Integrity Evaluation for Elbows based on TES Collapse Load

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Abstract. Structural integrity evaluation of piping with local wall thinning due to erosion-corrosion is increasingly important in maintenance of carbon steel piping systems in nuclear power plants. Though a few programs for integrity assessment of thinned pipe have been developed in domestic nuclear industry, they are limited to straight pipes using methodology proposed in ASME Section XI Code Case N-597. An engineering program for integrity evaluation of all kinds of piping items such as straight pipe, elbow, reducer and branch connection was successfully developed, which was denominated as PiTEP® (Pipe Thinning Evaluation Program). The developed program includes three-step evaluation for integrity assurance, such as evaluation of minimum wall thickness by the construction code (ASME Section III), evaluation of thickness criterion based on ASME CC-N597, stress calculation by construction code, and fitness-for-service assessment based on twice elastic slope collapse load. In this paper, the theoretical background, framework, and verification test of PiTEP® was introduced.

1. INTRODUCTION

Wall thinning in piping systems can be caused by various mechanisms. It is well known that wall thinning in carbon steel piping systems of nuclear power plants and other industrial plants arises due to flow accelerated corrosion (FAC) [1]. The wall thinning degradation in pressurized water reactor is mainly generated in secondary side carbon steel piping system. As shown in Figure 1, even a single event of a high-energy pipe rupture can be a serious resulting in casualties and economical loss.
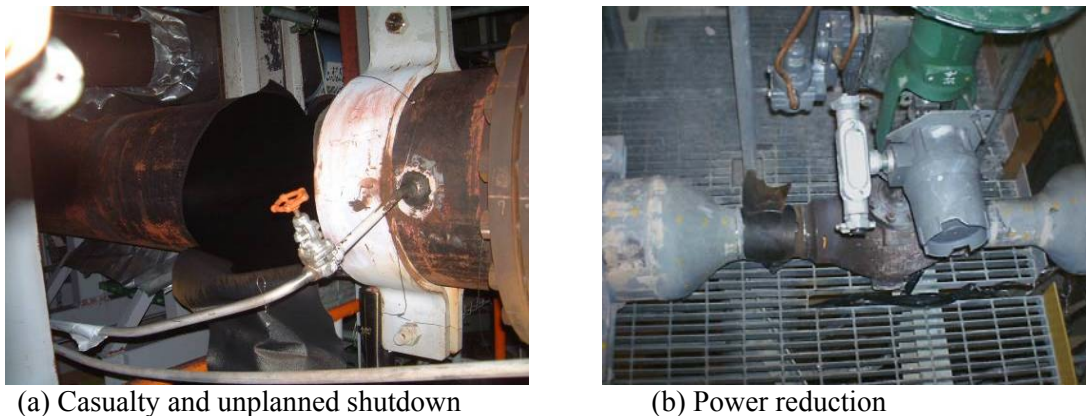

(a) Casualty and unplanned shutdown   (b) Power reduction

Fig. 1. Consequences of excessive wall thinning

Because the thinning is mainly occurred in base material unlike cracking occurred in the welds, in-service inspection to detect the wall thinning is often time consuming job. In spite that many studies for the proper assessment of thinned pipe integrity have been done, the assessment methodology has not been settled down as a rational standard [2]. The wall thinning degradation may progress toward a sudden pipe rupture without the previous warning like leakage, and subsequently result in unplanned reactor trip. Therefore, the wall thinning degradation has become a very important issue in the management of carbon steel piping systems and a variety of the studies for the integrity assessment have accordingly been conducted (Miyazaki *et al.*, 1999, Kim *et al.*, 2001, Kim[a] *et al.*, 2003, Oh *et al.*, 2007).

There are some methodologies to evaluate the wall thinning degradation in operating nuclear power plants, such as the method of ASME Section XI App. H (ASME[c], 1995) treating wall thinning as a crack, the method of construction codes (ASME[a], 1995 or ASME[b], 1995) suggesting minimum required wall thickness (t_{min}), the method in ASME CC-N597 [3], and the method based on owner's criteria reflecting the recent researches (KHNP, 2003/2008). Although there are many methodologies and programs to evaluate the wall thinning degradation suggested from researches, plant engineers have appealed to researchers to develop a program for easier access.

