Numerical Evaluation of Bending Load Effect on the Failure Pressure of Wall-Thinned Pipe Bends

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1. Introduction

During the normal operating conditions, piping systems in nuclear power plants (NPPs) are subject not only to internal pressure but also to bending loads induced by deadweight, thermal expansion, and internal pressure [1]. Bending is thus considered to be an important factor in evaluating the integrity of piping components in NPPs. Local wall-thinning due to flow-accelerated corrosion is a main degradation mechanism of carbon steel piping components in NPPs [2], and the integrity evaluation of wall-thinned piping components has become an important issue [3]. This study investigated the effects of bending load on the failure of wall-thinned pipe bends under internal pressure. Our previous study experimentally evaluated the bending load effects on the failure pressure of wall-thinned elbows under displacement controlled in-plane bending load [4], but the numbers of experimental data were insufficient to determine the effects of bending load on the failure pressure of wall-thinned pipe bends. Therefore, the present study systematically evaluates the effects of bending load on the failure pressure of wall-thinned pipe bends using parametric finite element analyses.

2. Failure Pressure Evaluation

2.1 Analysis Condition

Parametric finite element analyses were performed on a 90-degree elbow with an outer diameter (D_o) of 400 mm, a nominal thickness (t_{nom}) of 20 mm, and bend radius (R_b) to mean radius (r_m) ratio of 3. The elbow contained local wall thinning at the extrados and intrados, whose axial and circumferential shapes were circular. Table 1 lists the dimensions of the wall-thinning defects used in the analysis. In that table, L is the equivalent axial thinning length defined at the flank of the elbow, and t_p is the minimum thickness of the wall-thinned area.

The failure pressure was evaluated under simple internal pressure and under combined bending and internal pressure. Both constant load- and displacement-controlled bending loads, which were applied as in-plane closing- and opening-mode bending, were considered when applying combined loads. The constant moment for load-controlled bending was determined from the maximum moment where a defect-free elbow satisfies the requirement of ASME B&PV code section III NC-3600 given by Eq. (1) [5]:

$$\frac{iM_D}{Z} \leq 3.0S_C \tag{1}$$

where i is the stress intensification factor, M_D is the moment by non-reversing anchor movement, S_C is the material allowable stress at the cold temperature, and Z is the section modulus of the pipe. The constant displacement for displacement-controlled bending was determined by a rotation corresponding to M_D on the moment–rotation curve.

Table 1 Dimensions of wall-thinning defects considered in the parametric analyses

Thinning length, L/D_o	Maximum thinning depth, $(t_{nom}-t_p)/t_{nom}$	Thinning angle, θ/π
0.25, 0.5, 1.0, 1.5, 2.0	0.75, 0.5, 0.25	0.0625, 0.125, 0.25, 0.50

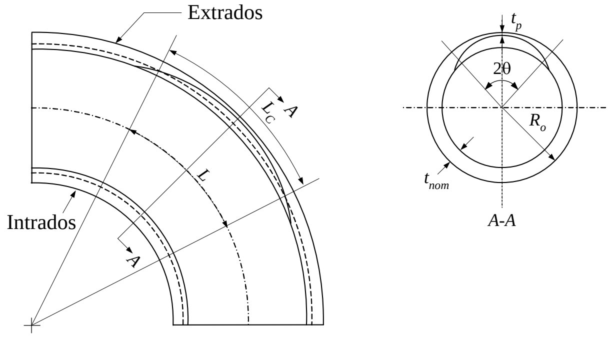

Fig. 1 Geometries of wall-thinning defect in the elbow

2.2 Finite Element Model

Three-dimensional finite element models, which consisted of 20 node-break elements with a reduced integration order, were used in the analyses. Only one-fourth of the elbow was modeled by considering its geometrical symmetry. The elbow was connected to straight pipes with lengths equal to 10 times the mean pipe radius ($10r_m$) to permit free ovalization of the elbow end-section. An internal pressure of 10 MPa was initially applied for analysis under combined loads, and then the constant in-plane bending moment or rotational displacement was applied. Finally, internal pressure was applied again up to the point of final failure. The failure pressure was determined from the analysis results using a local failure criterion, which assumed the failure occurred when the average equivalent stress over the ligament at the deepest wall-thinned area exceeded the true tensile strength of material (σ_{ut}).

