

## Preliminary Seismic Fragility Analysis of Fuel Assembly in NPPs Using SOV Approach

Na-Hyun Kim <sup>a\*</sup>, Jae-Wook Jung <sup>a</sup>, Minkyu Kim <sup>a</sup>

<sup>a</sup> Korea Atomic Energy Research Institute, Smart Structural Safety & Prognosis Research Division, 111, Daedeok-daero 989 beon-gil, Yuseong-gu, Daejeon, 34057, Korea

\*Corresponding author: nhkim@kaeri.re.kr

### 1. Introduction

After the earthquake in Gyeongju (2016) and Pohang (2017) in South Korea, the concerns about the seismic safety of NPPs (Nuclear Power Plants) has increased. Accordingly, it is necessary to re-evaluate the existing fragility analysis on structures and equipment of NPPs, and additionally, the seismic fragility analysis of fuel assembly is also required.

Since the fuel assembly is directly related to safety, securing the seismic safety of the fuel assembly is considered an important issue. The beyond design basis earthquake may cause buckling of the spacer grid, deformation of nuclear fuel, and impact between components of the fuel assembly, which may lead to structural damage to the fuel assembly. In addition, if the beyond design basis earthquake occurs and key operating parameters exceed the safe operating limits, a reactor trip occurs. When a reactor trip occurs, the control rods that control fission are dropped into the core within the required time to prevent related accidents. The control rod is inserted into the core through the CRDM (Control Rod Drive Mechanism), the control rod cluster guide tube and the guide thimble of the fuel assembly. At this time, the components included in the control rod insertion path may be damaged by the earthquake, thereby the control rod insertion can be failed. Therefore, both the structural integrity of the fuel assembly and the possibility of control rod insertion should be considered in the seismic fragility assessment of the fuel assembly.

In this paper, seismic fragility assessment of fuel assembly was performed according to the EPRI (Electric Power Research Institute) SOV (Separation Of Variable) approach [1, 2]. First, failure modes related to the structural damage of the fuel assembly and control rod insertion mentioned above were derived, and a preliminary evaluation of seismic fragility according to the EPRI methodology was performed for the most vulnerable failure modes.

### 2. Defined Failure Mode

In order to evaluate the seismic fragility of the fuel assembly, the relevant failure modes were first defined. The failure modes of the fuel assembly were derived by considering the structural damage of the fuel assembly and the possibility of control rod insertion. And among them, the critical failure mode judged to be the most vulnerable was selected for preliminary seismic fragility analysis.

### 2.1 Potential failure modes

The failure modes of the fuel assembly were mainly defined for the components of fuel assembly and the components related to the control rod insertion. In addition, the damage mode was defined for control rod, and the components of the RVIs that could affect the damage to the aforementioned components.

First, the representative components of the fuel assembly related to the failure mode are as follows; 1) Spacer grid 2) Fuel rod 3) Guide thimble tube. And, the components included in the control rod insertion path related to the failure mode are as follows; 1) CRDM 2) Control rod guide tube 3) Guide thimble tube.

The failure modes related to each component are summarized in the table below. Not only the direct failure of the components related to fuel assembly, but also the case where the control rod insertion path is restricted or the insertion time is delayed from required time were considered as failure mode.

Table I: Potential failure modes related to fuel assembly [3, 4, 5]

Component	Failure mode
Control rod	Damage to upper end plug
	Damage to cladding
CRDM	Bending of CRDM housing
	Damage to CRDM housing support
	Deformation of / Damage to CRDM tubes
Control rod guide tube	Deformation of / Damage to guide tube
RPVIs	Damage to core support
	Damage to core shroud
	Damage to lower support
Spacer grid	Damage to spacer grid
Fuel Assembly	Bending of fuel rod
	Detachment of fuel rod
	Deformation of / Damage to guide thimble tube

### 2.2 Critical failure mode

Among the failure modes defined above, if the seismic margin is large, or the occurrence probability is low, or it does not significantly affect the structural and functional failure of the fuel assembly and control rod

insertion, it can be screened out. In the domestic licensing procedure, it is judged whether fuel is failed when an earthquake occurs, by the impact load from the spacer grid and damaged to the guide thimble tube. In particular, the guide thimble tube is a component of the fuel assembly as well as a component of the control rod insertion path. If the guide thimble tube is damaged due to damage to other components of fuel assembly, the control rod insertion may be delayed or impossible. In addition, the NRA(Japan Nuclear Regulation Authority) identified that damage to the guide thimble tube of the fuel assembly was the biggest factor that limits the control rod insertion [5]. Accordingly, loss of control rod insertion function due to plastic deformation of guide thimble tube was selected as a critical failure mode.