2. KOREAN THINNED PIPE MANAGEMENT PROGRAM

The history of thinned pipe management program in Korea is briefly illustrated in Figure 2.

Through the first study on Kori Unit 3&4, the effectiveness of the management methodology based on NSAC-202L guideline [4] and the usage of CHECWORKS computer code [5] was verified. In the second project for other 14 Units, the thinned pipe management program was developed as a standard procedure. After fatal accident of Mihama Unit 3, KEPRI and KHNP had conducted the third study to optimize the current thinned pipe management program by reflecting the recently presented management guidelines from EPRI [4], WANO [6], and INPO [7]. The lessons learned from existing plants have been feed-backed to the units which are under design and construction through material upgrade, schedule change to thicker pipe, establishment of plant FAC model, obtaining of baseline thickness data, and so on.
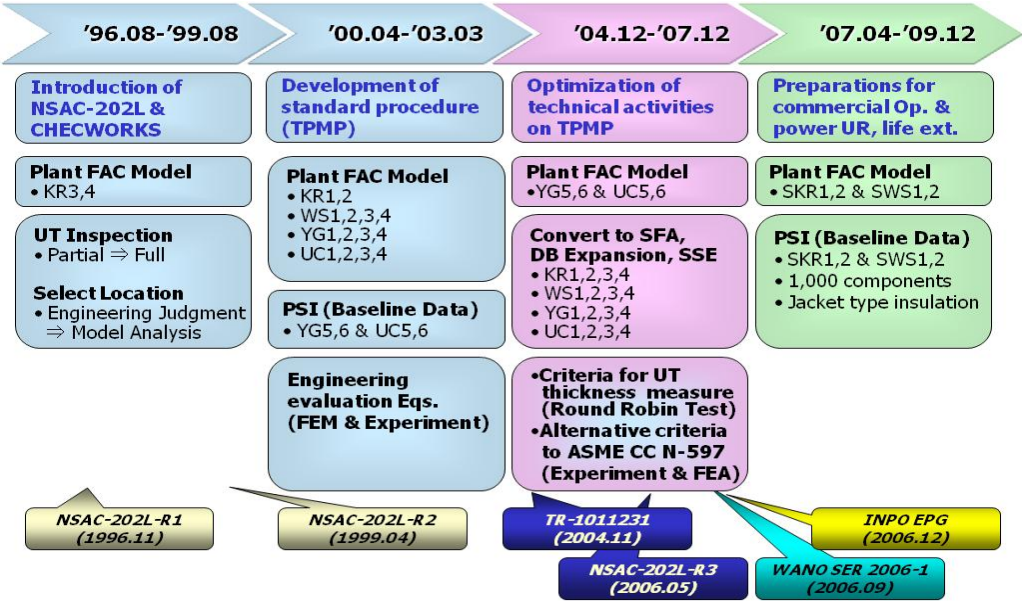

