# Numerical ductile fracture simulation of Through-Wall Cracked Pipe Test under Very Low Cyclic Loading Condition at Very Low Cycle Fatigue

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## 1. Introduction

The seismic load consists of a dynamic loading reflecting the effect of strain rate and cyclic loading which reverses the loading direction. Under seismic loading, fracture toughness of pipe material in nuclear power plant is more influenced by cyclic loading than dynamic loading [1]. Therefore, the safety margin of cracked equipment should be predictable under cyclic loading condition to ensure the structural safety of the plant. Damage analysis using numerical simulation is one of the methods to predict crack safety. This method considers the accumulative damage effect by cyclic loading and can increase the margin by mitigating the conservativeness of the existing elastic stress analysis [2-3]. In this study, through-wall cracked pipe tests were simulated for damage analysis under monotonic and cyclic loading conditions. The pipes were composed of SA508 Gr.1a (low alloy steel) was applied. The damage model required for numerical simulation was multi-axial fracture strain energy model based on the stress triaxiality [2-3]. The energy-based damage model parameters were determined by simulating standard tensile and monotonic pipe test. To simulate different material hardening at cyclic loading, A/F [4] and Chaboche [5] model were applied, which consisted of one and three non-linear kinematic hardening term. As a result, both models simulated crack growth similar to experiment under load-controlled fully reversed cyclic loading (R=-1).

## 2. Experiment

The test material was SA508 Gr. 1a, which is used for nuclear power plant pipe. Tensile and pipe tests were performed at room temperature. Tensile test were carried out round bar specimen with a diameter of 5 mm and a gage length of 25 mm as given in ASTM E8/8M. The tensile properties are summarized in Table 1.

The small size real cracked pipe specimen had an outer diameter of 72.5 mm, a thickness of 8.5 mm, and pipe length of 250 mm. The loads were given at 430 mm and 1630 mm with four-point bending. Figure 1 shows pipe test apparatus. The cracked pipes were subjected to monotonic and cyclic loading. The peak load of cyclic loading was applied in fully reversed cycle at 85% maximum load under monotonic loading conditions ($P_{mono}$ = 30.3 kN).

Table 1 Summary of material tensile properties

| Material | Temp | YS | TS | RA |
|---|---|---|---|---|
| SA508 Gr. 1a | 23 °C | 313 MPa | 479 MPa | 78.9 MPa |

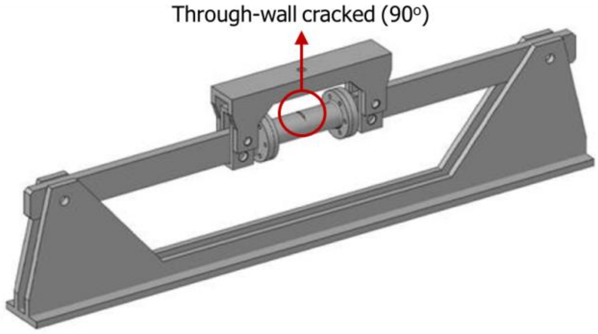


Fig.1 Through-wall cracked pipe test apparatus

## 3. Determination of damage model

Multi-axial plastic strain energy damage model was function of the stress triaxiality and plastic strain energy [2-3]. The multi-axial fracture strain energy locus, a variable in the damage model, was determined by tensile test as follows.

$$W_f = 2780 \cdot \exp\left(-1.81 \cdot \frac{\sigma_m}{\sigma_e}\right) [\text{MPa/mm}^3] \quad (1)$$

Critical damage value and element size were determined by simulating through-wall cracked pipe test under monotonic loading using ABAQUS v2016 [6]. Figure 2 shows FE pipe mesh using damage analysis. The FE model was 1/4 symmetric model with C3D8 element type, and the crack tip element size of 0.6 mm. Figure 2 compares the crack growth simulated by damage analysis with experiment data. The critical damage value was determined as a value ($\omega_c$=0.48) simulating ductile tearing similarly. Damage model determined by monotonic loading was applied to cyclic loading simulation by law of energy conservation [4].

### 4. FE simulation under cyclic loading condition

Non-linear constitutive equations were applied to simulate kinematic hardening of cyclic loading [4-5]. Figure 3 compares true stress-true plastic strain curve with hardening models with different number of back stress term. Figure 4 shows comparison of experimental crack growth with simulated results under load-controlled cyclic loading with R=-1. Both hardening models showed similar ductile tearing and predicted the experiment well.

