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Quantification of Thickness Effects for Circumferential Through-Wall Cracked Pipe Bend with Un-Uniform Thickness under In-Plane Opening Bending

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Abstract

An Elbow is one of the major component that make up the piping system of a nuclear power plant and chemical plant facilities. In general, the elbow is made by welding a straight pipe and bend part. So, periodic welding inspection is required due to the potential defects in weld zone. Recently, the application of induction heating pipe bend is increasing in order to reduce this problem. Pipe bend made by induction heating band is not necessary welding process because it is made by bending a straight pipe but the intrados thickness and the extrados thickness are different. On the other hand, J-integral is widely used to evaluate a structural integrity (to check crack stability) but the J estimation of pipe bend with un-uniform thickness is very difficult because of the thickness differences in each locations.

This paper proposes a reference stress based J estimation scheme of circumferential through-wall cracked pipe bend with un-uniform thickness under in-plane opening bending loading condition. The pipe bend with un-uniform thickness is assumed to have different thickness between intrados and extrados and the crack to be located in the entre of the pipe bend, either at the intrados or extrados.

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Keywords: Circumferential through-wall crack, Elbow, Pipe bend, *J*-integral, Optimized reference load, Equivalent thickness

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1. Introduction

In many industries associated with large-scale plants, the piping system has been configured using the fittings such as elbows and straight pipes. As the use of fitting is increased, the welding portion of the pipeline system is also increased. The quality and reliability of the welding parts has a major impact on the integrity and reliability of the whole pipeline system. Generally, the fitting elbow made by welding is widely used for layout requirement and increase the piping flexibility, however, it should inspect periodically because the welding part has a potential vulnerability. On the other hands, the pipe bend can be produce by bending process a straight pipe without welding. Due to the bending process, it is characterized in that there is a thickness difference between intrados and extrados. Recently, the application of the pipe bend is increasing in order to reduce maintenance cost and potential flaw.

Nomenclature

E	Young's modulus
J	J-integral
Je	elastically calculated J
M	moment
ML	limit moment of a cracked elbow
M_{OR}	optimised reference moment for the reference stress
n	strain hardening index ( ) Ramberg-Osgood model
R	bend radius
r	mean pipe radius
α	coefficient of Ramberg-Osgood model
ν	Poission's ratio
ε	strain
ε_{ref}	reference strain
θ	half circumferential angle of a circumferential crack
λ	bend characteristic, =Rt/r2
σ_0	limiting stress of a perfectly plastic material; 0.2% proof(yield) stress
σ_{ref}	reference stress
t_{int}	intrados thickness
t_{ext}	extrados thickness
t_{avg}	averaged thickness of the intrados and extrados

LBB (leak-before-break) concept to design and integrity analyses of nuclear piping system has been applied to safety improvements and cost reductions in design and maintenance [1]. In order to apply the LBB concept, elastic-plastic fracture mechanics analyses should be performed to estimate the J-integral for checking the crack stability and crack opening displacement (COD) for evaluation the leak rate. For a straight pipe with a through-wall circumferential crack, many extensive studies have been conducted [2-5]. Also, elastic-plastic J and COD estimation for through-wall cracked elbow has been actively performed by an Indian research group [6-8]. They developed J and COD estimation scheme for circumferential through-wall cracked elbows under in-plane bending using extensive elastic-plastic finite element solutions, which similar to the GE/EPRI approach [9]. However, the GE/EPRI approach is difficult to extend to various cases because it requires extensive FE solutions for specific geometries, thus would not be practical. For more general applicability, the reference stress based J and COD estimation equations for LBB analysis have developed and an optimized reference normalizing moment has been introduced to define the reference stress and improve the accuracy prediction of the estimated J and COD [10]. However, most of the existing works on elastic-plastic J and COD estimation methods has been limited to elbow with a uniform thickness and there is little research for the pipe bend with un-uniform thickness.

This paper proposes a reference stress based J estimation scheme of circumferential through-wall cracked pipe bend with un-uniform thickness under in-plane bending. The pipe bend is assumed to have un-uniform thickness and the crack to be located in the entre of the elbow, either at the intrados or extrados. To find a J-integral, three-dimensional finite element analysis was performed. The material properties are assume to be a Ramberg-Osgood model.

