Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 19-20, 2022

Difference in Thermo-Mechanical Fatigue Evaluation according to Plastic Correction Factors of ASME B&PV Code

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1. Introduction

When designing components for nuclear reactor, fatigue integrity assessment is conducted in accordance with design standards such as ASME B&PV Code Section III [1]. The ASME fatigue evaluation procedure is based on linear elastic analysis, and when plastic deformation occurs, it presents a simplified elastic-plastic analysis to conservatively consider the plastic effect by using a plasticity correction factor (K_e). The simplified elastic-plastic analysis is a method of correcting an elastic analysis-based strain using the K_e, and it is confirmed through tests and theoretical considerations that it is easy to apply but contains excessively large conservatism [2-3]. Due to this background, ASME Code Case (CC) N-779 was proposed to supplement the excessive conservativeness of the simple elastic analysis of the ASME Code [4].

In this paper, the simplified elastic-plastic analysis method of the ASME code and the alternative method to reduce excessive conservatism of the ASME code are applied to the thermo-mechanical fatigue evaluation of the nozzle part of the small modular reactor steam generator, and the difference is compared and analyzed.

2. Simplified elastic-plastic analysis method of ASME B&PV Code Section III

ASME NB-3228.5 describes the use of the K_e factor if the primary plus secondary stress intensity (S_n) is exceeded than the 3Sm limit. The calculation method for K_e from NB-3228.5 (b) is given in Eq. (1):

$$K_e = \begin{cases} 1 & S_n \le 3S_m \\ 1 + \dfrac{1-n}{n(m-1)}\left(\dfrac{S_n}{3S_m} - 1\right) & 3S_m < S_n < 3mS_m \\ \dfrac{1}{n} & S_n \le 3mS_m \end{cases} \quad (1)$$

where m and n are given in Table NB-3228.5(b)-1. The n means the strain hardening exponent of the material. For austenitic stainless steels, m = 1.7 and n = 0.3. Thus, K_e reaches a maximum of 3.33 for austenitic stainless steels when values of $S_n/3S_m$ above 1.7.

3. Alternative method of ASME Code Case N-779

ASME Code Case N-779 is based on the proposal by Adams [5]. ASME CC N-779 differs from ASME Sec. III as it explicitly distinguishes between stresses arising due to mechanical and thermal loads. To apply CC-N779 requires determination of three categories of stress intensity range, the thermal bending stress intensity range (S_{tb}), the local thermal stress intensity range (S_{lt}), the total stress intensity range less the contribution of S_{tb} and S_{lt} ($S_{p\text{-}tb\text{-}lt}$). The plasticity-corrected alternating stress amplitude is then determined by Eq. (2):

$$S_{alt} = 0.5\begin{bmatrix} K_e^{N-779}(S_{p-tb-lt}) + K_v^{N-779}S_{lt} \\ +K_v^{N-779}K_n^{N-779}S_{tb} \end{bmatrix} \quad (2)$$

where $K_e^{N\text{-}779}$ is equivalent to the Eq. (1); $K_v^{N\text{-}779}$ is a Poisson's ratio correction factor, defined by Eq. (3):

$$K_v^{N-779} = \begin{cases} 1 & S_p \le 3S_m \\ 1 + 0.4\dfrac{S_p - 3S_m}{S_{tb+lt}} & S_p > 3S_m \text{ and } S_{p-lt-tb} < 3S_m \\ 1.4 & S_p > 3S_m \text{ and } S_{p-lt-tb} > 3S_m \end{cases} \quad (3)$$

$K_n^{N\text{-}779}$ is a notch plasticity correction factor defined by Eq. (4):

$$K_n^{N-779} = \begin{cases} 1 & S_{p-lt} \le 3S_m \\ 1 + \left[\left(\dfrac{S_{p-lt}}{S_n}\right)^{\frac{1-n}{1+n}} - 1\right]\dfrac{S_{p-lt} - 3S_m}{S_{p-lt}} & S_{p-lt} > 3S_m \end{cases} \quad (4)$$

where $S_{p\text{-}lt}/S_n$ is numerical stress concentration factor.

4. SMR steam generator nozzle shape and boundary conditions

Due to the space constraints of small modular reactors, the secondary feedwater and steam are designed to enter and exit through a single reactor pressure vessel nozzle in some integrated reactors under development (e.g. REX-10 (Korea), CAREM (Argentina), RITM-200 (Russia), IP-200 (China), etc).

As low-temperature feedwater and high-temperature superheated steam enter and exit from one nozzle, a large temperature difference occurs in some parts as shown in Fig. 1.

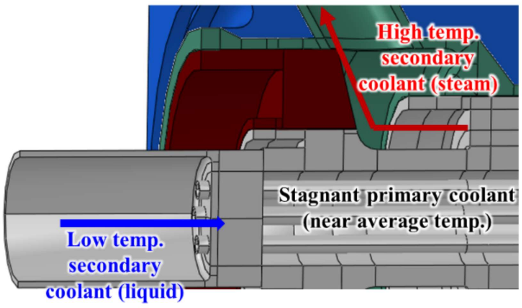

Fig. 1 Example shape of SG nozzle

5. Comparison of thermal fatigue evaluation results according to the two methods

The thermal fatigue evaluation of the SG nozzle part according to the start operation with the greatest temperature change was performed through two methods, and the alternating stress amplitude of the location where the maximum stress occurred are shown in Table 1.

Table 1. ASME B&PV Code Sec. III

	K_e or $K_{eff}^{N\text{-}779}$	S_{alt}
ASME Section III	3.33	1127 MPa
ASME CC N-779	1.18*	555 MPa

* $K_{eff}^{N\text{-}779}$ is calculated as S_{alt}/S_p for comparison.

6. Conclusion

S_{alt} obtained by applying the alternative method of CC N-779 was reduced to a level of 50% compared to the S_{alt} obtained by the ASME Section III method. This is because simplified elastic-plastic analysis was developed assuming only the primary load that does not decrease even when plasticity is occurred and simple shape. In the case of secondary load, stress relaxation occurs as plastic deformation occurs. Since the thermal stress of the SG nozzle is a typical secondary load stress, applying an appropriate plasticity correction factor to the primary and thermal stress as in CC N-779 is considered to be effective in predicting the actual fatigue life. It was confirmed that applying the alternative method of ASME Code Case N-779 can significantly reduce the conservatism of ASME Section III simplified elastic-plastic analysis.

NOMENCLATURE

ASME American Society of Mechanical Engineers
S_{alt} Alternating stress amplitude
S_m Design stress intensity
S_n Linearized stress intensity range
S_p Total stress intensity range
S_{tb} Thermal bending stress intensity range
S_{lt} Local thermal stress intensity range

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