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Limit loads and fracture mechanics parameters for thick-walled pipes

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ABSTRACT

In this paper, information on plastic limit loads and both elastic and elastic-plastic fracture mechanics parameters is given for cracked thick-walled pipes with mean radius-to-thickness ratios ranging from two to five. It is found that existing limit load expressions for thin-walled pipes can be applied to thick-walled pipes, provided that they are normalized with respect to the corresponding un-cracked thick-walled pipe values. For elastic fracture mechanics parameters, FE values of the influence functions for the stress intensity factor and the crack opening displacement are tabulated. For elastic-plastic *J*, it is shown that existing reference stress based *J* estimates can be applied, provided that a proper limit load for thick-walled pipes is used.

1. Introduction

The assessment of crack-like defects in pipes is an important issue in design and maintenance of power plant components. Accordingly, numerous works have been published up to the present, and reviewing the literature in detail would be too lengthy. Interested readers can refer, for instance, to Refs. [1–8]. However, it should be noted that existing works mainly cover the cases of cracked pipes having mean radius-to-thickness ratios greater than five. Recently, in the design of critical piping components, the pipe thickness tends to be larger due to the requirement of longer service life, and thus the mean radius-to-thickness ratio tends to be smaller. Furthermore, overlay welding of critical piping components (such as pressurizer nozzle components in pressurized water nuclear reactors) for either repair or mitigation purposes also tends to make the mean radius-to-thickness ratio smaller. Another example is the use of polyethylene pipes in nuclear power plants. The mean radius-to-thickness ratio tends to be small in this case due to the large thickness required against seismic design. As shown in the above examples, there are several cases where the significance of a crack needs to be assessed for pipes having mean radius-to-thickness ratios less than five, which in turn requires a method for defect assessment. Such a method includes, for instance, the need for stress intensity factor solutions for elastic fracture mechanics analysis, limit load solutions for fully plastic fracture mechanics analysis and *J*-estimation methods for elastic-plastic fracture mechanics analysis. For thick-walled pipes, stress intensity factor solutions for through-wall and semi-elliptical surface cracks are given in [3,5,7,9–16]. Although solutions for semi-elliptical surface cracks are useful for practical information, those for constant-depth surface cracks would be also of interest. For limit loads, limited solutions for thick-walled pipes are given in Refs. [3,17,18].

This paper presents plastic limit loads and both elastic and elastic-plastic fracture mechanics parameters for thick-walled pipes where the mean radius-to-thickness ratio is less than five. Both axial and circumferential surface cracks are considered, together with the limiting through-wall crack cases. Internal pressure, axial tension and global bending loads are considered. Section 2 summarizes finite element (FE) analyses performed in this work. Section 3 presents plastic limit load results. Elastic and elastic-plastic fracture mechanics parameters are presented in Section 4 and Section 5, respectively. The present work is concluded in Section 6.

2. Finite element analysis

2.1. Geometry

Consider a cracked pipe with mean radius r and thickness t subject either to internal pressure P, axial tension N or global

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Nomenclature

a	crack depth
c	half crack length
E	Young's modulus
E'	$=E/(1-\nu^2)$ for plane strain; = E for plane stress
F	shape function for linear elastic stress intensity factor
V	shape function for linear elastic crack opening displacement
J, J_e	J-integral and its elastically calculated value
K	linear elastic stress intensity factor
n	strain hardening index ($1 \le n < \infty$) for the Ramberg-Osgood model, Eq. (2)
P, N, M	internal pressure, axial tension, and bending moment
P_o, N_o, M_o	limit load (pressure, tension and moment) for an un-cracked pipe
P_L, N_L, M_L	limit load (pressure, tension and moment) for a cracked pipe
P_{OR}, N_{OR}, M_{OR}	optimized reference load (pressure, axial tension and bending moment) for reference stress based J estimates
Q, Q_{ref}, Q_L	generalized primary load, reference load to define the reference stress and limit load
r, r_o, r_i	mean radius, outer radius and inner radius of a pipe, respectively
t	thickness of a pipe
δ	crack opening displacement (COD)
ν	Poisson's ratio
ε, ε_{ref}	strain and reference strain
σ, σ_{ref}	stress and reference stress
σ_o	limiting stress of an elastic-perfectly plastic material; yield strength for hardening materials
θ	half circumferential angle of a circumferential crack
ρ	$=c/\sqrt{rt}$, see Eq. (1)
γ	multiplication factor to relate the optimized reference load and limit load
FE	finite element
COD	crack opening displacement