2. Finite element analysis

Figure 1 depicts a schematic illustration of circumferential through-wall cracked ideal elbow and pipe bend with un-uniform thickness. An ideal elbow made by fitting has the same thickness, however, the pipe bend has a different thickness between intrados and extrados by heat induction bending process. Generally, if the pipe bend is manufactured by bending process such as an induction heating bending, the intrados thickness is increased and the extrados thickness is decreased. In this present works, the intrados thickness and the extrados thickness are assumed as $1.750t_n$ and $0.875t_n$. The pipe mean radius, thickness and bend radius are denoted by r, t and R. Two cases were considered, intrados crack and extrados crack. The value of R/r and r/t is R/r=3 and r/t=5 for all cases. The length of the attached straight pipe was chosen to be L=20r, which is sufficiently long to avoid end effects of bending moment.

Also, the present study considers the in-plane bending moment. The half crack angle, θ, were considered in θ/π =0.125, 0.250 and 0.375. The material in the FE analysis is assumed to be the Ramberg-Osgood relation. The elastic modulus and yield stress are E=200GPa, σ_o=200MPa.

Figure 2 depicts a FE model for elastic-plastic finite element analyses to calculate elastic-plastic J for a circumferential through-wall cracked ideal elbow and pipe bend under in-plane bending. The numbers elements/nodes in the FE meshes were 4,591 elements/23,990 nodes for elbow and 13,120 elements/63,386 nodes for pipe bend. A quarter model was used because of symmetry conditions. The deformation plasticity option and multi-point constraint (MPC) option in ABAQUS were used.

3. Reference stress based J estimation

3.1. Elastic-plastic J estimation Equations

Based on the reference stress approach, elastic-plastic *J* can be estimated from:

$$\frac{J}{J_e} = \frac{E\varepsilon_{ref}}{\sigma_{ref}} + \frac{1}{2}\left(\frac{\sigma_{ref}}{\sigma_0}\right)^2 \frac{\sigma_{ref}}{E\varepsilon_{ref}} \tag{1}$$

where ε_{ref} denotes the reference strain at the reference stress σ_{ref} , determined from true stress-strain data of the material; and σ_{ref} is the reference stress, defined by

$$\sigma_{ref} = \frac{M}{M_{ref}}\sigma_0 \tag{2}$$

where M and M_{ref} denote the applied the bending moment and the reference normalizing moment, respectively. In Eq. (1), J_e is the elastically calculated *J*.

3.2. Reference stress based and plastic collapse load

A plastic limit or collapse load is commonly used as a reference normalizing load. Based on the FE solutions, the plastic limit load solutions for through-wall cracked elbows under in-plane bending were proposed by Kim [11]. It can be summarized as follows.

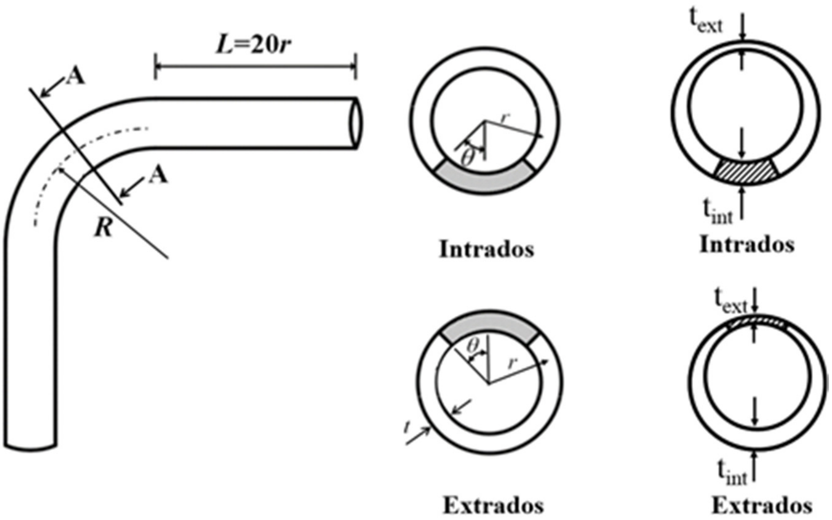


Fig. 1. Schematic illustration of circumferential through-wall cracked ideal elbow with uniform thickness and pipe bend with un-uniform thickness.

