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Failure Cycle Prediction of Pipe Elbow Cyclic Bending Test Using Strain-based Very Low Cycle Fatigue Evaluation Model

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1. Introduction

When beyond design basis earthquake (BDBE) is applied to the piping system, failure due to very low cycle fatigue could be occurred. To ensure the structural integrity, it is necessary to evaluate the very low cycle fatigue. However, fracture mechanism of very low cycle fatigue is different from low cycle fatigue, so a new evaluation method is required. The author have recently proposed strain-based very low cycle fatigue evaluation model [1]. In this paper, the failure cycle of pipe elbows under in-plane cyclic bending load are evaluated using very low cycle fatigue evaluation model, and the experimental results and evaluation results are compared.

2. Experiment

In this section, experimental results are described. This paper consider in-plane cyclic bending test results using SA403 WP316 pipe elbow specimen [2]. Tensile tests were also conducted to determine material properties and fatigue evaluation model. All experiments were performed at room temperature.

2.1 Tensile Test

Tensile properties were obtained from quasi-static tensile test using smooth round bar. Specimens were extracted from SA403 WP316 pipe elbow. The minimum diameter and gage length of round bar specimen was 2.5mm and 16mm, respectively. Mechanical properties are tabulated in Table 1.

2.2 Pipe Elbow Cyclic Bending Test

In-plane cyclic bending test using 4-inch SA403 WP316 pipe elbow specimen was conducted. In the experiment, two types of elbow specimen with different thickness were used. Nominal thickness of pipe elbow is 6.0mm for Sch. 40 and 13.5mm for Sch. 160. Experiment was performed under displacement-controlled cyclic load with and without internal pressure. The applied internal pressure was operating pressure of pipe elbow of the same specification. In all tests, leak due to fatigue crack were occurred. Fatigue crack was observed in crown for Sch. 40 elbow and intrados in Sch. 160.

Table I: Mechanical properties of SA403 WP316 stainless steel.

Yield Strength (MPa)	Tensile Strength (MPa)	Total Elongation (%)	Reduction of Area (%)
271.5	605.9	72.1	80.9

Table II: The parameters of Chaboche combined hardening model used in FE analysis

<table>
<tr><td colspan="6">Isotropic hardening parameters</td></tr>
<tr><td colspan="2">σ_0 (MPa)</td><td colspan="2">Q (MPa)</td><td colspan="2">b</td></tr>
<tr><td colspan="2">192.4</td><td colspan="2">80</td><td colspan="2">4.0</td></tr>
<tr><td colspan="6">Kinematic hardening parameters</td></tr>
<tr><td>C_1 (MPa)</td><td>γ_1</td><td>C_2 (MPa)</td><td>γ_2</td><td>C_3 (MPa)</td><td>γ_3</td></tr>
<tr><td>68,372</td><td>700</td><td>1,814</td><td>14.6</td><td>1,200</td><td>0</td></tr>
</table>

3. Very Low Cycle Fatigue Evaluation

In this section, the strain-based cyclic void growth model [1] used in very low cycle fatigue evaluation and evaluation results are described. To simulate the stress and strain history in pipe elbow specimen, elastic-plastic FE analysis was performed.

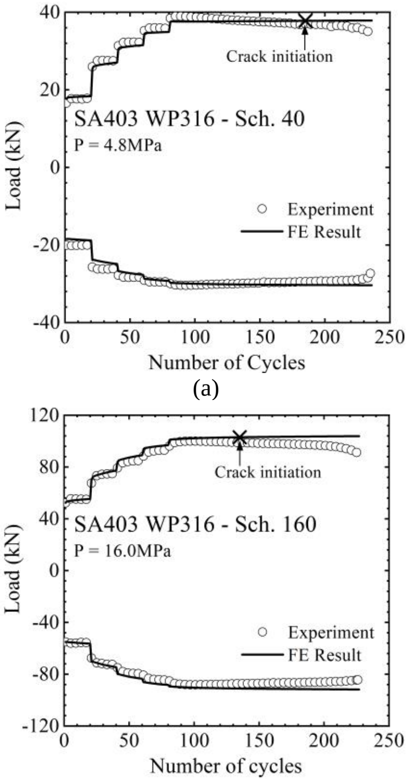
3.1 Elastic-plastic Finite Element Analysis

Elastic-plastic FE analysis was performed to simulate pipe elbow cyclic bending test using commercial FE analysis program ABAQUS [3]. Chaboche combined hardening model was used for the simulation, and the parameters of the hardening model were tabulated in Table 2. A 3-D quarter model with first order brick element with incompatible mode (C3D8I in ABAQUS) was used. The large geometry change option was also invoked.

