Transactions of the Korean Nuclear Society Autumn Meeting
Gyeongju, Korea, October 24-25, 2013

Quantification of J-integral for the circumferentially cracked pipes under mechanical and thermal loads between R6 and A16

Hyun-Suk Nam [a], Chang-Young Oh [a], Yun-Jae Kim [a*]
[a] *Department of Mechanical engineering, Korea Univ., Seoul, Republic of Korea*
[*] *Corresponding author: kimy0308@korea.ac.kr*

1. Introduction

As most part of pressurized plant components are subject to various stresses. Stresses applied to plant components can be classified into primary (mechanical loading) and secondary stress (such as thermal and residual stress). When a crack is found in a pressurized plant component under combined primary and secondary stress, it is important to estimate relevant fracture mechanics parameters[1~3]. *J*-integral is one of the fracture mechanics parameters used for elastic-plastic analysis. Detail procedure for *J*-integral estimation under combined stresses are tabulated in R6 and A16. This paper compares the estimated *J*-integral between R6 and A16 for combined stresses through FE analysis results.[4,5]

2. *J* estimates under combined mechanical and thermal load in R6, RCC-MR A16

2.1 J estimates for Combined Load in R6 Code[4]

Reference stress based *J* estimates was developed by Ainsworth. In the reference stress method, the elastic-plastic *J*-integral for a cracked pipe under the primary stress only, J^p, is estimated as

$$\frac{J^p}{J_{el}^p} = \frac{E\varepsilon_{ref}}{\sigma_{ref}} + \frac{1}{2} L_r^2 \frac{\sigma_{ref}}{E\varepsilon_{ref}} \tag{1}$$

Where the reference stress, σ_{ref} , and the proximity parameter for plastic collapse, L_r, are defined by the reference load, P_{ref}, as

$$L_r = \frac{\sigma_{ref}}{\sigma_y} = \frac{P}{P_{ref}} \tag{2}$$

In Eq. (2), *P* denotes the generalized mechanical load. The reference strain is defined as the true strain at the reference stress, determined from true stress-strain data of the material. J_{el}^p represents the elastically calculated value of J due to mechanical load. J_{el}^P is defined by the stress intensity factor due to the primary stress, K^P, as

$$J_{el}^p = \frac{(K^p)^2}{E'} \tag{3}$$

The elastic-plastic *J* under combined primary and secondary stress, J^{p+s}, can be estimated as

$$J^{p+s} = \frac{(K^p + V \cdot K^s)^2}{E'} \left(\frac{E\varepsilon_{ref}}{\sigma_{ref}} + \frac{1}{2} L_r^2 \frac{\sigma_{ref}}{E\varepsilon_{ref}} \right) \tag{4}$$

Where K^S is the stress intensity factor due to secondary stress and *V* is multiplying factor, interaction between primary stress and secondary stress is defined to be covered.

R6 provides both simplified and detailed procedure to estimate *V*-factor for calculating the elastic-plastic value of *J* under combined stress. Simplified procedure is based on the elastic analysis. To quantify the magnitude of the secondary stress, a non-dimensional parameter, β_1 is introduced. The equation is defined as

$$\beta_1 = \frac{K_I^S}{(K_I^P / L_r)} \tag{5}$$

V-factor is assumed to be a function of the coefficient, β_1 and L_r, given by

$$V = \begin{cases} 1+0.2L_r+0.02\beta_1(1+2L_r) & for \quad L_r < L_r^* \\ 3.1-2L_r & for \quad L_r^* < L_r < 1.05 \\ 1 & for \quad L_r > 1.05 \end{cases} \tag{6}$$

L_r^* is determined by the intersection of the first and second lines in Eq. (6). In detailed method, a method of calculation to V-factor is given by

$$V = \zeta \cdot V_o \tag{7}$$

In R6, a number of procedures to calculate the V_o are suggested.

$$V_o = \frac{\sqrt{E' J^S}}{K^S} = \sqrt{\frac{J^S}{J_e^S}} \tag{8}$$

Where J_s is estimated by elastic-plastic FE analysis. And ξ is a function of β_1 and L_r, which is tabulated in R6

2.2 J estimates for Combined Load in A16 Code[5]

The elastic-plastic *J* under combined primary and secondary stress, J^{P+S}, can be estimated from

$$J^{p+s} = \left[\sqrt{J^{me}} + k_{th2}^* \sqrt{J_{el}^{th}} \right]^2 \tag{9}$$

Where J^{me} is calculated by EPS option, k_{th2}^* is coefficient of the stress redistribution under combined loading and J_{el}^{th} is calculated using FE analysis. In EPS option J^{me} can be estimated from,

$$J^{me} = J_{el}^{me} \cdot \frac{E \cdot \varepsilon_{ref}^{me}}{\sigma_{ref}^{me}} \tag{10}$$