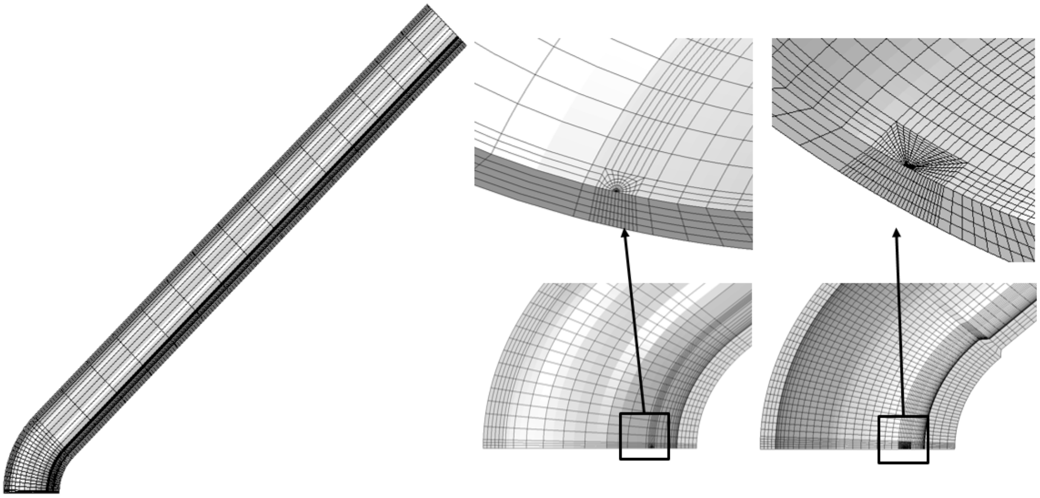


Fig. 2. A finite element (FE) model for ideal elbow with uniform thickness and pipe bend with un-uniform thickness.

For circumferential through-wall intrados cracked elbow under in-plane opening bending, the plastic collapse load M_L is given by

$$\frac{M_L}{M_0} = \exp\left(-\frac{(\theta/\pi)^2}{0.1682}\right) \tag{3}$$

where M_o is the limit moment solution for the un-cracked elbow, given by

$$\frac{M_0}{M_0^{ref}} = \min\left[\frac{\varepsilon_0}{0.001}(A-1)+(2-A), 1.85-71.4\varepsilon_0-0.152\left(\frac{r/t}{10}\right)\right];$$

$$A = 0.16\left(\frac{r/t}{10}\right)+0.96 \tag{4a}$$

$$\frac{M_0^{ref}}{\left(4\sigma_o r^2 t\right)} = 1.048\lambda^{1/3}-0.0617 \tag{4b}$$

For circumferential through-wall extrados cracked elbow under in-plane opening bending, the plastic collapse load M_L is given by

$$\frac{M_L}{M_0} = \begin{cases} \min\left[1.0, -2.113\frac{\theta}{\pi}+1.44\right] & \text{for} \quad 0 \le \frac{\theta}{\pi} \le 0.5 \\ 3.12\left(1-\frac{\theta}{\pi}\right)^3 & \text{for} \quad 0.5 \le \frac{\theta}{\pi} \le 1.0 \end{cases} \tag{5}$$

where M_o denotes the plastic collapse load for the un-cracked elbow under in-plane closing bending, and is given by

$$\frac{M_0}{M_0^{ref}} = \left[\frac{\varepsilon_0}{0.001}(A-1)+(2-A)\right] \tag{6a}$$

$$A = 0.22\exp\left(-\frac{r/t}{20}\right)+0.79$$

$$\frac{M_0^{ref}}{\left(4\sigma_o r^2 t\right)} = 0.800\left(\frac{r}{t}\right)^{-0.017}\left[\lambda+1.460\left(\frac{r}{t}\right)^{-0.911}\right]^{n_c} \tag{6b}$$

$$n_c = 0.423\left(\frac{r}{t}\right)^{0.127}$$

where $\varepsilon_0 = \sigma_0/E$. It can be noted that the plastic collapse load for un-cracked elbows, M_o, depends not only on r/t and λ but also on ε_o.

