Transactions of the 17th International Conference on *Paper # G07-5*
Structural Mechanics in Reactor Technology (SMiRT 17)
Prague, Czech Republic, August 17 –22, 2003

Criterion for Failure of Internally Wall Thinned Pipe Under a Combined Pressure and Bending Moment

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ABSTRACT

Failure criterion is a parameter to represent the resistance to failure of locally wall thinned pipe, and it depends on material characteristics, defect geometry, applied loading type, and failure mode. Therefore, accurate prediction of integrity of wall thinned pipe requires a failure criterion adequately reflected the characteristics of defect shape and loading in piping system. In the present study, the finite element analysis was performed and the results were compared with those of pipe experiment to develop a sound criterion for failure of internally wall thinned pipe subjected to combined pressure and bending moment. By comparing the predictions of failure with actual failure load and displacement, an appropriate criterion was investigated. From this investigation, it is concluded that true ultimate stress criterion is the most accurate to predict failure of wall thinned pipe under combined loads, but it is not conservative under some conditions. Engineering ultimate stress estimates the failure load and displacement reasonably for all conditions, although the predictions are less accurate compared with the results predicted by true ultimate stress criterion.

KEY WORDS: pipe wall thinning, failure criteria, combined loads, integrity assessment

INTRODUCTION

Wall thinning due to flow accelerated corrosion (FAC) is recently considered as a main degradation mechnism of carbon steel piping in nuclear power plant.[1,2] Also, the integrity assessment of pipe with wall thinning defect is getting more attension because the integrity of piping system influences directly on safety and operability of nuclear power plant. Recently, several researchs performed to develop a more accurate integrity assessment procedure and acceptance criteria for a pipe containing wall thinning defect.[3-8] According to the results of theses studies, the integrity assessment of wall thinned pipe is influenced by defect shape, failure criterion, and type of loading. Particularly, the failure criterion directly affects the result of integrity analysis, and it depens on material toughness, loading type, defect shape, and failure mode. To accurately assess the integrity of wall thinned pipe, therefore, it is important to employ a failure criterion to be adequately reflected the characteristics of defect shape and loading of piping system.

The previous studies reported that wall thinned pipe of high toughness is failed by plastic instability of the remaining ligament, and they proposed several failure criteria as a form of local stress criterion.[3,5-8] However, most of these criteia were develpoed to predict the bust pressure in oil and gas pipe line containing wall thinning defect on the exterior. Thus, applying these criteria to the integrity evaluation of nuclear piping without any investigations would deteriorate the reliability of evaluation result, because for nuclear piping the wall thinning occurs inside wall and combined internal pressure and bending loads is applied.[3] However, to date no validated failure criterion has been investigated for internally wall thinned pipe under combined loading conditions. In order to accurate assessment of integrity of wall thinned pipe in nuclear power plant, therefore, it is necessary to develop an appropreate failure criterion.

The purpose of this study is to develop a sound criterion for failure of internally wall thinned pipe subjected to combined internal pressure and bending loads. Thus, the finite element analysis is performed to simulate the full scale pipe tests conducted in the previous our study,[9] and the results were compared with those of pipe test. From the comparisons, the failure criterion to be able to adequately predict the actual failure load and displacement was proposed.

PIPE EXPERIMENT

Pipe Material and Specimen

Pipe tests were performed using the 102mm(4in)-schedule 80 pipe containing an artificial wall thinning defect. The pipe material used in the experiment is carbon steel designated by ASTM A333 Gr.6, which is commonly used in secondary piping system of nuclear power plant. The pipe specimens were prepared by welding three pieces of pipe segment with length of 400mm and were end-capped to accommodate the internal pressure. All pipe segments were machined to obtain the uniform dimensions of outer diameter and thickness (D_o = 113.8mm, t = 7.8mm) prior to machining of wall thinning defect. Thinning defect was machined at inner side of the center pipe segment, and the configurations of pipe specimen and defect of wall thinning are illustrated in Fig. 1. As listed in Table 1, the various axial lengths (L) and circumferential angles (2θ) of wall thinning were considered in the present experiment. Dimensions of defect represented in Table 1 are specified by the region where the wall thickness is thinner than the minimum thickness (t_{min}) required by construction codes, such as ASME B&PV Sec.III [10] and ANSI/ASME B31.1.[11] The circumferential and axial shapes of thinning area were assumed as circular.

