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Probabilistic elastic-plastic analysis of cracked pipes subjected to internal pressure load

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HIGHLIGHTS

- In this paper presents, circumferentially cracked pipes under internal pressure load.
- For the elastic the shape function is obtained by interpolation of numerical results.
- For elastic-plastic the effect of ratios (a/t), (σ_{ref}/σ_y) and (w/t) are presented.
- The Monte Carlo method is used to predict the distribution function of (J/J_e).

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ABSTRACT

A probabilistic model was developed for predicting elastic-plastic fracture response and reliability of circumferentially cracked pipes under internal pressure load. For the elastic case, the results are in a good agreement with those in the literature. For elastic-plastic the effect of ratios (a/t), $(\sigma_{ref/}\sigma_y)$ and (R_m/t) are presented. The function of (J/J_e) is obtained by interpolation of numerical results, the effect of the ratio (a/t), $(\sigma_{ref/}\sigma_y)$ and (R_m/t) becomes important for evaluating the J integral. The Monte Carlo method is used to predict the distribution function of the mechanical response. According to the obtained results, we note that the stress variation is important factors influencing on the distribution function of (J/J_e).

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1. Introduction

Pipes and elbows are important components in any piping systems for transportation of hydrocarbons, internal cracks can occur in many structural components of cylindrical form. They are the cause of premature damage in structures such as piping, bolts, pins and reinforcements of aircraft. The fracture prediction and the reliability of such piping systems in various practical applications are primordial given their impact on the economic plan and security.

Several authors (Chapuliot, 2000; Kim and Shim, 2005; Marie et al., 2007; Shu, 2002) have been studied pipe fracture problems by means of numerical simulation in order to assess the mechanical integrity, taking into account different crack shapes. Mechab et al. (2011) obtained solutions of J integral for pipes with part circumferential surface cracks under bending load. Kim et al. (2002) analysed non-linear fracture mechanics parameters for pipes with part circumferential inner cracks, subject to internal pressure and global bending load.

The probabilistic EPFM analyses based on both methods have been reported (Rahman, 2000, 1995; Rahman and Brust, 1997; Francis and Rahman, 2000; Rahman, 1997). Probabilistic fracture mechanics is a means of quantifying the failure probability resulting from uncertainties in the values of the parameters used to perform a failure assessment of cracked structures through probabilistic analysis techniques (Sandvik et al., 2006, 2008). A probabilistic model was developed by the author for elastic-plastic analysis of circumferential through-wall cracks in pipes for leak-before-break applications (Rahman, 2000; Rahman et al., 1995).

In this paper a probabilistic model was developed for predicting elastic-plastic fracture response and reliability of circumferentially cracked pipes under internal pressure load. For elastic-plastic the effect of ratios (a/t), (σ_{ref}/σ_y) and (R_m/t) are presented. The function of (J/J_e) is obtained by interpolation of numerical results.

2. Finite element analyses

2.1. Geometrical model and FE analyses

This study presents a three-dimensional finite element analysis of the code ABAQUS (ABAQUS, 1998) for semi-elliptical inner cracks

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Nomenclature

J	J-integral
a	crack depth
n	strain hardening index in the (R–O) Ramberg–Osgood
P, P_L, P_{OR}	internal pressure, limit pressure and optimised reference load
Q, Q_L, Q_{OR}	generalised load, plastic limit load and optimised reference load
t	wall thickness of the cylinder
α	coefficient for the (R–O) Ramberg–Osgood
ε_o	normalising strain
ε_{ref}	reference strain
Φ	angle reflecting the location along the semi-elliptical crack front
β, θ	half of total crack angle in the part circumferentially cracked cylinder
γ	non-dimensional factor relating the limit load and the optimised reference load
R_i, R_m, R_o	inner radius, mean radius and outer radius of the cylinder
υ	Poisson's ratio
σ_y	Yield stress
σ_{ref}	reference stress
σ_{ap}	applied stress
FE	finite element
ERSM	reference stress approach
EPFM	elastic-plastic fracture mechanic

in pipes under internal pressure load. The normalised crack length ($\theta/\pi = 0.1$, 0.25 and 0.4) the ratio of crack depth to wall thickness (a/t) ranged from 0.2 to 0.8, and the ratio of the internal radius of the wall thickness (R/t) varied from 5 to 20 (Fig. 1).

