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A Study on the Coupled FEM-Analysis for Reactor Vessel Lower Head of APR1400 under the Severe Accident Scenario

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1. Introduction

During a severe accident causing core meltdown in the pressurized water reactor (PWR), the reactor pressure vessel (RPV) integrity may be threatened by the relocation of molten core material into the lower head and the formation of a molten pool. In such a scenario, heat exchange between the pool and the vessel may provoke localized overheating, and cause partial melting. For the stabilization of the RPV the in-vessel retention strategy with external reactor vessel cooling (IVR-ERVC) is adopted in APR1400.

Under this severe accident condition, a good understanding of the mechanical behavior of the reactor vessel lower head (RVLH) is necessary both for verification of structural integrity and for improving the design applying appropriate accident mitigation strategies.

The purpose of this study is to develop the analysis method of the RVLH with thermo-mechanical analysis using FEM tool (ANSYS v.15) in case of core-melting severe accident condition, and then analyze the RVLH of APR1400 including creep behavior.

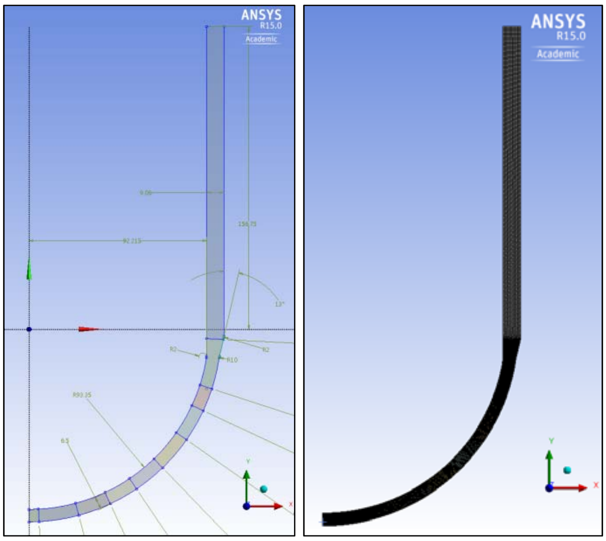
2. Methods

ANSYS v.15 workbench and mechanical APDL are used for FEM analysis to realize realistic analyzing. 2D axisymmetric finite element model was adopted based on APR1400 design data and relevant physical phenomena such as heat conduction and convection, thermal expansion, elastic-plastic strain relations, and creep behavior.

2.1 Finite Element Modeling

The study is focused on the lower head of the vessel where the core melt is located. Therefore, the hot- and cold-legs, the hole for the ICI nozzle, and all other detail parts are not included in the model. This has the main advantage that an axis symmetric model can be established. Geometry of the modeling from RVLH up to bottom of hot-leg piping is made based on dimension data of APR1400 with actual scale. Fig. 1 (a)

The elements used for modeling the RPV are 4-node structural elements. Since the lower part of the vessel is in the focus, it is modeled with finer elements than the upper part of the RPV. Node numbers and element numbers are 10,626 and 10,027, respectively. Fig. 1 (b)



(a) (b)

Fig. 1. 2D FE Model of RPV : (a) Dimension, (b) Mesh

2.2 Material Properties

The material of the RPV was chosen from the material data base for the APR1400 steel SA-508 class 1 grade 3. Temperature dependent material properties such as melting temperature, enthalpy, elastic modulus, poisson's ratio, yield strength, density, coefficient of thermal expansion, coefficient of thermal conductivity, and specific heat were obtained from *T. W. Kim* [1]. The stress-strain curve such as non-linear material properties based on multi-linear isotropic hardening (MISO) principles was obtained from *A. Chintapalli et al.* [2]. The creep data [3] also should be applied to constitute the creep behavior.

2.3 Boundary Conditions

<u>Heat Flux</u>

The internal heat flux distribution resulted by melt pool circulation is major input data for evaluating the mechanical behavior of the vessel. Normalized heat fluxes were obtained by average internal heat flux after the relocation of molten core material into the lower head and the formation of a molten pool. The heat flux is applied according to the TLOFW (Total Loss of Feed Water) scenario sketched in Fig. 2. [1] TLOFW was most severe case, highest heat flux, resulting from severe accident analysis. Bottom of RVLH is 0 degree, matching part of RVLH and RPV shell is 90 degree.

