Development of seismic fragility assessment methodology for seismic isolated NPP structures

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ABSTRACT: As demonstrated by the 2011 East Japan Great Earthquake, earthquakes are a major risk contributor to nuclear power plants (NPPs). Seismic isolation is one of the most effective alternatives for enhancing the seismic safety of NPPs. When we consider seismic isolated NPP structures, we should consider the seismic risk of a seismic isolated NPP structure. Unlike conventional structures, NPPs do not see improved seismic safety only by the reduction of seismic ground motion. In the case of conventional structures, seismic isolation systems should be considered for only a decrease of acceleration responses. In the case of seismic isolated NPP structures, however, because isolation displacement is an important issue for the seismic safety of an NPP structure, seismic risk should be considered. When considering the seismic risk of a seismic isolated NPP structure, seismic PRA methodology can be used. A seismic PRA procedure can be divided into a seismic hazard analysis, a seismic fragility analysis, and an accident sequence analysis. The additional seismic hazard analysis is not needed compare to the conventional NPPs. Seismic fragility should be reconsidered because of the change of input seismic motion. An accidence sequence analysis also should be reconsidered. In this study, seismic fragility assessment methodology for seismic isolated NPP structures are considered. For the assessment of seismic fragility of seismic isolated NPP structures, target structures, systems, and components were selected. Failure mode and criteria were also taken into account. For the assessment of seismic fragility of seismic isolation devices, previous ultimate test results were reviewed. As a result, seismic fragility assessment methodologies are proposed in this study.

1. INTRODUCTION

Even though seismic isolation is one of the most effective approaches for enhancing the seismic safety of nuclear power plants (NPPs), NPPs should satisfy a safety goals. In the case of conventional structures, a decrease of response acceleration is enough for applying a seismic isolation system. For NPPs, even the response acceleration decreases if NPPs cannot satisfy safety goals, and the seismic isolation system design consequently fails.

Performance goals of a seismic isolated NPP should match those of non-isolated counterparts. According to risk-based regulations, the performance goals of NPPs require core damage frequencies (CDFs) and large early release frequencies (LERFs) to be below the specified standard. The performance goals of NPP structures may be presented by re-analyzing the aforementioned goals of NPPs from a structural perspective. With regards to earthquakes, RG1.208 and ASCE 43-05 of the NRC are applicable.

The CDFs and LERFs for NPPs are reviewed by regulatory authorities as per relevant laws. In general, the CDF and LERF applicable to new NPPs are 10E-05/yr and 10E-06/yr, respectively. However, these are

aggregates of all possible risks that may occur in a single NPP, not just seismic events, and therefore, the risk of earthquakes alone should be lower. The performance goals of seismic isolated NPPs with regards to earthquakes may thus be determined in consideration of all other risks.

Unlike in conventional NPPs, the main components of seismic isolated NPPs are divided into isolation systems and umbilical lines. A seismic isolation system consists of the isolation layer formed by a group of seismic isolators, along with the foundation and basemat, while umbilical lines refer to elements that are supported across the isolation interface. Once the performance goals for these two items are satisfied, the performance goals for conventional NPPs must also be met. As seismic isolation systems have no redundancy, their performance goals should guarantee safety with higher reliability or demonstrate proactive mechanisms to prevent damage. The performance goals of umbilical lines shall be defined depending on their importance in relation to the safety of NPPs.

For performing a seismic risk assessment for seismic isolated NPP structures, a seismic hazard assessment is the same as for non-isolated NPP structures, although in the case of seismic fragility, it is totally different than that of non-isolated structures. Target structures and systems are different than those of non-isolated NPPs. A floor response spectrum of seismic isolated NPP structures is totally different than that of non-isolated NPPs. Seismic fragility development methodologies for seismic isolated NPP structures are shown in this paper. Seismic fragility assessment for a seismic isolation system containing a seismic isolator, a basemat, and a pedestal are considered. Seismic fragility assessment methodology for umbilical lines including interface piping systems are also considered in this paper.

2. RISK OBJECTIVES OF SEISMIC ISOLATED NUCLEAR POWER PLANTS

A typical diagram for a seismic isolated NPP is shown in Figure 1. In Figure 1, all nuclear power plant structures located on the isolation system consist of a basemat, an isolator, pedestals, and a foundation. As in Figure 1, a moat, a moat wall, and clearance to hard stop (CHS) are new concepts compared to non-isolated NPPs.

The moat is a space to allow for relative movement, and the CHS is a distance large enough to limit pounding.

