Transactions of the Korean Nuclear Society Autumn Meeting
Changwon, Korea, October 20-21, 2022

Temperature and Strain rate Dependent Material modeling of SA533B1 steel for IVR-ERVC simulation

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1. Introduction

The lower head of the nuclear power plant reactor pressure vessel (RPV) can be subjected to severe thermal, and pressure loads in the event of a core meltdown accident. As effective accident management strategy, IVR-ERVC (In-Vessel Retention of molten corium through External Reactor Vessel Cooling) strategy is to reduce the possibility of a reactor containment failure by terminating the severe accident progress inside a reactor.

The mechanical behavior of the reactor vessel lower head is of importance both in severe accident assessment and the assessment of accident mitigation strategies. In this study, a stress-strain and creep constitutive model to quantify the strain hardening and softening behaviour and time dependent inelastic behaviour were determined. The prediction capacity of constitutive models was verified by simulating pressure vessel lower head failure test performed by the OLFH (OECD Lower Head Failure) program.

2. Quantification of temperature and strain rate effect on deformation

2.1 Plastic deformation model

Takahashi [1] proposed a constitutive model to quantify the strain hardening and softening behaviour using stress-inelastic strain slope as follows,

$$\frac{d\sigma}{d\varepsilon_{in}} = \sigma_0{}^m \left[\frac{1}{m\sigma^{m-1}} - \frac{\left\{ \left(1 + A\varepsilon_{in}\right)\sigma \right\}^p}{\sigma_r{}^{m+p-1}} \right] \qquad (1)$$

where, the parameters of σ_o and m represent the material hardening and σ_r and p represent the material softening. Both hardening and softening parameter, σ_o and σ_r, are dependent on temperature and strain rate characterized by Zener-Holloman type parameters [2]. By integrating Eq. (1) constitutive model of material can be derived as

$$\sigma\left(T,\dot{\varepsilon}\right) = \sigma_y\left(T,\dot{\varepsilon}\right) + \int \frac{d\sigma}{d\varepsilon_{in}} d\varepsilon_{in} \qquad (2)$$

where, σ_y is yield stress. Detailed equation of the model can be seen in [1].

2.2 Modified plastic deformation model

The constitutive model described in section 2.1 can be applied to the range of yielding to ultimate tensile strength and up to 1,100°C in temperature.

In order to simulate IVR-ERVC condition, the material models up to failure and melting temperatures are necessary. Thus, we extended the constitutive model to be applied up to failure strain as follows,

$$\sigma\left(T,\dot{\varepsilon}\right) = \sigma_{UTS}\left(T,\dot{\varepsilon}\right) + \int_{\varepsilon_u}^{\varepsilon_f} \frac{d\sigma}{d\varepsilon_{in}} d\varepsilon_{in} \qquad (3)$$

where, the parameters are newly determined by comparing finite element (FE) analysis with tensile test to predict material deformation up to fracture, and the parameters extrapolated to melting temperature.

2.3 Creep model

A Bailey and Norton creep constitutive model [3], commonly applied for the primary and secondary creep region, was used to predict time dependent inelastic behaviour, as given by

$$\dot{\varepsilon} = K(T)\sigma^{n(T)} \qquad (4)$$

where, K and n are temperature dependent parameters.

NUREG/CR-5642 [4] reported the creep tensile test performed on constant stress and temperatures from 600°C to 900°C respectively. The parameters were determined by comparing FE simulation using ABAQUS with the test results.

3. OLFH Test Simulation

The OLHF (OECD Lower Head Failure) program [5] performed test to provide the data and insight to characterize the mode, timing and size of reactor pressure vessel lower head failure using typical PWR (Pressure water reactor) lower head fabricated by SA533B1 steel. The lower head test specimen was modeled as 1 to 4.85 linear scale of typical PWR lower head. The test was performed for the case of low to moderate pressure including both constant and transient pressurization, and different across lower head wall temperature, providing temperature, pressure, and displacement data as shown in Fig 1 and 2.

Figure 1 shows the internal pressure and internal and external surface temperature measured at one of the OLHF test case. Because wall thickness of specimen was increased to provide a large range of temperature differences throughout the wall, 12MPa test pressure equivalent to RCS (reactor coolant system) pressure of 5MPa was applied.

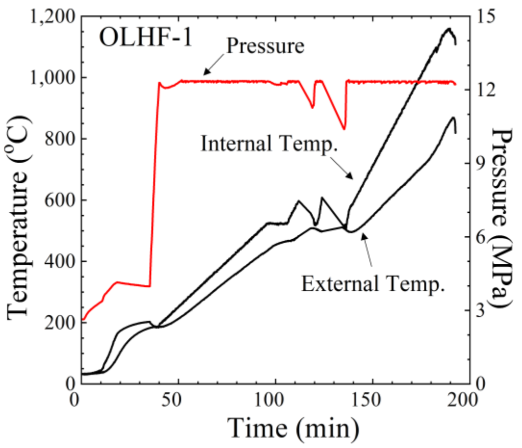

Fig. 1 Internal pressure, internal and external surface temperature measured at one of the OLHF test.

For this study, the OLHF test was simulated using FE analysis to verify the predicting capacity of material model determined in Section 2 by comparing displacement and deformation behaviour with test results under varying temperatures and strain rate until failure. The stress-strain curve and creep model proposed on NUREG/CR-5642 [4] was also used for simulation to compare.

Figure 2 shows the comparison of vertical displacement at external surface of vessel measured by test with FE results calculated using material model of NUREG/CR-5642 and KU (determined at Section 2). The theta (θ) is latitude of test vessel, 90^o is corresponding to the bottom point of vessel. Both FE results calculated by two material model shows the conservative prediction capacity, and the conservativeness can be reduced by using KU material model.

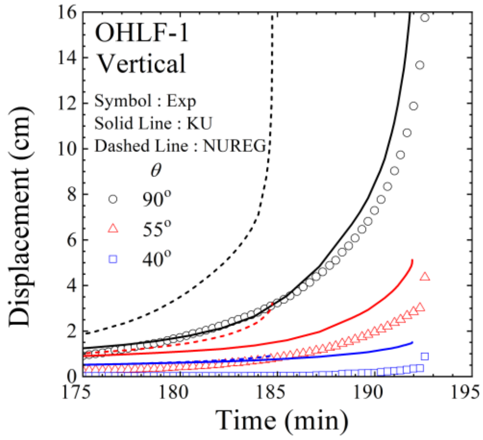

Fig. 2 Comparison of vertical displacement measured at external surface of test vessel with FE results calculated by using NUREG/CR-5642 and KU (determined at Section 2) material model.

4. Conclusions

To assess severe accident and mitigation strategy of IVR-ERVC on lower head of reactor pressure vessel subjected thermal and pressure loads using FE simulation, stress-strain and creep constitutive model was determined. For stress-strain constitutive model, the Takahashi model was used and extended to the failure. And for the creep model, Bailey and Norton creep constitutive model was used. The prediction capacity of constitutive models was verified by simulating OLFH test.

Acknowledgement

This work was supported by the Nuclear Safety Research Program through the Korea Foundation of Nuclear Safety (KoFONS) using the financial resource granted by the Nuclear Safety and Security Commission (NSSC) of the Republic of Korea. (No. 2103079)

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