3.3. Optimized reference load

To obtain better J estimates, an optimized reference load M_{OR} is introduced to define the reference stress by Kim [10]. The optimized reference load can be obtained simply by multiplying the plastic collapse load in a correction factor. The optimized reference moment, M_{OR} is expressed as below:

$$M_{OR} = f(\lambda)\gamma\left(\frac{\theta}{\pi}\right)M_L \tag{7}$$

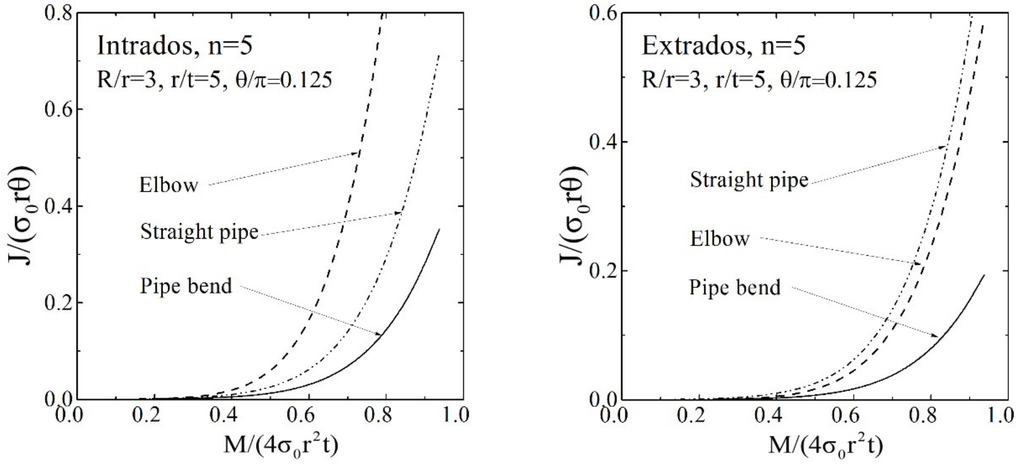
Based on the extensive FE results, the correction factor for crack length, $\gamma(\theta/\pi)$, has been suggested

$$\gamma\left(\frac{\theta}{\pi}\right) = 0.82 + 0.75\left(\frac{\theta}{\pi}\right) + 0.42\left(\frac{\theta}{\pi}\right)^2 \tag{8}$$

Also, the correction factor for the bend characteristic, *f(λ)*, is expressed by

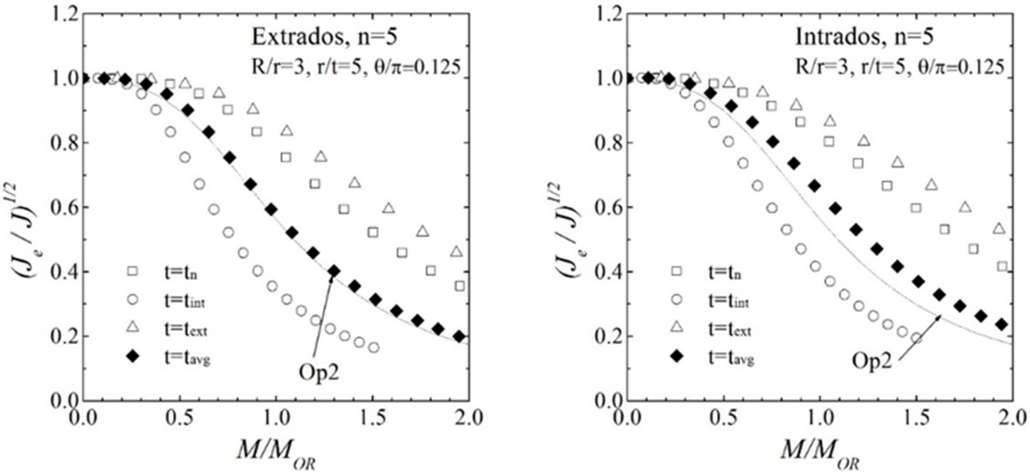
$$f(\lambda) = 0.284\lambda + 0.744 \tag{9}$$

4. Elastic-plastic J analysis



(a) (b)

Fig. 3. Comparison of J results for r/t=5: (a) intrados crack and (b) extrados crack.



