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Finite Element Limit Pressures for Circumferential Through-Wall Cracks in the Interface between Elbow and Pipe

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1. Introduction

For the last 30 years, many fracture mechanics integrity assessments for a cracked pipe have been performed[1,2]. Among integrity assessment method based on a fracture mechanics concept for piping system, a limit load method is one of the important way to predict a maximum load carrying capacity in the materials with high ductility in the sense that it is used to either assess directly structural integrity of pipe based on fully plastic fracture mechanics or calculate elastic-plastic fracture mechanics parameters based on reference stress concept.

In nuclear power plants, piping system often involves elbows welded to straight pipe. Since welded regions are vulnerable to cracking, it is important to predict an accurate limit load for pipes with a crack in the interface between elbows and attached pipes. However, although extensive works have been made for developing limit analysis methods for cracked pipes, they were mainly for straight pipes[3,4]. Recently, limit moment solutions[5] for elbow that is attached to straight pipe with a circumferential through-wall crack(TWC) in the interface were proposed, whereas limit pressure for this geometry is not suggested yet.

In this context, plastic limit pressures of circumferential TWCs between elbow and straight pipe were calculated in the present study considering geometric parameters such as an elbow curvature, a pipe size and a crack length.

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2. FE limit analyses

2.1 Geometry and FE mesh

Figure 1 depicts an elbow welded to straight pipe employed in the present study. The material of FE model is assumed to be homogeneous and isotropic material without weld part. The bend characteristic is considered by using λ which is defined as following equation (1).

$$\lambda = \frac{R / r_m}{r_m / t} \tag{1}$$

where, R, r_m and t denote a curvature of elbow, a mean radius of pipe and a pipe thickness, respectively.

Non-dimensional geometric variables such as r_m/t and R/r_m were considered to quantify the effect of a pipe thickness and elbow curvature on limit pressure. Three different values of r_m/t (=5, 10 and 20) were considered, whereas five different values of R/r_m (=2, 3, 4, 5 and 6) were considered in the present study. Then, the λ is ranging from 0.1 to 1.2.

The length of the attached straight pipe was assumed to be 10 times mean radius (L=10r_m) to avoid the end effect due to the applied loading[6].

A circumferential TWC was assumed to be located at the extrados in the interface between an elbow and attached straight pipe, as shown in Fig. 1(a). The circumferential TWC is characterized by its relative circumferential half angle (θ) as depicted in Fig. 1(b). Values of θ/π were varied ranging from θ/π=0.125 to 0.5.

Symmetric conditions were fully utilized in FE model to reduce computing time. To avoid problems associated with incompressibility, reduced integration elements within ABAQUS element library (C3D20R) were used. The number of elements and nodes in FE meshes is 7650 and 36532, respectively. For all cases, 5 elements are used through the thickness.

2.2 FE analysis

As for loading condition, internal pressure was applied to the inner surface of an elbow assembly where an equivalent axial tension due to internal pressure was also applied to the end of the pipe to consider the end cap effect. In addition, a half of internal pressure was applied to the crack face. The RIKS option within ABAQUS was invoked to avoid problems associated with convergence in elastic-perfectly plastic calculations.

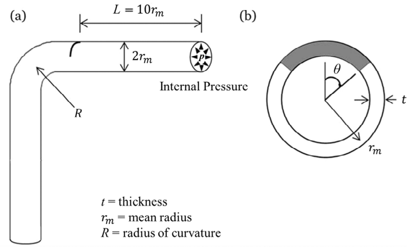
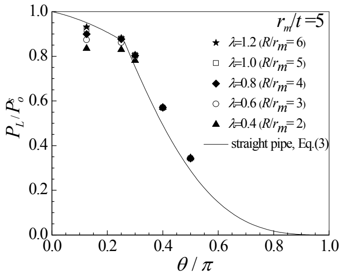
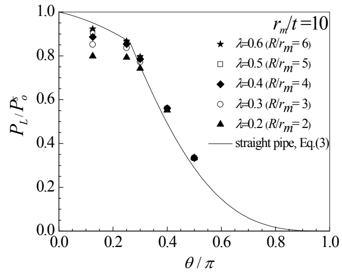


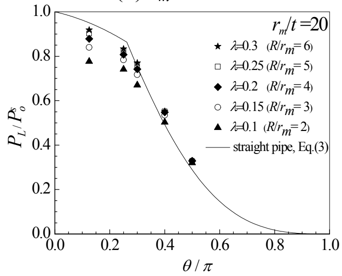
Fig. 1. Schematics of an elbow assembly: (a) circumferential TWC in the interface between an elbow and attached straight pipe and (b) geometry of circumferential TWC



(a) r_m/t=5



(b) r_m/t=10



(c) r_m/t=20

Fig. 2. Variations of FE limit pressures with crack length and elbow curvature

3. Result and Discussion

Figure 2 shows the variations of FE limit pressures of circumferential TWCs between elbows and pipes due to change of crack length and elbow curvature. In these figures, the FE limit pressure results were normalized with respect to limit pressures of an un-cracked straight pipe (P_o^S) as given below.

$$P_o^S = \frac{2}{\sqrt{3}}\frac{\sigma_y t}{r_m} \tag{2}$$

The FE limit pressures of straight pipe with circumferential TWC (Eq. (3)) which was proposed by Huh et al. [7] were also shown in these figures.

$$P_L^S = \begin{cases} P_o^S[-0.92(\theta/\pi)^2 - 0.28(\theta/\pi) + 1] & \text{for } 0 < \theta/\pi < 0.263 \\ \frac{2\sigma_y t}{r_m}\left[1 - \frac{\theta + 2\sin^{-1}(\frac{\sin\theta}{2})}{\pi}\right] & \text{for } \theta/\pi > 0.263 \end{cases} \tag{3}$$

As shown in Fig. 2, plastic limit pressures of circumferential TWCs between elbow and pipe tend to be slightly higher than those of the straight pipe for longer crack length($\theta/\pi \geq 0.3$). However, noting that Eq. (3) has been derived as lower bound solution, limit pressure solutions of straight pipe with circumferential TWC could be used for predicting those of elbow with circumferential TWCs between elbow and pipe. On the other hand, limit pressures of cracks between elbow and pipe tend to be lower than those of straight pipe as crack length decreases. As thickness of pipe decrease, the differences of limit pressures between straight pipe and elbow increase. Thus, it can be concluded that limit pressure solutions based on straight pipe is not appropriate for circumferential TWC in the interface between elbow and pipe for shorter crack length.

Another notable point is that limit pressures are getting smaller as λ (or R/r_m) decreases for shorter crack length whereas the curvature of elbow does not affect limit pressures of circumferential TWC in the interface of elbow and pipe regardless of thickness of pipe for longer crack length.

4. Conclusion

In the present study, the FE plastic limit analyses for circumferential TWC in the interface between elbow and pipe under internal pressure were conducted based on elastic perfectly plastic assumption.

Based on the present FE results, it is found that plastic limit pressures of straight pipes with circumferential TWC are not appropriate for predicting plastic limit pressures of circumferential TWC in the interface between elbow and pipe for shorter crack length. Thus, plastic limit pressures for elbow attached to pipe with relatively short circumferential TWC in the interface between elbow and pipe should be evaluated by considering the elbow curvature and pipe thickness.

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