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Simulation of ductile fracture toughness test under monotonic and reverse cyclic loading

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ABSTRACT

This paper presents a ductile crack growth simulation method for monotonic and reverse cyclic loading with large-scale yielding using the damage model based on the multi-axial fracture strain energy. The damage model has two parameters which can be determined from tensile and fracture toughness data under the monotonic loading condition. The determined damage model then can be used to simulate ductile crack growth subjected to reverse cyclic loading with large-scale yielding. The proposed method is validated against test data for SA508 Gr.1a and TP316 under monotonic and reverse cyclic loading with three different reverse loading ratios.

1. Introduction

Performing full-scale test is important to develop and to validate structural integrity analysis methods of piping systems. However, it can be time-consuming and expensive. Furthermore, it is not easy to perform tests reflecting complex geometries and various loading conditions. An efficient way to minimize expensive and time-consuming full-scale tests and to design complex tests is ductile tearing simulation based on the local approach. Various models for ductile tearing simulation, such as Gurson-Tvergaard-Needleman model [1–4], Rousellier model [5] and multi-axial fracture strain model [6–9], have been reported up to present and applied to simulate ductile tearing in various cracked components under monotonic loading condition.

In order to apply this method to piping component, it is important to consider not only the normal operating loading conditions but also severe conditions such as seismic loading conditions. Note that seismic loading can be characterized by the high strain rate and low cycle loading condition. Under high strain rates, tensile properties can be affected by the strain rate [10–17] and accordingly various constitutive equations have been reported to quantify the effect of the strain rate on tensile and fracture properties [18–21]. Based on these constitutive equations, several researcher have already published a number of papers on ductile fracture simulation using the Gurson-Tvergaard-Needlman model [10,11,14], the cohesive zone model [10–13] and the multi-axial fracture strain model [17]. However, it has been also shown that the strain rate effect is minimal on fracture toughness properties and piping component fracture behaviours for material typically used in nuclear power plant piping components [17].

In contrast to the strain rate effect, cyclic loading effect on piping component fracture behaviour has been shown to be very significant. Some experimental tests have been carried out to quantify effects of the cyclic compressive load level and frequency on *J*-resistance curves [22–27]. It has been found that “apparent” *J*-resistance curves can significantly decrease under reverse cyclic loading, compared to those under monotonic loading. The degree of reduction in *J*-resistance curves was dependent on the load ratio and frequency. Compared to existing experimental works to quantify the cyclic loading effect on fracture behaviour, works on numerical ductile fracture simulation under reverse cyclic loading are limited [28–30]. Sherry and Wilkes [28] and Klingbeil et al. [29] reported ductile fracture simulation of compact tension (C(T)) test under cyclic loading conditions based on the Gurson-based modeling. The model was determined using notch tensile and fracture toughness test under the monotonic loading condition. For cyclic hardening rules, an isotropic hardening model was considered in Ref. [28], whereas the kinematic hardening model in Ref. [29]. Based on the determined damage model, the C(T) test under cyclic loading conditions could be simulated relatively well. Khoei et al. [30], on the other hand, presented ductile crack growth simulation under cyclic and dynamic loading using a damage-visco-plasticity model. To define the cyclic hardening properties, rate-dependent constitutive model and combined hardening model were considered. The damage model was determined from tensile and notch tensile test results under monotonic loading condition. Several

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Nomenclature

A, B, C	material constants in multi-axial facture strain energy locus, Eq. (2)
a, a_0	crack length and its initial value
C_i, γ_i (i = 1–3)	material constants in kinematic hardening model, Eq. (8)
E	elastic modulus
J	J-integral
L_e	finite element size
W_p, W_f	equivalent plastic strain energy and fracture strain energy, respectively
P_{max}, P_{min}	maximum and minimum load in cyclic loading
R	load ratio = P_{min}/P_{max}
R_n	notch radius in a notched tensile bar
Q, b	material constants in isotropic hardening model, Eq. (7)
Δa	crack growth
σ_e, σ_m	effective stress and mean normal stress, respectively
σ_1, σ_2, σ_3	principal stress components
$\Delta\omega$, ω, ω_c	incremental, accumulated and critical damage, respectively
δ	displacement increment
ε^{pl}	equivalent plastic strain
σ_y, σ_{yo}	yield strength and initial yield strength

Abbreviation

C(T)	compact tension
FE	finite element
J-R	J-resistance
LLD	load-line displacement
RT	room temperature

tests using Arcan, C(T) and double-notched tests under dynamic and cyclic loading conditions were simulated using the determined damage model. Although existing methods could predict well ductile crack growth in cracked specimens under cyclic loading, determination of damage model parameters such as the Gurson-based damage model may not be straightforward. Determination of the parameters in the damage-visco-plasticity model requires many tests and elaborate calibration procedures.

