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Evaluation Model for Restraint Effect of Pressure Induced Bending on the Plastic Crack Opening of Circumferential Through-Wall-Crack

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1. Introduction

Most of the pipe crack evaluation procedures, including leak-before-break (LBB) analysis, assume that the cracked pipe subjected to remote bending or internal pressure is free to rotate.[1] In this case, the pressure induced bending (PIB) enhances crack opening of a through-wall-crack (TWC) in a pipe. In a real piping system, however, the PIB will be restrained because the ends of the pipe are constrained by the rest of the piping system. Hence, the amount of restraint affects the crack opening of a TWC in a pipe, and the restraint effect on crack opening directly affects the results of LBB evaluation [2,3]. Therefore, it is necessary to investigate the restraint effect of PIB on crack opening displacement (COD) to quantify the uncertainties in current analysis procedures and to ensure the application of LBB concepts to nuclear piping systems.

Recently, several researches were conducted to investigate the restraint effect of PIB on COD [4-6], and they proposed a simplified model to evaluate COD under restrained conditions. However, these results are quite limited because the restraint effect was evaluated only in terms of linear-elastic crack opening. In practice, the TWC in a pipe behaves plastically under normal operating loads, and the current LBB analysis methodologies require elastic-plastic crack opening evaluation [1]. Therefore, this study evaluates the restraint effect of PIB on the plastic crack opening of a TWC in a pipe using finite element analysis under various influencing parameters. Based on these results, a closed-from model to be able to estimate the restraint effect of PIB on plastic crack opening is proposed.

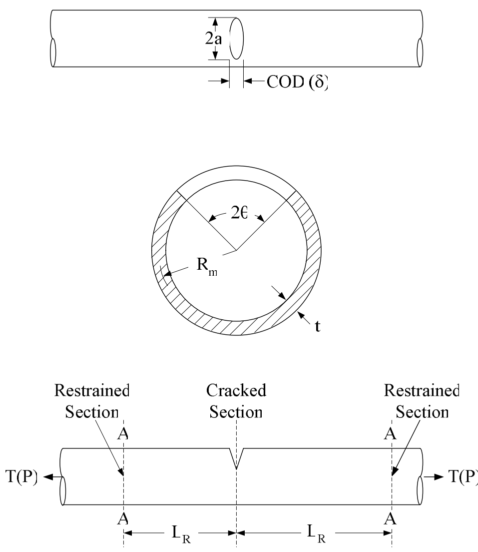
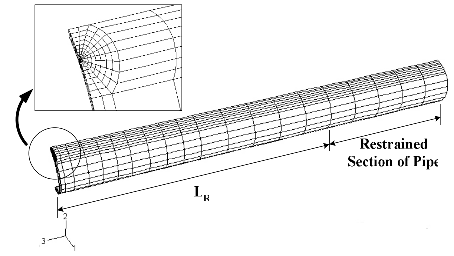
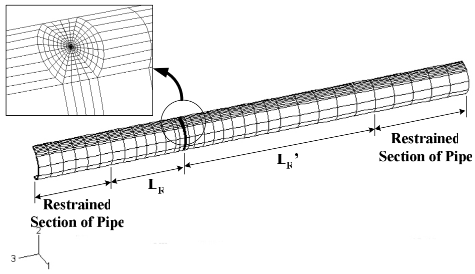


Figure 1. Schematics of through-wall cracked pipe under conditions of PIB restraint



(a) Symmetry model



(b) Asymmetry model

Figure 2. Finite element models for COD calculation

2. Finite Element Analysis

2.1 *Evaluation Method and Procedure*

In order to evaluate the restraint effect of PIB on COD, as illustrated in Fig. 1, a TWC was considered in a pipe with mean radius, R_m, wall thickness, t, and initial crack angle, 2θ. The pipe is subjected to an axial tension load, T, corresponding to internal pressure, P, with and without the restraint of pressure induced bending at distance, L_R and L_R' on either side of the cracked plane. L_R and L_R' are restraint lengths defined simply by the locations of the restrained pipe cross-sections from the cracked plane.

The restraint effect of PIB on COD was quantified by normalizing a restrained COD (δ_R) with an unrestrained COD (δ_F) as represented in Eq. (1), below.

$$r_{COD,P} = \delta_R / \delta_F \qquad (1)$$

Thus, the restraint effect of PIB on COD is significant when $r_{COD,P}$ approaches to zero, and the effect is negligible when $r_{COD,P}$ approaches to one. Both restrained and unrestrained CODs must be calculated to evaluate the restraint effects of PIB. In the present analysis, both CODs were computed by finite element analysis.

