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A prototype of crack evaluation criterion for nuclear secondary system piping under tensile loading

Seung-Wan Woo[a], Doo-Ho Cho[a], Yoon-Suk Chang[a], Jae-Boong Choi[a], Young-Jin Kim[a*], Myung-Jo Jhung[b], Young-Hwan Choi[b]

[a] *School of Mechanical Engineering, Sungkyunkwan Univ., 300 Chunchun-dong, Jangan-gu, Suwon, Kyonggi-do 440-746, Korea*

[b] *Korea Institute of Nuclear Safety 19 Gusong-dong, Yusong-gu, Daejeon 305-338, Korea*
**Corresponding author: yjkim50@skku.edu*

1. Introduction

Recently, the integrity of secondary system piping becomes an important issue in relation to nuclear power plant risk from a core damage perspective. The main difference between primary and secondary system piping is that the later has relatively thin thickness and higher R/t ratio, which may cause different pipe fracture behavior during operation. So, it is necessary to develop appropriate flaw evaluation criteria under diverse loading conditions. In this paper, a new J-estimation equation for secondary system piping is proposed. Firstly, applicability of existing solution for secondary system piping was assessed. And then detailed finite element(FE) analyses are carried out for typical pipes with a circumferential semi-elliptical surface crack and limitation of existing solution was confirmed. Finally, using the FE analysis results, a prototype of J-estimation equation for secondary system piping is developed by using response surface method.

2. Applicability of Existing Solution

Data for 8 units of operating power plant recorded in CHECWORKS computer code were assessed to classify the R/t ratio of secondary system piping. It was observed that the average R/t ratio was 10.88~16.37, the maximum R/t ratio was 63.5 and the minimum R/t ratio was 2.35.

There are several J-estimation equations dealing with different loading conditions and crack shapes. Especially, in Ductile Fracture Handbook[1] prepared by Zahoor, an EPFM equation for pipe with a circumferential semi-elliptical surface crack(refer to Eq. (1)) is suggested but its applicability is limited to R/t=10. So, it may not appropriate for pipe having higher R/t ratio such a secondary system piping.

$$J = f_t P^2 / 4\pi R^2 tE + \alpha\sigma_0\varepsilon_0 t \cdot H_1 \cdot (\sigma_t / \sigma_0)^{n+1} \qquad (1)$$

where, H_1 is depends upon θ/π, a/t, n and R/t.

3. Finite Element Analyses

Detailed finite element analyses were carried out by using the general-purpose finite element analysis program, ABAQUS[2]. Analysis model was generated for circumferential semi-elliptical surface cracked pipes under tensile loading condition.

3.1. Model Verification

Before main analyses, verification of FE model was conducted by calculating the stress intensity factor(K_I) when R/t=10. The equation used for comparison was as below.

$$K_I = \sigma_t (\pi t)^{0.5} \cdot F_t \qquad (2)$$

where, F_t is shape factor and H_1 depends upon θ/π, a/t, n and R/t. Resulting difference of K_I between FEA and Zahoor equation was 1.2 %. Based on this result, the FE model was used for EPFM analysis.

3.2. Limitation of Zahoor Equation

As mentioned previously, applicability of Zahoor equation is R/t = 10. To investigate its limitation, J-integral values obtained from FEA and Zahoor equation were compared. In case of R/t=10, difference of two methods was 5.78%. It means a good agreement of J-integral value between FEA and Zahoor equation. Further comparison results, when R/t=2.5 and 60, are also shown in Fig. 1. As depicted in the figure, Zahoor equation becomes invalid if R/t≠10.

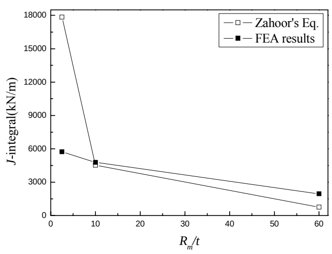

Fig. 1 Comparison of J-integral values

3.3. Detailed FE Analysis

Eight detailed finite element analyses were performed for 2.5≤R/t≤60. The typical analysis model is shown in Fig. 2. Analysis matrix and material properties are summarized in Table 1 and 2.

Table 1 Analysis matrix

Case	R/t	a/t	θ/π
1	2.5	0.5	0.25
2	5		
3	10		
4	20		
5	30		
6	40		
7	50		
8	60		

Table 2 Mechanical properties of SA106 Gr.C steel

E(GPa)	σ_o(MPa)	α	n
219	320	6.68	3.80

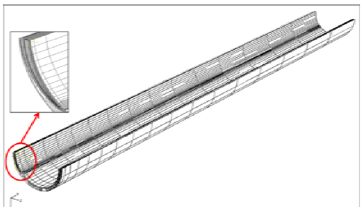

Fig. 2 Typical FE model (Case 3)

4. Development of a Crack Evaluation Equation

Based on detailed finite element results, a prototype of J-estimation equation for secondary system piping was developed in use of response surface method.

4.1 Response Surface Method(RSM)

Since the RSM is practical, economical and relatively easy to use, many researchers utilized it for several optimizing processes as well as engineering problems [3,4]. The calculated data were utilized to build mathematical model(generally first-order and second order models) by regression method. This mathematical model could be optimized using any mathematical or analytical approaches to obtain the most suitable process parameters.

4.2 Crack Evaluation Equation

To consider the estimation model of J-integral, two independent parameters were used for derive the secondary regression equation. And statistical validity was carried out by regression analysis and analysis of variance. The results were summarized in Table 3. According to the verify data in Table 3, validity of estimation model was confirmed by amplitude of t-value and p-value. Also, coefficient of β_3 was not meaningful and interaction term should have considered. Because the CD(Coefficient of Determination) was 98.9%, thus the estimation model was confirmed. Coefficients of secondary regression equation were used for J-estimation as Eq. (3).

$$J = 2870.57 + 56.078(R_m/t) - 26.25(F) + 0.216(R_m/t)(F) + 0.0614(F)^2 \quad (3)$$

where, F is the tensile load in MPa.

And the difference between FEA results and estimated equation were confirmed. These results were summarized in Table 4. So, further optimizing process will be needed to decrease the difference.

Table 3 Coefficient of regression model

Coefficient	t-value	p-value	Remarks
$\beta_0 = 2870.57$	4.37	1.1E-04	Values are meaningful when t≠2 and p<0.05
$\beta_1 = 56.078$	8.54	5.5E-10	
$\beta_2 = -26.25$	-7.36	1.6E-08	
$\beta_3 = 0.0523$	0.81	0.4E+00	
$\beta_4 = 0.0614$	12.89	1.2E-14	
$\beta_5 = -0.2160$	-15.36	7.2E-17	

Table 4 Comparison of estimated J- values

R_m/t	Tension	FEA	Eq. (3)	Difference
10	320	625.8	640.1	2.2%
20	420	1903.5	2006.4	5.4%
30	370	950.9	857.8	10.8%
40	420	1514	1311.3	15.4%
50	470	1696.7	1849.7	9.2%
60	270	125.2	126.2	0.7%

5. Conclusions

Crack integrity evaluation criterion for nuclear secondary system piping under tensile loading was investigated. First, applicability of existing solution was examined and then the limitation of it was proven. Thereby, detailed finite element analyses were carried out by employing deformation plasticity theory. Based on finite element results, a new prototype of J-integral estimation equation was derived. Further analyses are being performed to finalize the proposed equation.

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