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Structural Integrity Evaluation of APR1400 Beyond Design Basis Earthquake

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1. Introduction

A demand for securing structural safety of Nuclear Power Plants (NPPs) against earthquakes has been ongoing for a long time. Therefore, structural integrity evaluations for Operational Basis Earthquake (OBE) and (Safety Shutdown Earthquake) SSE were performed on structures, systems, and components of NPPs. After the Fukushima nuclear power plant accident in 2011, the issue of structural safety of NPPs against Beyond Design Basis Earthquake (BDBE) has emerged. A strong motion that exceeds the design basis cause the NPPs to undergo elasto-plastic behavior beyond the elastic regions. In order to evaluate the structural integrity for BDBE, elasto-plastic analysis of NPPs should be performed. Therefore, many studies have been conducted to derive elasto-plastic responses to excessive earthquake loadings [1-4]. Because the elasto-plastic response has nonlinear characteristics, it exhibits different behavior from the elastic response. It is necessary to investigate the structural integrity evaluated considering these different behavioral characteristics.

The target rector for this study is Advanced Power Reactor 1400 (APR1400), a pressurized-water reactor with a power generation capacity of 1400 MW. In particular, this study focuses on the Reactor Vessel and Internals (RVIs) among the Reactor Coolant System (RCS) equipment of APR1400. A finite element model for seismic analysis was constructed based on the scaled-model experiment and similarity theory. For the elasto-plastic analysis, bilinear hardening material properties of SA508 Gr.3 Class 1 and SA240 TP304, which are materials for reactor vessel and internals, were used for seismic analysis. In addition, artificial seismic waves for BDBE to be used as input in the three-axis directions were generated. These artificial waves were amplified to level that could cause local plastic deformation of the reactor vessel and internals. After that, seismic responses were derived by performing elastic and elasto-plastic analysis on the reactor vessel and internals, respectively. Finally, the structural integrity of the reactor vessel and internals was evaluated based on the derived seismic responses.

2. Seismic analysis

In this section, the process of performing seismic analysis on the reactor vessel and internals of the APR1400 is described. It includes construction of finite element model, process of seismic analysis, and result of seismic analysis.

2.1 Finite element model

The finite element model of the reactor vessel and internals is based on a scaled-model experiment. Nodal tests in air and water were performed on scaled-model. Based on the experimental results, the finite element model with natural frequency error of less than 10% was constructed by tuning the boundary conditions and fluid-structure interaction. After that, similarity theory and Non-dimensionalized Added Virtual Mass Incremental (NAVMI) factor were applied to expand to finite element model for real-size reactor vessel and internals. Some parts of the constructed finite element model have been simplified and omitted to be suitable for dynamic analysis. Finite element model for reactor vessel and internals to be used in this study is shown in Fig. 1. In addition, Fig. 2 shows the elasto-plastic material properties applied to the finite element model of the reactor vessel and internals for elasto-plastic analysis. In consideration of aging deterioration due to neutrons emitted from nuclear fuel, hardened material properties were used for internals. In the finite element model, hexahedral elements were mainly used for analysis accuracy, and tetrahedral elements were used for components that are not the region of interest.

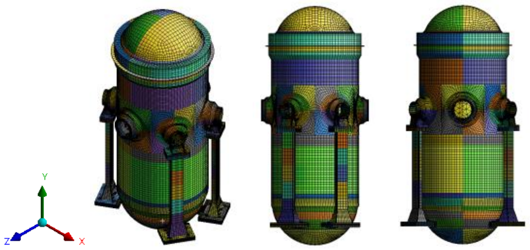

Fig. 1. Isometric, x-axis, and z-axis view of finite element model for APR1400 reactor vessel and internals.

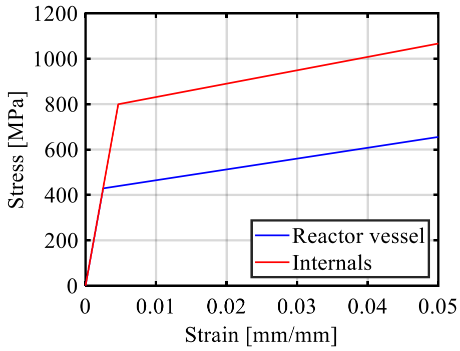

Fig. 2. Elasto-plastic material properties of SA508 Gr.3 Class 1 and SA240 TP304 applied to finite element model for reactor vessel and internals.

