Structural Analysis of WH-type Reactor Lower Head ICI Penetration Failure under Severe Accident using Coupled MAAP–ABAQUS Analysis

Jun-Won Park[a], Yun-Jae Kim[a*], Miro Seo[b], Sangwoo Shin[b], Hyun Sun Park[c], Tae Hoon Lee[c]
[a]*Mechanical Engineering, Korea University, Seoul, 02841, Korea*
[b]*Korea Hydro & Nuclear Power Co., Ltd., Daejeon, 34101, Korea*
[c]*Nuclear Engineering, Seoul National University, Seoul 08826, Korea*
[*]*Corresponding author: kimy0308@korea.ac.kr*

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1. Introduction

The Modular Accident Analysis Program (MAAP5) is a system-level severe accident analysis code widely used for evaluating the progression of core damage and the overall plant response. By incorporating simplified thermal-hydraulic and containment models, MAAP5 can efficiently simulate complex accident scenarios such as loss-of-feedwater (LOFW) or large-break loss-of-coolant accidents (LLOCA). Its strength lies in providing fast and conservative predictions of system behavior, which makes it highly useful for decision-making and accident management.

However, due to its system-level nature, MAAP5 has limitations in accurately representing the local structural integrity of the reactor pressure vessel (RPV) lower head, which is one of the most critical components for ensuring containment of molten core materials during severe accidents. In particular, the penetration welds at the RPV lower head are known to be vulnerable regions, where local creep, plastic deformation, and damage accumulation strongly influence the onset of vessel failure.

To address this limitation, this study performed a detailed structural analysis using a coupled MAAP–ABAQUS analysis. In previous work [1], the coupled approach was applied to assess RPV lower head integrity under an LBLOCA scenario without considering ICI penetrations. The present study extends this methodology to include ICI penetration welds for a more realistic assessment.

In this study, MAAP5 was first employed to determine the critical injection times for in-vessel coolant injection under LOFW conditions, identifying both failure and near-failure cases. In the subsequent detailed structural analysis, a constitutive material model incorporating plasticity, creep, and failure characteristics based on experimental data was applied. By combining the efficiency of system-level accident progression analysis with the accuracy of detailed structural modeling, this study aims to provide a more comprehensive evaluation of RPV lower head integrity under severe accident conditions.

2. MAAP Analysis result

For a Westinghouse-type nuclear power plant, thermal boundary conditions were generated by MAAP5 considering molten corium behavior. In the MAAP analysis, the RPV lower head was hemispherical, and its nodalization was configured by symmetrically dividing this hemisphere. It consisted of 25 nodes, starting from the bottom-most part of the RPV lower head (node 1) and increasing in elevation up to the maximum height of the hemisphere.

Under the LOFW (Loss of Feedwater) severe accident scenario, the in-vessel injection was initiated 2 hours after the severe accident entry time on the secondary side and 2.5 hours after the severe accident entry time on the primary side. Thereafter, the injection time was incrementally delayed by 10 minutes to determine the onset of reactor vessel failure. Table 1 summarizes the corresponding results. As the injection time was delayed, the onset of core relocation occurred earlier, and vessel failure was observed when the injection was delayed by 80 minutes. In the failure cases, the predicted failure mode from MAAP analysis was RPV failure due to ICI tube failure, occurring at the penetration farthest from the vessel center (node 8 in MAAP).

In this study, two cases were analyzed: the failure case (80 minutes delay) and the case just prior to failure (70 minutes delay). Through the MAAP analysis, the inner and outer surface temperatures of 25 nodes constituting the RPV lower head were obtained. The maximum inner wall temperature in the failure case was almost twice as high as in the non-failure case. The calculated inner and outer wall temperatures were linearly interpolated through the thickness, which was mapped onto the finite element model. From the MAAP analysis results, the variation in wall thickness was also checked, but no ablation was observed.

Table 1. MAAP results (LOFW) according to injection time.

