Transactions, SMiRT-24
BEXCO, Busan, Korea - August 20-25, 2017
Division IX (include assigned division number from I to X)

PERFORMANCE BASED DESIGN OF LRB SYSTEMS FOR NUCLEAR POWER PLANTS

In-Kil Choi[1], Jung Han Kim[1], Min Kyu Kim[1]

[1] Researcher, Korea Atomic Energy Research Institute, Korea

ABSTRACT

A seismic isolation system is emerging as an alternative method to secure the seismic safety of nuclear power plants instead of the traditional aseismic design method. Some seismic isolation systems have been applied to some nuclear facilities. The effectiveness of seismic isolation systems were proven from recent large earthquakes. After the Great East Japan Earthquake on 11 March 2011, the seismic safety of nuclear power plants for large earthquakes which exceed the design basis earthquake became an essential requirement.

The performance based seismic design guidelines specifies acceptable performance criteria for two earthquake levels, DBE (Design Basis Earthquake) and BDBE (Beyond DBE). The unacceptable performance of a seismic isolation system can be defined as the shear failure by large displacement. The design displacement should be determined considering the shear strain level at DBE. An isolated nuclear power plant requires a hard stop to secure the seismic safety by preventing excessive displacement of the isolation system. The isolation system should satisfy the performance requirements for a DBE and BDBE in the CHS (Clearance to Hard Stop) displacement. If the strain level of the isolation system under DBE condition is greater than a certain level, the performance requirement cannot be satisfied owing to the large strain level at a BDBE. The design guidelines for the seismic isolation system do not generally limit the strain levels at a DBE. In this study, the performance based design method of a LRB (Lead Rubber Bearing) is proposed considering the design displacement and its strain level based on the fragility analysis of the LRB in a CHS.

INTRODUCTION

A seismic isolation system is considered as an effective method to increase of the seismic safety of a nuclear power plant. In Korea, an extensive study on seismic isolation system applied to an APR 1400 nuclear power plant designed for 0.3g earthquake is conducted. The 0.3g design earthquake level is not sufficient to export a reactor to a strong seismicity area where the site specific earthquake level is higher than 0.3g. To improve the design earthquake level for an APR 1400, the seismic isolation system is an efficient method compare with a new seismic design or strengthening the structures and systems to endure the strong earthquakes. Most of the next-generation reactor also adopt a seismic isolation system to improve the seismic safety.

The safety feature of a nuclear power plant is based on the defense in depth concept. Most nuclear power plant have a multi barrier system to prevent the release of the radioactive materials to the environment. A nuclear power plant has alternative systems for safety-related systems to prevent the loss of safety functions. The safety of nuclear power plant is very important and should be maintained during the life time of the plant. The seismic isolation system also should be maintained its safety during the plant life time.

A seismic isolation system is emerging as an alternative method to secure the seismic safety of nuclear power plants instead of the traditional aseismic design method. The unacceptable performance of a seismic isolation system can be defined as the shear failure by a large displacement. The design displacement should be determined considering the shear strain level at the DBE. An isolated nuclear power plant requires a hard stop to secure the seismic safety by preventing excessive displacement of the isolation system. The isolation system should satisfy the performance requirements for a design basis earthquake (DBE) and a beyond design basis earthquake (BDBE). In this study, the shear displacement and corresponding strain level are proposed for a beyond design basis earthquake level in a performance based seismic design.

PERFORMANCE REQUIREMENTS FOR DBE AND BDBE

Some design guidelines for a nuclear power plant, such as ASCE 43-05, require a target performance against a DBE and BDBE. The target performance goals of ASCE 43-05 [ASCE, 2005] are as follows.

- Less than about 1% probability of unacceptable performance for the DBE ground motion
- Less than about 10% probability of unacceptable performance for a ground motion equal to 150% of the DBE ground motion

The unacceptable performance of an isolation system can be defined as a shear failure of isolators owing to the excessive horizontal displacement and impact of the superstructure to moat wall. In order to prevent the impact possibility, the isolated nuclear power plant has a sufficient gap from the superstructure to the moat wall.

It means that the maximum displacement of the isolation system should be less than the gap, which is called as CS (Clearance to Hard Stop). And the isolation system should be maintained the integrity at this shear displacement level.