2.2 Seismic analysis

In this study, seismic analysis is divided into two types of analysis. It is divided into elastic seismic analysis and elasto-plastic seismic analysis considering the plastic behavior of the reactor vessel and internals. The analysis information such as input seismic waves, boundary conditions, and damping of the two types of analysis is the same, only whether or not elasto-plastic material properties are considered.

For seismic analysis, an artificial seismic acceleration time history to be used as an input was generated. For sine and cosine function, artificial seismic acceleration was generated to include 100 Hz, which is cut-off frequency of the earthquake with random phase. A response spectrum, which is the basis for generating artificial seismic acceleration, was determined by selectively combining the design spectra for APR1400 [5,6]. Then, it was amplified with PGA 0.6 g for the BDBE. The target response spectrum of the artificial seismic acceleration is called Required Response Spectrum (RRS), and the response spectrum calculated for the generated artificial seismic acceleration is called Calculated Response Spectrum (CRS). Fig. 3 shows the RRS and CRS of the EW, NS and V-directions in this study. CRS is no more than 10% less than RRS and no more than 30% greater than RRS in any frequency range. This satisfies the criteria for generating artificial seismic acceleration in U.S. NRC SRP 3.7.2 [7]. Finally, Fig. 4 shows the determined three-axis acceleration time histories of EW, NS, and V-directions. The maximum accelerations in the EW, NS, and V-directions are 1.79 g, 2.54 g, and 1.31 g, respectively. Compared to the PGA 0.6 g, the acceleration applied to the reactor vessel and internals is greatly amplified by the dynamic characteristics of the building. In addition, 3% Rayleigh damping was applied for the seismic analysis of reactor vessel and internals. This is a conservative approach with lower damping values compared to general structures. The seismic analysis was performed with a time increment of 0.005 seconds for a total of 20 seconds.

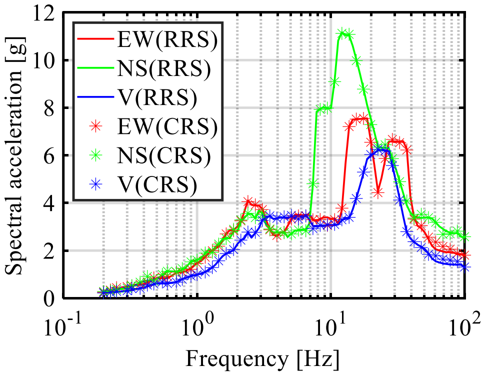

Fig. 3. EW, NS and V-directions response spectrum used for artificial acceleration generation.