In this paper, a method to simulate ductile crack growth under monotonic and reverse cyclic loading with large-scale yielding is proposed. In the method, the damage model is postulated based on the multi-axial fracture strain energy model which is an extension to our previous multi-axial fracture strain model used to simulate ductile tearing under monotonic loading conditions [31]. For validation, simulation results of C(T) tests under cyclic loading conditions with different loading ratios are compared with experimental data. Section 2 summarizes experimental data of tensile and C(T) test under monotonic and cyclic loading conditions. Section 3 explains how to determine the damage model from tensile and C(T) test data under monotonic loading condition. In Section 4, simulation results of C(T) tests under cyclic loading are compared with experimental data. Section 5 discuss the effects of crack closure and the loading ratio on C(T) J-R curves. The presented work is concluded in Section 6.

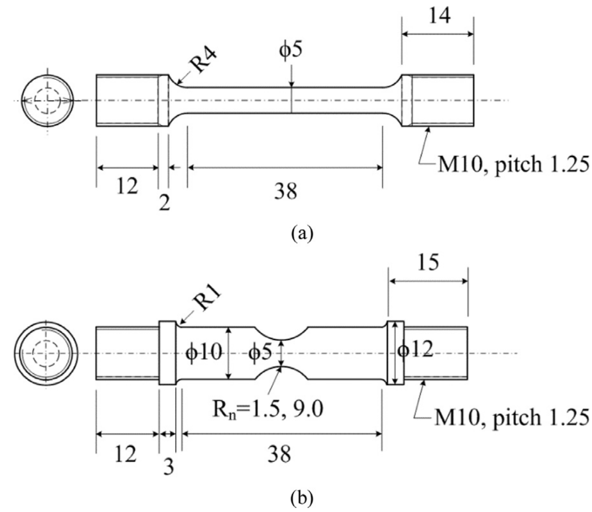

Fig. 1. Schematic illustration of (a) smooth bar and (b) notch bar tensile specimen. (unit: mm).

Table 2
Summary of the tensile properties (mean value of two experiments) [16].

Material	Yield strength (MPa)	Tensile strength (MPa)	Reduction of area (%)
SA508 Gr. 1a	359.9	543.6	74.8
TP316	266.1	573.1	82.8

2. Summary of experiments

2.1. Material

Two piping materials, SA508 Gr. 1a low-alloy steel and SA312 TP316 stainless steel, were considered in experiments, commonly used for structural materials in pressurized water reactor nuclear power plants. Chemical compositions of two materials are given in Table 1.

2.2. Monotonic tensile test results

Tensile properties were obtained from smooth and notched round bars with two different notch radii (the notch radius R_n = 1.5 and 9.0 mm), as schematically shown in Fig. 1. Tensile tests were conducted at room temperature according to ASTM standard [32]. Tensile tests were performed with the displacement rate of 0.9 mm/min and the axial displacement was measured using extensometer with the gage length of 25 mm. For each case, two specimens were tested and test results were very close.

Tensile test data are summarized in Table 2 and engineering stress-strain curves are shown in Fig. 2a and b. True stress-strain curves, obtained from smooth bar tensile tests using Bridgman correction [33], are shown in Fig. 2c.

2.3. Cyclic tensile bar test results

To characterize cyclic tensile properties of SA508 Gr. 1a and TP316, low cycle fatigue tests were conducted under the strain controlled

Table 1
Chemical composition of SA508 Gr. 1a and TP316 [16].

wt% Materials	C	Mn	P	S	Si	Ni	Cr	Mo	V	Al	Cu
SA508 Gr. 1a	0.223	1.27	0.009	0.005	0.225	0.242	0.118	0.026	0.003	0.024	0.2
TP316	0.021	1.25	0.038	0.004	0.45	12.21	16.31	2.06	–	–	–