Requirements of ASCE 4-16

The new ASCE 4-16 [ASCE, 2016] standard includes detailed criteria for the design of seismically isolated structures to apply the isolation systems to a nuclear power plant and structures. The criteria are limited to the horizontal seismic isolation only. The performance requirements are specified for two levels of design demand based on the ASCE 43-05. In this guideline, the CS is required at a 90%th displacement demand for BDBE (1.5 x DBE) input ground motions. Table 2 shows the detailed performance expectations for a seismic isolation system in a seismically isolated nuclear power plant proposed by ASCE 4-16[ASCE, 2016].

Table 1: Performance expectations for a seismic isolation system by ASCE 4-16 [ASCE, 2016]

	DBE	BDBE
Isolation system displacement	Mean and 80^{th} percentile isolation system displacement	90^{th} percentile isolation system displacement
Performance	No damage to the isolation system for DBE shaking	Greater than 90% probability of the isolation system surviving BDBE shaking without loss of gravity-load capacity
Acceptance criteria	Production testing of each isolator for the 80^{th} percentile isolation system displacement and corresponding axial force. Isolator damaged by testing cannot be used for construction	Prototype testing of a sufficient number of isolation for the CS displacement and the corresponding axial force. Isolator damage is acceptable but load-carrying capacity is maintained

Requirement of NUREG Draft

US NRC are preparing the NUREG report on a seismic isolation system to provide the technical information necessary for NRC staff to develop new regulatory guidance on the issue of seismic isolation technology [US NRC, 2012]. The draft report proposes a performance-based and risk-informed design methodology for a seismically isolated nuclear power plant. In this draft report, the seismic hazard for the design is defined as having two levels, GMRS+ (Ground Motion Response Spectrum +) and EDB (Extended Design Basis). The performance expectations for the hazard levels are shown in Table 2. The EDB hazard level as a beyond design basis shaking is more rigorous than the ASCE standard.

Table 2: Performance and design expectations for a seismic isolation system by the NUREG draft [US NRC, 2012]

Ground motion level	Isolation units and system design and performance criteria	Approach to demonstrating acceptable performance of isolator unit
GMRS+ The envelope of the RG1.208 GMRS and the minimum foundation input motion 3 for each spectral frequency	No long-term change in mechanical properties. 100% confidence of the isolation system surviving without damage when subjected to the mean displacement of the isolator system under the GMRS+ loading.	Production testing must be performed on each isolator for the mean system displacement under the GMRS+ loading level and corresponding axial force.
EDB GMRS The envelope of the ground motion amplitude with a mean annual frequency of exceedance of 1x10-5 and 167% of the GMRS+ spectral amplitude	90% confidence of each isolator and the isolation system surviving without loss of gravity-load capacity at the mean displacement under EDB loading.	Prototype testing must be performed on a sufficient number of isolators at the CHS5 displacement and the corresponding axial force to demonstrate acceptable performance with 90% confidence. Limited isolator unit damage is acceptable, but load-carrying capacity must be maintained.

Requirements of Japanese Standard

Seismic isolation technology has been widely used in Japan for buildings and conventional civil structures. Recently, a seismic isolation system has been used for the construction of the emergency response centre in Japanese nuclear power plants. The design method of a seismic isolation system for FBR (Fast Breeder Reactor) was developed by CRIEPI (Central Research Institute of Electric Power Industry) [Hirata et al., 1998]. This design method is based on various tests and simulation conducted through a long-term research program, and became the basis of Japanese design guideline.

The Japanese design guidelines for seismic isolation systems, JEAG 4614-2013 [JEA, 2013], proposes the design guidelines for NRB (Natural Rubber Bearing), LRB (Lead Rubber Bearing), and HDRB (High Damping Rubber Bearing). In these guidelines, the allowable displacement is proposed in the elastic displacement limit with a safety margin. However, these guidelines do not consider the BDBE condition.

JNES (Japan Nuclear Energy Safety) developed regulatory guidelines for the design of seismically isolated nuclear power plant in Japan [JNES, 2009]. These guidelines require a residual risk evaluation to minimize the residual risk for a beyond design earthquake. The residual risk evaluation should be performed for the entire nuclear facility through a deterministic or probabilistic method.

