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Fracture Mechanics Parameters Benchmark Analysis for Elastic K_I Evaluation of Nuclear Pipes under Mechanical Loading

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1. Introduction

Fracture mechanics parameters, such as *K*(stress intensity factor) and *J*-integral, are commonly used to evaluate integrity of cracked components in the nuclear industry. For the safety assessment and maintenance of these components, the various codes (ASME B&PV Section XI, R6 Rev.4, RSE-M, RCC-MRx Appendix 16, API and etc.) propose compendia of stress intensity factors in terms of component geometry, type of defect and loading conditions[1~3]. In order to compare and analyze these different estimation schemes on the fracture mechanics parameter evaluation, a benchmark program on the analytical evaluation of the fracture mechanics parameters *K* and *J* for different components and loads is organized by OECD-NEA-IAGE group. As a part of this benchmark, elastic *K* evaluation in cracked cylinders under mechanical loads and cracked plates under thermal loads is investigated using different code such as ASME B&PV Code Section XI, RCC-MRx Appendix A16. Furthermore, the analysis results from these different estimation schemes are compared with a reference analysis results done by finite element method for representative cases.

2. Description of Related Codes

In this section stress intensity factor calculation method in the existing codes are briefly described.

2.1 ASME Code Sec. XI

The stresses normal to the crack plane at the flaw location are represented by polynomial fit over the thickness by following relationship in ASME Code Sec. XI App. A.

$$\sigma = A_0 + A_1\left(\frac{x}{a}\right) + A_2\left(\frac{x}{a}\right)^2 + A_3\left(\frac{x}{a}\right)^3 \quad (1)$$

where, x is distance through the wall measured from the flawed surface and a is crack depth.

For the surface flaw, stress intensity factors are calculated using stress distribution obtained from non-cracked geometry under given loading conditions by following equation.

$$K_I = \left[\left(A_0 + A_p\right)G_0 + A_1G_1 + A_2G_2 + A_3G_3\right]\sqrt{\frac{\pi a}{Q}} \quad (2)$$

$$Q = 1 + 4.593\left(\frac{a}{l}\right)^{1.65} - q_y \quad (3)$$

$$q_y = \frac{\left[\left(A_0G_0 + A_pG_0 + A_1G_1 + A_2G_2 + A_3G_3\right)/\sigma_{ys}\right]^2}{6} \quad (4)$$

where, A_0~A_3 are coefficient from eq. (1) that represent the stress distribution over the flaw depth, A_p is the internal vessel pressure, G_0~G_3 are free surface correction factors and Q is a flaw shape parameter.

When the linearization method is used, following equation shall be used to calculated stress intensity factor.

$$K_I = \left[\left(\sigma_m + A_p\right)M_m + \sigma_bM_b\right]\sqrt{\pi a/Q} \quad (5)$$

$$q_y = \left[\left(\sigma_0M_m + A_pM_m + \sigma_bM_b\right)/\sigma_{ys}\right]^2/6 \quad (6)$$

Where M_m is G_0 and M_b is G_0-2(a/t)G_1.

Stress intensity factor calculation procedures of App. C and Code Case N-494 are omitted in this paper.

2.2 RCC-MRx Code

The stress intensity factor calculation method for the various geometries and loading conditions are provided in RCC-MRx code, and influence coefficient such as F_m, F_b, i_0~i_4 and stress distributions normal to crack plane are used. For the through wall crack, following equation is used.

$$K_I = \left[\sigma_m \cdot F_m + \sigma_b \cdot F_b + \sigma_{gb} \cdot F_{gb}\right] \cdot \sqrt{\pi \cdot c} \quad (7)$$

where, σ_m is membrane stress and σ_b is bending stress.

For the surface flaw, eqs. (8)~(9) are used.

$$\sigma\left(\frac{u}{L}\right) = \sigma_0 + \sigma_1 \cdot \left(\frac{u}{L}\right) + \sigma_2 \cdot \left(\frac{u}{L}\right)^2 + \sigma_3 \cdot \left(\frac{u}{L}\right)^3 + \sigma_4 \cdot \left(\frac{u}{L}\right)^4 \quad (8)$$

$$K_I = \left[\sigma_0 \cdot i_0 + \sigma_1 \cdot F_1 \cdot \left(\frac{a}{L}\right) + \sigma_2 \cdot F_2 \cdot \left(\frac{a}{L}\right)^2 + \sigma_3 \cdot F_3 \cdot \left(\frac{a}{L}\right)^3 + \sigma_4 \cdot F_4 \cdot \left(\frac{a}{L}\right)^4 + \sigma_{gb} \cdot F_{gb}\right] \cdot \sqrt{\pi \cdot a} \quad (9)$$

3. Evaluation of Stress Intensity Factor

3.1 Problem Definition

In this part, a cracked pipe under mechanical loading are considered. 177,000 MPa of Young's modulus and 0.3 of Poisson's ratio are considered as material properties for the elastic analysis. All geometries of benchmark problem are summarized in Table 1 and representative geometry (CDSI-circumferential internal semi-elliptical) was shown in the Fig. 1.

