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Validation of creep deformation for OLHF-1 experiment using ANSYS

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1. Introduction

When the core materials relocate to the lower plenum during severe accidents, the lower head can be subjected to the combination of thermal and mechanical loads. The high thermal load is by the decay heat from the relocated core materials and mechanical load is by the pressure in the reactor vessel and the weight of the core materials and the lower head itself [1]. It is known that these loads can cause the deformation or failure of a lower head by creep from the experiments such as LHF and OLHF [2-3].

Several integral codes for severe accident analyses have models to predict the creep failure time only by using time-creep failure correlation such as Larson-Miller parameters without calculation of mechanical behavior of the lower head. However, the application of the time-creep failure correlation is only validated for those tests and not for a full-size nuclear power plant. The finite element method has been considered as an appropriate alternative way to calculate the mechanistic creep behavior for the reactor lower head.

In the present study, the OLHF-1 experiment is validated using ANSYS to check the applicability of the finite element method for the prediction of creep deformation of the reactor lower head.

2. Analysis Methods

2.1 Analysis Model

The lower head which is used in the OLHF experiment is scaled down to 1/4.85 as shown in Fig. 1. ANSYS mechanical Ver. 18.0, which is the commercial finite element code, is used to simulate the experiment. The OLHF-1 experiment among the four OLHF experiments is selected for the validation for the comparison of the results with the other previous benchmark results. The geometry of the specimen is assumed to be axisymmetric in the finite element model as shown in Fig. 2. The plane183 element with mid-node is selected and the total number of elements and nodes is 144 and 513 respectively.

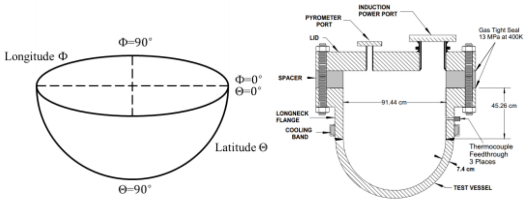


Fig. 1. Schematics of the OLHF experiment [2]

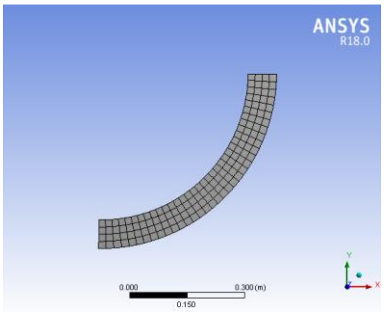


Fig. 2. Finite element model

The cylindrical part connected to the lower head in Fig. 1 is simply expressed as an axisymmetric boundary condition by fixing the vertical displacement of the topmost nodes in Fig. 2. The loads on the in-vessel wall are shown in Table 1. The ex-vessel wall is cooled down by atmosphere using convective heat transfer. The creep model used in the analysis is Norton-Bailey model shown in Eq. (1), which is the simplest model only considering the minimum creep rate of the creep curve. The coefficients in Eq. (1) are estimated by fitting the creep curves of SA533B1 material for the lower head [1, 3]. The correlation of A(T) in Eq. (1) is obtained and compared to the LHF correlation[2] as shown in Fig. 3. And m in Eq. (1) is a fitting parameter and it is shown in table 2 according to temperature.

$$\dot{\varepsilon}_{cr} = A(T)\sigma^{m}, \quad A(T) > 0 \qquad \text{Eq. (1)}$$

Table 1 : Loads on the in-vessel wall

Mechanical load	Self-weight of the lower head by gravity
	Internal pressure (P = 12MPa)
Thermal load	Wall heating (definition of the wall temperature, see Fig. 3)

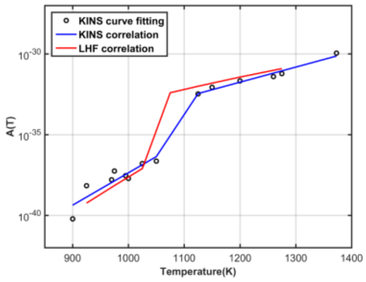


Fig. 3. Correlation of A(T) for the Norton-Bailey model

Table 2 : Fitting parameter for the Norton-Bailey model

	T ≤ 1050 K	T > 1050 K
m	4.2152	3.6675

The in-vessel temperature shown in Fig. 4 in different azimuthal angle has small differences but it is spatially averaged to apply it to the axisymmetric geometry.

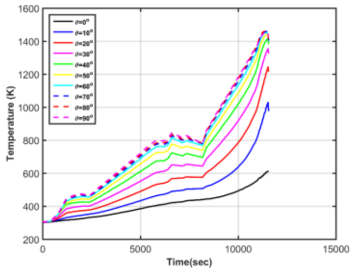


Fig. 4. Temperature of the in-vessel wall

2.2 Material properties

The material properties of SA533B1 are obtained mainly from the OLHF report [3] and some thermophysical properties at very high temperature are applied from the recent INL report [4].

3. Analysis results and discussions

3.1 Heat transfer analysis

The temperature field of the lower head is obtained by the transient heat transfer analysis. Fig. 5 shows the ex-vessel wall temperature as a result of the thermal calculation.

