Conservatism of ASME Section III Stress Indices for Various Pipe Bends with Circumferential Cracks

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Keywords: Elbow pipe, Limit moment, Circumferential crack, ASME BPVC Section III

1. Introduction

Pipe bends are critical components for the structural integrity of nuclear power plant piping systems. Calculating the limit moment is essential for evaluating the integrity of these bends. ASME Section III provides design guidelines and stress indices based on the limit moment [1]. However, operating pipe bends can develop circumferential cracks due to aging degradation. These cracks directly affect the limit moment of the structure. Current ASME codes manage flaw-free designs under Section III [1] and flaw evaluations under Section XI [2]. While traditional research has focused on 90º elbows, recent manufacturing advances allow for various bending angles. It is important to analyze how the Section III design philosophy, which does not consider flaws, maintains its conservatism when cracks actually occur.

In this study, the conservatism of ASME Section III stress indices ,which do not explicitly account for defect, was evaluated by comparing them with the reduction in limit moments observed when circumferential cracks occur. By considering various bending angles and piping geometries, this research emphasizes the importance for piping manufacturers to utilize finite element analysis to verify the structural margins of Section III [1].

2. FE Analysis for Calculating Limit Moments

Figure 1 shows the finite element model developed to evaluate the limit moments of a 90° elbow with a circumferential crack. The model was constructed using the commercial software ABAQUS v2024, applying C3D20R elements. The mesh was configured with 8 elements through the thickness, 24 elements in the radial direction, and 24 elements along the elbow section. The defect was modeled using the keyhole element, with a keyhole size of 0.05 mm. To determine the limit moment, nonlinear analysis was performed using the RIKS option in ABAQUS, and the MPC option was utilized to apply rotation to the reference node. The material properties of the stainless steel were defined with an elastic modulus of 195 GPa, a Poisson's ratio of 0.3, and a yield strength of 205 MPa. All simulations were conducted under small-deformation.

The limit moments for elbow, $(M_L)_e$, obtained from the FE analysis were normalized by the limit moments of straight pipes, $(M_L)_s$, of the same pipe geometry. The normalized value, $(M_L)_e/(M_L)_s$, is interpreted in the same form as moment stress index (B_2) in ASME BPVC Sec. III [1] as follows:

$$\frac{(M_L)_e}{(M_L)_s}=\frac{1}{B_2}=\frac{\lambda^{2/3}}{1.3};\ \lambda=\frac{R/r_m}{r_m/t} \quad (1)$$

where R is bend angle; r_m is normal radius; t is thickness. In this study, the design conservatism of moment stress index, B_2, is evaluated according to the elbow geometry and circumferential defect length.

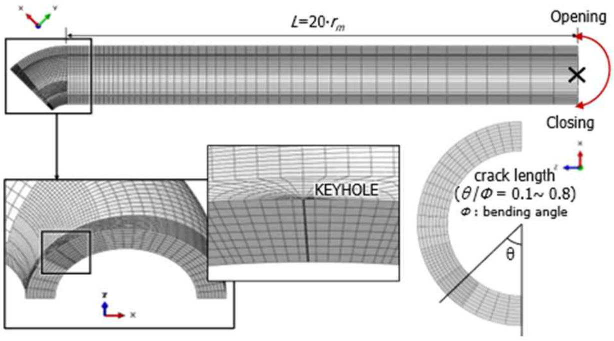

Fig. 1. FE mesh for pipe bends with through-walled circumferential crack.

3. ASME Sec.III Stress Index vs Limit Moment for Cracked Elbow

Figure 2 shows the variation of the normalized limit moments for a 45° elbow according to the circumferential defect length. For thick-walled pipe (r_m/t=3), the FE results for cracked elbow remained consistent with the ASME BPVC Sec. III stress index within the range of $\theta/\pi \leq 0.25$. For r_m/t=5 and 10, it was confirmed that the evaluation remained valid up to the range of $\theta/\pi \leq 0.3$, maintaining levels like the code-based indices.

Figure 3 shows the variation of the normalized limit moments for a 90° elbow according to the circumferential defect length. Within the range of $\theta/\pi \leq 0.25$, the structural behavior was like the reference line regardless of the defect location, indicating that code-based assessment is applicable.

