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Fatigue failure behaviour of pipe elbows under very low cycle dynamic loading: Part II – Strain-based fatigue evaluation

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ABSTRACT

This paper presents application of strain-based methods for very low cycle fatigue loading to SA234 WPB pipe elbow tests under dynamic cyclic loading (presented in Part I). Dynamic FE analysis was performed using Rayleigh damping model with 0.5 % damping ratio and a bi-linear kinematic hardening model according to JSME Code Case. The acceleration of mass in the elbow specimen and the opening displacement between both ends of the elbow calculated from the FE simulation were compared to experimental results, showing good agreement. Using FE simulation results, Cumulative Usage Factor (CUF) values were calculated using two strain-based very low cycle fatigue evaluation methods: (1) ASME BPVC Sec. VIII Div. 2 Part 5 and (2) the model incorporating the void shrinkage effect. The calculated CUF using the ASME BPVC Sec. VIII Div. 2 Part 5 were ranged from 11.1 to 25.5, while the CUF using the model incorporating the void shrinkage effect were from 1.7 to 5.0.

INTRODUCTION

After the Fukushima nuclear power plant accident, the structural integrity of nuclear power plant piping under Beyond Design Basis Earthquake (BDBE) has become an important issue. In power plant piping systems, elbows are typical structural discontinuities where large deformation is expected to occur under seismic loading. In order to investigate very low cycle fatigue failure of elbows under seismic loading, several dynamic cyclic loading tests for piping systems have been performed (Kiran et al, 2018; Nakamura and Kasahara, 2017). In these experiments, crack occurred in an elbow, implying that an elbow is the most vulnerable to failure. Accordingly, an appropriate evaluation method for predicting failure in an elbow under very low cycle fatigue loading is required to assure structural integrity of the nuclear power plant piping.

The current fatigue assessment procedure presented in ASME BPVC Sec. III is a stress-based evaluation method based on elastic stress analysis, but it is known to be very conservative. To reduce the conservatism, strain-based evaluation method based on elastic-plastic stress analysis had been presented in ASME BPVC Sec. VIII Div. 2 Part 5. In our previous study, strain-based model that considers the void shrinkage effect under compressive loading was proposed and applied to evaluate the crack initiation cycle in the notched C(T) specimen under cyclic loading (Lee et al, 2022).

In Part I, very low cycle fatigue tests of SA234 WPB pipe elbows were performed under dynamic loading condition. In the test, 4-inch schedule 40 pipe elbow were tested with and without internal pressure. Sine and random wave cyclic dynamic loading were applied to the pipe elbow specimen. Failure location and cycles were measured from the test.

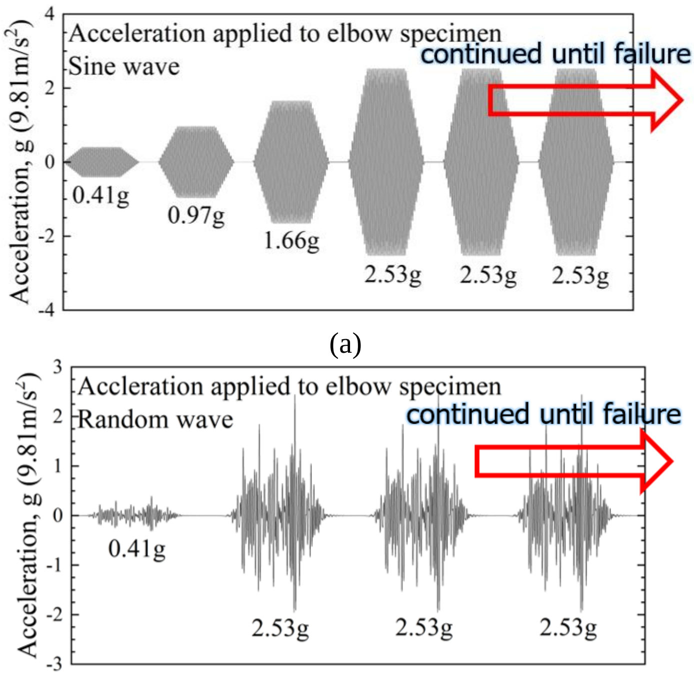
In this study, dynamic finite element simulation of the SA234 WPB elbow tests was performed to investigate the applicability of the strain-based evaluation methods. In the simulation, a bi-linear kinematic hardening model and a Rayleigh damping with 0.5% damping ratio was applied according to JSME Code Case (JSME, 2019). The acceleration of the mass in the tests, the opening displacement between both ends of the elbow and the location of the maximum plastic strain occurrence were compared to experimental results, showing good agreement. Using simulation results, the Cumulative Usage Factor (CUF) was calculated using the two strain-based evaluation methods to investigate the conservatism of the methods.