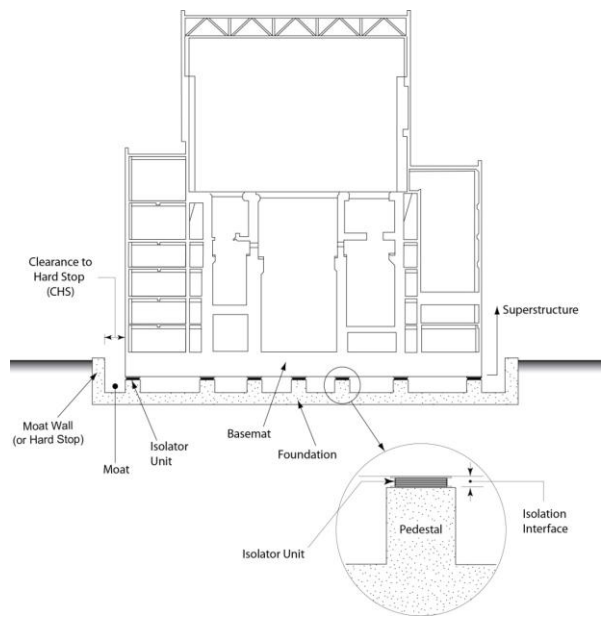

Figure 1: Schematic diagram for seismic isolated nuclear power plants (USNRC, NUREG Draft, 2016)

The NUREG Draft shows risk objectives of seismic isolated NPPs. The NUREG Draft defines performance goals of seismic isolator units and systems, CHS, and isolator unit as:

- Isolation unit and system: 90% probability of each isolator and the isolation system surviving without loss of gravity-load capacity at the mean displacement under EDB GMRS loading
- Clearance to Hard Stop (CHS): equal to or greater than the 90th percentile isolation system displacement under EDB GMRS loading
- Isolator unit: Prototype testing must be performed on a sufficient number of isolators at the CHS displacement

3. SEISMIC FRAGILITY OF SEISMIC ISOLATION SYSTEM

3.1. Failure Mode of Seismic Isolation System

A seismic isolator is a structural element that is simultaneously subject to shear, compression,

and tensile forces. Therefore, the key failure modes and criteria of seismic isolators shall be determined and assessed by combining these three types of loads. Key failure modes can be classified into shear, compression, tensile, compression-shear, and compression-tensile. Failure criteria are determined based on the capacity to maintain the three critical functions of vertical load bearing capacity, restoring force toward the origin, and damping. However, cases in which the limit-state is deemed to be affected by distortion are assessed under the assumption of the maximum possible distortion under the EDB load.

There are three general failure modes for rubber bearings: Shear, compression-shear (buckling), and compression-tensile. All failure modes of seismic isolators are schematically shown in Figure 2. As an earthquake load involves shearing behavior, the possibility of pure compression or pure tensile force is negligible. In addition, as the structure of a NPP is designed for the greatest possible match between the stiffness center and the mass center in the superstructure of a seismic isolation system, as well as to have a large basemat, changes incurred by distortion in each seismic isolator are expected to be minor.

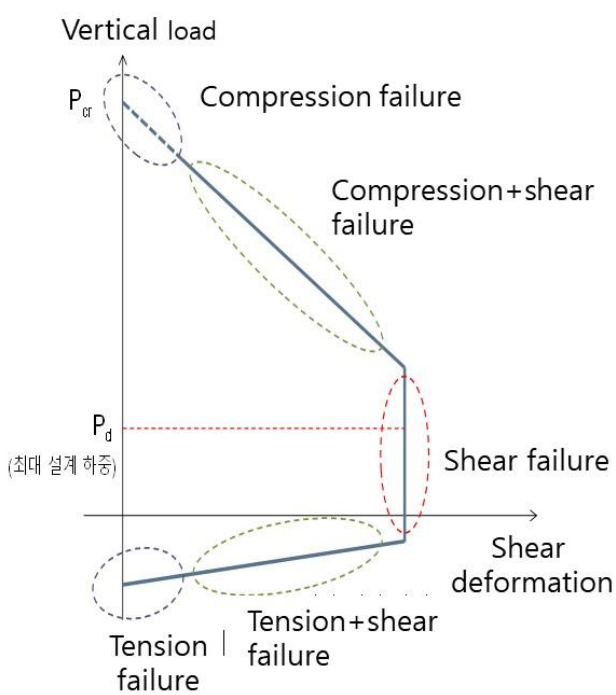

Figure 2: Schematic diagram of failure mode for seismic isolator

Failure modes and criteria should be defined prior to the calculation of the seismic fragility of a seismic isolation system. The failure modes of a seismic isolation system may be classified as follows.