The maximum and minimum load in each cycle calculated from FE analysis are compared with experimental results in Fig. 1.

3.2 Very Low Cycle Fatigue Evaluation Model

In this study, cyclic void growth model considering void growth and shrinkage under cyclic load was considered to predict crack initiation due to very low cycle fatigue of pipe elbow specimen. In this model, the incremental damage due to plastic strain is expressed as follows,



(a)

(b)

Fig. 1. Comparison of FE analysis results with experimental test data: (a) Sch. 40 elbow with internal pressure and (b) Sch. 160 elbow with internal pressure.

$$dD = \frac{d\varepsilon_{eq}^{p}}{\varepsilon_f}\ ;\ \varepsilon_{eq}^{p} = \int_0^t \left(\frac{2}{3}\dot{\boldsymbol{\varepsilon}}_{ij}^{p}\dot{\boldsymbol{\varepsilon}}_{ij}^{p}\right)^{1/2} dt \qquad (1)$$

where $d\varepsilon^{p}_{ep}$ and ε^{p}_{ij} denotes incremental equivalent plastic strain and plastic strain rate tensor, respectively: and ε_f denotes multi-axial fracture strain, and according to Rice and Tracey [4], it is expressed as a function of stress triaxiality as follows,

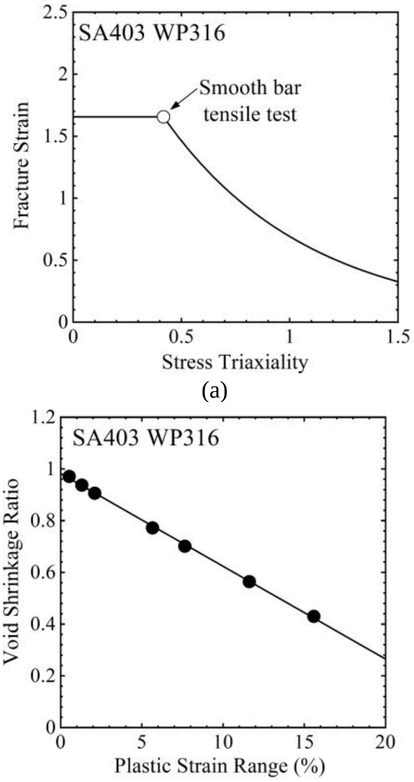
$$\varepsilon_f = A\exp(-1.5\cdot\eta),\ \eta = \frac{\sigma_m}{\sigma_e} \qquad (2)$$

where σ_e and σ_m denote von Mises equivalent stress and hydrostatic stress, respectively: and A is material constant which can be determined using tensile test result.

Under cyclic loading, the damage increases as the void growth when tensile load applied, but under compressive load, damage decreases as the void shrinkage. Accordingly, the cumulated damage is expressed as follows,

$$D = \int dD = \int_T \frac{d\varepsilon_{eq}^{p}}{\varepsilon_f(|\eta|)} - k\int_C \frac{d\varepsilon_{eq}^{p}}{\varepsilon_f(|\eta|)} = D_T - kD_C = 1 \qquad (3)$$

where the subscript T and C denote tensile and compression, respectively: and k is void shrinkage ratio which is defined as a function of plastic strain range.



(a)

(b)

Fig. 2. Determined very low cycle fatigue evaluation model: (a) multi-axial fracture strain locus and (b) void shrinkage ratio.