Table I: Problem Description

Cases	Defect	a/h	c/a	h (mm)	De (mm)
K1	CDAI	0.1, 0.25, 0.5, 0.75	-	60	660
K2	CDAE	0.1, 0.25, 0.5, 0.75	-	60	660
K3	CDSI	0.1, 0.25, 0.5, 0.75	3	60	660
K4	LDII	0.1, 0.25, 0.5, 0.75	-	60	660
K5	LDSI	0.1, 0.25, 0.5, 0.75	3	60	660

3.2 Comparison and Analysis Results

The stress intensity factors were calculated by selecting applicable calculation procedure according to ASME and RCC-MRx Codes. And corresponding elastic FE analyses were performed using commercial FE analysis program, ABAQUS[4]. Fig. 2 shows representative FE model used in present study, quarter model and 20-node brick element was used and equivalent tensile stress was considered for the internal pressure of loading condition.

In the case of K1 and K2, RCC-MRx Code provided good agreement with FE results within 1% of difference. However, difference of ASME App. A and App. C with FE results increased with increasing crack depth. Among them, ASME App. A was most conservative.

In the case of K3, stress intensity factor from the ASME App. C was overall conservative due to the geometry of crack which has rectangular shape of flaw. ASME Sec. XI App. A also give conservative results, it is caused by the equation of stress intensity factor in ASME Sec. XI App. A which is based on geometry of simple plate. This difference influences the results. On the other hand, RCC-MRx Code gives small difference when comparing the FE results. In the case of K4 and K5, overall tendency was similar to the K1 and K2, but difference between RCC-MRx code and FE results was increased up to 55%. For these cases (longitudinal defect), more comprehensive analyses are required.

Table II: Comparison of Stress Intensity Factor (K3 case)

Loading Condition 1 (P=25 MPa, M2=3.50E+09 N·mm)					
a/h	ASME App. A ($MPa\sqrt{m}$)	ASME App. C ($MPa\sqrt{m}$)	RCC-MRx ($MPa\sqrt{m}$)	FE ($MPa\sqrt{m}$)	Error(%) FE vs. RCC-MRx
0.1	35.70	38.94	35.03	37.00	-5.34
0.25	60.50	64.10	58.11	58.82	-1.22
0.5	101.20	105.58	93.09	89.84	3.61
0.75	140.50	160.82	134.04	125.12	7.13
Loading Condition 2 (M1=1.70E+09 N·mm, M2=5.20E+09 N·mm)					
a/h	ASME App. A ($MPa\sqrt{m}$)	ASME App. C ($MPa\sqrt{m}$)	RCC-MRx ($MPa\sqrt{m}$)	FE ($MPa\sqrt{m}$)	Error(%) FE vs. RCC-MRx
0.1	37.60	46.30	37.06	32.20	-13.12
0.25	64.20	76.12	61.78	60.39	-2.26
0.5	108.20	125.58	99.71	96.48	-3.23
0.75	151.30	191.55	144.19	134.54	-6.70

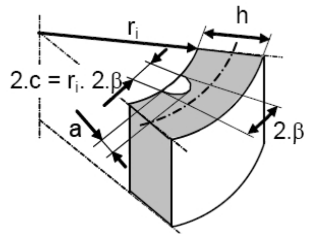

Fig. 1. Geometry of CDSI defect (RCC-MRx Code)

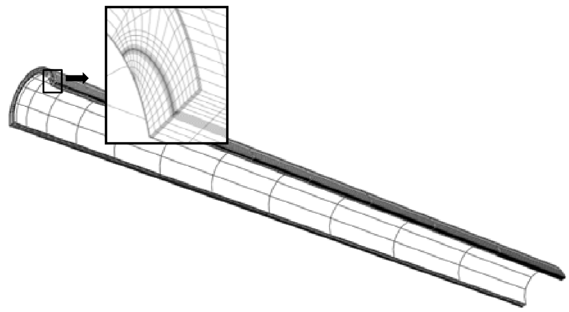

Fig. 2. Typical FE model (CDSI)

4. Conclusions

In this paper, stress intensity factors was calculated by ASME and RCC-MRx codes for the given problems, and the results were compared to corresponding finite element analysis(FEA) results. On the whole, ASME code estimated the stress intensity factors more conservatively than FEA results, but RCC-MRx code showed a good agreement with the FEA results. When applying ASME codes for the calculation of stress intensity factors, the results by Appendix C and Code case N-494-4 are less conservative and more accurate than those by Appendix A. Finally, based on the participants' analysis results (although all results of participants are not provided herein), R6 and RCC-MRx codes seem to provide a relevant fracture mechanics parameters and good homogeneity of the results.

REFERENCES

[1] ASME Boiler & Pressure Vessel Code, Section XI, Appendix A, Rules for Inservice Inspection of Nuclear Power Plant Components: Appendix A-Analysis of Flaws, ASME International, 2007.
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[3] RCC-MR(MRx) Code, Design and Construction Rules for Mechanical Components of Nuclear Installations Applicable for High Temperature Structures and ITER Vacuum Vessel, 2010.
[4] ABAQUS, INC., User's Manual, ABAQUS Version 6.9-1, 2010.