The first failure mode of a seismic isolation system is a failure mode of a group of seismic isolation systems. Such a failure mode includes loss of restoring force toward the origin and loss of vertical bearing capacity.

The second failure modes are failure of the basemat and foundation. These failure modes are deformation of the basemat due to loss of vertical bearing capacity of some seismic isolators and deformation of the foundation due to the settlement of the ground below the foundation.

The third failure modes involve failure caused by a hard stop collision. These failure modes are shearing of the hard stop exceeding the displacement for shear failure criteria of isolators due to impact load and tensile failure of seismic isolators due to the overturning moment caused by the hard stop collision.

3.2. Failure Criteria of Seismic Isolation System

The failure criteria of each failure mode are herein summarized.

Failure criteria of a group of seismic isolation systems can be defined as follows: When the restoring force falls below a certain proportion of the superstructure's weight following a horizontal deformation. The acceptable number of seismic failed isolators are calculated in accordance with the failure criteria of the foundation.

Failure criteria of the basemat and foundation should be considered as: Some isolators lose their vertical bearing capacity and exceed their elastic limit; the deformation of the foundation causes structural damage to the superstructure.

Failure criteria based on hard stop collision can be defined as: Velocity of hard stop collision exceeding the displacement for shear failure criteria. Velocity exceeding the tensile failure

margin of isolators caused by an impact-induced overturning moment.

For the determination of failure criteria of a seismic isolation system, failure tests for scale model seismic isolators were performed. For the failure test of seismic isolators, 20 specimens were used. Through the test, failure mode and criteria can be determined according to the isolation unit and isolator devices. Even though a failure mode of seismic isolation unit was buckling failure, a global failure mode of seismic isolation system might be shear failure. Figure 2 shows the relation between shear strain and vertical load for the shear failure test of a seismic isolator. As shown in Figure 3, failure of an isolation device can be determined according to the failure mode. It can be determined peak load, 80% of peak load after passing the peak load, and secondary hardening and shear failure can be determined as failure of a seismic isolator. One of the interesting things is that even the peak load, 80% peak load, and second hardening points are different according to the vertical load cases, but shear failure capacities do not show many differences. The definition of each failure point is shown in Figure 4. The failure of a seismic isolator is shown in Figure 5.

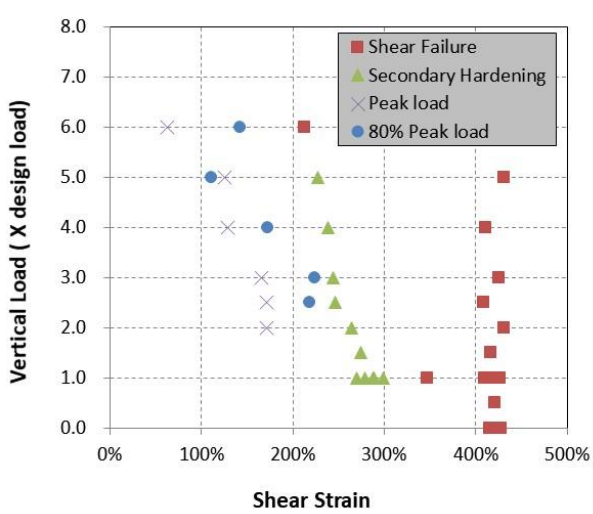

Figure 3: Relation between shear strain and vertical load for different seismic isolator tests