DISPLACEMENT RESPONSE OF LRB FOR BDBE

Nonlinear Characteristics of LRB System

The LRB system is a nonlinear system in which the displacement response at the BDBE is not proportional to the response for DBE ground motion. The horizontal displacement response for the BDBE ground motion is much larger than that for the DBE. Figure 1 shows typical hysteretic load-displacement curves of the LRB system for several strain levels.

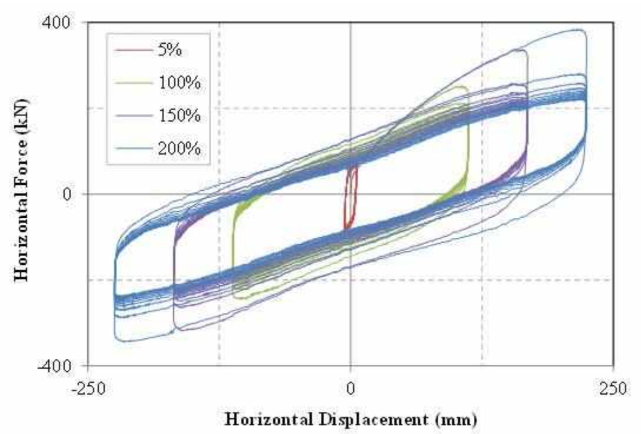

Figure 1. Typical hysteretic load-displacement curves of LRB system

Ultimate Displacement Capacity of LRB

Various tests of LRB were performed to evaluate the ultimate shear displacement capacity of the LRB system by using the scaled and full-scale isolators [Kim et al, 2016]. The ultimate horizontal displacement capacity depends on the vertical load and applied load direction. The ultimate capacity for the one-dimensional load test of the full scale model shows more than 500% of strain. However, in the two-dimensional test, the shear failure occurred slightly over the 400% strain level. This result shows that the actual ultimate capacity of LRB is 20% lower than the one-dimensional test results. Figure 2 show the shear failure of an LRB isolator.

EXAMPLE PERFORMANCED BASED DESIGN OF LRB

Parameters for Case Study

The acceptable performance of an isolator system can be evaluated based on the failure probability at the ground motion level. The ASCE performance requirement is used for this study. The ASCE 43-05 requires less than 1% of failure probability for DBE condition and less than 10% of failure probability for BDBE condition [ASCE, 2005]. In this study, the failure probability of LRB system was evaluated based on a fragility analysis. For a case study, the design parameters for the LRB system are as follows.

- PGA of DBE: 0.5 g
- Median displacement for DBE ground motion: 25 cm
- 80%ile displacement for DBE ground motion: 30 cm
- Median displacement for BDBE: 75 cm
- Total thickness of rubber layer: 30 cm
- Median shear strain capacity of the LRB: 400 %

Figure 2. Shear failure of LRB

The CS was determined based on the results by Huang et al. [Huang et al., 2009]. This research proposed that the median response of a best-estimate model subjected to DBE ground motions should be increased by a factor of 3 to achieve the performance objectives of ASCE 43-05. This means that a factor of larger than 3 should be considered to satisfy the requirement of the NUREG draft. In this study, a factor of 3 is used for the required displacement for the beyond design basis earthquake level.

For a fragility analysis of the LRB system, the logarithmic standard deviations for randomness and uncertainty are assumed as 0.3 and 0.3, respectively. The composite lognormal standard deviation is 0.424.

Seismic Fragility Analysis of Example LRB System

The median capacity of the example LRB system is assumed to be 400% of the shear strain. Based on these fragility parameters, Figure 3 shows the seismic fragility curves for the isolator. From the fragility curves, it can be seen that the isolator displacements at 1% and 10% of failure probability are 44.7 cm and 69.7 cm, respectively. The displacement response for DBE is less than the allowable displacement (44.7cm), and the displacement response for BDBE is greater than the allowable displacement (69.7 cm). This isolation design cannot satisfy the performance requirement for BDBE condition.

Parametric Study for Performance-Based Isolator Design

Figure 4 shows the seismic fragility curves of an LRB for various composite logarithmic standard deviations. The ultimate capacity of this case is assumed 500%. As shown in this figure, the allowable strain levels for DBE and BDBE are increased according to the decrease in composite variability.

