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Evaluation of Primary Stress Index for Small-Radius Pipe Bends in ASME BPVC Section III

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1. Introduction

Piping systems are essential across industries, and elbows are widely used to meet design constraints and improve space efficiency. Small-radius pipes (R/rm = 2–5) are increasingly applied in high-reliability facilities such as nuclear power plants, offering benefits such as fewer welds and greater construction efficiency. However, broader application requires reliable structural integrity assessment. The ASME BPVC uses stress indices to evaluate elbow integrity, but since these are mainly based on 90° elbows, their applicability to actual geometric variations must be reviewed.

In previous studies [1, 2], the differences in limit load and stress distribution between 45° and 90° elbows were analyzed. However, research on bending angles extended to 180° elbow pipe (U-bend) and other practical angles used in industry has not been conducted.

In this study, the stress indices of ASME BPVC Sec. III [3] were extended to evaluate the stresses of piping with various bending angles (45°, 90°, 145°, 180°) and curvature ratios (R/r_m = 2 – 5). First, the background of the pressure and bending stress indices presented in the code was reviewed, and based on this, finite element analyses were performed to assess the applicability of the existing stress indices. Subsequently, stress index equations were derived with bending angle, curvature ratio, and thickness ratio as variables, and their applicability for design was verified through finite element analyses.

2. Stress indices for elbow pipe in ASME BPVC

The ASME BPVC is an internationally recognized standard that ensures the safety and reliability of nuclear facilities, defining stress evaluation procedures for Class 1 piping systems. In Section III, NB-3652 provides an equation based on the limit load theory using stress indices B_1 and B_2, which requires that the combined stresses from internal pressure and bending moment do not exceed 1.5 times the allowable stress intensity, S_m. The internal pressure stress index B_1 and the bending stress index B_2 are given by

$$B_1 = -0.1 + 0.4\lambda \quad \left(0 \le B_1 \le 0.5\right)$$
$$B_2 = \frac{1.3}{\lambda^{2/3}} = \frac{\left(M_L\right)_s}{\left(M_L\right)_c} \quad \left(1 \le B_2\right) \tag{1}$$

where (ML)s and (ML)c are limit bending moment of straight pipe and curved pipe. The geometric parameter λ is defined as

$$\lambda = \frac{R \cdot t}{r_m^{\;2}} \tag{2}$$

where R is bending radius; r_m is pipe radius, t is nominal pipe thickness. The stress indices provided by ASME do not account for the bend angle as a variable.

3. Development of Stress Index for Bending Moment

Figure 1 shows the FE model of a 145° pipe bend. The FE mesh with C3D20R elements was developed using ABAQUS v2024. A total of 8 elements were assigned through the pipe thickness and 25 elements in the radial direction. The bending moment was imposed on the reference node through a prescribed rotation angle using the MPC option. The material properties of stainless steel were defined using an elastic-perfectly plastic model, with a elastic modulus of 195 GPa, a Poisson's ratio of 0.3, and a yield strength of 205 MPa. A large deformation analysis (NLGEOM option) was considered in the simulation.

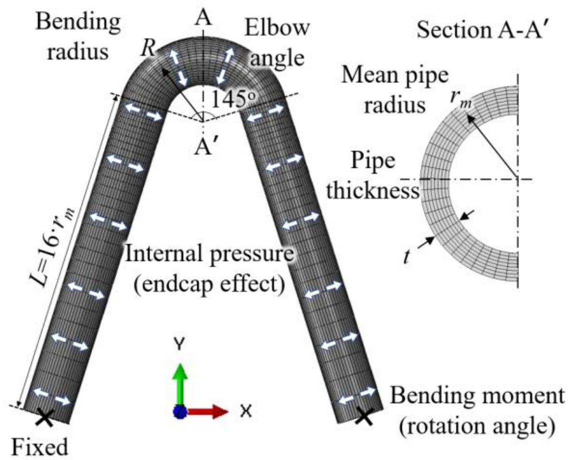

Fig. 1. FE mesh for 145° pipe bend.