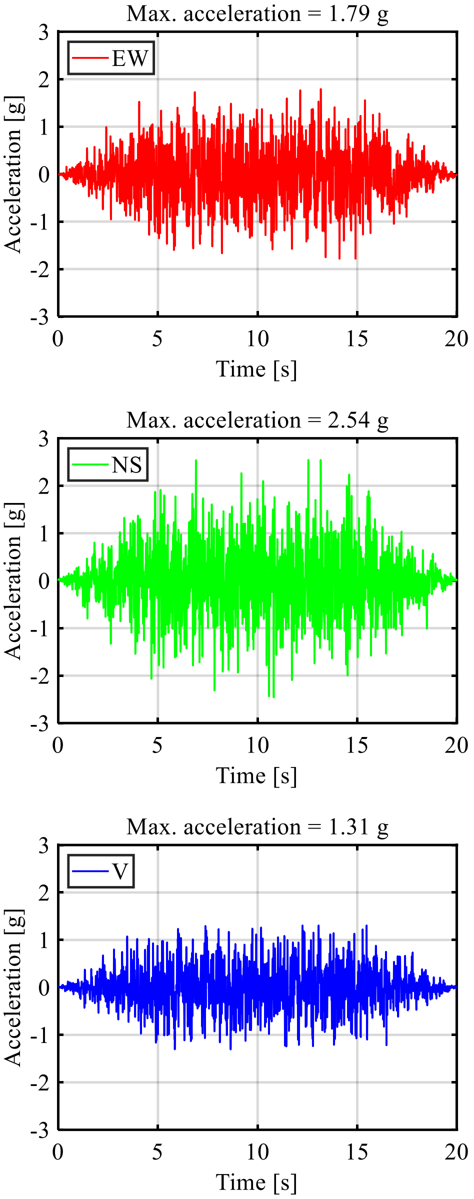

Fig. 4. EW, NS and V-directions time history artificial acceleration used for seismic analysis.

2.3 Results

Table I shows the elastic seismic analysis results for locations and times at which the maximum stress occurs for each component of the reactor vessel and internals. In the reactor vessel, the upper reactor head mainly behaves due to the bending mode, and high stress is generated in the shear key, which serves as a restraint at the lower hemisphere. Core support barrel also undergoes bending behavior, and high stress occurs at the snubber, which serves to limit the lateral behavior of the lower part of the core support barrel. In cores shroud, upper guide structure and inner barrel assembly, stress concentrations occur to geometrical discontinuities and sharp edges of each component.

Table I: Critical locations and times of elastic analysis for reactor vessel and internals

Components	Critical location	Critical time [s]
Reactor vessel	Shear key	8.245
Core support barrel	Snubber	6.385
Core shroud	Bottom plate - rib	14.825
Upper guide structure	Flange	14.955
Inner barrel assembly	Flange	8.655

Similar to the elastic analysis results, high stress and plastic deformation occur at the same locations in the elasto-plastic analysis results. However, due to energy dissipation by plastic deformation, the load distribution acting on the internals is relaxed. Therefore, the responses of the internals are relatively low.

3. Structural integrity evaluation

When evaluating the structural integrity of NPPs, different criteria are applied depending on the analysis method. ASME B&PV Code Section III. Appendix XXVII provides stress-based acceptance criteria for reactor coolant system equipment [8]. To evaluate the acceptance criteria, calculate the membrane stress intensity and bending stress intensity acting on the equipment and compare with them with the material property standards to determine whether the acceptance criteria are satisfied. The formula for the acceptance criteria is as follows.

$$P_m \leq Min[2.4S_m, 0.7S_u] \quad (1)$$

$$P_L \leq 1.5 \times Min[2.4S_m, 0.7S_u] \quad (2)$$

$$(P_m \ or \ P_L) + P_b \leq 1.5 \times Min[2.4S_m, 0.7S_u] \quad (3)$$

Here, P_m is general primary membrane stress intensity, P_L is local membrane stress intensity, and P_b is bending stress intensity. S_m is design stress intensity and S_u is tensile strength of material. S_m and S_u are provided by ASME B&PV Code Section II, Part D [9].

The strain-based acceptance criteria can be expressed as acceptance criteria for ductile failure. The formula presented in ASME B&PV Code Section III. Appendix FF is as follows [8].

$$Max[TF(t)\varepsilon_{eq}^{p}(t)] \leq [\varepsilon_u + 0.25(\varepsilon_f - \varepsilon_u)] \quad (4)$$

Here, TF(t) is triaxiality factor, $\varepsilon_{eq}^{p}(t)$ is equivalent plastic strain, ε_u is uniform strain. and ε_f is fracture strain, respectively.

For the same input seismic wave, structural integrity was evaluated for two types of acceptance criteria based on elastic and elasto-plastic analysis results. According to each acceptance criterion, it was checked whether the acceptance criteria of the APR1400 reactor vessel and internals were satisfied. In addition, a conservatism of each acceptance criterion was compared.

4. Conclusions

In this study, elastic analysis and elasto-plastic analysis were performed on the reactor vessel and internals of APR1400. After that, structural integrity was evaluated based on the elastic response and the elasto-plastic response derived from each analysis result. In addition, structural integrity results were compared with each other to investigate the conservatism of each evaluation criteria. The findings of this study can contribute to the development of analysis and evaluation methods for NPPs against BDBE.

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