Fig. 2. History of Korean thinned pipe management program

As illustrated in Figure 3, thinned pipe management program consists of several technical items, such as performing FAC model analyses, prioritizing pipe components for inspection, obtaining reliable thickness data, calculating the wear and wear rate, and making decisions regarding replacement necessity or continuous service acceptability based on the remaining life of the component.
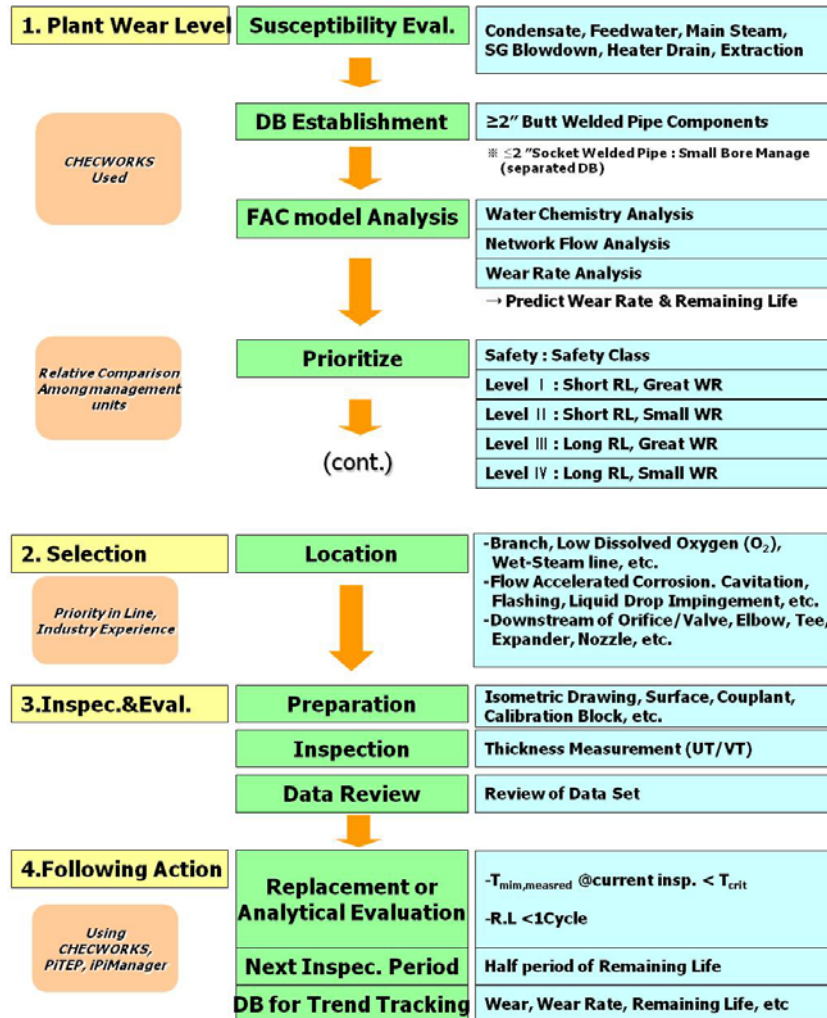
Fig. 3. Scheme of Korean thinned pipe management program

3. DEVELOPMENT OF ALTERNATIVE INTEGROTY EVALUATION CRITERIA

3.1. Necessity and Purpose

The structural integrity evaluations of thinned piping are mainly performed based on the minimum thickness requirement of ASME Section III and the integrity evaluation method based on ASME CC-N597 [3]. The evaluation method described in ASME CC-N597, as illustrated in Figure 4, was originally suggested to apply the safety related piping system. It is composed of two-step evaluations such as the thickness-based and the stress-based evaluation. In a recent study on wall thickness criteria in ASME CC-N597, a large discrepancy was found to exist between the thickness criteria for repair and actual thickness at failure [8]. To dissolve the discrepancy, it is necessary to develop an integrity evaluation criterion which is applicable for non-safety related piping system (possessing 95~98% of length requiring management of thinning) in operating nuclear power plants. Accordingly an engineering program, PiTEP® was developed and successfully implemented for integrity evaluation of secondary non-safety related piping system [9].
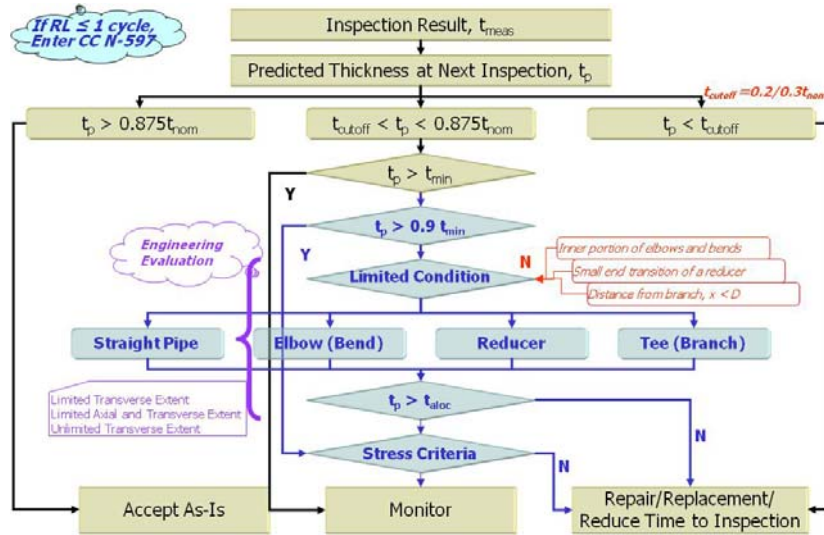
Fig. 4. Outline of ASME Code Case N-597

