Ductile Tearing Simulation of Piping System with Circumferential Through-wall Cracked under Seismic Loading

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1. Introduction

A structural integrity assessment of piping systems that constitutes a nuclear power plant is very important. Since the great east Japan earthquake, failure prediction of a piping system under seismic loading is important in maintenance of nuclear power plant components. Prediction of the fracture behavior of cracked plant components is difficult for both cost and time reasons. For this reason, various damage analysis methods were developed by various researchers to predict crack behavior [1-5]. Among various methods, the multiaxial fracture strain energy damage model was applied to simulated crack growth in a CT specimen, cracked pipe and piping system with circumferential surface crack, and the simulation results were shown to be good agreement with experimental results [3-5].

In this paper, ductile tearing in a piping system with a circumferential through-wall cracked pipi under seismic loading condition is simulated using multiaxial fracture strain energy damage model and simulation results are compared with published experimental data [6].

2. Experimental results

Battelle test [6] results on piping system with circumferential through-wall cracked pipe under seismic loading condition are considered in this paper. A106 Gr. B carbon steel was considered. The experiment was performed at 288°C. Figure 1 shows the saturated stress strain curve under cyclic loading condition.

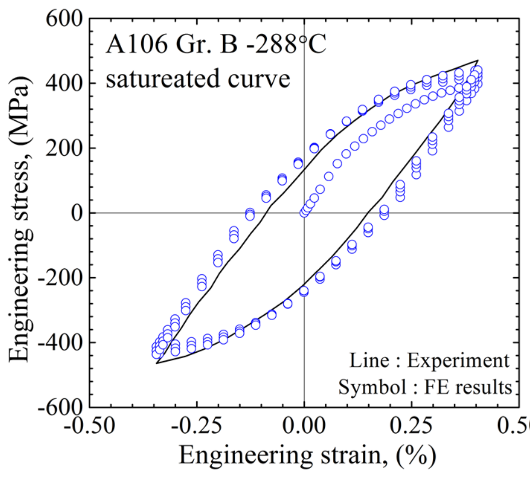

Fig.1. Comparison of experimental saturated stress-strain curve with simulated results under cyclic loading condition.

Figure 2, 3 show the illustration of the piping system test facility and crack geometry. The pipe loop was fabricated from predominantly 16-inch nominal diameter Schedule 100 pipes. The average outside diameter and wall thickness for the pipe section were 407 mm and 25 mm for the surface cracked pipe. Two ends of the pipe loop were welded to a 1500 pound class weld neck flange. Several points in the system were restrained in both the vertical and horizontal direction to the pipe axis, as shown in Fig. 2. The pipe was pressurized with internal pressure of 15.5MPa. A system load in the y-axis was applied by a piston actuator with the 457mm-stroke capacity, as indicated in Fig. 3. Figure 4 shows the experimental moment data at crack plane.

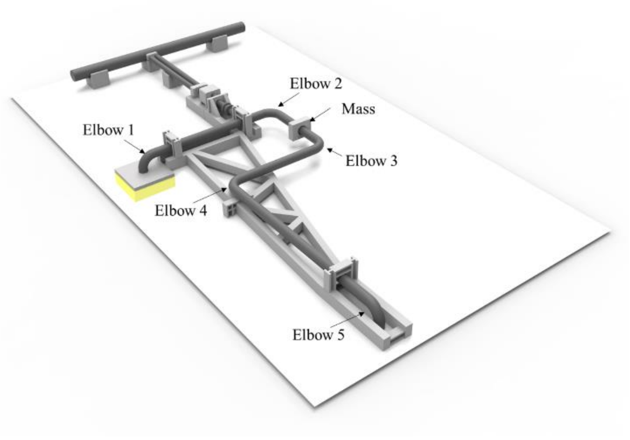

Fig. 2. Illustration of the piping system test facility [6]