### 3. Preliminary seismic fragility analysis

The preliminary seismic fragility analysis of the fuel assembly based on EPRI SOV fragility approach was performed by considering the damage of the guide thimble tube as a failure mode. An accurate value for fragility analysis has not yet been obtained as the associated tests and analyses are currently being carried out. For this reason, an evaluation was performed preliminarily using arbitrary values.

The assumptions in the preliminary analysis are as follows; 1) For reference earthquake, assuming the UHS (Uniform Hazard Spectrum) of NPP sites as a GMRS (Ground Motion Response Spectrum), and applying the scaling approach 2) Assuming the natural frequency of the fuel assembly as a 3 Hz.

#### 3.1 Fragility model

The fragility model for the SSC (System, Structure, and Component) corresponding to a particular failure mode can be expressed by the median ground acceleration capacity,  $A_m$ , and two parameters representing the variabilities,  $\beta_R$  and  $\beta_U$ . The  $\beta_R$  and  $\beta_U$  are the logarithmic standard deviations for randomness and uncertainty, respectively. In the SOV approach, it is required to evaluate the median factors of safety and the corresponding logarithmic standard deviations for each variable that affects the response and capacity of the SSC by earthquakes. From the SOV approach, realistic median ground acceleration capacity is estimated first, and the variabilities in the ground acceleration capacity are quantified. The ground acceleration capacity is expressed as the product of several random variables as shown in Equation 1. The variables  $F_{EC}$ ,  $F_{ER}$ , and  $F_{RS}$  are the equipment capacity factor, equipment response factor and structure response factor, respectively. The  $PGA_{RE}$  is peak ground acceleration of reference earthquake.

$$A_m = F_{EC} * F_{ER} * F_{RS} * PGA_{RE} \quad (1)$$

$F_{EC}$ ,  $F_{ER}$ , and  $F_{RS}$  are the products of a series of factors. And the logarithmic standard deviations for randomness and uncertainty are the SRSS of logarithmic standard deviations for the corresponding variables. In the following sections, the values of the corresponding factors and logarithmic standard deviations are estimated.

#### 3.2 Equipment response factor

$F_{ER}$ , depends on the response characteristics of the equipment and is affected by the following variables; Qualification method, damping, modeling(equipment frequency and mode shape), equipment response phasing (mode combination) and earthquake component combination. For each variable, the value of factor and variabilities were arbitrarily estimated, and the equipment response factor and corresponding variabilities were calculated. The arbitrary values were selected conservatively. Since it was regarded as the analysis is performed using realistic response analysis procedure and material properties, the variability due to uncertainty in qualification method ( $\beta_{U_{QM}}$ ) is zero. And the variability due to uncertainty in damping ( $\beta_{U_{dmp}}$ ) was arbitrarily considered as 0. The calculated  $F_{ER}$  and  $\beta_{ER}$  are as follows.

$$F_{ER} = F_{QM} * F_{dmp} * F_{mod} * F_{mc} * F_{ECC} \quad (2)$$

$$= 1.0 * 1.0 * 1.0 * 1.0 * 1.0 = 1.0$$

$$\beta_{R_{ER}} = \sqrt{\beta_{R_{mc}}^2 + \beta_{R_{ECC}}^2} \quad (3)$$

$$= \sqrt{0.15^2 + 0.18^2} = 0.234$$

$$\beta_{U_{ER}} = \sqrt{\beta_{U_{QM}}^2 + \beta_{U_{dmp}}^2 + \beta_{U_{mod}}^2} \quad (4)$$

$$= \sqrt{0.0^2 + 0.0^2 + 0.335^2} = 0.335$$

#### 3.3 Equipment capacity factor

$F_{ER}$ , is evaluated according to the failure mode of the equipment. In the ductile failure mode, it is calculated based on the capacity up to yield, and the additional capacity due to the nonlinear response is considered as inelastic energy. In this study, the capacity factor was calculated based on the failure of the guide thimble tube. The variabilities due to uncertainty and randomness in nonlinear response ( $\beta_{U_{\mu}}$  and  $\beta_{R_{\mu}}$ ) are arbitrary considered as zero.