3.2. Program Background and Structure

3.2.1. Theoretical background

PiTEP® program is in principle based on the integrity evaluation criteria and procedure of CC-N597. For the purpose, we investigated the theoretical background of the code case N-597 at first (Gerber *et al.*, 1988). Since the CC-N597 was originally suggested for safety-related piping system and had some limits in applicability, however, we tried to develop an alternative integrity evaluation criterion as owner's evaluation methodology. The alternative criterion is based on the reference stress σ_{ref} as in equation (1).

$$\sigma_{ref} = \frac{P}{P_L / \sigma_y} \tag{1}$$

where, P is the applied load, P_L is the limit load and σ_y is the ultimate stress.

3.2.2. Finite Element Analysis

Detailed three-dimensional (3–D) finite element analyses for pipe bends, reducer, and tee under combined pressure and bending were performed based on elastic–perfectly plastic materials with the small geometry change option. A wide range of parameters related to the thinning dimension, thinning location, and the internal pressure. Figure 5 shows the example of finite element analysis model for thinned pipe components.
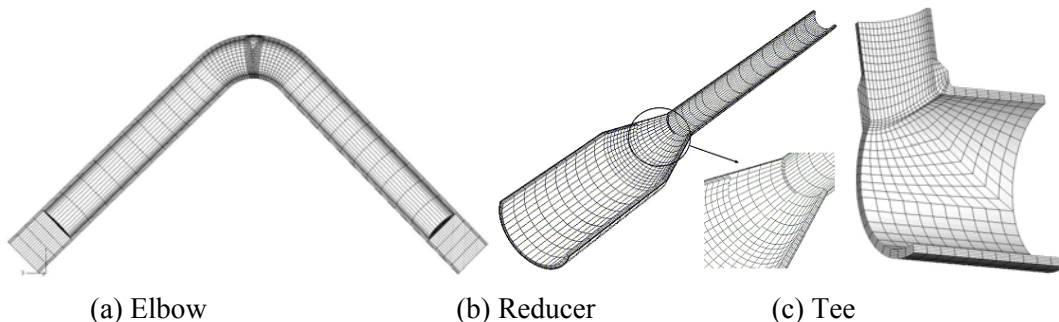

(a) Elbow   (b) Reducer   (c) Tee

Fig. 5. Examples of finite element analysis model for thinned pipe components

3.2.3. Program structure and evaluation procedure

Figure 6 shows the structure and evaluation procedure of PiTEP® program. Program structure is composed of evaluation parts by construction code, ASME CC-N597, and owner's evaluation methodology. Evaluation of minimum thickness, t_{min}, by the construction code is followed by the evaluation of allowable local thickness, t_{aloc}, by CC-N597. The owner's evaluation methodology as a fitness-for-service assessment includes the limit load method applying to straight pipes, bends, reducers, branch connections, etc., and the fitting for fitness method applying to straight pipes and bends based on the failure load by finite element analysis. The result of this program, as illustrated in Figure 7(b), includes the safe margin in moment, pressure, and thickness aspect of thinned component. These safe margins mean the ratio of endurable moment of thinned pipe component and allowed moment of not thinned pipe component by construction code, and that of burst pressure of thinned pipe component and design pressure.
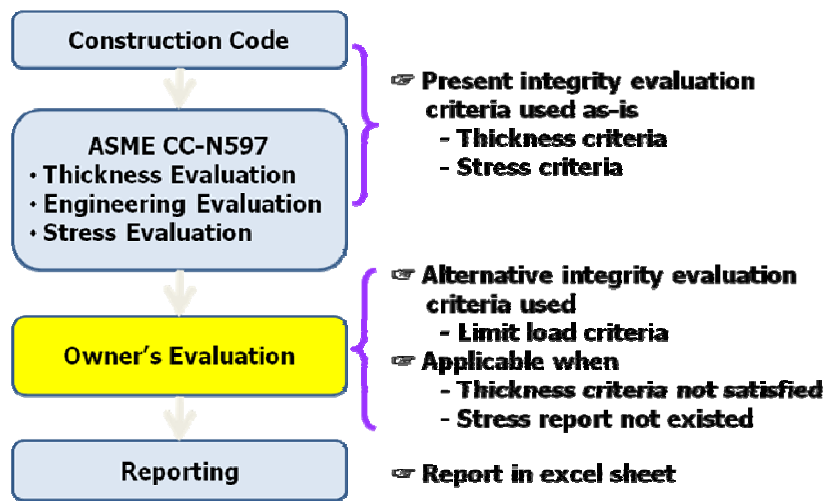

