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Original Article

Numerical Ductile Tearing Simulation of Circumferential Cracked Pipe Tests under Dynamic Loading Conditions

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ABSTRACT

This paper presents a numerical method to simulate ductile tearing in cracked components under high strain rates using finite element damage analysis. The strain rate dependence on tensile properties and multiaxial fracture strain is characterized by the model developed by Johnson and Cook. The damage model is then defined based on the ductility exhaustion concept using the strain rate dependent multiaxial fracture strain concept. The proposed model is applied to simulate previously published three cracked pipe bending test results under two different test speed conditions. Simulated results show overall good agreement with experimental results.

1. Introduction

Ductile tearing simulations under dynamic loading conditions are important in structural integrity analyses of pipelines and nuclear piping under impact or seismic loading conditions. Under high strain rates, material properties such as tensile and fracture toughness can depend on the strain rate; thus strain rate effects on material properties must be properly considered in ductile tearing simulations.

A number of constitutive equations have been proposed to characterize the strain rate effect on tensile properties and multiaxial fracture strain [1–5]. Using these constitutive equations, various methods for finite element (FE) ductile tearing simulations under dynamic conditions have been reported [6–10]. For instance, in Refs. [6–9], a cohesive zone model was used to simulate ductile tearing under dynamic loading conditions. In Ref. [10], the Gurson–Tvergaard–Needleman model was utilized. In both models, a critical issue is to determine the parameters in the damage model. For instance, in the cohesive zone model, two parameters (cohesive strength and cohesive energy) must be determined, and under dynamic conditions, these two parameters can depend upon the strain rate. For ductile tearing simulations, strain-rate-dependent parameters are determined from tensile and fracture toughness data, which is not an easy task to perform [9]. It should be further noted

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Nomenclature

$A, B, C, D, \dot{\varepsilon}_{o2}$	material constants in the multiaxial fracture strain locus, see Eq. (3)
a	crack depth
t	pipe thickness
r, r_o	mean and outer radius of a pipe
$\alpha, \beta, \gamma, n, \dot{\varepsilon}_{o1}$	material constants in the material model, see Eq. (1)
$\varepsilon, \dot{\varepsilon}$	strain and strain rate
ε_f	multiaxial fracture strain
ε^{pl}	equivalent plastic strain
σ_e, σ_m	effective stress and mean normal stress, respectively
$\sigma_1, \sigma_2, \sigma_3$	principal stress components
θ	half circumferential crack angle
$\omega, \Delta\omega$	accumulated and incremental damage, respectively
ω_c	critical damage for cracking
Abbreviations	
CMOD	crack mouth opening displacement
FE	finite element
LLD	load-line displacement
Exp	experiment
YS	yield strength
TS	tensile strength
Eqs	equations

that no previous work has compared simulation results with full-scale pipe test data.

The authors recently proposed a numerical method to simulate ductile tearing under quasistatic loading conditions, based on the ductility exhaustion concept that uses the multiaxial fracture strain model [11–13]. The damage model is determined from tensile and fracture toughness data, which is then used to simulate ductile tearing of circumferential through-wall and surface cracked pipes. Simulated results were compared with experimental pipe test data, showing overall good agreement. Although our previous studies have focused on ductile tearing under quasistatic loading conditions, the above method can be extended to dynamic loading conditions, as the strain rate effect on tensile properties and multiaxial fracture strain has been quantified (e.g., [14]).

In the current paper, the numerical method to simulate ductile tearing is extended to consider dynamic loading conditions. The presented method is applied to dynamic fracture test data sets performed at Battelle Memorial Institute, Columbus, OH, USA [15]. A finite element damage analysis for circumferential cracked pipes was performed and simulation results are compared with experimental data.

2. Summary of pipe test data

Battelle Memorial Institute has performed mechanical and full-scale cracked pipe tests under various test speeds [15]. Test data consist of a tensile test, fracture toughness test and full-scale circumferential cracked pipe test, made of A106 Gr. B carbon steel, typically used in Class 1 piping of light water reactors. Chemical compositions of A106 Gr. B are shown in Table 1. Essential information on these test data sets is presented herein, while more detailed information can be found in Ref. [15].

2.1. *Tensile test results*

Tensile tests were performed at 288°C under a wide range of strain rates to characterize the strain rate effect using a flat specimen with a width of 6.35 mm, thickness of 3.18 mm and gage length of 25.4 mm. The strain was measured using an optical extensometer, and the tensile tests were conducted in a servohydraulic machine at strain rates of 4×10^{-4}/s, 3.4/s, and 11.6/s.

The resulting engineering and true stress–strain curves under different strain rate conditions are shown in Fig. 1A and B. The 0.2% proof (yield) strength, ultimate tensile strength and elongation at different strain rates are summarized in Table 2. The ultimate tensile strength decreases with increasing strain rates, as shown in Fig. 1C.[1] Such behavior differs from typical carbon steels, likely due to the presence of the dynamic strain aging phenomenon [16,17]. Yield strength also decreases with an increase the strain rate but the data for the 11.6/s strain rate condition show the opposite trend. Of course, this might be due to measurement problems. The effect of the strain rate on the strain hardening coefficient is shown in Fig. 1D, suggesting that the strain hardening coefficient decreases slightly when the strain rate increases.

2.2. *Fracture toughness test results*

Two fracture toughness [J-resistance (J-R) curve] tests were performed at 288°C using 0.5T compact tension (C(T)) specimens machined from A106 Gr. B pipes. The specimens were oriented such that crack growth occurred in the circumferential direction (L-C orientation) and were side-grooved on both sides. One test was performed under a quasistatic condition and the other under a high speed condition. Load-line displacement (LLD) rates from the quasistatic test were elected to cause crack initiation within 5–20 minutes. In the dynamic fracture toughness test, the displacement rate was selected to cause initiation within approximately 0.2 seconds. Note that the LLDs in these tests were measured from the actuator in the testing machine. Both tests employed the direct-current electric potential method to monitor crack initiation and growth. The J values were obtained according to ASTM E813-81 [18].

The resulting J-Rand LLD curves are displayed in Fig. 2. The experimental results show that the J-R curve is not sensitive to the test speed.

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[1] More than three test data are shown in Fig. 1C. According to Ref. [15], more than three tests were performed but, due to measurement problems, only tensile strengths were reliably measured. Fig. 1C includes all measured test data.

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