

Seismic Fragility Assessment of NPP Cabinet Equipment under Initial, Aged, and Retrofitted Conditions

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1. Introduction

Continued long-term operation of nuclear power plants (NPPs) requires seismic safety evaluations that reflect the actual conditions of both building structures and installed equipment. Aging of reinforced concrete structures can modify floor response by changing structural stiffness and modal properties, while aging of cabinet-type electrical equipment can reduce functional and structural capacity through deterioration of internal components, loosening of connections, and loss of cabinet stiffness. Evaluating only the as-designed condition may therefore overestimate the remaining seismic margin of equipment in operating plants.

In this study, an integrated seismic fragility evaluation was conducted for cabinet equipment such as motor control center (MCC) and load center considering initial, aged, and retrofitted conditions. Location-specific in-structure response spectra (ISRS) were first derived from three-dimensional (3D) structural models representing the initial and degraded building conditions. Cabinet specimens were then tested in their initial and aged configurations, and the resulting response and damage patterns were used to select targeted retrofit details. The retrofitted specimens were subsequently retested and reevaluated using the same test framework. This procedure enabled changes in seismic demand, equipment capacity, and retrofit effectiveness to be assessed consistently.

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2. Methods and Results

2.1 Integrated Fragility Assessment

Equipment fragility was evaluated using the separation of variables (SOV) method recommended for seismic probabilistic safety assessment [1,2]. The test response spectrum (TRS) at the functional or structural limit state was used to characterize equipment capacity, and the required response spectrum (RRS) was derived from the location-specific ISRS of the 3D structural model. Median capacity and the logarithmic

randomness and uncertainty parameters were used to construct fragility curves and derive the high confidence of low probability of failure (HCLPF) capacity. The initial condition combined the initial structural demand with the intact equipment capacity, whereas the aged and retrofitted conditions used the degraded structural demand with the corresponding aged or retrofitted equipment capacity.

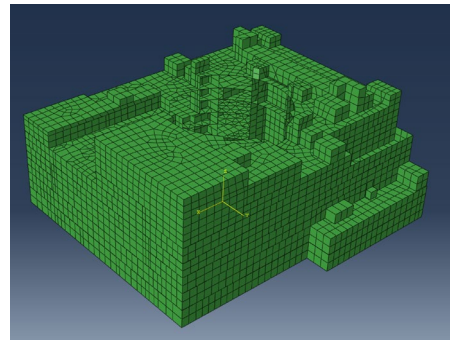


Fig. 1. 3D model of a representative NPP auxiliary building in Korea

The 3D model explicitly represented shear walls and floor slabs and incorporated chloride-induced deterioration only in exposed external walls. The effects of reduced reinforcement-concrete bond and cover-concrete spalling were translated into effective stiffness changes. Probabilistic response analysis sets were generated by Latin Hypercube Sampling (LHS) of ground motion characteristics, structural stiffness, and damping. Structural aging shifted the natural frequencies and individual ISRS peaks rather than uniformly increasing or decreasing demand. The resulting demand variation depended on the equipment location, direction, and interaction between the structural modes and input motion frequency contents.

2.2 Aging Tests and Retrofit Configurations

The experimental program was organized as a continuous sequence of initial state evaluation, aging, aged state evaluation, retrofit, and post retrofit reevaluation. For each equipment condition, the shaking table input was increased stepwise until functional anomalies or structural damage were identified. Functional limit states included switch trip or contact

chatter exceeding the adopted duration criterion, while the structural limit state was defined from damage that impaired cabinet integrity. The measured TRS at each limit state was used consistently in the test based fragility calculation.

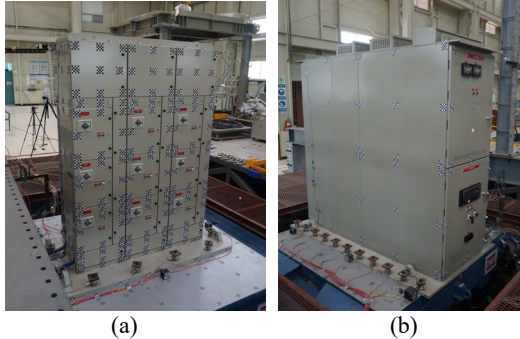


Fig. 2. Shaking table test setup for (a) MCC and (b) Load center

The aged stated response was used to identify the deformation and damage mechanisms requiring reinforcement. The MCC was stiffened by adding an external frame around the cabinet, thereby increasing its global lateral stiffness and controlling cabinet distortion. For the load center, local stiffness was increased at the connections where structural damage had initiated. The retrofitted specimens were then subjected to the same progressive excitation and limit state identification procedure.



Fig. 3. Structural damage observed at the door hinge of the load center

2.3 Fragility Assessment of Cabinet Equipment

The fragility assessment results showed clear differences among the initial, aged, and retrofitted conditions. Structural aging produced non-uniform changes in seismic demand whereas equipment aging reduced the capacity associated with both functional and structural limit states.

Following external frame stiffening, the MCC fragility curves shifted toward higher PGA levels compared with the aged state, demonstrating recovery of both functional and structural seismic margins. The improvement was attributed to reduced global cabinet deformation, more stable support of internal components, and suppression of deformation concentration in the cabinet frame.

For the load center, local reinforcement delayed recurrence of the connection damage that governed the aged state structural limit and improved the corresponding fragility capacity. This result indicates that damage informed local stiffening can be effective without replacing the entire cabinet.

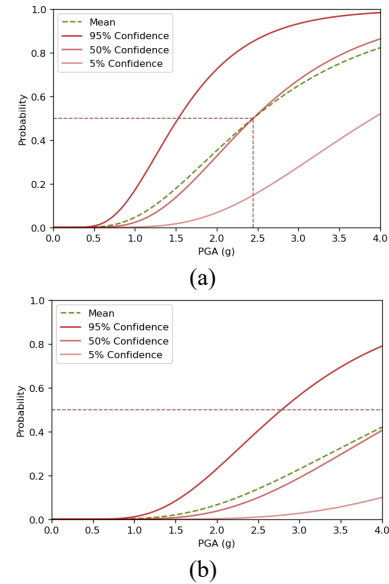


Fig. 4. Seismic fragility curves of the load center (a) before and (b) after retrofit

3. Conclusions

In this study, an integrated procedure was applied to evaluate cabinet-type electrical equipment under initial, aged, and retrofitted conditions with experimental program. Structural aging modified the location specific ISRS in a non-uniform manner, while equipment aging directly reduced the test based capacity. Targeted retrofit improved the measured seismic performance of both cabinet types. External frame stiffening was effective for the MCC, whereas local stiffening of damage prone connections was effective for load center. This initial-aged-retrofitted framework can support risk informed prioritization of cabinet maintenance, reinforcement, and replacement for continued operation.

ACKNOWLEDGEMENT

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