Fig. 2 gives a typical FE mesh of the cracked pipe. Twenty-node isoparametric quadratic brick elements with reduced integration (C3D20R in ABAQUS) were used to construct a quarter model of the pipe. The J integral values were extracted using a domain integral method within ABAQUS. This method provides high accuracy with rather coarse models in three-dimensions. The J integral values were extracted using a domain integral method within ABAQUS. This method provides high accuracy with rather coarse models in three-dimensions. The resulting finite element model consists of 12,547 elements, as shown in Fig. 2. The crack tip was modelled with focused elements composed with 7 contours.

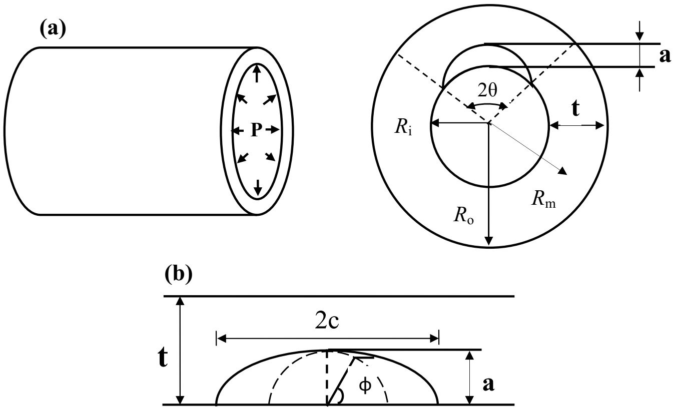

Fig. 1. (a) Schematic illustration for surface cracked pipes under internal pressure P; (b) definition of the crack angle ϕ.

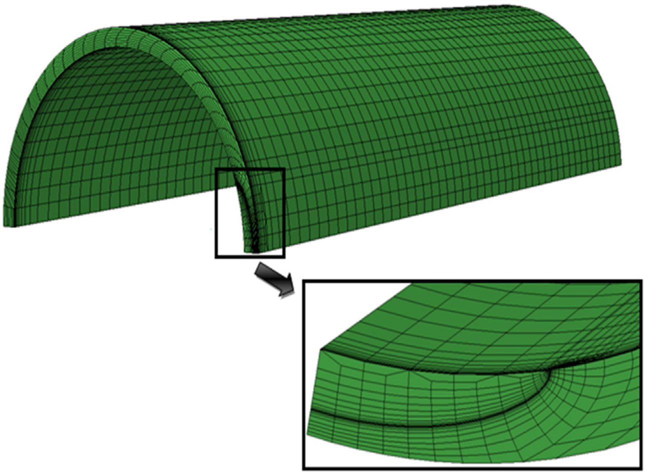

Fig. 2. Meshing model of the cylinder.

2.2. Material model

Elastic and elastic-plastic FE analyses were also performed to calculate elastic and elastic-plastic fracture mechanics parameters. For elastic analyses, an isotropic, elastic material was assumed with Young's modulus $E = 204.33$ GPa and Poisson's ratio, $\upsilon = 0.3$.

For elastic-plastic analyses Table 1 gives the mechanical properties of the material used in this study.

3. Analysis and results

3.1. Elastic analyses

The elastic FE results (the case of $n = 1$) (Ainsworth, 1984) provide the elastic component of the J-integral, J_e, from which the stress intensity factor K_I can be found as:

$$J_e = \frac{K_I^2}{E'} \tag{1}$$

where $E' = E$ for plane stress and $E' = E/(1 - \upsilon^2)$ for plane strain.

$$K_I = \sigma\sqrt{\pi a}F \tag{2}$$

$$\sigma = \frac{PR_m}{2t} \tag{3}$$

A shape factor function F is obtained by interpolation of the numerical results.

The fitted solution in this work of F for semi-elliptical inner cracks in pipes under internal pressure load is:

(Applicable range: $0.1 \le a/t \le 0.75$; $0.1 \le \theta/\pi \le 0.4$; $5 \le R_m/t \le 20$; $\phi = 90^\circ$)

$$F\left(\frac{a}{t}, \frac{R_m}{t}\right) = A_1\left(\frac{a}{t}\right)^2 + A_2\left(\frac{a}{t}\right) + A_3 \tag{4}$$

Table 1
Summary of tensile properties for **SA312** Type **304** stainless steel (Kim et al., 2004).

E (GPa)	σ_y (MPa)	σ_u (MPa)	υ	α	n
204.33	268.91	558.50	0.3	7.33	3.52

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