bending M (Fig. 1). As a thick pipe is of main concern, three different values of r/t, $r/t = 2$, 3 and 5 were considered. However, for comparison purposes, the case of $r/t = 10$ is additionally considered. Internal, axial and circumferential surface cracks are addressed (Fig. 1). The crack is assumed to be constant-depth and thus to have a straight crack front (as depicted in Fig. 1), being characterized by its depth, a, and length, $2c$. The results for the limiting case of $a/t \rightarrow 1$ then recover those for through-wall cracks. For circumferential cracks, the crack length, $2c$, at the mid-thickness position is related to the circumferential crack angle, 2θ, by $2c = 2r\theta$. The value of θ/π was varied up to $\theta/\pi = 0.5$. For axial cracks, the normalized crack length, ρ, is introduced, defined by

$$\rho = \frac{c}{\sqrt{rt}} \tag{1}$$

2.2. Finite element mesh and loading

Fig. 2 depicts typical FE meshes for circumferential and axial cracked pipes. Symmetry conditions were fully utilized in the FE models to reduce the computing time, and thus quarter models were used. For computational efficiency, twenty-node iso-parametric quadratic brick elements with reduced integrations (C3D20R within ABAQUS [19]) were employed. The crack-tip was designed with collapsed elements, and a ring of wedge-shaped elements was used in the crack-tip region. For through-wall crack cases, two elements for circumferential cracks and three elements for axial cracks were used through the thickness. For surface crack cases, a total of eleven or twelve elements were used through the thickness; four elements in the cracked ligament, and seven to eight elements in the un-cracked ligament. Such FE meshes are believed to be sufficiently fine for the present analysis. The number of elements for through-wall cracks ranged from 1328 to 2682 and, for part-through cracks, from 3852 to 6426.

For the loading condition, internal pressure, axial tension and global bending were considered. Internal pressure was applied as a distributed load to the inner surface of the FE model. To simulate the closed end condition, an axial tension equivalent to the internal pressure was also applied at the end of the pipe. The effect of the crack face pressure was fully considered, that is, 100% of the internal pressure was applied to the crack face for surface cracks, and 50% for through-wall cracks. For axial tension and for global bending, loading was applied either by displacement or by rotation to a node in the pipe end, constrained using the MPC (multi-point constraint) option within ABAQUS. The corresponding tensile force and bending moment were determined from the nodal forces and moments.

2.3. Limit analysis

Elastic-perfectly plastic limit analyses were performed using ABAQUS [19]. The materials were assumed to be elastic-perfectly plastic, and non-hardening J_2 flow theory was employed using a small geometry change continuum FE model. For internal pressure, the analysis was performed using load boundary conditions. To avoid problems associated with convergence in elastic-perfectly plastic calculations, the RIKS option within ABAQUS was invoked. The corresponding fully plastic limit pressures could be easily obtained directly from the RIKS factor given by the FE analysis. For axial tension and global bending, all the nodes at the end of the pipe were constrained using the MPC option within ABAQUS to apply the loading, as discussed above in Section 2.2. Sufficiently large displacements (for axial tension) or rotations (for bending) were applied to the constrained node. The resultant loads can be obtained directly from the nodal force or moment. When the applied displacement (or rotation) is sufficiently large, the load

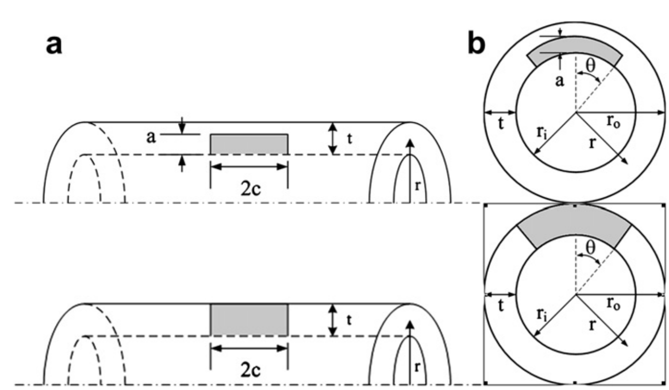

Fig. 1. Schematic illustrations of (a) axial and (b) circumferential through-wall and surface cracked pipes.