Figure 4 shows the variation of the normalized limit moments for a 135° elbow according to the circumferential defect length. A trend was observed where the overall limit moment decreased as the bending angle of the elbow increased. However, it was confirmed that for $\theta/\pi \leq 0.25$, evaluations using the ASME BPVC

Sec. III reference line are feasible, irrespective of the defect position.

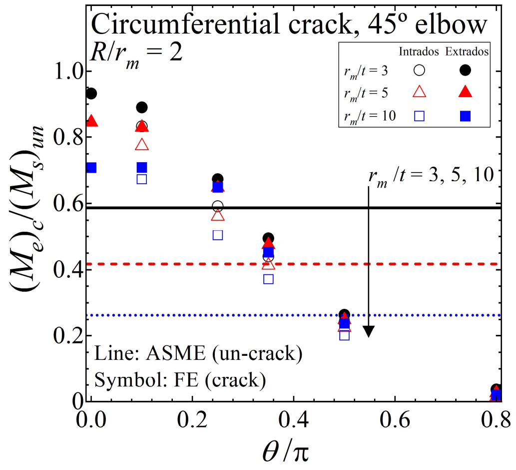

Fig. 2. Comparison of limit moment in FE results for a 45° elbow applied by circumferential defect with ASME Sec.III moment stress index.

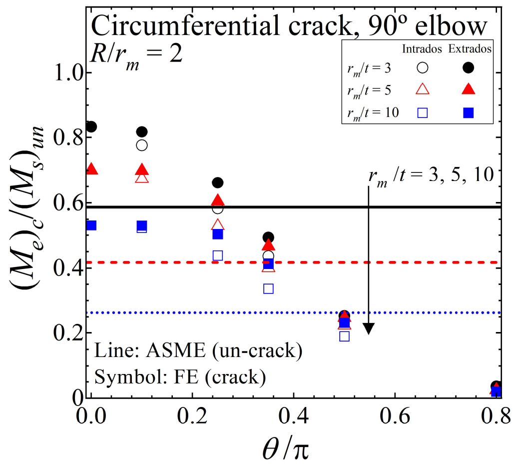

Fig. 3. Comparison of limit moment in FE results for a 90° elbow applied by circumferential defect with ASME Sec.III moment stress index.

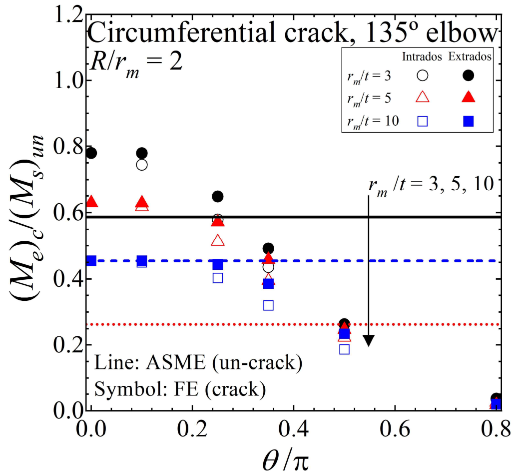

Fig. 4. Comparison of limit moment in FE results for a 135° elbow applied by circumferential defect with ASME Sec.III moment stress index.

4. Conclusions

In this study, the limit moments of elbows with circumferential defects were determined using FE analysis for bend angles of 45°, 90°, and 135°. These values were normalized by the limit moments of straight pipes to analyze the reduction in load-carrying capacity. The normalized limit moment was expressed in the same form as the moment stress index (B_2) defined in ASME BPVC Sec. III. By comparing the B_2 index with the normalized limit moments of cracked elbows, the applicability of ASME Sec. III to cracked conditions was evaluated. The FE results indicated that for 45° cracked elbows, the B_2 index is valid within the range of $\theta/\pi \leq 0.25$ for thick-walled elbows (r_m/t=3), while for relatively thin-walled elbows (r_m/t=5, 10), the assessment remains applicable up to $\theta/\pi \leq 0.35$. For 90° and 135° elbows, the structural integrity can be evaluated using existing criteria within the range of $\theta/\pi \leq 0.25$, regardless of the defect location.

ACKNOWLEDGEMENT

This research was supported by the Nuclear Safety Research Program through the Regulatory Research Management Agency for SMRs(RMAS) and the Nuclear Safety and Security Commission (NSSC) of the Republic of Korea. (No. RS-2024-00509653)

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