Figure 2 shows the FE analysis results for a 145° pipe bend with R/r_m = 2 and r_m/t = 3 under bending moment. The bending moment was obtained from the reaction moment at the reference node. The plastic collapse moment for pipe bend, $(M_L)_C$, was determined using the Twice-Elastic-Slope (TES) method. For the given geometry, the plastic collapse bending moment of the 145° pipe bend was approximately 70% of that of a straight pipe.

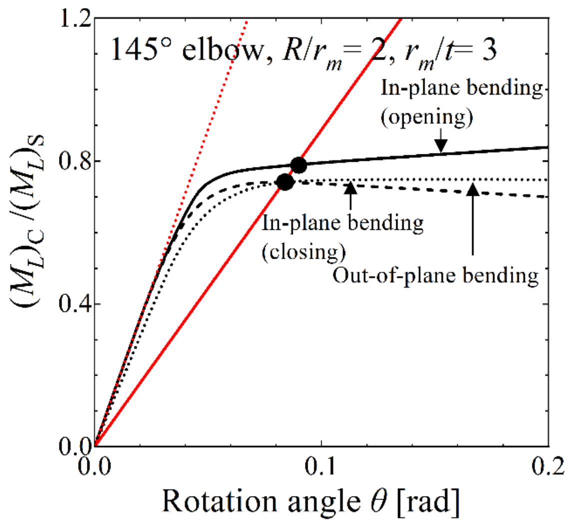

Fig. 2. Induction of the moment of plastic collapse with TES

The stress index for the bending moment was derived based on the definition given in Eq. (3). For a conservative assessment, the $(M_L)_C$ was taken as the smaller of the values obtained from in-plane and out-of-plane bending. The proposed bending moment stress index is given by

$$(B_2)' = (1-\cos\theta)^{0.3} \cdot \frac{0.7}{\lambda^{2/3}} + 1 \qquad (3)$$

where θ represents the total bending angle, such as 180° for a U-bend pipe. Figure 3 shows the bending moment stress index referred in the ASME BPVC and proposed in this study. The stress index in the ASME BPVC is given as a constant, regardless of the bending angle. The proposed stress index exhibited improved agreement with the B_2 values derived from FE analysis.

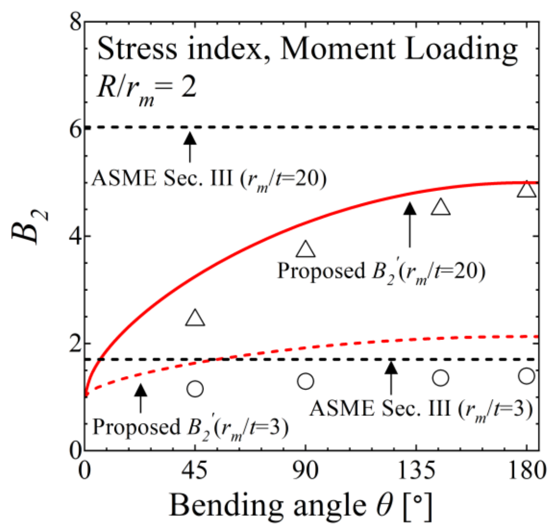

Fig. 3. Comparison of bending moment stress indices between ASME BPVC and the present study.

4. Verification of Stress Index for Pipe Bend

Equation (5) represents the maximum bending moment derived using the equation for evaluating the primary stress condition as defined in ASME BPVC Section III.

$$(M_L)_{max} = \left[1.5S_m - B_1\left[\frac{P_D r_o}{t}\right]\right]\left[\frac{Z}{B_2}\right] \qquad (4)$$

where Z is section modulus based on the pipe geometry; S_m is allowable stress intensity values specified in Section II, Part D, Subpart 1, Tables 2A and 2B [4]. According to the ASME BPVC, B_1 was applied as given in Eq. (1), and S_m was taken as 138 MPa. $(M_L)_{max}$ denotes the maximum allowable moment when the proposed B_2 is applied.