FINITE ELEMENT SIMULATION OF DYNAMIC PIPE ELBOW TEST

The dynamic elbow tests were simulated by elastic-plastic FE analysis for strain-based fatigue failure evaluation. In this study, the elbow tests (made of SA234 WPB carbon steel) with and without internal pressure under sinusoidal and random wave amplitude was considered, as tabulated in Table 1. For sinusoidal wave tests, cycle blocks with the acceleration of 0.41g, 0.97g, 1.66g, and 2.53g were sequentially applied to the elbow specimen. For random wave tests, cycle blocks with acceleration of 0.41g and 2.53g were applied. The cycle blocks with an acceleration amplitude of 2.53g were repeatedly applied until failure. The sequence of applied cycle blocks is shown in Fig. 1.

Table 1. Summary of dynamic cyclic elbow test and test results.

Input wave	Internal pressure (MPa)	Applied cycle blocks until failure	Crack location
Sine wave	0.18	0.41g+0.97g+1.66g+2.53g×8	Inner crown
	4.80	0.41g+0.97g+1.66g+2.53g×3	Inner crown
Random wave	4.80	0.41g+2.53g×40	Inner crown

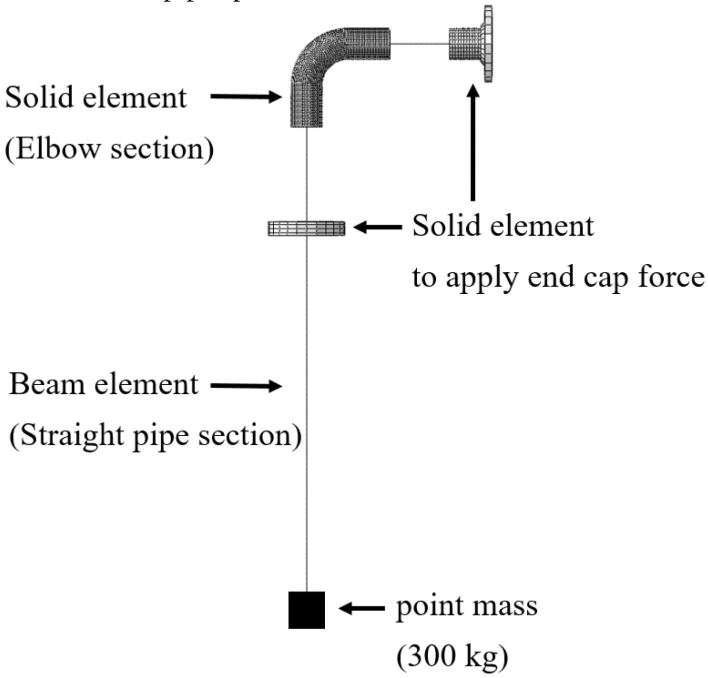


(b)

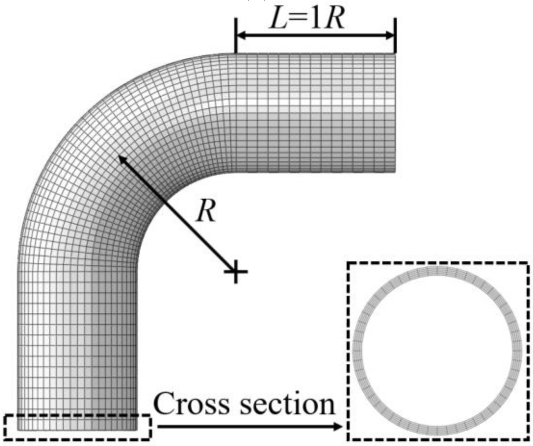
Figure 1. The schematic of cycle blocks applied to elbow specimens: (a) sine wave and (b) random wave