Table 3 shows the allowable isolator strain levels for DBE and BDBE according to the ultimate shear strain values of an LRB and the composite variability. It is noted that the large ultimate strain capacity of LRB with low uncertainty level is desirable for the performance-based isolator design.

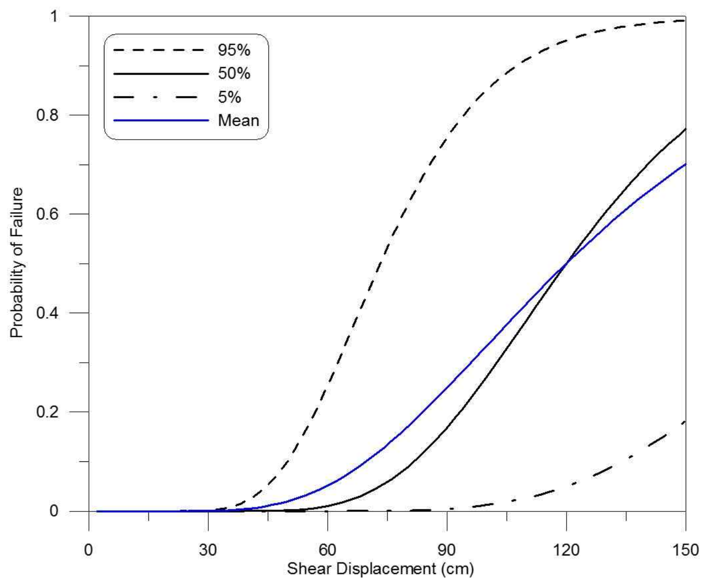

Figure 3. Seismic fragility curves of the example LRB

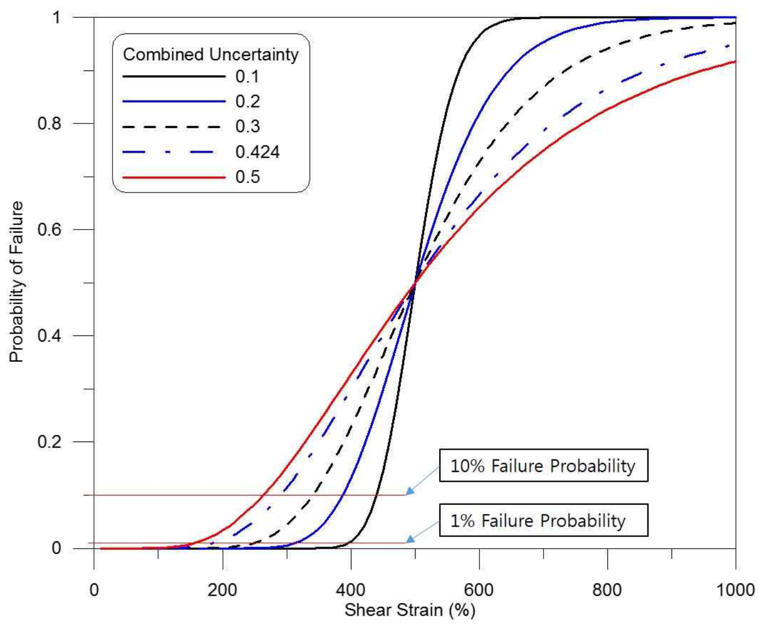

Figure 4. Allowable shear strain levels according to the combined uncertainty

Table 3: Isolator strain at 1% and 10% failure probability for example LRB

Median Capacity (Strain, %)	1% Probability of Failure					10% Probability of Failure				
	0.1	0.2	0.3	0.424	0.5	0.1	0.2	0.3	0.424	0.5
400	316.9	251.0	198.8	148.9	124.8	351.9	309.5	272.3	232.3	210.7
450	356.5	282.4	223.7	167.6	140.4	395.9	348.2	306.3	261.3	237.0
500	396.1	313.8	248.5	186.2	156.0	439.8	386.9	340.4	290.3	263.4

Table 4 shows the isolator displacement at 1% and 10% failure probability for an LRB with various ultimate strain capacities and various composite variabilities for several design displacement levels. In this case, it is assumed that the design displacements of the LRBs are 20, 25, and 30 cm and its corresponding strain level is 100%.