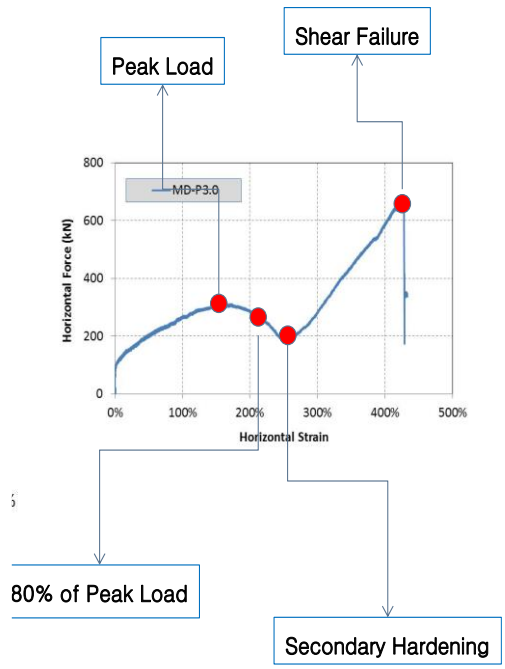

Figure 4: Relation between horizontal shear strain and force

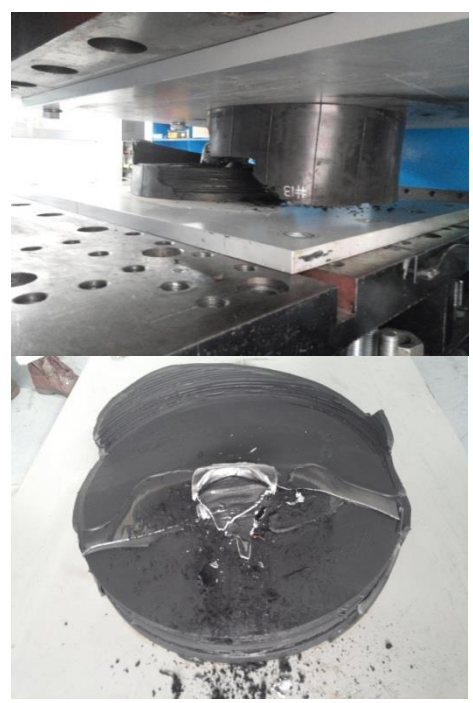

Figure 5: Failure of seismic isolator

4. SEISMIC FRAGILITY OF UMBILICAL LINES

4.1. Seismic Fragility Assessment Framework of Piping Elements

In order to evaluate the seismic fragility of piping elements, the following procedure should be followed.

① Conduct sensitivity analysis of elbow component responses

② Sample random variables

③ Determine the input relative displacement motions

④ Undertake detailed modeling of critical elbow components

⑤ Perform numerical simulations of elbow components

For the sensitivity analysis of elbow component responses, selection of random variables and ranges, evaluation of the responses of elbows under cyclic loading (stress, strain, etc.), and the definition of the important random variables should be conducted.

In the case of the sampling of random variables, a DB should be constructed for each random variable by coupon tests or measurement and the probability distribution function of random variables should be defined.

For determining the input relative displacement motions, determine the number of cycles from the strong motion duration and the representative input relative displacement motions (sine-wave form).

Afterward, detail numerical modeling should be performed for elbow components.

When performing the numerical simulations of elbow components, evaluate the response at critical points (crowns, etc.), compute the failure probabilities with regard to the load intensities (e.g., MRD), and compute the component level fragility parameters (e.g., in terms of MRD).

4.2. Seismic Fragility Assessment Framework of Piping System

In order to evaluate the seismic fragility assessment of the piping system, the following procedure should be followed.

① Sample random variables
- Define important random variables
- Evaluate the probability distribution of random variables

② Produce simplified modeling of global piping system
- Best estimate model of piping system
- Construction of input model set considering random variables

③ Perform numerical simulations of piping system
- Selection of input ground motions
- Evaluate the relative displacements between the ends of critical elbow components

④ Undertake detailed modeling of critical elbow components

⑤ Perform numerical simulations of elbow components
- Evaluate the response at critical points (crowns, etc.)
- Compute the failure probabilities w.r.t. the load intensities

⑥ Estimate the fragility capacity of piping system
- Estimate the median capacities & uncertainty parameters at each critical component
- Condensate the fragility curves at each critical point
- Compute the piping system level fragility parameters

5. SEISMIC FRAGILITY OF SEISMIC ISOLATED EQUIPMENT

The components of seismic isolated NPPs are not inclusive of the umbilical lines crossing the isolation interface, and are divided into those

located at the superstructure and other components. The components in the superstructure should be assessed by calculating the FRS of the seismic isolated structure, while the latter may be assessed with the same approach used for conventional NPPs. The FRS of the seismic isolated structure should be calculated by reflecting its characteristic in that its nonlinearity increases along with seismic intensity.

6. CONCLUSION

Even though seismic isolation is one of the most effective methodologies for enhancing the seismic safety of nuclear power plants (NPPs), a NPP should satisfy a safety goals. For the validation of seismic isolation systems for NPPs, a seismic PRA for seismic isolated NPPs should be performed. In order to perform a seismic PRA, a seismic fragility assessment methodology for seismic isolated NPP structures was explained in this paper. Failure modes and criteria for seismic isolators and seismic isolation systems were also discussed. Additionally, seismic fragility procedures for umbilical lines and seismic isolated equipment in NPPs are summarized in this paper.

7. ACKNOWLEDGEMENTS

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