(a) (b)

Fig. 4. Thickness effects for through-wall cracked pipe bend: (a) intrados crack and (b) extrados crack.

Figure 3 shows the comparison of J results for circumferential through-wall cracked straight pipe, ideal elbow with uniform thickness and pipe bend with un-uniform thickness. For intrados crack, the value of elbow is the highest and the value of pipe bend is the lowest. But, for extrados crack, the value of straight pipe and elbow is similar and the value of pipe bend is still the lowest. The results can be evaluated in that the pipe bend relatively safe than elbow.

5. J estimation of pipe bend

5.1. Elastic-plastic J estimation Equations

The most important feature of pipe bend is the thickness difference between intrados and extrados cause by bending process. The RCC-M 3642.1 and 3642.2 have proposed a minimum required thickness of elbow and pipe bend [12]. Unlike straight pipe, the required thickness values of elbow and pipe bend are expressed below:

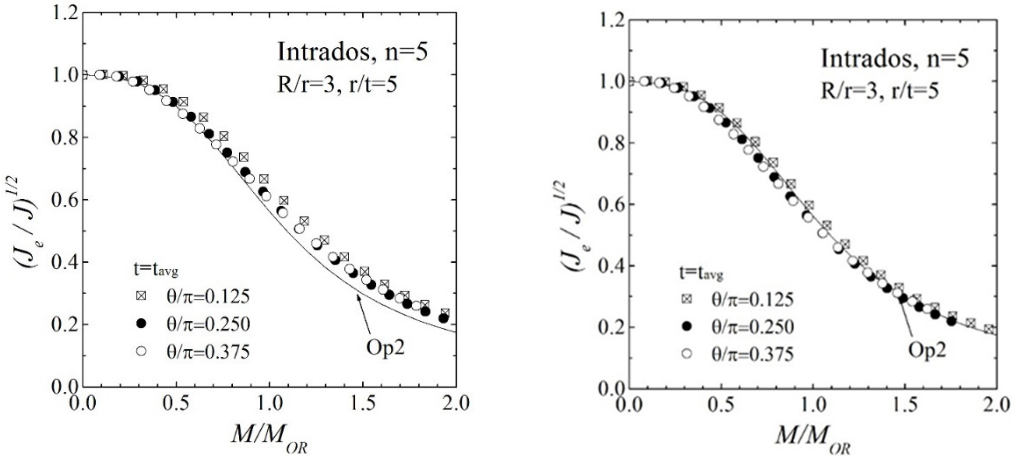
$$t_{int} \geq \left(\frac{R/r - 0.5}{R/r - 1.0} \right) t_n \text{ for intrados} \tag{10}$$

$$t_{ext} \geq \left(\frac{R/r + 0.5}{R/r + 1.0} \right) t_n \text{ for extrados} \tag{11}$$

If the ratio of the bending radius and the pipe radius is R/r=3, the extrados thickness (thinning part) is a $0.875t_n$. The intrados thickness of pipe bend can be determined by the volume constant condition and the values of intrados thickness is a $1.750t_n$. In this study, the averaged thickness was defined as follows. The equivalent thickness which is representative of the thickness of pipe bend is assumed as the averaged thickness of intrados and extrados.