The shaded area in this table shows an allowable isolator displacement of less than 90 cm, which is the minimum CS of the previous example study. This means that the isolator design with a shaded area cannot satisfy the performance requirement of an LRB systems. The unacceptable performance of an isolated nuclear power plant is generally impact of the superstructure to the moat wall. These criteria are based on the assumption that the isolator sustain its integrity in the minimum CS displacement. However, the shaded case, the isolation system cannot secure its own integrity.

Table 4: Isolator displacement at 1% and 10% failure probability for example LRB

Uncertainty / Ultimate Strain (%)	1% Failure Probability					10% Failure Probability				
	0.1	0.2	0.3	0.424	0.5	0.1	0.2	0.3	0.424	0.5
Design displacement (100% strain) = 20cm										
400	63.4	50.2	39.8	29.8	25.0	70.4	61.9	54.5	46.5	42.1
450	71.3	56.5	44.7	33.5	28.1	79.2	69.6	61.3	52.3	47.4
500	79.2	62.8	49.7	37.2	31.2	88.0	77.4	68.1	58.1	52.7
Design displacement (100% strain) = 25cm										
400	79.2	62.8	49.7	37.2	31.2	88.0	77.4	68.1	58.1	52.7
450	89.1	70.6	55.9	41.9	35.1	99.0	87.1	76.6	65.3	59.3
500	99.0	78.4	62.1	46.5	39.0	110.0	96.7	85.1	72.6	65.8
Design displacement (100% strain) = 30cm										
400	95.1	75.3	59.6	44.7	37.4	105.6	92.9	81.7	69.7	63.2
450	106.9	84.7	67.1	50.3	42.1	118.8	104.5	91.9	78.4	71.1
500	118.8	94.1	74.6	55.9	46.8	132.0	116.1	102.1	87.1	79.0

CONCLUSIONS

A performance-based LRB design method is proposed based on a seismic fragility analysis of the isolation system. The parametric study shows that the strain level at the design displacement should be determined considering the performance requirement of the isolation system under BDBE conditions. In addition, a quality control of the manufacturing used to reduce the variability of the mechanical properties of an LRB is required to satisfy the performance requirement.

The basic safety concept of a nuclear power plant is a defence in depth with redundancy and diversity. However, there is no redundancy for the isolation system in a seismically isolated nuclear power plant. The safety of seismic isolation system is very important to secure the seismic safety of a nuclear power plant. It is necessary to consider in the design of an isolated nuclear power plant, not only preventing impact of the superstructure to the moat wall, but also the isolator safety itself.

ACKNOWLEDGEMENT

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIP) (No. 2017M2A8A4014829)

REFERENCES

American Society of Civil Engineers (2005). *Seismic Design Criteria for Structures, Systems, and Components in Nuclear Facilities*, ASCE/SEI 43-05, USA.

American Society of Civil Engineers (2016). *Seismic Analysis of Safety-Related Nuclear Structures*, ACSE/SEI 4-16, USA

Japan Nuclear Energy Safety (2009). *Regulatory Guidelines for Reviewing Seismic Isolation Structures*, JNES-SS-1001.

Japan Electric Association (2013). *Seismic Design Guidelines for Base-Isolated Structures of Nuclear Power Plant*, JEAG 4614-2013.

Kim, Jung Han, Min Kyu Kim, In-Kil Choi (2016). "Experimental Study on the Ultimate Limit State of a Lead-Rubber Bearing," *Proceedings of the ASME 2016 Pressure Vessels and Piping Conference*, Vancouver, Canada.

Kirata, K., S. Yabana, Y. Ohtori, K. Ishida, Y. Sawada, H. Shiojiri and T. Mazda (1998), Study on Design Method for Seismically Isolated FBR Plants, CRIEPI.

US NRC (2012). *Technical Considerations for Seismic Isolation of Nuclear Facilities*, NUREG-XXXX.

Huang, Yin-Nan, Andrew S. Whittaker, Robert P. Kennedy and Ronald L. Mayes (2009), *Assessment of Base-Isolated Nuclear Structures for Design and Beyond-Design Basis Earthquake Shaking*, MCEER-09-0008, MCEER.