Engineering Fracture Mechanics 77 (2010) 671–684

Contents lists available at ScienceDirect

Engineering Fracture Mechanics

journal homepage: www.elsevier.com/locate/engfracmech

Constraint effect on the ductile crack growth resistance of circumferentially cracked pipes

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ARTICLE INFO

Article history:
Received 14 April 2009
Received in revised form 7 September 2009
Accepted 12 November 2009
Available online 18 November 2009

Keywords:
Axisymmetric model
Pipes
Biaxial loading
Ductile crack growth
The complete Gurson model
Large scale yielding

ABSTRACT

A systematic study has been carried out by using 2D axisymmetric models to understand the ductile fracture behavior of pipes with internal and external circumferential cracks. Crack growth resistance curves have been computed using the complete Gurson model. Pipes with various diameter-to-thickness ratios, internal pressure, crack depths and material properties are analyzed. The results have been compared with those of corresponding SENT and standard SENB specimens. It clearly indicates that the SENT specimen is a good representation of circumferentially flawed pipes and an alternative to the conventional standard SENB specimen for the fracture mechanics testing in engineering critical assessment of pipes.

1. Introduction

Crack initiation and stable growth in ductile materials are usually described by *J–R* curves obtained from standard fracture specimens. The original idea was that a single parameter, *J*-integral (energy release rate) or crack tip opening displacement (CTOD), can be used to characterize the crack-tip stress filed and the unique fracture resistance curve, *J–R* or CTOD-*R*, is sufficient to represent the material behavior. However, there has been growing evidence showing that the fracture toughness and resistance curves are strongly geometry-dependent [1–5]. Therefore, two-parameter fracture theory (e.g. elastic *T*-stress [6] and *J–Q* theory [7,8]) has developed to characterize the crack-tip stress field and quantify constraint filed levels for various geometries and loading configurations in elastic–plastic materials.

Crack-like defects in pipe systems often develop during fabrication or in-service operation. The standard single edge notched bending (SENB) specimen with crack depth of $a/W = 0.5$ has a significantly higher geometry constraint than actual pipes with circumferential surface cracks, which therefore introduces a high degree of conservatism in engineering critical assessment of pipes. Moreover, it is difficult to know how conservative the results are, because the geometry constraint is highly material-dependent [9].

For circumferential surface flaws in pipes, the single edge notched tension (SENT) specimen has frequently been used because it has a geometry constraint in front of the crack tip that is similar to the cracks in pipes. Much work has been carried out on tensile testing for the SENT specimen as an alternative fracture mechanics specimen, and examples can be found in Refs. [10–16].

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doi:10.1016/j.engfracmech.2009.11.005

Nomenclature

a	crack depth
Δa	amount of crack growth
W	specimen width
$2L$	specimen length
t	pipe wall thickness
r_i	inner radius of the pipe
D	outer diameter of the pipe
E	Young's modulus
v	Poisson's ratio
n	strain hardening exponent
σ_0	yield stress
σ_f	flow stress
σ_m	mean normal stress
ε_0	yield strain
ε_p	equivalent plastic strain
$\boldsymbol{\varepsilon}^{\mathbf{P}}$	plastic strain tensor
$\mathbf{I}$	second-order unit tensor
q	von Mises stress
q_1, q_2	constants introduced to modify the Gurson model
f	void volume fraction
f_0	initial void volume fraction
f_c	critical void volume fraction
f_F	void volume fraction at final failure
SENT	single edge notched tension
SENB	single edge notched bending
CTOD	crack tip opening displacement
ECA	engineering critical assessment

In studying fully circumferential cracks in pipes, the crack geometry, applied load and boundary conditions are symmetrical about the axis of revolution. A typical radial plane containing the axis of rotational symmetry can represent these axisymmetric bodies, therefore the three-dimensional analysis can be reduced to a two-dimensional problem.

This work systemically applies 2D axisymmetric models to study the ductile fracture behavior of pipes with internal and external circumferential cracks under large scale yielding conditions. The complete Gurson model developed and implemented by Zhang et al. [17] was utilized to predict the ductile crack growth resistance curves. Pipes with various diameter-to-thickness ratios, internal pressure, crack depths and material properties, as denoted by hardening and initial void volume fraction, have been analyzed. The results have been compared with those of corresponding clamped-loaded SENT (with same crack depth) and standard SENB specimens.

The paper is organized as follows. In Section 2, numerical procedure, including the complete Gurson model used for predicting ductile crack growth behavior, material properties, 2D axisymmetric finite element models are described, respectively. Section 3 provides the details of the numerical analyses and results. The opening stress distribution ahead of the growing cracks is included in Section 4. The paper is closed with concluding remarks.

2. Numerical procedure

2.1. The complete Gurson model (CGM)

Ductile crack growth in metals is a result of nucleation, growth and coalescence of microvoids. A large number of investigations have been made in developing the constitutive models for elastic–plastic materials incorporating void mechanisms and the best model appears to be the one originally introduced by Gurson [18] and later modified by Tvergaard and Needleman [19–21], which thus is mostly often referred as the Gurson–Tvergaard–Needleman (GTN) model.

The yield function of the Gurson–Tvergaard–Needleman model has the following form:

$$\phi(q,\sigma_f,f,\sigma_m)=\frac{q^2}{\sigma_f^2}+2q_1 f\cosh\left(\frac{3q_2\sigma_m}{2\sigma_f}\right)-1-(q_1 f)^2=0 \tag{1}$$

where q is the von Mises stress, σ_f is the flow stress of the matrix material, f is the void volume fraction and σ_m is the mean normal stress component. q_1 and q_2 are constants introduced by Tvergaard [19,20] to modify the original Gurson model. Fixed values of q_1 = 1.5 and q_2 = 1.0 are applied as usually been taken in the GTN model in this work neglecting the dependence of q-parameters on flow and hardening properties of the matrix material [22].