The reference stress, σ_{ref} is deduced from elastic and plastic equivalent stresses on the tensile curve, and this process is shown in Fig.2. A estimation method of equivalent stresses is presented in A16 for each crack geometry and stress condition. A16 proposed k_{th2}^* option to estimate the interaction between primary and secondary stress. k_{th2}^* is obtained using following equation,

$$k_{th2}^* = \beta_2 + \kappa_1 \cdot (k_{th2} - 1) \tag{11}$$

Where each coefficients are given in,

$$\kappa_1 = \frac{\sigma_{el}^{th}}{\sigma_{el}^{th} + \sigma_{ref}^{me}}, \quad \kappa_2 = 0.5 \cdot \frac{\sigma_{2m}}{\sigma_{1m} + \sigma_{gb} + \sigma_{12}} \quad \begin{array}{l} \bullet CDAI: \beta_2 = 1 + 0.3 \cdot \left(1 - \kappa_2^{0.5}\right) \\ \bullet\ CDSI: \beta_2 = 1 + 0.3 \cdot \left(1 - \kappa_2^{0.5}\right) \end{array} \tag{12}$$

And k_{th2} is obtained following the equation,

$$k_{th2}^2 = \left(\frac{\sigma^{th}}{\sigma_{el}^{th}}\right)^2 \cdot \frac{E \cdot \varepsilon_{ref}^{th}}{\sigma_{ref}^{th}} \tag{13}$$

Where σ_{ref}^{th}, ε_{ref}^{th} and σ^{th} is calculated in accordance with Fig. 3. The value of follow up factor, r_{th} in Fig. 3 is given for each crack geometry in A16. σ_{el}^{th} is defined by following equation.

3. Result

This paper analyze for fully circumferential surface crack cases with a/t= 0.1 and n=10(Ramberg-osgood equation, E=200GPa and σ_y=500MPa). Axial tension was the only considered factor for the mechanical loading. To generate secondary stress, radial gradient temperature type of thermal load was only applied to the pipes. To confirm load order effect under combined load, two different types of load order were applied to the pipes. First type is applying thermal loading before the mechanical loading and second type is applying thermal loading after the mechanical loading. Elastic-plastic analysis of circumferentially cracked pipes was performed using ABAQUS. This paper compares R6 and A16 J estimates for combined stresses with FE result. Fig 3. compare R6 and A16 J estimates with FE results

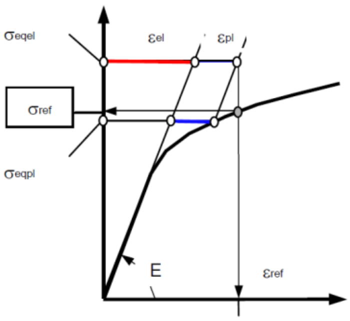

Fig. 1. Concept of EPS option in RCC-MR A16 code

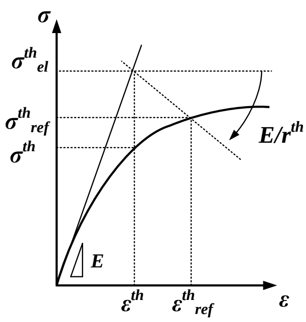

Fig. 2. Concept of k_{th2} option in RCC-MR A16 code

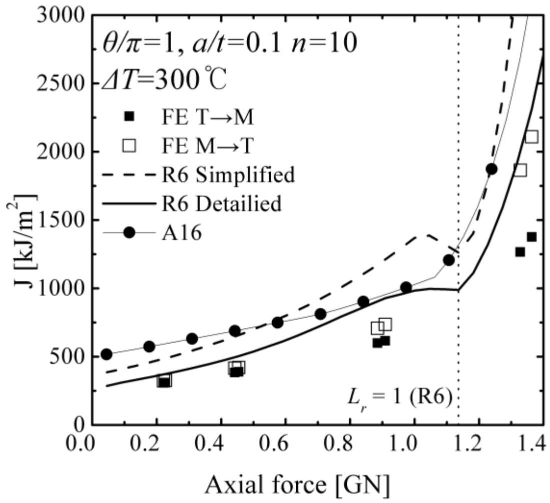

Fig. 3. Comparison of J-integral with R6, A16 and FE result

4. Conclusion

J value for the fully circumferential surface crack are conservative in contained yielding regime in A16 method. But in R6 method, less conservative result in contained yielding regime. Under large scale yielding (LSY) regime, R6 simplified method and A16 method produced similar result to J estimation. But detailed method are close to the FE results even for large L_r values. And this paper revealed that occurs when thermal loading is applied after mechanical loading the most severe loading sequence.

This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology (No. 2012M2A7A 1051939, 2013M2B2A9A03051295)

REFERENCES

[1] Ainsworth, R. A., The treatment of thermal and residual stresses in fracture assessments, Engineering fracture mechanics, Vol.24, pp 65~73. , 1986.
[2] Song, T.K, Kim Y. J, Nikbin. K, and Ainsworth, R. A., Approximate J estimates for circumferential cracked pipe under primary and secondary stresses, Engineering fracture mechanics, Vol.76, pp.2109~2125, 2009.
[3] Oh, C. Y, Kim Y. J, Budden. P and Ainsworth, R. A., Biaxial stress effects on estimating J under combined mechanical and thermal stresses, International Journal of Pressure Vessels and Piping,, Vol.88, pp.365-374, 2011.
[4] R6, Revision 4 : assessment of the integrity of structures containing defects, British Energy Ltd., Gloucester, UK
[5] RCC-MR, 2010 edition, Design and Construction Rules for Mechanical Components of FBR Nuclear Islands and high temperature applications, appendix A16,Tome I, Vol. Z, Paris, AFCEN, Paris