Effect of In-Structure Response Spectra on the Inelastic Energy Absorption Factor in Seismic Fragility Assessment

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1. Introduction

Seismic Probabilistic Safety Assessment (SPSA) of Nuclear Power Plants (NPPs) is a methodology for quantitatively evaluating seismic risk by integrating seismic hazard and fragility analysis, and system analysis of accident scenarios. Seismic fragility analysis quantitatively evaluates the seismic performance of structures, systems, and components (SSCs) by expressing the conditional probability of damage at a given level of seismic intensity. In conventional seismic analyses of NPPs, structural responses are generally evaluated using linear analysis, based on the assumption that the structures behave within the elastic range; however, under high intensity ground motions, actual structural and equipment responses may extend into the inelastic range. Because detailed nonlinear analysis of NPPs involves highly complex analytical models and substantial computational effort, the effects of inelastic behavior are commonly accounted for inelastic analyses through the use of an inelastic energy absorption factor, F_μ. EPRI [1] and ASCE [2] provide recommended F_μ for various types of structures and equipment based on empirical data, analytical results, and engineering judgment. For structures, approximate methods based on equivalent linear analysis are also available for estimating F_μ. However, equipment installed within a structure is subjected to floor motions characterized by narrow-band in-structure response spectrum (ISRS), which differ substantially from the broad-band characteristics of ground motion response spectrum used in structural evaluations. Consequently, the equipment F_μ may exhibit frequency-dependent behavior, including pronounced peaks near the dominant frequencies of the ISRS, and may differ significantly from the conventional recommended values. Therefore, this study compares the recommended F_μ used in existing seismic fragility methodologies with those obtained from nonlinear response analyses considering narrow-band in-structure motions. The conservatism associated with the conventional F_μ is subsequently investigated, with the aim of developing a more realistic approach for evaluating the inelastic energy absorption capacity of NPP equipment.

2. Evaluation Method of Inelastic Energy Absorption Factor

2.1 Inelastic Energy Absorption Factor

A fundamental assumption in the structural analysis of NPPs is that the structures behave within the elastic range and can therefore be evaluated using linear elastic analysis. However, when seismic demands exceed the design basis, actual structural response may extend beyond the yield point into the inelastic range. In this range, a portion of the input seismic energy is dissipated through plastic deformation and ductile behavior, allowing the structure to sustain the seismic demand with a lower strength than that predicted by purely elastic analysis. The inelastic energy absorption factor, F_μ, is introduced to account for the difference between elastic and inelastic response. As shown in Fig. 1, F_μ is defined as the ratio of the elastic strength demand to the corresponding inelastic strength demand and represents the reduction in required strength resulting from inelastic deformation and energy dissipation. In seismic fragility analysis of NPPs, F_μ is commonly applied to the results of linear elastic analyses to indirectly account for the response reduction effects associated with inelastic behavior, thereby avoiding the need for detailed nonlinear analysis.

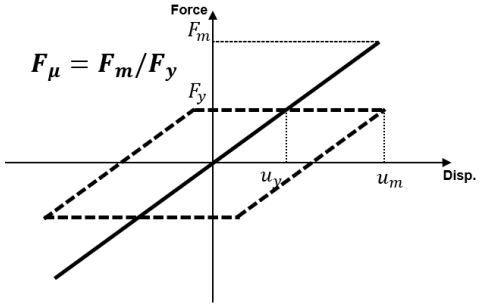


Fig. 1. Definition of the F_μ based on elastic and inelastic force-displacement curve.

2.2 Calculation and Limitation of F_μ Based on Existing Methodologies

EPRI seismic fragility analysis methodologies provide recommended F_μ for various types of structures and equipment. For structures, procedures based on equivalent linearization are also provided to estimate F_μ. These procedures have generally been developed under the assumption of broad-band ground motion response characteristics.

In seismic fragility analysis of equipment, ISRS is used to represent the seismic demand. Unlike broad-band ground motion response spectrum, ISRS generally exhibits narrow-band characteristics, with amplified responses concentrated near the natural frequencies of the structure. Therefore, structural F_μ estimation procedures developed on the basis of broad-band ground motions may not be directly applicable to equipment subjected to narrow-band in-structure motions. In particular, near frequencies at which dynamic interaction or resonance effects become significant, the equipment F_μ may exhibit pronounced frequency-dependent peaks and may differ substantially from the recommended values provided by EPRI. Furthermore, because the basis for deriving the recommended equipment F_μ in EPRI is not clearly documented, their applicability to narrow-band in-structure response conditions and the associated conservatism should be examined separately.

2.3 Estimation of Equipment F_μ Using Narrow-Band In-Structure Response Spectrum

To confirm the characteristics of the equipment F_μ, linear and nonlinear analyses were performed using a 2-degree-of-freedom lumped-mass model. The model was configured with dominant natural frequencies of approximately 8 Hz and 21 Hz, and the resulting floor acceleration time histories were used to calculate the frequency-dependent F_μ spectrum, as shown in Fig. 2. Pronounced peaks in F_μ were observed near the first and second modal frequencies, respectively, and the calculated values in these frequency ranges exceeded the corresponding values recommended by EPRI. These results indicate that the conventional equipment F_μ may conservatively represent the inelastic response reduction capacity of equipment subjected to narrow-band in-structure motions, particularly near resonance-dominated frequency range. To derive more realistic equipment F_μ, this study further confirms the effects of parameters associated with nonlinear response characteristics, including strong-motion duration, the number of effective loading cycles, and hysteretic behavior models. Based on these parametric analyses, this study aims to develop a frequency-dependent methodology for evaluating equipment F_μ.

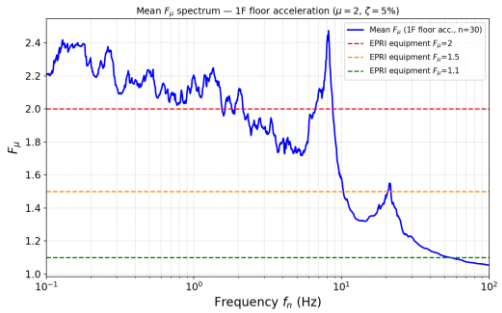


Fig. 2. F_μ spectrum for narrow-band in-structure response spectrum.

3. Conclusions

This study confirmed the characteristics of the inelastic energy absorption factor (F_μ) for NPP equipment subjected to narrow-band in-structure response spectrum (ISRS). The equipment F_μ exhibited strong frequency-dependent characteristics, with pronounced peaks near the dominant frequencies of the structure. These results suggest that existing F_μ may conservatively represent the inelastic response reduction capacity of equipment subjected to narrow-band in-structure motions. Further consideration of influential parameters, such as strong-motion duration and hysteretic behavior, is expected to enable the derivation of more realistic F_μ, thereby contributing to a more rational assessment of seismic risk in NPPs.

Acknowledgements

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