Experimental Procedures

In the experiment, a monotonic bending moment was applied to the pipe specimen by four-point loading with and without internal pressure at ambient temperature. The four-point loading system was designed to be able to accommodate the change of loading direction with pipe bending. The major and minor spans of four-point loading system are 940mm and 300mm, respectively. As represented in Table 1, two types of bending load were considered in the experiment, one is the tensile stress that applies to the thinning area and the other is the compressive stress that applies to thinned area. The bending moment was applied by displacement control at a rate of 0.033mm·s^{-1}. For the tests with internal pressure, a pipe specimen was firstly pressurized with water and nitrogen gas (N_2) to an internal pressure of 10MPa, and then loaded by monotonic bending moment. In the experiment, the load, load-line displacements, internal pressure, and strains were measured.

Results of Pipe Experiment

The experimental results showed that the failure mode depends upon defect shape and stress type at thinning area, and the mode is classified by cracking, local buckling, ovalization, and cracking after local buckling as summarized in Table 1. Also, the dependency of failure load of wall thinned pipe on the thinning shape is determined by stress type applied to thinning area. When tensile stress is applied to thinning area, the failure load increases with increase in length of thinning area for small circumferential angle ($2\theta < 180°$), whereas it decreased with increase in length of thinning area for large circumferential angle ($2\theta > 180°$). When compressive stress is applied to thinning area, the load is decreased as increase in length of thinning area regardless of circumferential thinning angle. On the other hand, the displacement to maximum load is proportionally increased with increasing axial length of thinning area for applying tensile stress to thinned area.

FINITE ELEMENT MODEL AND VERIFICATION

Finite Element Model

In order to simulate the pipe failure tests presented in Table 1, three dimensional elastic-plastic finite element analysis was performed using a commercial finite element program, ABAQUS. As shown in Fig. 2, only a quarter of full pipe was modeled considering symmetry condition of pipe specimen. In the model, 20 node isoparametric brick element was employed, and large strain option was used to consider the large deformation prior to final failure of pipe. For applying combined loads, the bending moment was applied as a four-point loading after applying internal pressure and tensile load induced by internal pressure. For considering bending moment only, four-point load was applied directly. The material properties were adopted from the tensile test results which were performed on the same material with the pipe experiment. Fig. 3 shows the true stress-strain curve used in analysis.

Verification of Finite Element Model

To verify finite element model and analysis procedure, the finite element analyses were performed for all conditions of pipe test, and the results were compared with the load-displacement curve and strains obtained from the pipe experiment. The comparisons show that the analysis results agree well with experimental data for most of testing conditions, except slightly underestimation of load-displacement curve in a few cases. Also, the predicted strains are good agreement with the strains measured on the surface of pipe with wall thinning up to large plastic strain. Fig. 4 represents the comparisons of load-displacement curves and strains for applying tensile stress to thinning area of $2\theta=180^{\circ}$, L = 100mm.

Additionally, the load at a given displacement was compared to quantitatively verify finite element analysis. Fig. 5 shows the results of comparison of predicted with experimental loads. In the comparisons, the load at a maximum displacement was compared for applying tensile stress to thinned area, and the load at a displacement of 17mm was compared for applying compressive stress to thinned area. As shown in Fig. 5, the predicted loads by finite element analysis agree well with experimental data in the range of -8.4 ~ 2.0% error bound regardless of defect shape, magnitude of internal pressure, and stress type at thinned area.

Therefore, it is recognized that the finite element model and analysis procedure employed present study reliably predict the failure behavior of internally wall thinned pipe under combined pressure and bending loads. Also, it is reasonable to derive a failure criterion through the comparison of finite element analysis with experimental results.