### Acknowledgment

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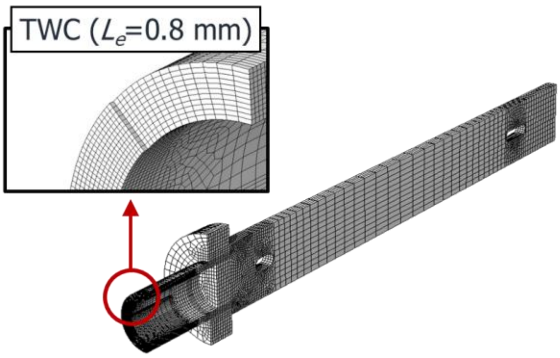


Fig.1 FE pipe mesh using damage analysis

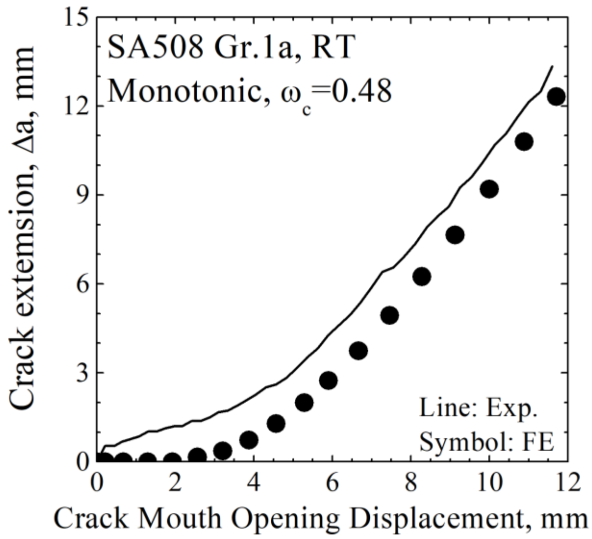


Fig.2 Crack extension versus CMOD

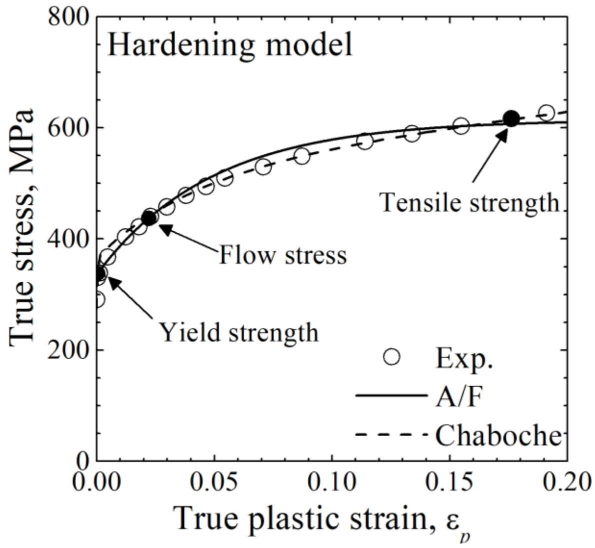


Fig.3 Non-linear kinematic hardening model

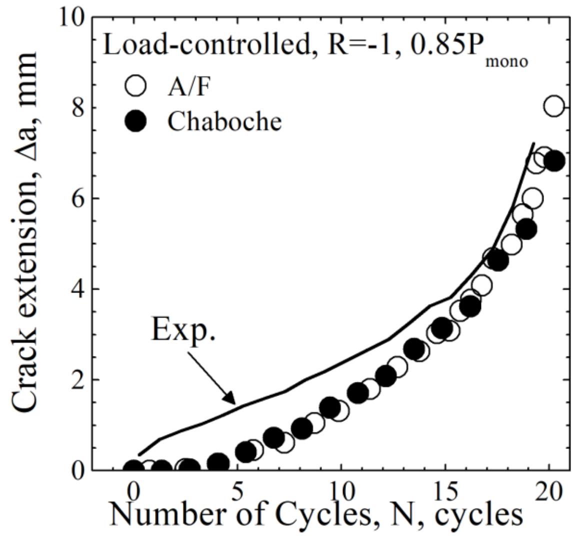


Fig.4 Comparison of experimental crack growth with simulated results for hardening model.