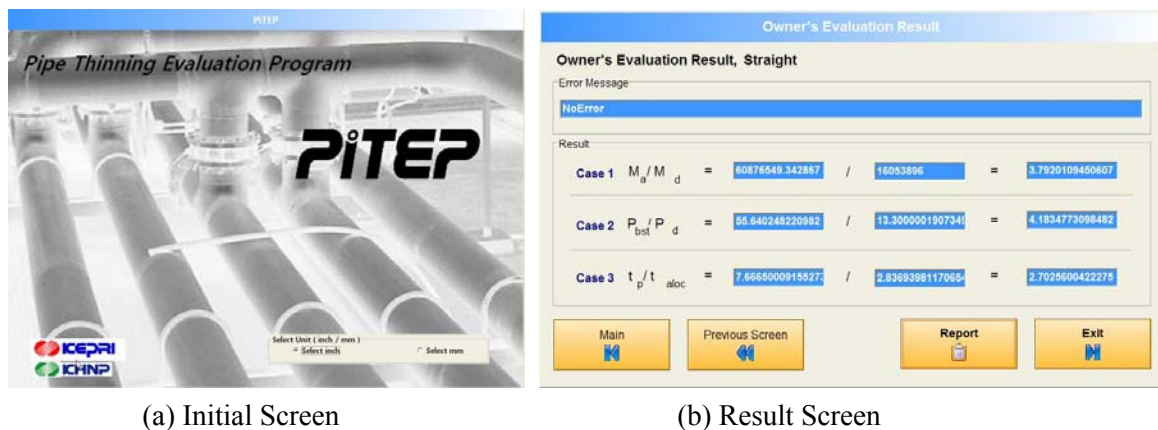*Fig. 6. Structure and evaluation procedure of PiTEP® program*

(a) Initial Screen	(b) Result Screen

Fig. 7. Pipe thickness evaluation program (PiTEP)

3.3. Program Verification by Comparison with Mock-Up Test

3.3.1. Specimens

The real scale failure tests were carried out using commercial carbon steel pipe components of 114.3mm in diameter (schedule 80), containing a simulated local wall thinning. As shown in Figure 8, the specimens were prepared by welding of 3 pieces of segment (pipe-elbow-pipe) and those were

end-capped to accommodate the internal pressure. The elbows were machined to obtain the uniform dimensions of outer diameter prior to wall thinning. Local wall thinning was made by machining at extrados or intrados of elbow segment located at center of specimen. In the experiment, various axial length (L), circumferential angles (2θ), and minimum wall thickness (t_p) were considered. The dimensions of wall thinning were specified by equivalent axial length (L/D_o), circumferential angle of area where the wall thickness is thinner than the minimum thickness (t_{min}=5.3mm, for pressure 10MPa and material A234 WPB) required by construction codes, ASME B&PV Sec. III or ASME B31.1. The axial and circumferential shapes of thinning area were assumed as circular.
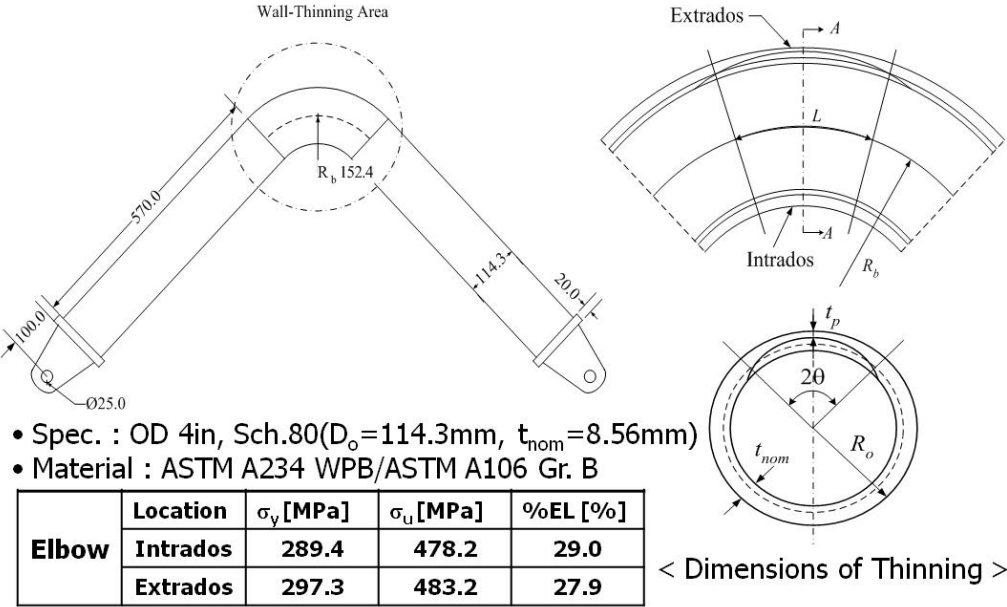