FAILURE CRITERION UNDER INTERNAL PRESSURE AND BENDING MOMENT

Failure Criterion

In the previous section, it is known that the failure behavior of wall thinned pipe is well predicted by finite element analysis developed in this study. Also, the previous experimental results showed that the wall thinned pipe under combined pressure and bending loads is filed by plastic instability of the remaining ligament of thinned area.[9] In the present study, therefore, the local stress was considered as a failure criterion for internally wall thinned pipe subjected to combined internal pressure and bending moment. As represented in Eq.(1), it is assumed that the failure occurs when the averaged equivalent stress at net-section of thinned area calculated by finite element analysis exceeds the failure stress criterion determined by material properties. To decide an adequate failure stress criterion, σ_{crit} in Eq.(1), firstly several stress criteria which have been introduced in the evaluation of failure of wall thinned pipe were selected and summarized in Table 2. Of these, the criterion that predicts experimental failure behavior appropriately would be proposed as a failure stress criterion. The appropriateness was investigated by comparison of analysis and experiment results on the viewpoint of load carrying capability and deformation ability of wall thinned pipe.

$$\sigma_{eq,app}(\text{sect. avg.}) \geq \sigma_{crit}(\text{ mat.}) \tag{1}$$

Assessment of Load Carrying Capability

To investigate the appropriateness of failure criterion on the aspect of load carrying capability, the maximum load was predicted by finite element analysis applying four criteria listed in Table 2, and it was compared with pipe experimental result. Fig. 6(a) represents the comparisons of predicted maximum loads with experimental maximum loads for applying tensile stress to thinned area. As shown in Fig. 6(a), the predictions by flow stress (σ_f) and modified B31G (σ_y+68.95MPa) underestimate the maximum loads about 46.4% and 30.0%, respectively. For employing engineering ultimate stress (σ_u) and true ultimate stress (σ_{ut}) as a stress criterion, also, the results underestimate the experimental maximum loads for all testing conditions. However, the data scattering for both criteria is less than 10%, and σ_{ut} relatively good predicts the actual failure load with 7.2% underestimation. For applying compressive stress to wall thinned area, the predicted maximum loads using by four criteria were compared with loads at δ = 17mm. As shown in Fig. 6(b), the predicted maximum loads applying flow stress and modified B31G criteria are lower about 47.2% and 18.0% than experimental loads. The engineering ultimate stress and true ultimate stress relatively well predict the experimental failure loads with about 8.7% and 4.1% underestimation, respectively. However, in some conditions the true ultimate stress overestimates the maximum failure load.

Therefore, these results indicate that the flow stress and modified B31G are too conservative criteria on the viewpoint of prediction of load carrying capability. True ultimate stress shows the most accurate prediction of maximum load, but it gives non-conservative prediction in a few conditions. Engineering ultimate stress conservatively estimates the maximum load of pipe with internally wall thinning defect, although the accuracy is less than for applying true ultimate stress.

Assessment of Deformation Ability

For a pipe subjected to bending loads, the pipe integrity has to be ensured under displacement controlled loading such as thermal expansion and seismic anchor motion as well as load controlled loading condition. Thus, a failure criterion was investigated on the aspect of deformation ability. As discussed previous section, the maximum allowable displacements were predicted by applying four criteria in Table 2, and they were compared with displacement to maximum load in the load-displacement curve obtained from the pipe tests. Fig. 7 represents the comparison of predicted maximum displacements with displacement to maximum loads for applying tensile stress to thinned area.

As shown in Fig. 7, the maximum allowable displacements predicted by flow stress and modified B31G are less about 90% than experimental maximum displacements. For applying engineering ultimate stress as a criterion, also, the predicted displacements are lower about 70% in comparison with experimental results. As investigated in the load carrying capability, true ultimate stress estimates the maximum allowable displacement with about 27.0% underestimation. In some conditions, however, the true ultimate stress overestimates the maximum allowable displacement.

Therefore, on the aspect of prediction of deformation ability, the criteria of flow stress and modified B31G give too conservative results. True ultimate stress shows relatively accurate estimation although the results are not conservative in some conditions.

CONCLUSION

In this study, the finite element analysis was performed and the results were compared with those of pipe experiment to propose a sound criterion for failure of internally wall thinned pipe subjected to combined pressure and bending loads. From these investigations, the following conclusions were obtained :

1) The flow stress (σ_f) and modified B31G criteria were too conservative on the viewpoint of predictions of load carrying capacity and deformation ability.
2) The true ultimate stress criterion (σ_{ut}) was the most accurate to predict failure of wall thinned pipe under combined loads, but it is not conservative under some conditions.
3) Engineering ultimate stress (σ_u) estimated the failure load and displacement reasonably for all conditions, although the predictions are less accurate compared with the results predicted by true ultimate stress criterion.
4) In the integrity analysis of internally wall thinned pipe under combined loads, consequently, the true ultimate stress is an appropriate stress criterion when accuracy of assessment is considered preferentially, whereas the engineering ultimate stress criterion is more appropriate than true ultimate stress criterion when the conservatism as well as accuracy of result is considered importantly.