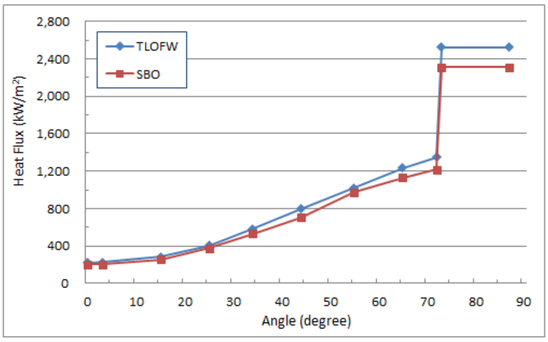
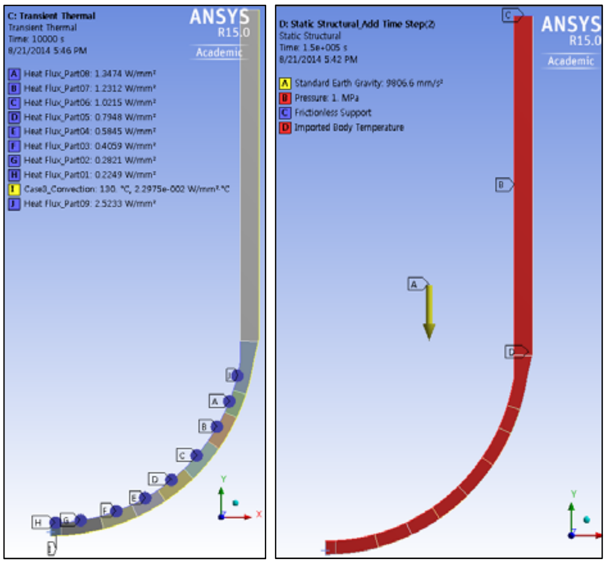


Fig. 2. Internal heat flux in case of TLOFW and SBO scenario

Assumptions

The description of the heat transfer from the RPV to the surrounding water is an important part of the model. The entire vessel is externally flooded up to cold leg level at severe accident as like IVR-ERVC. We assumed that outside wall temperature of RPV and ambient temperature are uniformly at 130°C. The convection coefficient of water at 130°C is applied to the outside of reactor vessel surface. The effects of phase change are assumed negligible at the outside wall.

The gravity acceleration is applied overall modeling, and internal pressure is 1MPa considering depressurization.

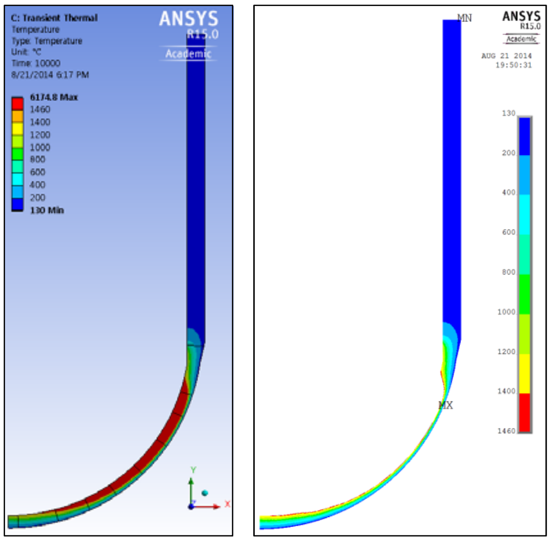


(a) (b)

Fig. 3. Thermal (a) and structural (b) boundary condition

2.4 Thermal Transient Analysis

A coupled thermal and mechanical analysis has to be solved. Since the structural elements do not allow for direct thermal mechanical coupling, a sequentially coupled analysis is necessary. At first, transient thermal analysis was carried out to calculate the temperature distribution of RPV with applied boundary conditions. After eliminating the element over melting temperature (1460 °C), elastic-plastic FE analysis including creep effect was carried out using the spatial temperature field as a body load.



(a) (b)

Fig. 4. (a) Temperature distribution of RVLH
(b) Post processing for eliminating melting elements

2.5 Structural Analysis including Creep

The lower head of the RPV is loaded by the deadweight of melting corium and the vessel, the internal pressure, and the temperature field which is the output of thermal transient analysis. The effects of corium weight can be negligible compare to other loads. The internal pressure and the gravity loads cause primary stresses, which are not relieved by the deformation of the vessel wall, but are even increased due to wall thickness reduction. Unlike this, the temperature gradients cause secondary stresses which is relieved by visco-plastic deformation.