- Spec. : OD 4in, Sch.80(D_o=114.3mm, t_{nom}=8.56mm)
- Material : ASTM A234 WPB/ASTM A106 Gr. B

Elbow	Location	σ_y[MPa]	σ_u[MPa]	%EL [%]
	Intrados	289.4	478.2	29.0
	Extrados	297.3	483.2	27.9

< Dimensions of Thinning >

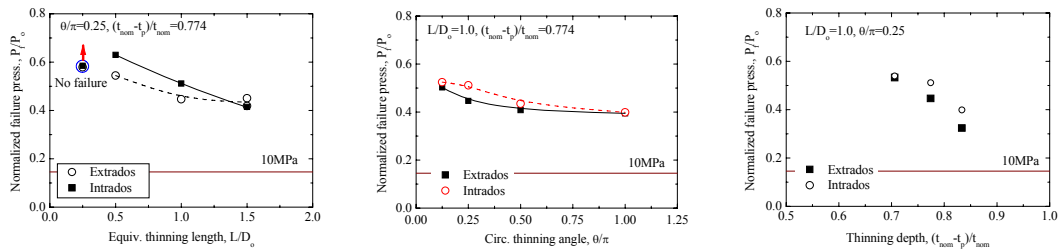*Fig. 8. Dimension of specimen for real scale failure tests*

3.3.2. Failure Pressure Tests

A series of burst tests using real scale pipe elbows containing simulated wall thinning defect were performed to evaluate the effects of local wall thinning on the failure pressure of elbows. The tests were conducted under simple internal pressure at room temperature. Figure 8 shows the results of burst tests of wall-thinned elbows. Figure 9(a) shows the burst modes according to the thinning location and the minimum thickness while Figure 9(b) comparison of burst pressure according to the thinning dimension.

From this burst tests, the following conclusions were derived. The dependences of failure pressure on thinning length and depth in the wall thinned elbow were similar to the results of wall thinned straight pipe. The failure pressure decreased with increasing circumferential thinning angle, which was different from that observed in the straight pipe. The existing failure pressure evaluation models for wall thinned elbow showed excessive conservatism. For intrados wall thinning case, the conservatism was significant and the variation in failure pressure with thinning dimensions could not be properly estimated. For extrados wall-thinning case, the existing models appropriately estimated the dependence of failure pressure on the thinning length and depth. All specimens tested were failed by bulging followed by axial cracking. For extrados and intrados wall-thinned elbows, the crack always occurred at the minimum wall thinned area. For entire circumferentially thinned elbow, however, the crack location was dependent on axial thinning length.
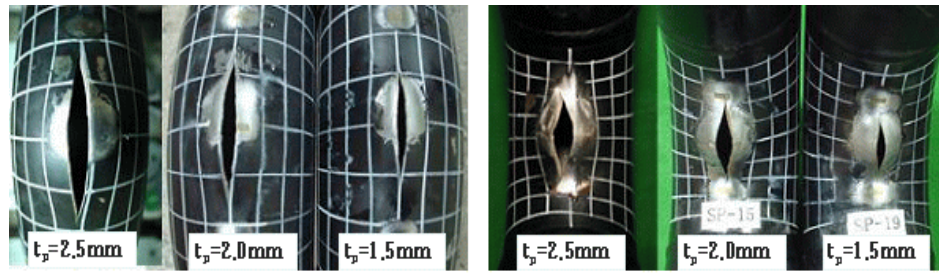
(a) Burst modes according to the thinning location and the minimum thickness