Solid-beam Hybrid Model

FE simulation for the dynamic cyclic loading elbow test was performed using the solid-beam hybrid model. Solid elements were used for the elbow section and attached straight pipes connected to the elbow. The length of attached straight pipes was equal to the radius of curvature of the elbow. Solid elements were also used at both ends of the elbow specimen to apply end cap force. Beam elements were used for the rest of the straight pipe. For solid elements, a first-order incompatible mode element (C3D8I in ABAQUS) was used, and for beam elements, a first-order pipe element (PIPE31 in ABAQUS) was used. The multi-point constraint option (MPC in ABAQUS) was used to connect the solid and beam elements and to apply dynamic loading by displacement. The weight was simulated using a point mass element (MASS in ABAQUS). Internal pressure was applied by distributed load (DLOAD in ABAQUS) inside the elbow specimen. The solid-beam hybrid model used in the simulation is shown in Fig. 2. Density is applied by assuming that the mass of water filled inside the elbow specimen is uniformly distributed over the elbow pipe specimen.



(a)



(b)

Figure 2. (a) Solid-beam hybrid finite element model used in the dynamic FE simulation (b) finite element mesh of the elbow section.

Rayleigh Damping Model

A modal analysis was performed to determine the elastic modulus that gives a similar natural frequency to the experiment. The elastic modulus used in simulation was determined 192.6 GPa, and the modal analysis gives 2.33 Hz of natural frequency of the excitation direction, with an error of 3.39% from the experiment. Rayleigh damping with 0.5% damping ratio was applied in simulation according to JEAG-4601 (JEA, 2009). The Rayleigh coefficient α and β was obtained by using the first mode frequency and 50 Hz. The determined damping coefficients are summarized in Table 2.

Table 2. Material parameters and damping coefficients applied in dynamic FE simulations.

Elastic modulus (GPa)	Tangent modulus (MPa)	Yield strength (MPa)
192.57	2,027	329.5
Material density (kg/m^3)		
11,776		
Rayleigh coefficient α	Rayleigh coefficient β	
0.1397	3.042 x 10^{-5}	

Bi-linear Kinematic Hardening Model

JSME Code Case (JSME, 2019) suggests the bi-linear kinematic hardening model for elastic-plastic analysis. In this model, yield function is expressed as follows:

$$F = f\left(\underline{\boldsymbol{\sigma}} - \underline{\boldsymbol{\alpha}}\right) - \sigma_y = \left[\frac{3}{2}\left(\underline{\mathbf{s}} - \underline{\mathbf{a}}\right):\left(\underline{\mathbf{s}} - \underline{\mathbf{a}}\right)\right]^{1/2} - \sigma_y = 0 \qquad (1)$$
$$d\underline{\boldsymbol{\alpha}} = E_2 \cdot d\underline{\boldsymbol{\varepsilon}}_p$$

where $\underline{\boldsymbol{\sigma}}$ and $\underline{\boldsymbol{\alpha}}$ denote stress and back stress tensor, $\underline{\mathbf{s}}$ and $\underline{\mathbf{a}}$ denote deviatoric component of stress and back stress tensor, $\underline{\boldsymbol{\varepsilon}}_p$ denotes plastic strain tensor, and σ_y and E_2 are the size of yield surface and the tangent modulus, respectively. In the bi-linear hardening model, two parameters, σ_y and E_2 should be determined. In this study, the parameters are determined according to the process described in the JSME Code Case using tensile test data. The determined bi-linear kinematic hardening parameters are summarized in Table 2.

Simulation Results

Figure 3 shows the comparison of simulation results with experimental results when an acceleration of 2.53g was applied. The acceleration of mass connected to the elbow specimen and the opening displacement between both ends of the elbow are compared. The simulation results show only the maximum and minimum values of each cycle. For the case of random wave, data was compared in the frequency domain by using Fast Fourier Transformation. It is shown that the mass acceleration and the opening displacement were calculated conservatively with overall good agreement with the experimental data.

Figure 4 shows that the contour of the equivalent plastic strain calculated in FE simulation for the internal pressure of 0.18 MPa with sine wave. The calculated maximum plastic strain occurred at the inner crown. This is consistent with the experiment result that the crack occurred inner crown of the elbow. These results show that the FE simulation was performed appropriately.