In-vessel injection time		Result
Secondary side	Primary side	
SA1)+3hr	SA+3.5hr	Relocation: O (4.68 hr) Vessel failure: X
SA+3hr + 10min	SA+3.5hr + 10min	Relocation: O (4.67 hr) Vessel failure: X
SA+3hr + 20min	SA+3.5hr + 20min	Relocation: O (4.67 hr) Vessel failure: O (7.20 hr)

1)SA : Severe Accident Entry time

3. Development of Material Models

3.1 Plastic and creep constitutive model

The material properties were determined for the base, weld and nozzle material used in a Westinghouse-type nuclear power plant. Under severe accident scenarios, the inner wall of the reactor vessel is exposed to extreme temperatures generated by the molten core, which can induce rapid and large deformations. To capture this behavior, Park et al. [2] proposed a constitutive model that combines plasticity and creep for A533B1 pressure vessel steel, enabling the prediction of deformation over a broad range of temperatures and strain rates. The plastic component of the model was derived from tensile test data obtained at a strain rate of 1%/s, a condition where creep effects are negligible. Furthermore, Takahashi's [3] formulations were extended to describe the full stress–strain response up to failure, leading to the development of closed-form equations, as presented in Ref. [2]. The creep behavior was represented by a power-law relationship:

$$\dot{\varepsilon} = K(T)\sigma^{n(T)} \tag{1}$$

where, K and n are parameters dependent on temperature.

For the nozzle and weld materials of the ICI penetration, Alloy 600 and Alloy 82, the plasticity model was determined in the same manner as for the base metal using experimental data [3] obtained over the temperature range from room temperature to 1100 °C and at strain rates of 1 to 0.001%/s. In addition, creep properties were derived from creep tests conducted under constant stress conditions at temperatures between 600 °C and 1000 °C [4,5].

3.2 Strain-based failure model

Park et al. [6] proposed a strain-based failure model to evaluate the failure behavior of pressure vessels under severe accident conditions. In this approach, the fracture strain is obtained by multiplying the temperature-dependent uniaxial fracture strain by a multiaxial ductility factor (MDF) that accounts for the influence of multiaxial stresses, as expressed:

$$\varepsilon_f^*(T) = \varepsilon_f(T) \cdot MDF \tag{2}$$

$$MDF = \exp\left(\frac{1}{2} - \frac{3}{2}\frac{\sigma_m}{\sigma_e}\right) \tag{3}$$

where MDF represents the multiaxial ductility factor. $\varepsilon_f^*(T)$ denotes the fracture strain under multiaxial loading, while $\varepsilon_f(T)$ corresponds to the uniaxial fracture strain. Considering the complexity of failure mechanisms, the authors suggested a simplified representation of the model using constant or linear functions.

For each of the base, nozzle, and weld material, the uniaxial fracture strain was determined based on various experimental analyses reflecting the temperature-dependent failure behavior. In this process, conservative criteria were applied to ensure applicability to severe accident assessments.

4. Structural Analysis using Coupled MAAP-ABAQUS Analysis

Figure 1 shows the finite element (FE) model used for structural analysis. A 3D 1/16 symmetry model was constructed to simulate both the center penetration and the most distant penetration (node 8 in MAAP) of the RPV lower head.

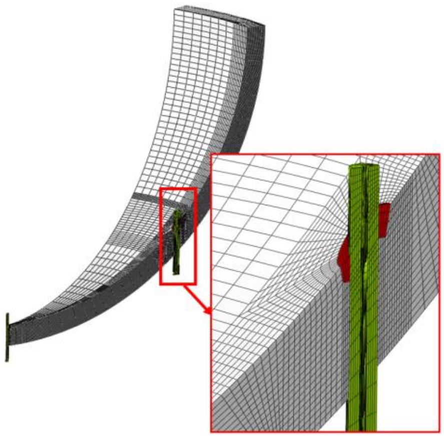

Fig. 1. 3D finite element model of the RPV lower head modeling the center and the most distant penetrations