2.2 *Finite Element Analysis*

Finite element analyses were performed to calculate CODs using the general purpose finite element program, ABAQUS [7]. As shown in Fig. 2, two types of three-dimensional finite element model were employed. One is a quarter model to simulate the symmetrically restrained cracked pipe ($L_R = L_R$'), and the other is a half model to simulate the non-symmetrically restrained cracked pipe ($L_R \neq L_R$'). Two elements were used through the thickness for both models, and the CODs were determined from the displacement of the mid-thickness node at the center of the crack mouth. In the analysis, only an axial tensile stress equivalent to internal pressure was considered as the applied load. The restraint of pipe rotation in the models was considered by constraining displacements, except in the longitudinal direction, of all nodes within a certain length of pipe beyond L_R and L_R'(see Fig. 2).

3. Closed-Form Model

3.1 *Evaluation of PIB Restraint Effect*

To investigate the dependence of PIB restraint effect on the plastic crack opening of circumferential TWC on each influencing parameter, elastic-plastic finite element analyses were performed and evaluated $r_{COD,P}$ under various crack size, restraint length, radius to thickness ratio, magnitude of internal pressure, and material property conditions.

The analysis results showed that the $r_{COD,P}$ decreased with increasing crack size and decreasing restraint length. As the axial stress corresponding to internal pressure increased, the $r_{COD,P}$ decreased abruptly at above a critical internal pressure. The critical internal pressure reduced with increasing crack size, but it was independent on the restraint length. Also, the value of $r_{COD,P}$ reached to $r_{COD,E}$, that is normalized COD evaluated from linear-elastic analysis, when the internal pressure approached to zero. On the other hand, $r_{COD,P}$ was significantly varied with the stress-strain curve of pipe material used in the analysis, and was in proportion to yield stress of pipe material. These characteristics of $r_{COD,P}$ with applied stress and material properties are associated with the fact that, for considering plastic crack opening behavior, the PIB restraint effect is governed by stress state in the crack ligament [6].

In this study, thus, the evaluation results were simplified by normalizing $r_{COD,P}$ with $r_{COD,E}$ and by normalizing applied stress with collapse stress at cracked section defined by Eq. (2).

$$\sigma_C = \frac{\sigma_y}{\pi}\left[\pi - \theta - 2\sin^{-1}(0.5\sin\theta)\right] \qquad (2)$$

In addition, the plastic behavior of material was assumed as perfectly-plastic to eliminate the different hardening characteristic of pipe material on the $r_{COD,P}$.

3.2 *Closed-Form Model*

It is known from the simplified results that the overall shape of σ_{app}/σ_C vs. $r_{COD,P}/r_{COD,E}$ curves are mainly governed by crack size, and the absolute value of $r_{COD,P}/r_{COD,E}$ for a given σ_{app}/σ_C is dependent on the normalized restraint length (L_R/D_m), R_m/t. But, the effect of non-symmetry restraint length and material properties are negligible. Based on these investigations and elastic-perfectly plastic finite element analysis results, the following equation that evaluates the restraint effect of PIB on the plastic crack opening was derived.

$$\frac{r_{COD,P}}{r_{COD,E}} = 2 - \exp\left[A\left(\frac{\sigma_{app}}{\sigma_C}\right)^B\right] \quad for\ \frac{\sigma_{app}}{\sigma_C} \le 1.0 \qquad (3)$$

$$\frac{r_{COD,P}}{r_{COD,E}} = 0 \qquad for\ \frac{\sigma_{app}}{\sigma_C} \le 1.0$$

where, A and B are given as functions of normalized crack size, normalized restraint length, and R_m/t.

To verify the accuracy of proposed model, the results calculated from Eq. (3) was compared with those obtained from finite element analysis. The comparison showed that the proposed model reliably estimated the restraint effect of PIB on the plastic crack opening of circumferential TWC in the range of $0.125 \le \theta/\pi \le 0.5$, $1.0 \le L_R/D_m \le 40.0$, and $5 \le R_m/t \le 20$.

4. Conclusions

Present study proposed a closed-form model to evaluate the restraint effect of PIB on the plastic crack opening of circumferential TWC in the pipe. In order to derive the model, elastic-plastic finite element analyses were performed under various crack size, restraint length, pipe radius to thickness ratio, magnitude of internal pressure, and material property conditions. The dependence of PIB restrained effect on each parameter was investigated from the results of parametric analysis. Based on these results, a closed-form model was derived. The proposed model accurately estimated the plastic crack opening of circumferential TWC in the restrained pipe under range of $0.125 \le \theta/\pi \le 0.5$, $1.0 \le L_R/D_m \le 40.0$, and $5 \le R_m/t \le 20$.

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