ACKNOWLEDGEMENT

This work has been supported by EESRI(01-local-01), which is funded by MOCIE(Ministry of commerce, industry and energy).

REFERENCES

1. Michel, F., Reck, H., and Schulz, H., “Experience with piping in German NPPs with Respect to Ageing-Related Aspects.,” Nucl. Eng. & Des., Vol. 207, pp. 307□316, 2001.
2. Chexal, B., Horowitz, J., Dooley, B., Millett, P., Wood, C., and Jones, R., “Flow- Accelerated Corrosion in Power Plant,” EPRI/TR-106611-R2, 1998.
3. Wilkowski, G., Stephens, D., Krishnaswamy, P., Leis, B., and Rudland, D., “Progress in Development of Acceptance Criteria for Local Thinned Areas in Pipe and Piping Components,” Nucl. Eng. & Des., Vol. 195, pp. 149□169, 2000.
4. Roy, S., Grigory, S., Smith, M., Kanninen, M.F., and Anderson, M., “Numerical Simulations of Full-Scale Corroded Pipe Tests with Combined Loading,” J. Pres. Ves. Tech., Vol.119, pp. 457□466, 1997.

5. Ahamined, M., “Prediction of Remaining Strength of Corroded Pressurised pipelines,” Int. J. Pres. Ves. & Piping., Vol.71, pp.213□217, 1997.
6. Japan Atomic Energy Research Institute, “Technical Reprt on the Piping Reliability Tests at the Japan Atomic Energy Research Institute (Japanese),” JAERI-M, 93-074, pp. 104□115, 1993.
7. Miyazaki, K., Kanno, S., Ishiwata, M., Hasegawa, K., Ahn, S. H., and Ando, K., “Fracture Behavior of Carbon Steel Pipe with Local Wall Thinning Subjected to Bending Load,” Nucl. Eng. & Des, Vol. 191, pp. 195□204, 1999.
8. Bin, F and Mike, G.K., “Criterion for Predicting Failure of Corroded Linepipe,” Underground Pipeline Engineering, pp89□101, 1994.
9. Kim, J.W. and Park, C.Y., “Experimental Investigation of Thinning Length and Internal Pressure Effects on the Failure Behavior of Pipe with Local Wall Thinning,” Nucl. Eng. & Des, Vol. 220, pp. 274□284, 2003.
10. American Society of Mechanical Engineer, ASME B&PV Code Sec.III, "Rules for Construction of Nuclear Power Plant Components.," 1995 ed.
11. American Society of Mechanical Engineer, ANSI/ASME B31.1, "Power Piping", 1995.

Table 1 Matrix of full - scale pipe tests and failure mode

Spec. ID	d/t	2θ	L(mm)	P(Mpa)	Loading Type		Failure Mode
SP-17	0.74	180^o	25	0	Monotonic Bending	Tension	Cracking
SP-18			200			Tension	Ovalization
SP-19			25			Compression	Local Bucking
SP-20			200			Compression	Local Buckling
SP-31		360^o	25			Tens.+Comp.	Local Buckling → Cracking
SP-32			200			Tens.+Comp.	Local Buckling→ Ovalization
SP-39		180^o	25	5		Tension	Cracking
SP-40			200			Tension	Cracking
SP-12		90^o	25	10		Tension	Cracking
SP-13			200			Tension	Ovalization
SP-15			25			Compression	Local Buckling
SP-16			200			Compression	Local Buckling
SP-01		180^o	25			Tension	Cracking
SP-02			50			Tension	Cracking
SP-03			100			Tension	Cracking
SP-04			200			Tension	Cracking
SP-05			25			Compression	Local Buckling
SP-06			50			Compression	Local Buckling
SP-07			100			Compression	Local Buckling
SP-08			200			Compression	Local Buckling
SP-09		360^o	25			Tens.+Comp.	Local Buckling→ Cracking
SP-10			200			Tens.+Comp.	Local Buckling→ Cracking