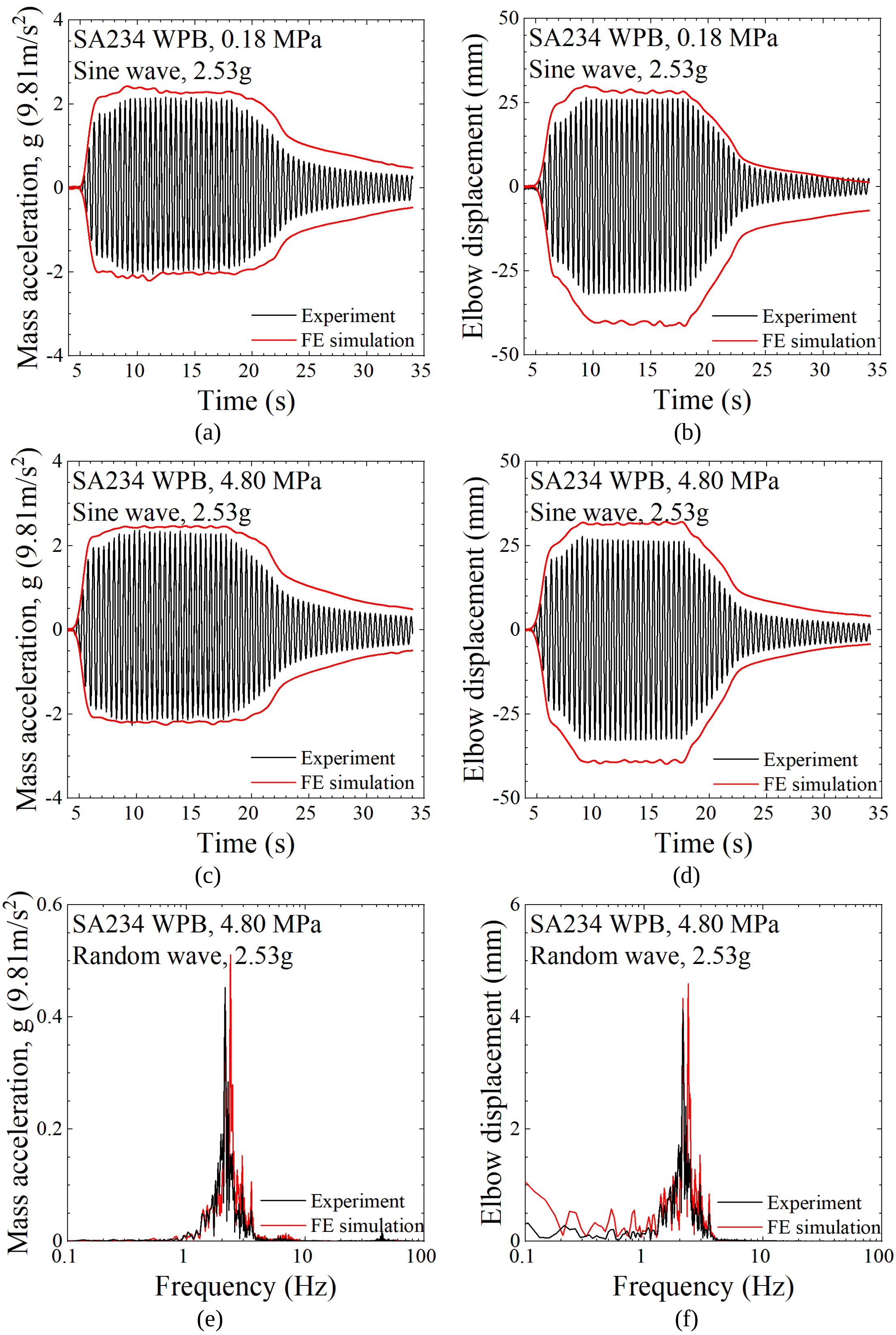


Figure 3. Comparison of the mass acceleration and the opening displacement between both ends of the elbow with simulation results (a), (b) Sine wave, 0.18 MPa, (c), (d) Sine wave, 4.80 MPa, (e), (f) Random wave, 4.80 MPa