For the case where MAAP predicted vessel failure, the structural analysis predicted failure at the most distant penetration, which is the same as the MAAP failure mode. A crack initiated at the interface between the weld and the base material, eventually leading to leakage. Figure 2 presents the time histories of creep and plastic damage, and cumulative damage at the failed element causing leakage, along with the average cumulative damage at the weld interface of the center penetration. In the failure case, the temperature increased to a level nearly twice as high as in the non-failure case. Because this temperature was high enough to induce significant creep, the creep damage rose sharply. When the weld material strain reached approximately 1.5%, corresponding to a critical level for failure, the damage parameter rapidly increased to 1, resulting in vessel leakage at 25,062 s. Compared with MAAP, vessel failure was predicted about 15 minutes earlier. At this point, the average cumulative damage at the center penetration remained around 10% and subsequently saturated, without causing failure.

The structural analysis results for the non-failure case are shown in Fig. 3. At the same location where leakage occurred in the failure case, cumulative damage and the equivalent stress histories were evaluated. Due to the relatively low stress and temperature, neither plastic nor creep deformation occurred, and consistent with the MAAP results, vessel failure did not occur.

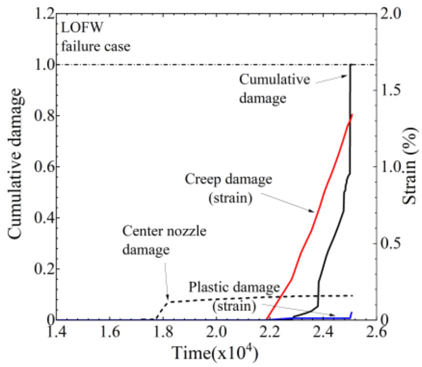

Fig. 2. Variation of cumulative damage and inelastic strain with time at the failed element causing leakage.

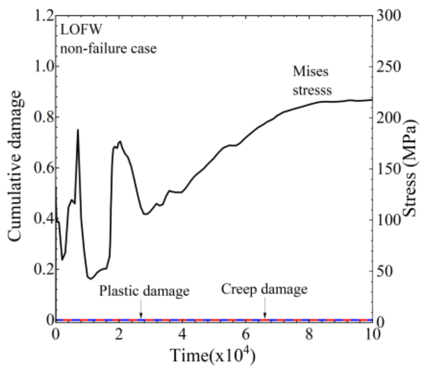

Fig. 3. Variation of cumulative damage and equivalent stress with time for the non-failure case.

5. Conclusion

This study coupled a system code (MAAP5) with detailed structural analysis (ABAQUS) to comprehensively evaluate the integrity of a reactor lower head ICI penetrations under the in-vessel injection strategy. MAAP analysis was first used to identify vessel failure and near-failure cases according to injection timing, and the resulting thermal boundary conditions were applied to the detailed structural analysis. To realistically simulate severe accident conditions, a refined material model was employed that incorporates plasticity, creep, and failure behavior based on experimental data and material characteristics.

The detailed structural analysis reproduced the same failure occurrence as MAAP, thereby enhancing the reliability of the predictions. Importantly, ABAQUS predicted vessel leakage about 15 minutes earlier than MAAP in the LOFW failure case, providing a more conservative estimate of the failure time. In addition, the analysis quantified that the average cumulative damage at the central penetration weld remained at only ~10% without leading to failure, whereas the most distant penetration weld reached the critical damage threshold (D=1), resulting in leakage. These quantitative results confirm that ABAQUS not only supports the system-level predictions of MAAP but also provides more detailed and conservative margins for safety assessment. Furthermore, the detailed structural analysis captured the creep–plasticity interactions and damage accumulation under severe accident conditions, thereby enabling a more precise explanation of the causes and progression of vessel failure.

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