(b) Comparison of burst pressure according to the thinning dimension

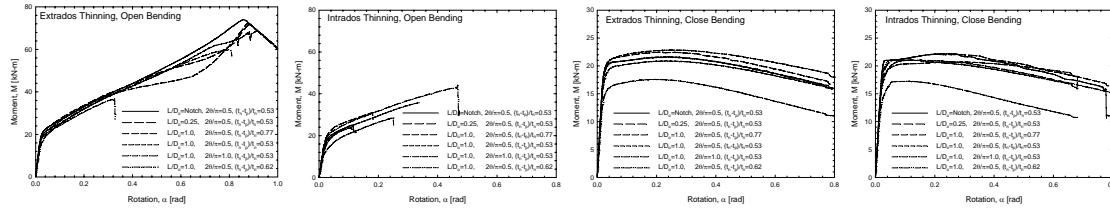*Fig. 9. Results of burst tests of wall thinned elbows*

3.3.3. Failure Load Tests

A series of combined load tests using real scale pipe elbows containing simulated wall thinning defect were performed to evaluate the effects of local wall thinning on the failure moment of elbows. Internal pressure and in-plane bending moment are considered as combined load. Figure 10 shows the results of combined load tests of wall-thinned elbows. Figure 10(a) shows the failure modes according to the thinning location and the bending direction while Figure 10(b) does the moment behaviors for the thinning location and the bending direction.

From this combined load tests, the following conclusions were derived. For both location of wall thinning and both type of bending, the plastic deformation of large arc thinned elbows was started at lower bending moment and smaller rotation than those of small arc thinned elbows. The plastic deformation of intrados thinned elbows was started at lower bending moment and smaller rotation than those of extrados elbows, especially in the open mode bending. The failure of local wall thinned elbow was classified into three modes, buckling, ovalization, and crack. For the open mode, buckling was occurred at the thinned region of which the extrados circumferential angle. And, crack was occurred at the intrados region for the other three cases. Ovalization was occurred for all cases, and it was extended to the some region of straight pipe. For the close mode, buckling was occurred at the intrados for all cases. No crack was occurred for all cases. Ovalization was occurred for all cases, and it was extended to the some region of straight pipe. All test cases had at least three times physical safe margin of twice elastic slope moment compared with maximum allowable moment based on construction code.

(a) Failure modes according to the thinning location and the bending direction

(b) Moment behaviors according to the thinning location and the bending direction

Fig. 10. Results of combined load tests of wall-thinned elbows

3.4. Verification

To verify the appropriateness of the integrity evaluation using PiTEP®, the results from PiTEP® was compared with the mock-up test results for elbows.

Data of the elbow used for comparison are as follows:

- Nominal thickness (t_{nom}): 7.8 mm
- Outside diameter (OD): 113.4 mm
- Pressure: 10.0MPa
- Allowable stress (S): 103.4 MPa
- Yield strength: 288 MPa
- Limit strength: 551 MPa
- Radius of curvature: 152.4 mm
- Measured thickness: 4 mm
- Maximum thinned length to axial direction: 76.158 mm
- Thinned length to radial direction: 41.064 mm

Figure 11 shows the comparison of failure moments obtained from mock-up tests (when applied with opening or closing moments) and owner's evaluation methodology used in PiTEP® (limit load method). It was found that the failure moments obtained from PiTEP® (11.8 kN-m) is more conservative by about 41% than those (about 20 kN-m) of the mock-up test. For comparison, the maximum applicable moment based on the elastic theory in plant design stage was estimated (5.2 kN-m, bar of most right-hand in figure 13). The maximum applicable moment was found to have excessive conservatism of about 53%. Therefore, it can be said that we can use PiTEP® for the integrity evaluation of thinned piping because the program can give us proper results with tolerable conservatism.