Table 2 Stress criteria for failure of pipe with wall thinned defect

No.	Stress Criteria	Ref.
1	$\sigma_{crit} = (\sigma_y + \sigma_u)/2$	[6]
2	$\sigma_{crit} = \sigma_y + 68.95\text{Mpa}$	[5]
3	$\sigma_{crit} = \sigma_u$	[3]
4	$\sigma_{crit} = \sigma_{ut}$	[8]

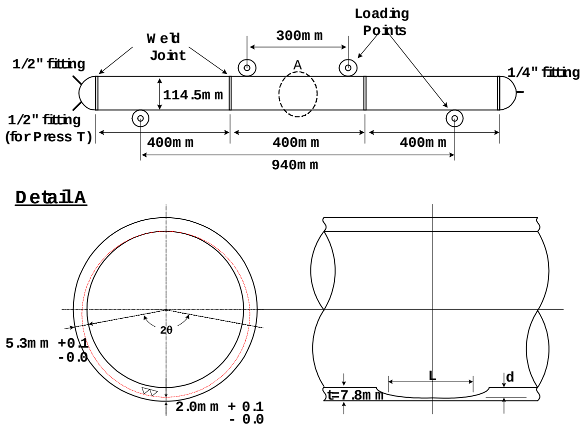


Fig. 1 Geometry of pipe specimen and internally wall Thinning shape

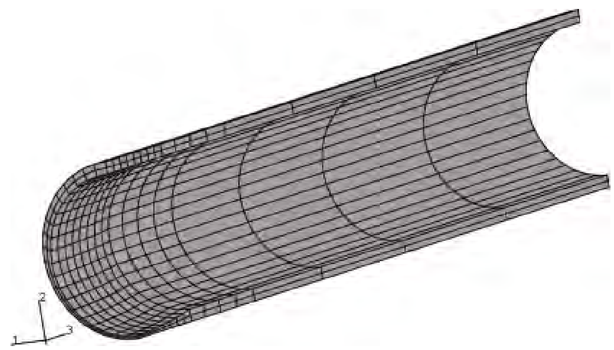


Fig. 2 Finite element model used in analysis

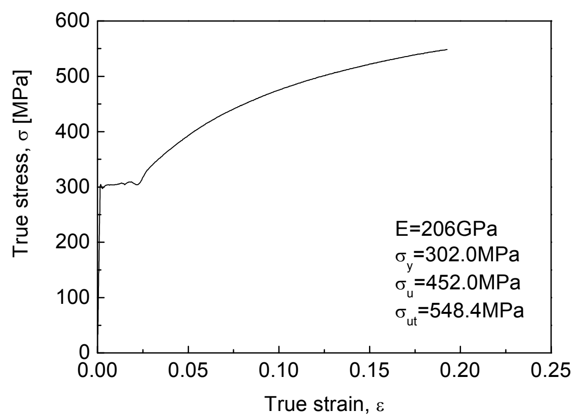
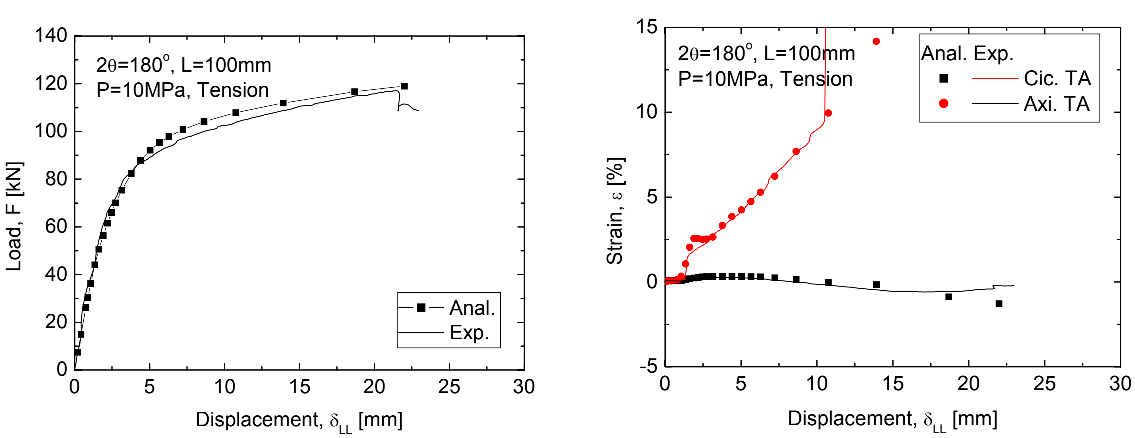