The ABAQUS program [6] was used for this study. Both geometric and material nonlinearities were considered for modeling the large deformation at the bend region and for modeling the plastic behavior of the material. The yield stress (σ_y), engineering tensile stress (σ_u), and true tensile stress (σ_{ut}) of the elbow material used in the analysis were 292, 482, and 583 MPa, respectively.

3. Results and Discussion

To evaluate the effect of bending load on the failure pressure of wall-thinned pipe bends, the failure pressures evaluated under combined bending and internal pressure were normalized to those evaluated under simple internal pressure. Figure 2 shows the normalized failure pressures as a function of thinning length for different wall-thinning angles and locations. For most wall-thinning cases the bending load decreased the failure pressure of wall-thinned pipe bends, although it slightly increased the failure pressure in some cases. The comparison of Fig. 2(a) with Fig. 2(b) shows that the bending load effect was more significant when the constant moment was applied than when the constant displacement corresponding to the moment was applied. The reduction of failure pressure by bending load was less than 10% for shallow wall-thinning cases, $(t_{nom}-t_p)/t_{nom} \le 0.5$, regardless of the thinning length and circumferential angle, location, or bending mode. For deeper wall-thinning cases ($(t_{nom}-t_p)/t_{nom}=0.75$) shown in Fig. 2, however, the effect of bending load on the failure pressure was considerable and depended on the bending mode, thinning location, thinning length, and circumferential angle. For intrados wall-thinning of $\theta/\pi=0.5$ subjected to opening mode bending and extrados wall-thinning of $\theta/\pi=0.5$ subjected to closing mode bending, the reduction of failure pressure by the bending load became significant as the thinning length decreased. As thinning length increased, however, the bending effect became significant for narrow intrados wall-thinning ($\theta/\pi=0.0625$) under opening mode bending. This behavior is associated with that the shorter and wider or the longer and narrower wall-thinning defects show higher stress concentration at wall-thinned area under bending conditions.

4. Conclusions

This study systematically investigated the bending load effect on the failure pressure of wall-thinned pipe bends from the results of parametric finite element analysis. The bending load effect was significant when a deeper intrados wall-thinning defect was subjected to load-controlled opening mode bending.

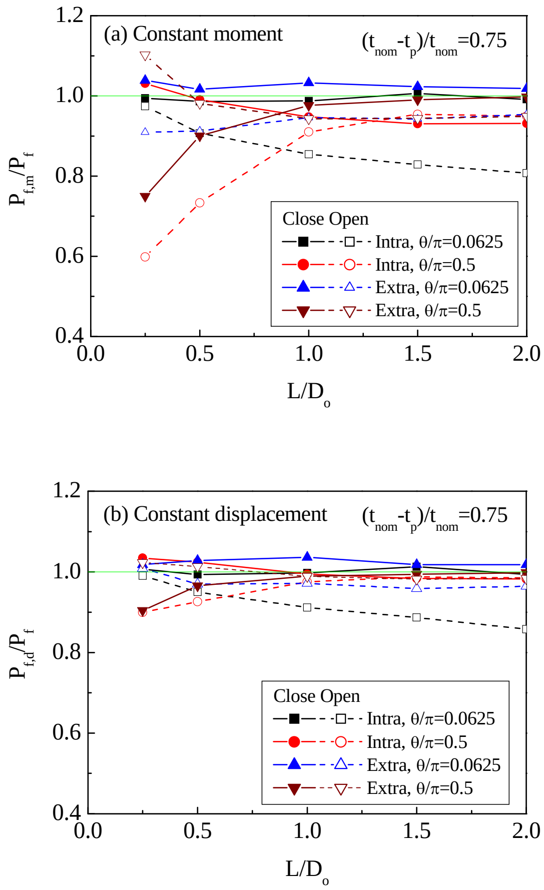

Fig. 2 Failure pressures under combined loads normalized to those under simple internal pressure

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