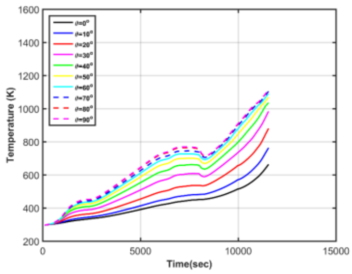
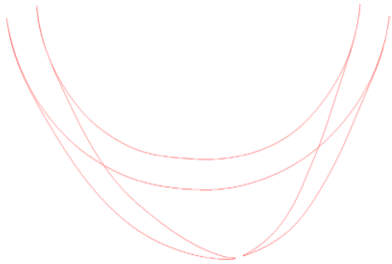


Fig. 5. Temperature at the external surface of lower head.

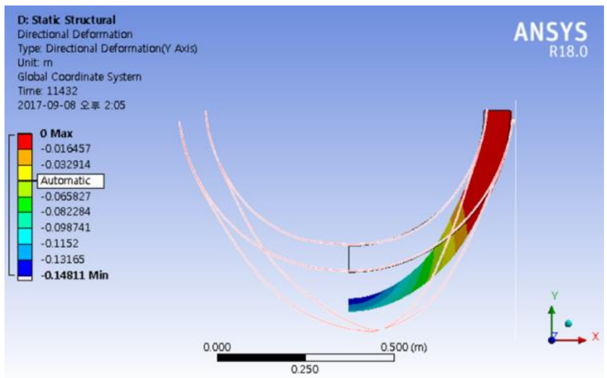
3.2 Structural analysis considering creep behavior

The structural analysis considering creep behavior including thermal expansion and elastoplasticity is performed based on the temperature field in section 3.1. The geometrical nonlinearity of large strain is considered.

Fig. 6 gives a comparison of the deformed shape at the end of the analysis and test. The deformation by the finite element analysis shown in Fig. 6 (b) predicts the deformation of the lower head shown in Fig. 6 (a) very well. The vertical displacement at θ = 90° and φ = 0° shown in Fig. 7. are compared to the other benchmark results [5]. The maximum displacement and the timing of the creep deformation are relatively well matched with the experimental data. The Von-Mises stresses at in- and ex-vessel wall are compared with the other analysis results in Fig. 8 and 9. The level of stress in Fig. 8 and 9 is relatively low. However, it becomes similar when the creep behavior is dominant from about 1e4 s.



(a) Cross-sectional slice through failure site from pre- and post-test vessel surface maps (OLHF-1 experiment)



(b) Deformed shape at the end of the analysis

Fig. 6. Comparison of the deformed shape (OLHF-1)

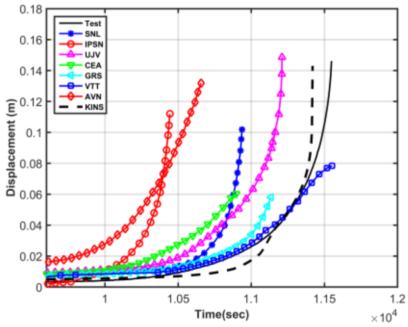


Fig. 7. Vertical displacement at the ex-vessel wall (θ = 90°, φ = 0°)

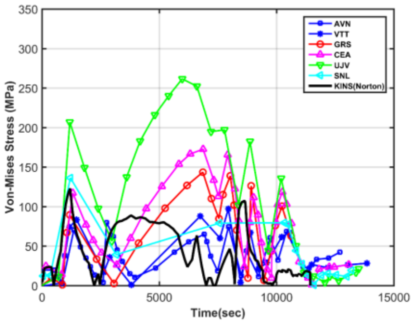


Fig. 8. Von-Mises stress at the in-vessel wall. ((θ = 90°, φ = 0°)

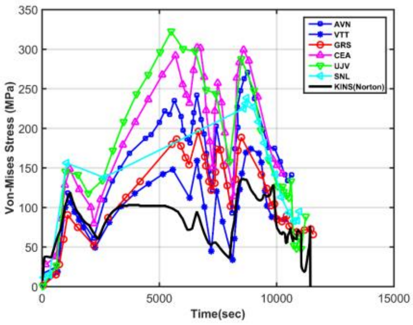


Fig. 9. Von-Mises stress at the ex-vessel wall. (θ = 90°, φ = 0°)

4. Conclusions

The creep behavior of the OLHF-1 experiment is analyzed using ANSYS mechanical in this study. The parameters of Norton-Bailey model are estimated by creep curve fitting. The deformed shape and the maximum displacement is well matched with the experiment. Therefore, it is shown that the creep model used in this analysis is appropriate to predict the creep deformation of OLHF-1 experiment. The actual lower head of a nuclear power plant is much larger than this experiment specimen, and the level of temperature at the in-vessel wall and the temperature difference between in- and ex-vessel walls is also greater than the experiment. The OLHF-2 experiment is going to be validated to investigate the effect of creep deformation at higher temperature and lower pressure. And the OLHF-4 will be also validated to investigate the early failure of the reactor vessel with the multiple penetration under creep deformation.

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