To verify the stress index to pipe bend with various bending angles, FE analysis was performed under combined loading of internal pressure and bending moment. The internal pressure was applied at 40% and 80% of the design pressure, and the plastic collapse moments were obtained in the same approach in Fig. 2. Figure 4 shows the ratio of limit bending moment from FE analysis to maximum bending moment in ASME BPVC, $(M_L)_{FE}/(M_L)_{max}$, depending on the applied internal pressure. The maximum limit moment calculated using the proposed B_2, $(M_L)_{max}$, was higher than the plastic collapse moment considering internal pressure from FE analysis, $(M_L)_{FE}$. It was confirmed that the evaluation equation is determined based on the lower plastic collapse moment compared to the FE analysis. The proposed B_2 overcomes the limitations of bend evaluation in the existing stress index in ASME BPVC Section. III.

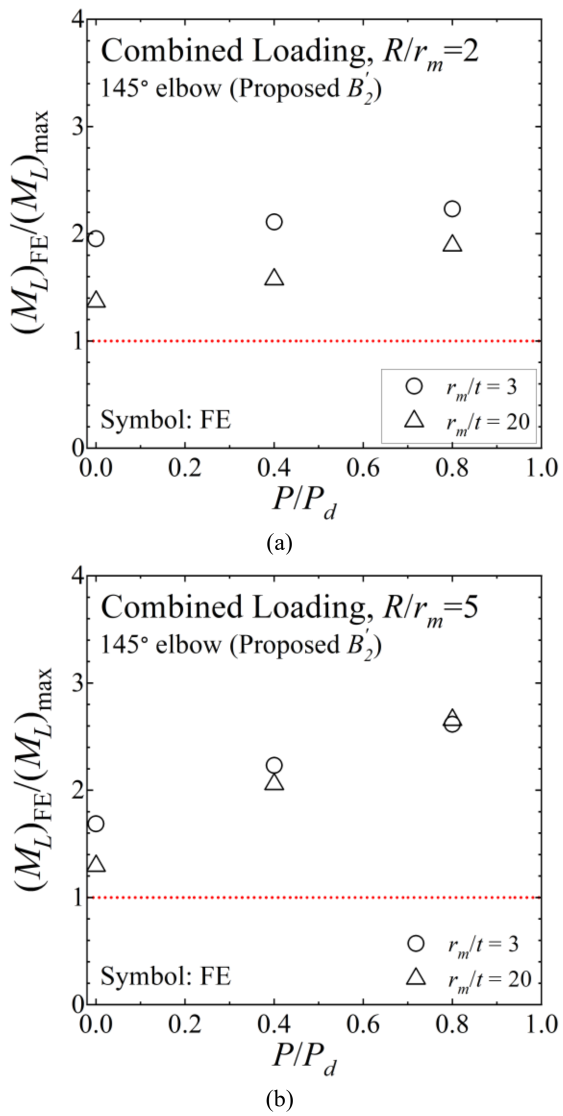

Fig. 4. Ratio of limit bending moment from FE analysis to maximum bending moment in ASME BPVC versus applied internal pressure; (a) R/r_m=2, (b) R/r_m=5.

5. Conclusion

In this study, a bending moment stress index was proposed for the stress evaluation of pipe bend with various bending angles, based on the existing ASME BPVC Section III. The stress index defined in the ASME BPVC does not include the bending angle parameter. The equation in ASME BPVC was confirmed up to 90°, it was found to be limited for bend angle exceeding 90°. To account for the bending angle, the proposed stress index was developed using FE analysis. The bending moment index was derived through a least-squares fitting method based on plastic collapse moments obtained from the FE analysis. The validity of the proposed stress index was verified by comparing the plastic collapse moments predicted by the evaluation equation with combined limit moment from FE analysis. The results confirmed that the proposed stress index is applicable to bending angles up to 180° under design conditions.

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[3] ASME, ASME Boiler and Pressure Vessel Code, Division I, Section III, Subsection NB, 2015.
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