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Performance Based Failure Criteria of the Base Isolation System for Nuclear Power Plants

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1. Introduction

For the quantification of the seismic risk for a nuclear power plant structure, the failure probabilities of the structural component for the various seismic intensity levels need to be calculated. The failure probability is evaluated as the probability when the seismic response of a structure exceeds the failure criteria. Accordingly, the failure mode of the structural system caused by an earthquake vibration should be defined first. The type of a base isolator appropriate for a nuclear power plant structure is regarded as an elastometric rubber bearing with a lead core. The failure limit of the lead-rubber bearing (LRB) is not easy to be predicted because of its high nonlinearity and a complex loading condition by an earthquake excitation. Furthermore, the failure mode of the LRB system installed below the nuclear island cannot be simply determined because the basemat can be sufficiently supported if the number of damaged isolator is not much. Therefore, the realistic approach to evaluate the failure state of the base isolation system is necessary. From this point of view, several concerns are reviewed and discussed in this study.

2. Capacity and Response of Base Isolation System

2.1 Capacity of Base Isolation System

Laminated rubber bearing has high stiffness and strength in the vertical direction compared to those in the horizontal direction. The critical axial load capacity of the LRB used to be larger than several times of the design axial load. However, the axial load applied at the edge of the basemat can be fluctuated by the overturning moment induced by a horizontal response of a superstructure. And the amplitude of a vertical ground motion increases more significantly than horizontal ground motion as the earthquake magnitude increases. It may give rise to serious axial load of isolators. Therefore, the failure criteria should be determined by not only horizontal shear strain, but also the excessive axial load out of the design load. This axial load can be a tensile load in some cases. The failure mode of a LRB is considered as follows.

- ✓ Shear fracture: a fracture by a large horizontal displacement with a relatively low axial load around the design axial load
- ✓ Buckling: compressive failure by a high axial load with small effective area resisting axial force
- ✓ Tensile failure: failure by the uplift tensile force which is prohibited in the LRB design because of its low strength

The failure criteria of the LRB can be represented by an ultimate property diagram (UPD) which shows the relationship between an axial load and a horizontal displacement of the ultimate state as depicted in Fig. 1.

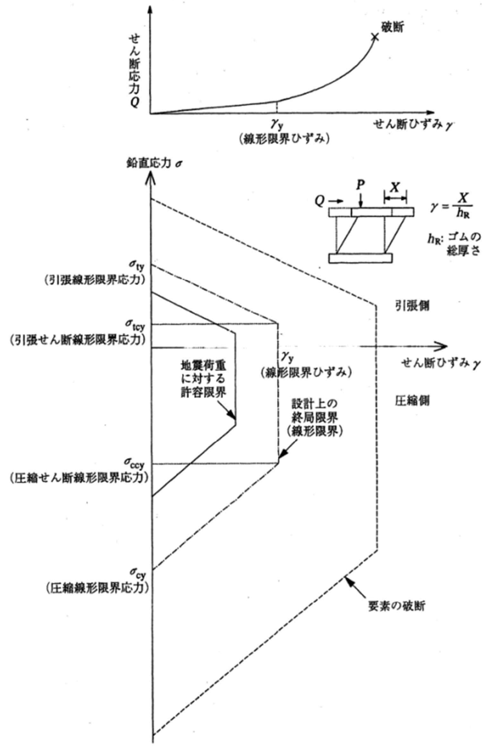

Fig. 1. Typical ultimate property diagram of a laminated rubber bearing [1]

In the isolated nuclear power plant, hundreds of isolators will be installed below the basemat of a nuclear island structure. The basemat is very stiff concrete block, so a few of the fractured isolator do not lead to the failure of the base isolation system. The major function of an isolator is to resist the weight of a superstructure and a re-centering capability. Therefore, the ultimate state of an isolation system may be defined as the settlement of the basemat locally loosing vertical resistant force by the buckling failure of isolators or the enough number of isolator failures causing the negative stiffness of the base isolation system.

2.2 Response of Base Isolation System

In the performance-based approach introduced in the seismic design criteria of nuclear power plants such as the ASCE 43-05 [2], the probability of unacceptable performance under the extended design basis earthquake is suggested. Therefore, the response of structures, in case of isolation system, the displacement responses of isolators should be evaluated considering all possible uncertainties. This uncertainty can be an uncertainty of mechanical properties of isolators and an uncertainty of the input earthquake ground motion.

The uncertainties of mechanical property of isolators include not only the initial variation at the time of a manufacturing, but also the change of the mechanical property by an ageing effect in the lifetime of a nuclear power plant. Also, the horizontal behavior of an isolator is affected by axial load, number of cycles, temperature and so on.

The effect on the displacement response by the uncertainty of an input ground motion used to be larger than that of the mechanical property [3]. And the non-stationary characteristics of the input ground motion increase the distribution of the response of a base isolation system [4]. The response of the vertical force will be widely distributed by the extended design basis earthquake. The frequency content of a vertical ground motion is stronger than that of a horizontal ground motion in high frequency region. It could amplify the vertical response of the basemat because the natural frequency of the base isolation system in the vertical direction also high.

3. Methodology for the Fragility Assessment of the Base Isolation System

For the seismic risk assessment, the failure probability along the ground motion intensity, which is seismic fragility, should be evaluated. The failure state is that the response is larger than the capacity. In case of base isolator, the capacity represented by the UPD and the response of a given seismic intensity can be placed on the plane of axial force and horizontal displacement. Therefore the response has the joint distribution and the failure probability can be calculated by the integration of it out of the capacity limit. Then, the failure probabilities of isolators are converted to the probability of unacceptable performance of a base isolation system. For the fragility curve of a base isolation system can be obtained from the calculations of failure probability with increasing seismic intensity by an appropriate increment.

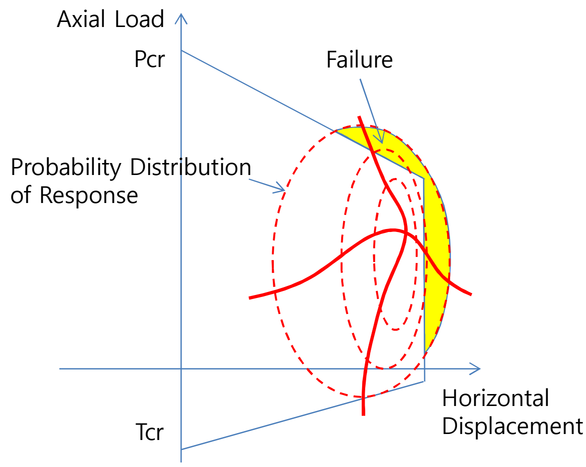

Fig. 2. Failure probability on the displacement-load plane

4. Conclusions

This is the preliminary study for the performance based risk assessment of a base isolated nuclear power plant. The items to evaluate the capacity and response of an individual base isolator and a base isolation system were briefly outlined. However, the methodology to evaluate the realistic fragility of a base isolation system still needs to be specified.

ACKNOWLEDGEMENT

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