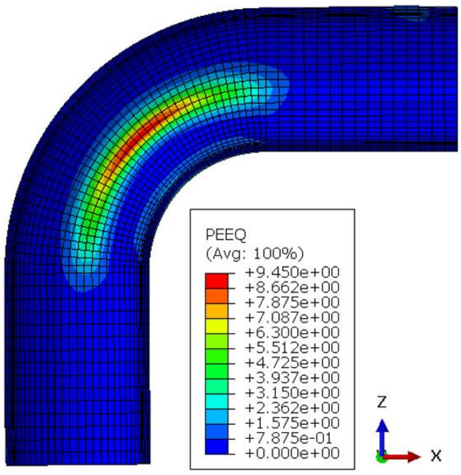


Figure 4. The accumulated equivalent plastic strain contour inside of the elbow specimen.

STRAIN-BASED FAILURE EVALUATION METHODS

In this study, two strain-based evaluation methods were applied to pipe elbows under dynamic cyclic loading. One is the evaluation method based on the ductile exhaustion theory presented in ASME BPVC Sec. VIII, Div. 2, Part 5. Another one is the method that considers shrinkage of void in a material under compressive loading.

ASME BPVC Sec. VIII Div.2 Part 5

The evaluation method presented in ASME BPVC Sec. VIII Div.2 Part 5 evaluates failure when the value of accumulated damage becomes 1. The accumulated damage is defined as

$$D_{\varepsilon} = \sum D_{\varepsilon,k} = \frac{\Delta\varepsilon^{p}_{eq,k}}{\varepsilon_L} \le 1 \tag{2}$$

where D_{ε} and $D_{\varepsilon,k}$ are accumulated damage and incremental damage, $\Delta\varepsilon^{p}_{eq,k}$ and ε_L are incremental plastic strain and limit strain respectively. ASME BPVC Sec. VIII Div. 2 Part 5 gives a method using the reduction of area in a tensile test for defining the limit strain. The limit strain for SA234 WPB carbon steel was determined as a function of stress triaxiality:

$$\varepsilon_L = 1.288\exp\left[-1.756\left(\eta - \frac{1}{3}\right)\right]; \eta = \frac{\sigma_1 + \sigma_2 + \sigma_3}{3\sigma_e} \tag{3}$$

where σ_e denotes von Mises equivalent stress; σ_1, σ_2, and σ_3 denote the principal stress respectively.

Cyclic Void Growth/shrinkage Model

In very low cycle fatigue region, cracks occur in the material due to the mechanism of void nucleation, growth, and coalescence (Kuwamura et al, 1997; Kanvinde et al, 2007; Shi et al, 2011). Recently, a model considering void shrinkage under compressive loading was proposed and applied to notched C(T) specimens under cyclic loading conditions to predict crack initiation cycles. In the cyclic void growth/shrinkage model, the accumulated damage is defined by adding the incremental damage under tensile stress and subtracting the incremental damage under compressive loading multiplied by the void shrinkage ratio, *k*:

$$D_{\varepsilon} = \sum\left(\int_{Tensile} \frac{\Delta\varepsilon^{p}_{eq}}{\varepsilon_L(|\eta|)} - k \int_{Compression} \frac{\Delta\varepsilon^{p}_{eq}}{\varepsilon_L(|\eta|)} \right) \le 1 \tag{4}$$

Failure is evaluated when the values of the accumulated damage become 1. The void shrinkage ratio, *k* can be defined as a function of the plastic strain amplitude using best-fit e-N curve shown in NUREG/CR-6909 (Chopra et al, 2007) and tensile test data. Void shrinkage ratio for SA234 WPB carbon steel was determined as:

$$k = 1.0 - 4.3\Delta\varepsilon_p \tag{5}$$

STRAIN-BASED FAILURE EVALUATION RESULTS

Data needed for fatigue evaluation were extracted from where the maximum equivalent plastic strain was calculated. The CUF was calculated using two strain-based evaluation methods for each cycle block. Figure 5 shows the point when the calculated CUF becomes 1 for the internal pressure of 4.80 MPa with sine wave. Noting that the failure occurred after the 3rd 2.53 g acceleration cycle block in the experiment, the Sec. VIII method predicted failure very conservatively. The CVGSM still predicted failure conservatively but more accurately than the Sec. VIII method.