$$F_{EC} = F_S * F_{\mu} \quad (5)$$

$$= 6.087 * 1.0 = 6.087$$

$$\beta_{R_{EC}} = \beta_{R_{\mu}} \quad (6)$$

$$= 0.0$$

$$\begin{aligned}\beta_{U_{EC}} &= \sqrt{\beta_{U_{\mu}}^2 + \beta_{U_S}^2} \\ &= \sqrt{0.0^2 + 0.2^2} = 0.2\end{aligned}\quad (7)$$

### 3.4 Preliminary seismic fragility of fuel assembly

The HCLPF (High Confidence of Low Probability of Failure) is defined as the capacity level at which there is 95% confidence that less than 5% of actual capacity levels will fall below. The HCLPF is defined as Equation 8.

$$\text{HCLPF} = A_m * \exp[-1.65(\beta_R + \beta_U)] \quad (8)$$

In order to calculate HCLPF,  $A_m$  and  $\beta_R$  and  $\beta_U$  were calculated from the previously obtained values. For the structure response factor, the existing fragility assessment results were referred to  $\text{PGA}_{RE}$  is 0.273.

$$A_m = 6.087 * 1.0 * 0.86 * 0.273 = 1.429 \quad (9)$$

$$\begin{aligned}\beta_R &= \sqrt{\beta_{R_{EC}}^2 + \beta_{R_{ER}}^2 + \beta_{R_{RS}}^2} \\ &= \sqrt{0.0^2 + 0.234^2 + 0.221^2} = 0.322\end{aligned}\quad (10)$$

$$\begin{aligned}\beta_U &= \sqrt{\beta_{U_{EC}}^2 + \beta_{U_{ER}}^2 + \beta_{U_{RS}}^2} \\ &= \sqrt{0.2^2 + 0.335^2 + 0.218^2} = 0.447\end{aligned}\quad (11)$$

By substituting the calculated values of  $A_m$  and  $\beta_R$  and  $\beta_U$  were into Equation 8, the HCLPF capacity of 0.402 can be derived.

## 4. Conclusion

In this paper, the preliminary seismic fragility analysis of fuel assembly was performed according to the EPRI SOV approach. Prior to performing the seismic fragility analysis, the failure mode of the fuel assembly by considering the structural failure of the fuel assembly and the possibility of control rod insertion was defined. Among the defined failure modes, damage to the guide thimble tube was considered as a critical failure mode, and a preliminary seismic fragility analysis of the fuel assembly was performed. Finally, the HCLPF capacity of 0.402 was derived.

In this study, the accurate value for fragility analysis has not yet been obtained as the associated tests and analyses are currently being carried out. For this reason, the analysis was performed preliminary using an arbitrary value. After obtaining actual values later, it is expected that the seismic fragility can be analyzed according to the procedure presented in this paper.

## REFERENCE

- [1]EPRI, Seismic Fragility and Seismic Margin Guidance for Seismic Probabilistic Risk Assessments, EPRI TR-3002012994, Palo Alto, CA, 2018.
- [2]J. W. Reed, and R. P. Kennedy, Methodology for Developing Seismic Fragilities, EPRI TR-103959, Palo Alto, CA, 1994.
- [3]M.Pellisetti, A. Nykyforchyn, P. Rangelow, K. Schramm, H. Keßler, J. Klügel and U. Klapp, Seismic Robustness of Reactor Trip via Control Rod Insertion at Increased Seismic Hazard Estimates, 23th International Conference on Structural Mechanics in Reactor Technology (SMiRT-23), Aug.10-14, 2015, Manchester, UK.
- [4] R.J. Budnitz, P.J. Amico, C.A. Cornell, W.J. Hall, R.P. Kennedy, J.W. Reed, and M. Shinozuka, An approach to the quantification of seismic margins in nuclear power plants, NUREG/CR-4334, 1985.
- [5] NRA, 原子力施設等の耐震性評価技術に関する試験及び調査 機器耐力その 2 (PWR 制御棒挿入性)に係る報告書, 2006.