Development of Empirical Stress Correction Factor for Creep-Rupture Model of Alloy 690 Steam Generator Tube

Jongmin Kim [a*], Minchul Kim [a], Joonyeop Kwon[a]
[a]*Materials Safety Technology Development Division, Korea Atomic Energy Research Institute, Yuseong-gu, Daejeon, Korea*
[*]*Corresponding author: jmkim@kaeri.re.kr*

1. Introduction

Steam generator (SG) tube is one of the important components that make up the pressure boundary, and there is a risk of a significant radioactive release to the outside due to high temperature damage of single tube and subsequent chain failure of tubes in case of severe accident condition. SG tubes exhibit creep behavior during the high temperature (>0.4×melting temperature), and damage is accumulated during temperature/pressure transient. Creep studies have been conducted on Alloy 600 SG tubes [1-2], but creep failure studies of the recently replaced or installed Alloy 690 material was insignificant. Since the creep and creep rupture prediction models so far was based on Alloy 600 material, the creep-rupture model for Alloy 690 material needs to be modified. In this study, creep-rupture tests were performed for Alloy 690 SG tubes with crack, and an empirical stress correction factor of the creep-rupture model for Alloy 690 SG tube was proposed.

2. Creep-Rupture Prediction

In this study, an Alloy 690 steam generator tube of the type used in domestic APR-1400 nuclear power plants was selected.

2.1 Material and Specimen

The geometry of specimen for tensile test is a half tube shape obtained by cutting a SG tube in the axial direction. The flow stress, which is used for flow stress model, from the tests are as follows,

$$k(\sigma_y + \sigma_u) = (5.09 \times 10^{-12}T^5 - 1.59 \times 10^{-8}T^4 + 1.71 \times 10^{-5}T^3 - 7.01 \times 10^{-3}T^2 + 4.02 \times 10^{-1}T + 7.39 \times 10^2) \quad (1)$$

Figure 1 shows a creep-rupture specimen. An EDM notch is inserted in the center of the specimen and both ends are welded. The specimen was designed to have a crack depth of 50% to 80% and crack length of 1 inch.

Fig. 1. Specimens for tube rupture test.

2.2 Creep-rupture test

The temperature for rupture tests were 600°C, 700°C, 800°C, and 900°C, and the pressure ramp rates were 2300 psi/min, 230 psi/min and 23 psi/min. In this study, a constant temperature-pressure ramp test was conducted until failure. The rupture test equipment was manufactured to simulate a change in the temperature and pressure.

2.3 Flow Stress Model

The flow stress model uses the material properties (yield strength, tensile strength) according to each temperature to determine failure when a specific stress and temperature condition is reached regardless of the temperature and stress history.

$$\sigma = \frac{\overline{\sigma(T)}}{m_p}, \quad \overline{\sigma(T)} = \sigma_{eff} = m_p\sigma \quad (2)$$

Here, m_p is the magnification factor for a part-through-wall crack. σ_{eff} is effective stress considering the stress concentration at the crack region. σ_{eff} is well established through the rupture tests for Alloy 600 SG tubes as presented in NUREG-1570.

2.4 Creep-Rupture Model

The creep rupture model considers the stress and temperature history. Accumulated damage in the creep rupture model is calculated based on the characteristics of the creep and is judged as damage when the accumulated damage reaches 1.

$$\int_0^{t_r} \frac{dt}{t_R(T, m_p\sigma)} = 1 \quad (3)$$

Where t_r and T are functions of time. t_r can be calculated using the LMP(Larson-Miller Parameter) of Alloy 690 tube material derived in Authors' previous research[3].

$$t_r = 10\hat{}\left(\frac{P_{LM}}{T} - 13.8\right) \quad (4)$$

Using the equations above, the cumulative damage of the Alloy 690 SG tube can be obtained by substituting Eq. (3). Table 1 compares the predicted values of the rupture test results and the flow stress model and the creep rupture model using m_p in NUREG-1570 (based on Alloy 600).