Figure 12 illustrates the comparison of thicknesses obtained from CC-N597 and owner's evaluation methodology used in PiTEP®. Since the measured thickness (or predicted at next inspection) is larger than the cut-off thickness but smaller than the thickness criterion ($0.9t_{min}$) in CC-N597, the allowable local thicknesses, t_{aloc}, should be calculated from the engineering evaluation method in CC-N597. As the measured thickness was found to be smaller than t_{aloc} (in this case, $0.899\ t_{min}$), the elbow might be recommended to repair or replace according to CC-N597. PiTEP® was used for the case as owner's evaluation method to reduce the excessive conservatism in CC-N597. The minimum thicknesses calculated from the limit load method and the fitting for fitness method in PiTEP® are shown in Figure 12 (two bars of most right-hand). Even with the measured thickness (4mm) smaller than criterion of $0.9\ t_{min}$ in CC-N597 (4.75mm), it can be said that the elbow has some safety margin of 2.4 (limit load method) ~ 4.4(fitting for fitness method) and that structural integrity of the elbow is confirmed until next inspection date.
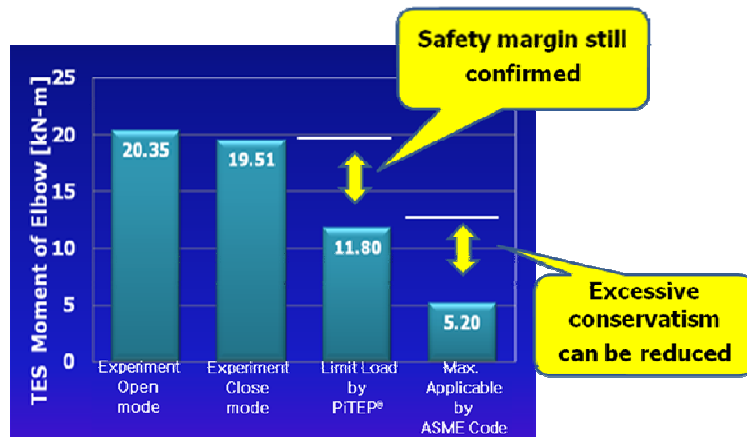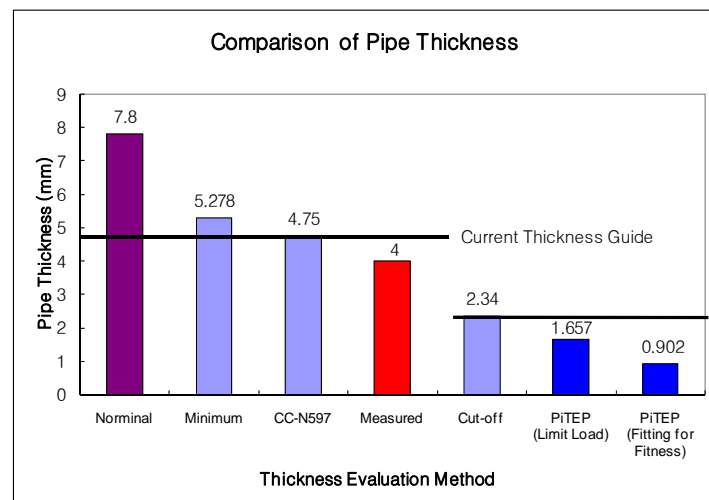
Fig. 11. Comparison of elbow failure moment

Fig. 12. Comparison of elbow wall thicknesses

4. CONCLUSION

An alternative integrity assessment criterion using limit load equations were developed by KEPRI, which is directly applicable to the secondary piping system of nuclear power plant. A lot of finite element analyses were done to set up the limit load equations for straight pipe, elbows, reducer, T-branch with reinforcement, etc. For easy implementation of the alternative criterion to plant operation, a computer programme (PiTEP®, Pipe Thinning Evaluation Programme) was developed. Mockup tests for elbow (pressure and bending) were also performed to verify the equation.

When PiTEP® is actually implemented in plant, some advantages are expected as follows:

- Integrity evaluation of all kinds of piping such as straight pipe, elbow, reducer, and branch connection is possible. Users can overcome the limitation of ASME CC-N597.
- Owner's method in PiTEP® was confirmed to have enough conservatism by verification test using mock-ups. It is possible for users to do optimal integrity evaluation.
- As PiTEP® is designed in user-friend environment, users can easily access it only with piping configuration, measured thickness data and basic operating parameters.

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