The main deformation mechanisms of the RPV wall can take account of creep and plasticity. Creep is a time-dependent process, and connected with elevated temperatures (above 600 °C). [4], whereas plasticity occurs promptly, that is, simultaneously with the load. The analysis was performed until 1, 5, 15, 25, 50, 100, and 200 hours to check trend of all strains, and then increase the time to find minimum time to reach 20% creep strain until 1,500 hours.

3. Failure Criteria

3.1 Plastic Strain

Plastic deformation is a prompt process occurring only above a yield strength. Failure criteria used by Bohl and Butler as well as Berman et al. were phenomenologically based on continuum mechanics. Each criterion based on failure on equivalent plastic strain which is defined in terms of the principal plastic strains by the following equation.

$$\varepsilon_p = \frac{\sqrt{2}}{3}[(\varepsilon_1 - \varepsilon_2)^2 + (\varepsilon_2 - \varepsilon_3)^2 + (\varepsilon_3 - \varepsilon_1)^2] \quad (1)$$

According to Bohl and Butler, failure should occur at 12% equivalent plastic strain. Berman et al. placed 18%.

[5] The failure criteria at 10% were adopted considering conservatism with uncertainty.

3.2 Creep Strain

Creep can be considered the main cause of failure of RPV by the high temperature load as a result of melt pool formation. It is well known that stress and temperature can affect significantly the creep rate of structural materials.

A typical creep curve consists of three stage before rupture : primary stage (transient creep), secondary stage (steady creep), and tertiary stage (accelerating creep). They correspond to a decreasing, constant, and increasing strain rates, respectively. A single equation or model cannot capture all the stages of the creep curve of a given material. To add more its complexity, there are different creep curves for different temperatures and stress. The creep strain is a function of time, temperature, and stress.

In our analysis, a modified time hardening (primary) creep model is chosen in ANSYS v.15,

$$\varepsilon_{cr} = \frac{c_1\, \sigma^{c_2}\, t^{c_3+1}\, e^{-c_4/T}}{c_3+1}, \qquad c_1 > 0 \tag{2}$$

where ε_{cr} is the equivalent creep strain, σ is the equivalent stress, t is time, and $c_1 \sim c_4$ are constants to be determined by curve fitting with experimental data. [6] Because of insufficient experimental data of SA-508, coefficients for the model are generated using the experimental creep data for SA-533 B1 taken from *Alstadt et al.* [3].

P. Kudinov et al. [6] had performed the validation test for the equation (2). Based on the validation test, we could adopt the time necessary to reach 20% strain as the minimum estimated vessel wall failure time. Indeed, it was proved that structures in such state are very close to its mechanical failure.

4. Results and Discussions

4.1 Results

Three parts of the deformation of the material have to be taken into account : elastic deformation, plasticity, and creep. Figure 5 shows three (3) strains that have steady state results except creep strain.

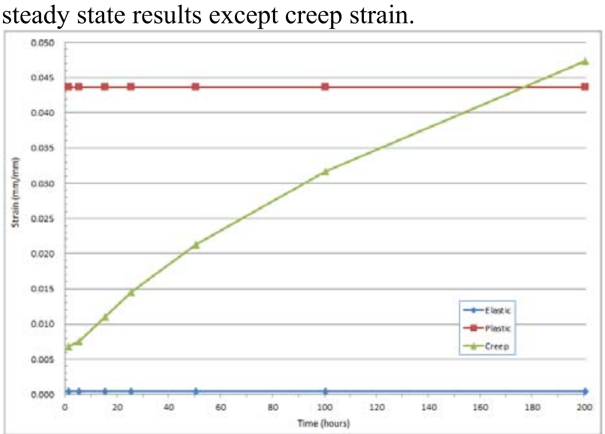
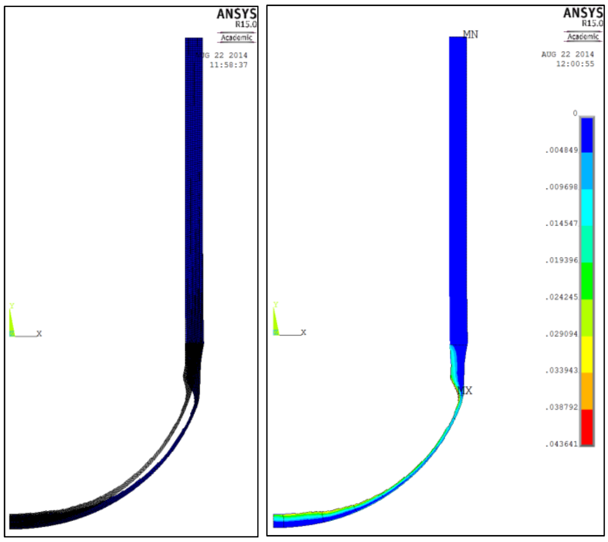