Fig. 3 True stress-strain curve used for FE analysis



(a) tensile stress (b) compressive stress

Fig. 4 Comparison of experimental and FE predicted load-displacement curves and strains at thinned area

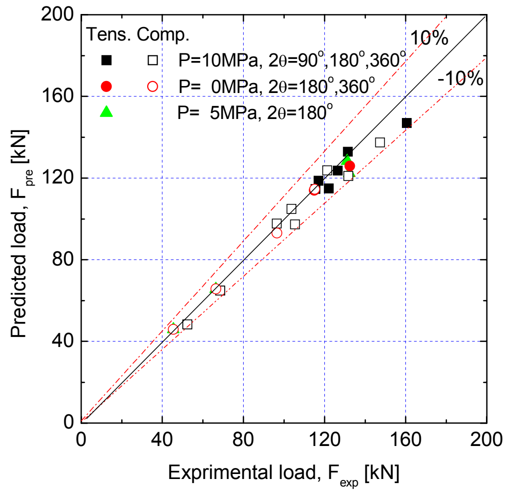
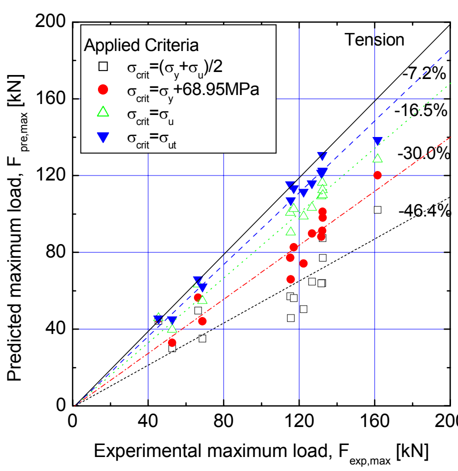
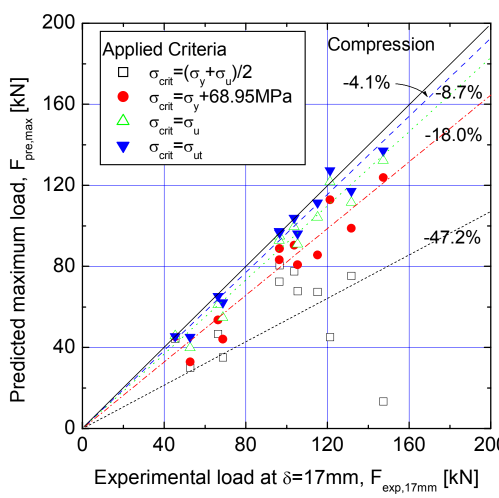


Fig. 5 Comparison of experimental and predicted loads at a given displacement



(a) tensile stress



(b) compressive stress

Fig. 6 Comparison of experimental and predicted maximum loads for various failure criteria

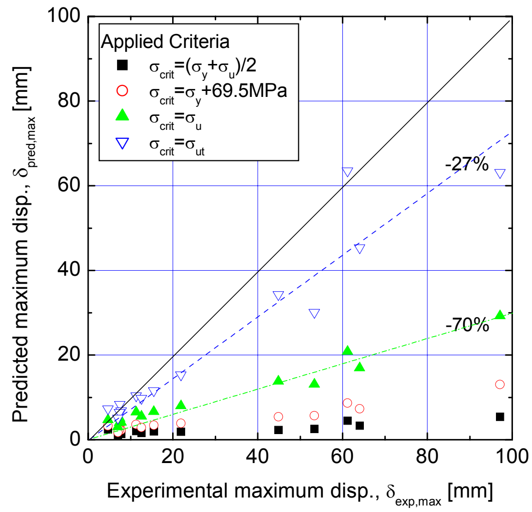


Fig. 7 Comparison of experimental and predicted displacements to maximum load for various failure criteria