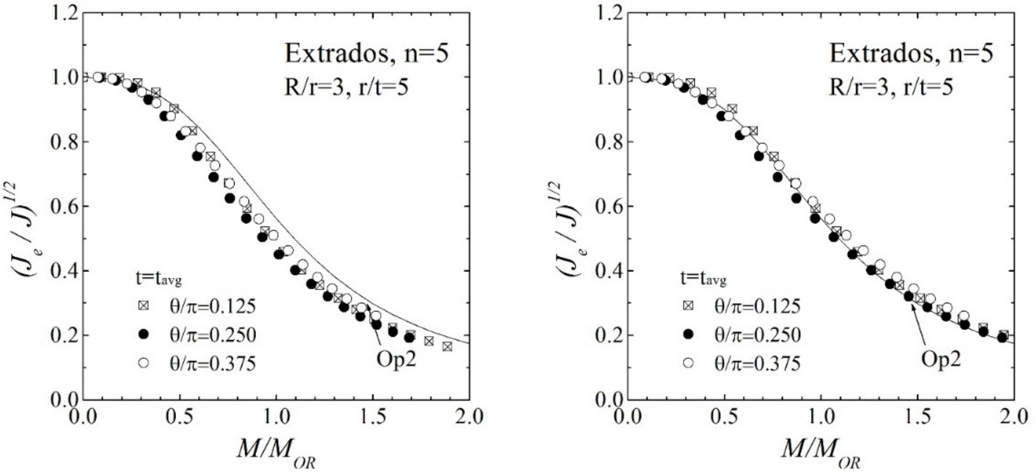
$$t_{avg} = \frac{1}{2}\left(t_{int} + t_{ext} \right) \tag{12}$$

Estimated *J* values using Eq. (1) are compared with FE results for R/r=3, r/t=5 and θ/π=0.125 in Fig. 5. Results are presented in the failure assessment diagram space, i.e. $(Je/J)^{1/2}$ versus M/M_{OR}, where M_{OR} is defined by the optimized reference moment given above. The results show that the use of the averaged thickness provides better *J* estimates than the use of nominal thickness, the intrados thickness and the extrados thickness.



(a) (b)

Fig. 5. Comparison of FE J results with reference stress-based J estimations for circumferential through-wall cracked pipe bend with intrados crack for various optional cases: (a) R/r=3, r/t=5 with option 2; and (b) option 3.



(a) (b)

Fig. 6. Comparison of FE J results with reference stress-based J estimations for circumferential through-wall cracked pipe bend with extrados crack for various optional cases: (a) R/r=3, r/t=5 with option 2; and (b) option 3.

5.2. J estimation of pipe bend with un-uniform thickness

In the previous section, it assumes the averaged thickness value that is representative of the pipe bend thickness, t_{avg}. For a more accurate prediction of the *J* value of the pipe bend with un-uniform thickness, in Eq. (7), it should be determined the coverage of the thickness in the correction factor for the bend characteristic and the limit load solutions. As follows, the three options may be assumed in Eq. (13).

$$M_{OR} = \text{Non-dimensional factor} \times (4\sigma_0 r^2 t) \times g(\lambda)\gamma\left(\frac{\theta}{\pi}\right) \tag{13}$$

Option 1. Only apply in the pipe moment calculation
Option 2. Apply in the pipe moment calculation and the bend geometry correction factor
Option 3. Apply in the whole equation.

Through the intensive research by author, the option 2 and option 3 have been determined more useful. Fig. 5 and Fig. 6 are the comparison of FE *J* results with reference stress based *J* estimations for circumferential through-wall cracked pipe bend with intrados crack and extrados crack for the optional cases. The estimated *J* values of two cases are all agree well with FE results. It is note that both two cases, option 2 and option 3, have a sufficiently accurate *J* value but the option 3 is more complex to fine an optimized reference moment using the averaged thickness for pipe bend.

6. Conclusions

This paper proposes a reference stress based estimation scheme of circumferential through-wall cracked pipe bend with un-uniform thickness under in-plane bending. The pipe bend is assumed to have different thickness at intrados and extrados and crack to be located in the entre of the pipe bend, either at the intrados or extrados. To find a J-integral, three-dimensional finite element analysis was performed. The material properties are assume to be a Ramberg-Osgood model.

The use of the averaged thickness for the pipe bend with un-uniform thickness provides better J estimates than the use of nominal thickness, the intrados thickness and the extrados thickness. Also, the estimated J values of two cases (option 2 and option 3) are all agree well with FE results.

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