Fig. 5. Maximum equivalent strains up to 200 hours



(a) (b)

Fig. 6. (a) Comparison deformed and initial shape (Scale factor : 5)
(b) Equivalent plastic strain distribution

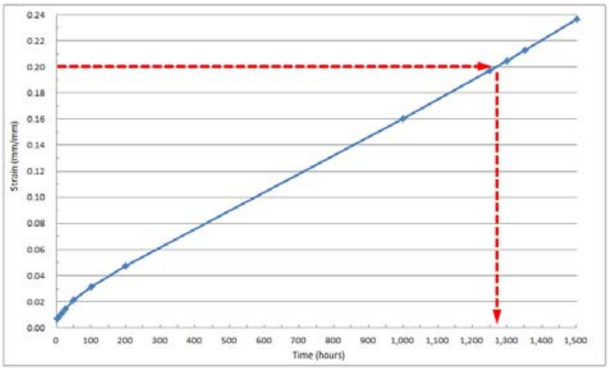


Fig.7. Maximum equivalent creep strain up to 1,500 hours

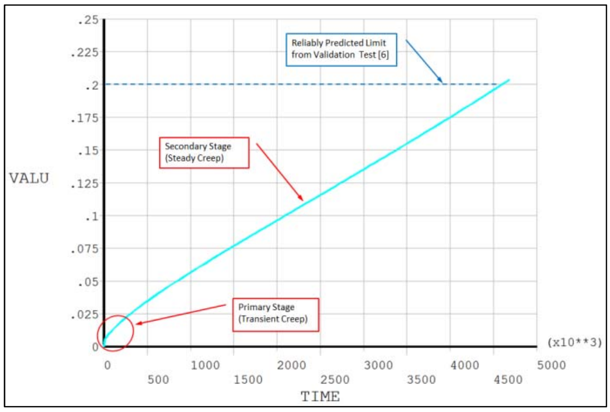


Fig. 8. Equivalent creep strain of maximum element at 1,300 hours (4,680 × 10^3 seconds)

4.2 Discussions

The strain-based failure criterial has been used for the standard of safety evaluation for the structures in high temperature condition rather than stress-based failure criteria. [7]

The maximum equivalent plastic strain is 0.0436 (4.36%) which is less than 10% of the failure criteria, and the maximum equivalent creep strain at the time was 0.0068 (0.68%) which is much less than 20% of the failure criteria compare to plastic strain. Thus the probability of prompt head failure under severe accident is very low.

The equivalent creep strain has trend increasing along the time in fig. 5. The minimum time to reach 20% strain was found in fig. 7, it is around 1,300 hours (54 days). The 1,300 hours is result of maintaining constant heat flux from core melt during analysis time. Since the heat flux is decreased as time goes on, the 1,300 hours is minimum and conservative analysis result.

Fig. 8 shows the equivalent creep strain of the element that has maximum equivalent creep strain among all elements. Primary and secondary stage of creep strain can be found in fig. 8. The time scale to reach 20% strain can provide the time scale for delay of emergency measures to mitigate the severe accident with proper actions.

5. Conclusion

The plastic strain can be the major cause of lower head failure on the reactor vessel, and the creep cannot be not negligible factor of the failure under the severe accident condition.

In the study, we applied constant convection coefficient at assumed temperature on the outside wall of RPV and substitute creep data of SA-508. In addition, it was found that the steel ablation at the interface between corium and vessel steel is not only a thermal phenomenon in the METCOR experiments. Corrosion processes and the formation of eutectics lead to the erosion of the vessel steel at temperatures that are significantly lower than the melting temperature of steel. It called thermo-chemical attack of the corium (corrosion). [4] Reduced wall thickness because of the thermo-chemical effect by corium increase the equivalent plastic strain, and decrease the minimum time to reach 20% creep strain.

Therefore, further study should be performed by considering thermo-chemical attack of the corium, temperature dependent convection coefficient at outside wall, and creep properties of SA-508 for more exact analysis under the severe accident condition.

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