Table I: Creep Rupture Test Results

ID	Temp. (°C)	Pressure Rate (psi/min)	Flaw Depth (%)	Test P_{sc} (bar)	Flow Stress Model P_{sc}(bar)	Creep Rupture Model P_{sc}(bar) : without stress correction factor
1	600	2300	50	304	299	526
2	600	2300	60	263	256	457
3	600	2300	70	211	212	380
4	600	2300	80	156	164	298
5	700	2300	50	265	243	434
6	700	2300	60	227	208	377
7	700	2300	70	187	172	318
8	700	2300	80	143	133	248
9	800	2300	50	236	167	337
10	800	2300	60	197	143	294
11	800	2300	70	165	118	248
12	800	2300	80	127	91	197
13	900	2300	50	156	90	242
14	900	2300	60	126	78	212
15	900	2300	70	116	64	181
16	900	2300	80	94	49	145
17	700	230	60	207	208	309
18	700	230	80	126	133	206
19	800	230	60	154	143	220
20	800	230	80	94	91	150
21	700	23	60	192	208	240
22	800	23	80	108	133	162
23	700	23	60	129	143	151
24	800	23	80	65	91	104

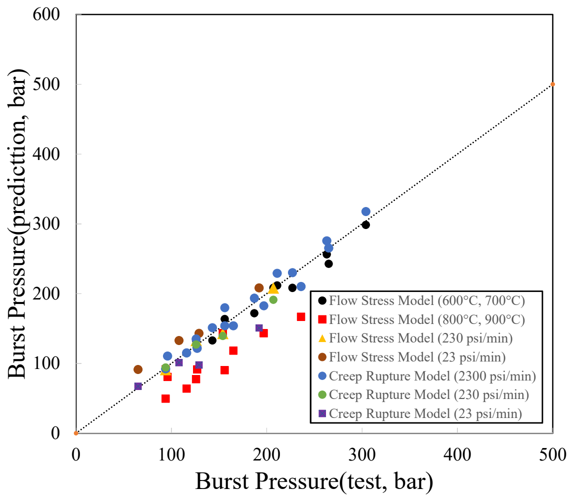

Fig. 2. Comparison of creep rupture model with experimental results. (with stress correction factor)

2.5 Stress Correction Factor

Compared to the experimental results, the difference between the flow stress models at 800°C and 900°C was substantial, and the creep rupture model showed a significant difference in the experimental results at all temperatures. This indicated that the flow stress model does not represent creep damage, and the m_p used in the creep rupture model was also not suitable for Alloy 690 material. There is a difference between creep damage mechanism and plastic deformation of Alloy 600 and Alloy 690 material. In this study, the following correction factor of the creep rupture model is proposed for the alloy 690 material:

$$\sigma_{eff} = G m_p \sigma \quad (5)$$

Here, G is the correction factor of the Alloy 690 material in the creep rupture model that specifies the stress state of a cracked tube. In this study, the correction factor G was determined to be 1.7 based on the experimental results.

As shown in Fig. 2, when the correction factor is applied, the creep rupture model is in good agreement with the experimental results at all temperatures and pressure rates.

In summary, predicted rupture pressure by the creep rupture model (correction factor is not applied.) in Table 1 shows large difference from the rupture pressure in tests. If the correction factor provided in this study is applied to the creep rupture model, it is in good agreement with the experimental results as shown in Fig. 2.

3. Conclusions

In this study, tensile tests and creep rupture tests were conducted on Alloy 690 SG tubes. Based on the creep rupture test results, the correction factor of the creep rupture model was proposed based on the constant-temperature ramped-pressure test result. The prediction results were in good agreement with the experimental results within all temperature ranges and pressurization conditions. It is expected that the creep rupture and failure of SG tube made of Alloy 690 material can be predicted appropriately using modified creep rupture model along with correction factor proposed in this study.

REFERENCES

[1] S. Sancaktar, M. Salay, R. Lyengar, A. Azarm and S. Majumdar, "Consequential SGTR Analysis for Westinghouse and Combustion Engineering Plants with Thermally Treated Alloy 600 and 690 Steam Generator Tubes," NUREG-2195, 2016.
[2] SGTR Severe Accident Working Group, USNRC, "Risk Assessment of Severe Accident-Induced Steam Generator Tube Rupture," NUREG-1570, 1998.
[3] J. M. Kim, W. G. Kim, M. C. Kim and J. Y. Kwon, "Creep Life Assessment of Alloy 690 Steam Generator Tube using Larson-Miller Parameter," Transactions of the Korean Nuclear Society Virtual Autumn Meeting, Dec. 17-18, 2020.