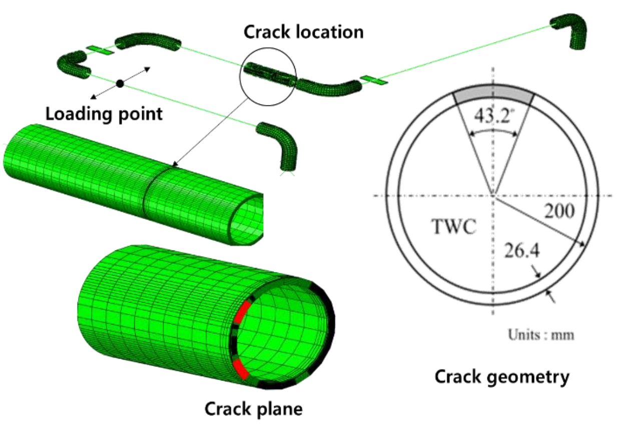

Fig. 3. Crack geometry of the through-wall cracked pipe..

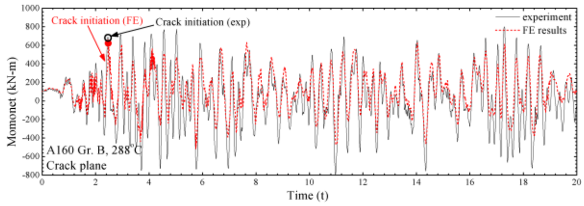

Fig. 4. Comparison of experimental moment data at crack plane pipe with simulated results.

3. FE analysis

3.1 Damage model

As mentioned in Section 1, multiaxial fracture strain energy damage model was used to simulate the piping system with circumferential through-wall cracked. In this model, the multiaxial fracture strain energy density W_f is assumed to be give by

$$W_f = A\exp\left(-1.5(n+1)\frac{\sigma_m}{\sigma_e}\right) + B \qquad (1)$$

where *A* and *B* are material constants, and *n* is the plastic strain hardening component. Local ductile failure is assumed to occur when the cumulative damage due to plastic strain energy reaches the critical vale ω_c.

$$\omega = \sum \Delta\omega = \omega_c, \quad \Delta\omega = \frac{\Delta W_p}{W_f} \qquad (2)$$

The incremental ductile damage is determined by incremental plastic strain energy density and multiaxial fracture strain energy density. In the previous study[4,5], the variables for A106 Gr. B material were determined. (A=599, B=29 , n=0.236, ω_c=0.4 at 0.6mm mesh size at crack tip) Failure of an element was implemented using ABAQUS [7].

3.2 Cyclic material properties

To determine the cyclic hardening properties, the 3rd order combined hardening rule was considered. In this model, as isotropic hardening model was considered to reflect the expansion of yield surface, give by

$$\sigma_y = \sigma_{yo} + f(\varepsilon^{pl}) = \sigma_{yo} + Q(1 - e^{-b\varepsilon^{pl}}) \quad (3)$$

The 'decomposed' nonlinear kinematic hardening rule proposed by Chaboche [8] was considered to reflected the kinematic hardening rule, give by

$$d\alpha = \sum_{i=1}^{3} \frac{2}{3} C_i d\varepsilon^{pl} - \gamma_i \alpha_i dp_i, where\ dp = |dp| \quad (3)$$

In the previous study[4,5], cyclic material property coefficients for A106 Gr. B were determined, as tabulated in Table I.

Table I: Cyclic material coefficient for A106 Gr. B [4, 5]

Isotropic hardening	Q			b		
	150 MPa			6		
Combined hardening	C_1	C_2	C_3	γ_1	γ_2	γ_3
	110000	20000	1000	1000	100	10

3.3 Damage simulation

To simulate the piping system with a circumferential crack under cyclic loading conditions, 3-D FE damage analysis was performed. The FE mesh described in Fig. 3 was used. To perform the time history analysis, the Rayleigh damping model was considered with α=2.0364 and β=0.000882. The FE analysis results for the through-wall crack case are compared with experimental data in Fig. 4.

4. Conclusions

In this paper, FE ductile tearing simulation results of a piping system with a through-wall cracked pipe under seismic loading conditions are compared with Battelle [6] test results. To perform the damage simulation, multi-axial fracture strain energy model was used. Simulated crack initiation moment is good agreement with experiment result.

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