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Numerical model for unstable ductile crack propagation and arrest in pipelines using finite difference method

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A B S T R A C T

Prevention of unstable ductile crack propagation has been a great issue in pipeline industry. For appropriate pipe design, the authors developed a numerical model to predict unstable ductile crack propagation/arrest using finite difference method. The features of the model are as follows: (1) pipe deformation and gas decompression are formulated based on one-dimensional partial differential equations; (2) the interaction among pipe deformation, gas decompression and crack propagation is considered; (3) soil backfill effect, which constrains pipe deformation, is considered as added density. In this paper, the model is described in detail, and applied to full-scale natural gas pipe burst tests.

1. Introduction

There are two types of crack in pipeline fracture: ductile crack and brittle crack. Because ductile crack occurs at higher temperature at which almost existing pipelines are now in operation, controlling ductile crack propagation/arrest is so important in pipeline industry.

It had been a mystery why ductile crack propagates long unsteadily although crack velocity is smaller than decompression velocity at initial pressure. Mimura first pointed out that because both decompression velocity and crack velocity decrease with decreasing pressure at a crack tip, comparison between both velocities leads to the evaluation for unstable ductile crack propagation/arrest [1]. However, Mimura just proposed a conceptual model and did not propose a quantitatively-descriptive model due to the lack of enough experimental data for establishing crack propagation resistance curve, which describes crack velocity as a function of a pressure at a crack tip. In 1960s and 1970s, Battelle memorial Institute (BMI) conducted a series of full-scale burst tests on natural gas pipelines and obtained much data for formulating the crack propagation resistance curve. W.A. Maxey proposed an empirical equation of the crack propagation resistance curve using Charpy upper shelf energy, and developed a predictive method for the evaluation of unstable ductile crack propagation/arrest, which is well-known as the Battelle Two-Curve Method (TCM) [2]. In the method, crack resistance curve and gas decompression curve are compared: unstable ductile crack is judged to occur if two curves have intersections, if not, the crack is judged to decelerate rapidly and be arrested. Two curves are considered independently, which means that the interaction between crack propagation and gas decompression is neglected.

In Japan, HLP committee, which consists of Japanese major pipe producers, was highly interested in unstable ductile fracture in pipelines, and aware of the fact that the empirical equation of the crack resistance curve established by BMI did not

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Nomenclature

ε_x	axial strain
ε_θ	circumferential strain
$\gamma_{x\theta}$	shear strain
κ_θ	circumferential curvature
v	circumferential displacement
w	radial displacement
R_0	pipe radius
ψ	shape parameter
N_x	axial force
$Q_{x\theta}$	shear force
M_θ	bending moment
W_{int}	internal work
W_{ext}	external work
p	internal pressure
ρ_{pipe}	density of a pipe
h	pipe wall thickness
S	whole mid surface of a pipe
$\dot{w}_{\text{pipe}}$	radial velocity of a pipe
h_b	soil depth
ρ_{soil}	density of the soil
θ_{open}	opening angle of a pipe
ρ_{add}	added density of a pipe
ρ	density of gas
u	velocity of gas
A	cross section of a pipe
ϕ	pipe opening width
$\dot{m}$	mass outflow rate per unit area
R	specific gas constant
T	temperature of gas
γ	specific heat ratio of gas
$\mathcal{G}$	dynamic energy release rate
W_g	work done by gas on pipe wall
U	accumulated strain energy
E_k	kinetic energy of pipe wall
J	crack propagation resistance
V	crack velocity
J_0	crack resistance on the quasi-static condition
Δx	spatial mesh size
Δt	time step size
n	the total number of time steps while a crack is judged not to propagate
API	American Petroleum Institute
ASTM	American Society for Testing and Materials

predict well the results of full-scale burst tests using the X70 pipes produced by Japanese pipe producers. Therefore, HLP committee started to investigate unstable ductile fracture since 1978 and conducted a series of full-scale burst tests on controlled rolled X70 pipe to obtain the crack propagation resistance curve suited for controlled rolled X70 pipe [3–5]. Meanwhile, HLP committee proposed the HLP method that is based on the TCM and improved by incremental formulation which enables calculation for the history of crack length and velocity [6].

The TCM and the HLP method have the same shortcomings that the interaction between crack propagation, gas decompression and crack propagation is neglected and the empirical equation for crack propagation resistance curve is determined based on limited experimental data of full-scale burst tests. To overcome these shortcomings, some physically-based model was proposed. Emery et al. proposed the numerical model with the assumption that a pipe is an assembly of rings and crack propagation is regarded as cutting of the rings [7,8]. Finite element based models also have been developed for the evaluation of unstable ductile crack propagation/arrest without empirical parameters. O'Donoghue et al. first proposed the finite element based model where gas flow, pipe deformation and crack propagation are coupled and the judgement for crack