*Transactions of the Korean Nuclear Society Autumn Meeting*
*Changwon, Korea, October 30-31, 2025*

# Seismic Fragility Assessment of Equipment in Nuclear Power Plants Considering Structural Aging in 3D Structural Model

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***Keywords :** seismic fragility, structural aging, 3D finite element model, in-structure response spectrum

## 1. Introduction

Recent earthquakes in Korea, such as the 2016 Gyeongju and 2017 Pohang events, have heightened public concern regarding the seismic safety of nuclear power plants (NPPs). Traditionally, seismic safety evaluations have been conducted primarily for the original 40-year design life of NPPs. However, in Korea and many other countries, the continued operation of nuclear plants beyond their initial design life has become inevitable. Under such extended operation, the influence of structural aging including stiffness reduction, cracking, and reinforcement corrosion becomes increasingly critical. Structural aging not only affects structural integrity but also modifies the dynamic properties of buildings, thereby altering the seismic demands imposed on safety-related equipment.

In the field of seismic fragility assessment, accurate evaluation requires realistic consideration of both site-specific seismic hazard characteristics and structural response behavior. Simplified models often fail to capture torsional effects, vertical coupling, and higher-mode contributions, particularly when structural aging is present. To enhance the quality and reliability of seismic fragility assessments, it is therefore essential to employ high-fidelity three-dimensional (3D) structural models capable of representing degradation effects and complex dynamic interactions.

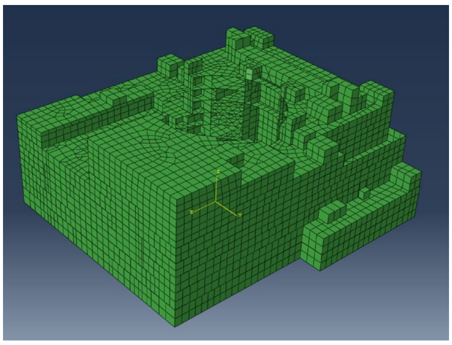

Fig. 1. 3D model of a representative NPP auxiliary building in Korea

In this study, seismic fragility evaluations were performed for representative cabinet-type electrical equipment such as motor control centers, load centers, and switchgears by explicitly reflecting the effects of structural aging (e.g., chloride-induced deterioration of reinforced concrete) as well as equipment aging. By deriving in-structure response spectra (ISRS) from a degraded 3D structural model and applying them to fragility analysis, this work aims to provide more realistic and higher-quality insights into the seismic safety of NPPs under conditions of extended operation beyond their original design life.

## 2. Methods and Results

### *2.1 Seismic Fragility Assessment*

The seismic fragility of equipment was evaluated using the separation of variables (SOV) method, which is a widely applied probabilistic approach for deriving fragility curves [1-2]. In this method, the seismic capacity of equipment is expressed by the median capacity ($A_m$) and lognormal variability parameters ($\beta_R$, $\beta_U$), accounting for both aleatoric and epistemic uncertainty. The high confidence of low probability of failure (HCLPF) capacity was derived as a conservative indicator suitable for seismic probabilistic safety assessment (SPSA).

For cabinet-type electrical equipment such as motor control centers, load centers, and switchgears, the fragility capacity depends strongly on the in-structure response spectra (ISRS) at the installation floor. Therefore, accurately deriving ISRS that reflect structural degradation is required for realistic fragility assessment.

### *2.2 3D NPP Model with Structural Aging*

A three-dimensional finite element (FE) model of a representative nuclear power plant (NPP) auxiliary building was developed to investigate the effects of degradation on in-structure seismic response. The 3D model explicitly represented major structural components, including shear walls and slabs, thereby allowing realistic simulation of translational, torsional, and vertical dynamic responses.

To reflect chloride-induced deterioration in reinforced concrete members, degradation was modeled not as a uniform stiffness reduction but through localized modifications to the external wall elements.

Specifically, the reduction of bond strength between reinforcement and concrete due to corrosion, as well as the spalling of cover concrete on externally exposed walls, was considered. These degradation mechanisms were translated into reductions in effective stiffness of the external walls.

### *2.3 Variation of Seismic Demand with Degradation*

Dynamic analyses were performed using ground motions generated from the NUREG/CR-0098 spectrum [3]. The resulting ISRS were derived at equipment installation floors for intact and degraded structural conditions.

The results indicated that changes in structural natural frequencies due to degradation affect the ISRS. In some cases, stiffness reduction shifted natural frequencies away from the dominant input spectral peaks, leading to reduced seismic demand. In other cases, frequency shifts aligned with peak regions, amplifying ISRS. These findings confirm that the influence of degradation is not uniform but depends on both the input motion characteristics and the structural dynamic properties.

By applying ISRS values obtained at the actual equipment locations (MCCs, LCs, and switchgears), more realistic seismic fragility curves were derived. This approach improves the accuracy of fragility evaluation compared with traditional simplified methods, thereby enhancing the quality of SPSA results.

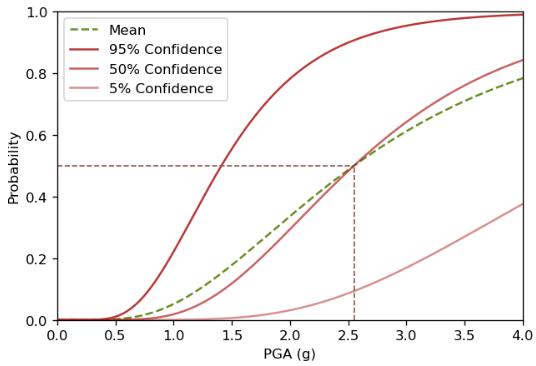


Fig. 2. Fragility curves of switchgear considering structural aging in 3D structural model

Fig. 3. Experimental shaking table setup of cabinet equipment (switchgear) for seismic fragility assessment

## 3. Conclusions

This study investigated the effects of structural aging on the seismic fragility of cabinet-type electrical equipment in nuclear power plants, with particular focus on conditions relevant to extended operation beyond the original design life. By employing a three-dimensional finite element model of the auxiliary building, chloride-induced deterioration of reinforced concrete was explicitly simulated through localized stiffness reductions in external wall elements, reflecting reinforcement bond degradation and cover concrete spalling.

The results demonstrated that structural degradation alters dynamic properties of the building and produces non-uniform changes in in-structure response spectra. In certain cases, degradation reduced seismic demand by shifting natural frequencies away from dominant input spectral peaks, while in other cases, it amplified response by aligning with peak spectral regions. These findings indicate that degradation effects are strongly dependent on both structural dynamic characteristics and ground motion features.

By incorporating degradation-sensitive ISRS at the actual installation locations of cabinet-type equipment including motor control centers, load centers, and switchgears, this study achieved more realistic and higher-quality fragility assessments compared with traditional approaches. The results underline the necessity of reflecting both structural and equipment aging in seismic fragility evaluation, particularly under scenarios of long-term operation.

Overall, the study highlights the importance of using high-fidelity 3D models that incorporate site-specific seismic input and explicit degradation mechanisms to enhance the reliability of seismic probabilistic safety assessment (SPSA). The methodology and findings presented herein provide valuable technical insights for ensuring the seismic safety of NPPs during continued operation beyond their original design life.

## ACKNOWLEDGEMENT

This work was supported by the Korea Institute of Energy Technology Evaluation and Planning (KETEP) and the Ministry of Trade, Industry & Energy (MOTIE) of the Republic of Korea (No. RS-2022-KP002849).

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