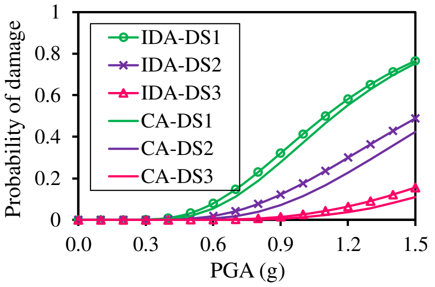


Fig. 10. Comparison of fragility curves of base-isolated NPP structures.

VI. CONCLUSIONS

Seismic performances of Nuclear Power Plants (NPP) structures are evaluated based on a series of time-history analyses considering the effects of base isolators. A set of 40 ground motion records are employed in dynamic analyses. Floor acceleration, displacement, and shear deformation of base isolators are quantified. Fragility curves are developed for different Damage States (DS), which are defined in terms of the shear strain of lead rubber bearings. The Incremental Dynamic Analyses (IDA) and Cloud Analysis (CA) methods are employed to derive fragility curves. Based on the numerical analysis results, the following conclusions are drawn:

- Base isolators can reduce floor acceleration significantly due to their hysteretic behavior, leading to a decrease in seismic demand for base-isolated structures.
- Fragility curves for three DS, slight, moderate, and extensive, are developed. The fragility curves obtained from IDA are compatible with those of CA.
- The fragility curve is a helpful tool for engineers or managers in evaluating the probability of damage to the structures subjected to earthquakes in the future.

The present study did not consider the torsional effects during the fragility evaluations. A further study on the effects of bi-directional and vertical ground motions should be conducted.

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