Table 3 shows the CUF per cycle block and the total CUF calculated by Sec. VIII method, and Table 4 is for CVGSM. The CUF calculated by Sec. VIII method is 24.79 and 11.13 for the sine wave test, and 25.53 for the random wave test, indicating very conservative results. On the other hand, the CUF calculated by CVGSM is 5.01 and 1.70 for the sine wave test, and 2.16 for the random wave test, showing that the accuracy is considerably increased, aligning the tendency of our previous study on the quasi-static cyclic elbow test (Lee et al, 2023).

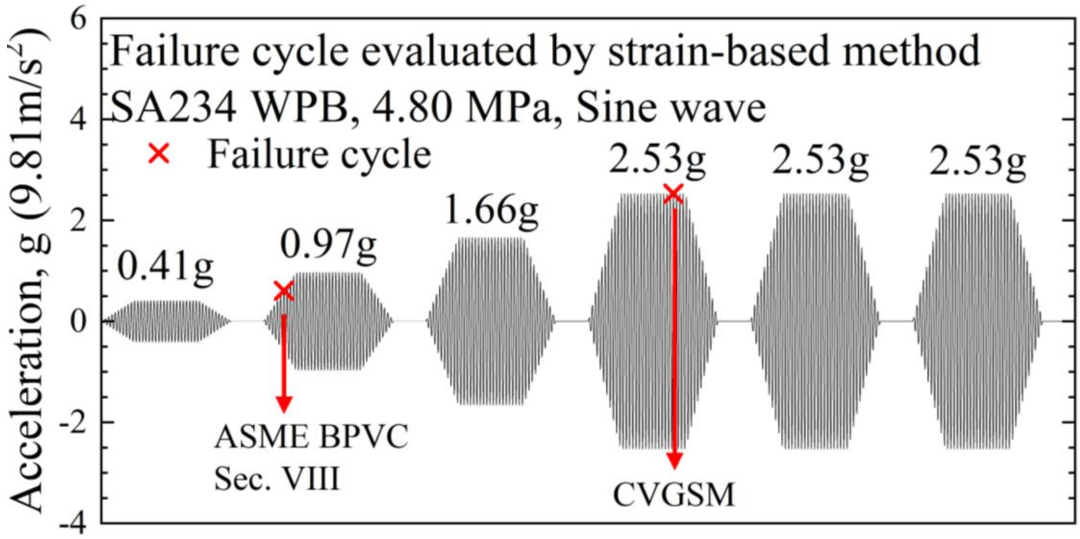


Figure 5. Predicted failure cycles evaluated by strain-based evaluation method: ASME BPVC Sec. VIII Div. 2 Part 5 and the cyclic void growth/shrinkage model.

Table 3. The CUF per cycle block and the total CUF calculated by method presented in ASME BPVC Sec.VIII.

Input wave	Internal pressure (MPa)	CUF per cycle block (Number of repetitions)				Total CUF
		0.41g	0.97g	1.66g	2.53g	
Sine wave	0.18	1.03(1)	1.58(1)	2.06(1)	2.52(8)	24.79
	4.80	0.92(1)	1.40(1)	1.86(1)	2.32(3)	11.13
Random wave	4.80	0.13(1)	-	-	0.63(40)	25.53

Table 4. The CUF per cycle block and the total CUF calculated by cyclic void growth/shrinkage model.

Input wave	Internal pressure (MPa)	CUF per cycle block (Number of repetitions)				Total CUF
		0.41g	0.97g	1.66g	2.53g	
Sine wave	0.18	0.10(1)	0.22(1)	0.37(1)	0.54(8)	5.01
	4.80	0.06(1)	0.14(1)	0.25(1)	0.42(3)	1.70
Random wave	4.80	0.01(1)	-	-	0.05(40)	2.16

CONCLUSION

In this study, the FE dynamic simulation of the pipe elbow test was performed, and simulation results were compared with the experimental data. The comparison of the acceleration of mass in the elbow specimen and the opening displacement between both ends of the elbow showed that the FE simulation was performed reliably. Using the simulation results, two strain-based evaluation methods were applied to the elbow under dynamic cyclic loading. The method presented in ASME BPVC Sec. VIII Div. 2 Part 5 gives very conservative results. The method incorporating the void shrinkage effect significantly improves the assessment results and still gives conservative results. These findings are consistent with the results for quasi-static cyclic loading.

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