The material constant A and void shrinkage ratio k required for fatigue evaluation are determined using the tensile test data and the best-fit fatigue curve presented in NUREG report [5]. The determined fracture strain locus and void shrinkage ratio of SA403 WP316 stainless steel were determined as following equation, and are shown in Fig. 2.

$$\varepsilon_f = 3.10\exp(-1.5\cdot\eta) \qquad (4)$$

$$k = 0.98 - 3.59\cdot\Delta\varepsilon_{eq}^{p} \qquad (5)$$

3.3 Fatigue Evaluation Results

The cumulated damage according to the number of cycles are shown in Fig. 2. The damages are calculated in crown and intrados of the pipe elbow specimen. Fatigue crack is predicted to occur in the crown for Sch. 40 elbow and the intrados for the Sch. 160 elbow. This is the same location where the fatigue crack occurred in the pipe elbow specimen in the experiment.

Table 3 compares the failure cycle measured in experiment and the predicted crack initiation cycle in the fatigue evaluation. The failure cycle of experiment is defined as the cycle in which leak occurs due to crack penetration. Also, The predicted crack initiation cycle is indicated by cross mark in Fig. 1. In all experimental cases, crack initiation is predicted prior to leakage in experiment.

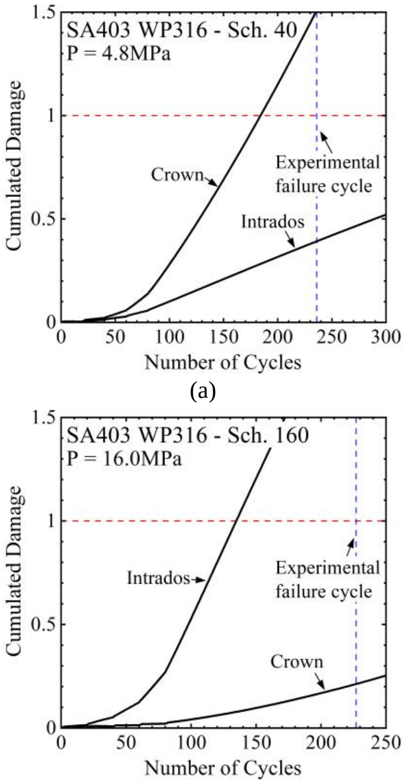


Fig. 3. Variation of the cumulated damage with the number of cycles: (a) Sch. 40 elbow with internal pressure and (b) Sch. 160 elbow with internal pressure.

4. Conclusions

In this paper, fatigue evaluation results for a pipe elbow under in-plane cyclic bending load is presented. A strain-based cyclic void growth model considering void shrinkage is used for very low cycle fatigue evaluation. The evaluation model for SA403 WP316 was determined from tensile test results and fatigue curve. The failure cycle and failure location in the experiment were compared with evaluation results. Using the evaluation model, the crack initiation location that varies depending on the thickness of pipe elbow can be predicted, and crack initiation of pipe elbow is predicted before leak occurred in the experiment.

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Table III: Comparison of predicted failure cycle of elbow specimen with experimental results.

	Pressure (MPa)	Failure Cycles	
		Experiment (cycles)	Evaluation (cycles)
Sch. 40	0.18	271	157
	4.8	236	187
Sch. 160	0.18	221	146
	16.0	227	135

REFERENCES

[1] J. M. Lee, Y. J. Kim, and J. W. Kim, Very Low Cycle Fatigue Life Evaluation Models and Validation Using Notched Compact Tension Test Data, International Journal of Fatigue, Vol. 155, p. 106635, 2022
[2] S. E. Kim, J. N. Hong, J. W. Kim, D. Y. Lee, and H. B. Park, Failure Behaviors of Pipe Elbows under a Large Amplitude Cyclic Loads, Trans. of KNS Autumn Met., 2020.
[3] ABAQUS, ABAQUS version 2018. Dassault systems, 2018.
[4] J. R. Rice, and D. M. Tracey, On The Ductile Enlargement of Voids in Triaxial Stress Fields. Journal of Mechanical Physics Solids, Vol. 17, p. 201, 1968.
[5] O. K. Chopra, and W. J. Shack, Effects of LWR Coolant Environments on the Fatigue Life of Reactor Materials, Final Report, NUREG/CR-6909, ANL-06/08, Argonne National Laboratory, 2007.