Engineering Fracture Mechanics 75 (2008) 4052–4065

Contents lists available at ScienceDirect

Engineering Fracture Mechanics

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

Application of the crack compliance method to long axial cracks in pipes with allowance for geometrical nonlinearity and shape imperfections (dents)

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ARTICLE INFO

Article history:
Received 2 April 2007
Received in revised form 22 March 2008
Accepted 26 March 2008
Available online 31 March 2008

Keywords:
Crack
Pipe
Dent
Stress intensity factor
Method of initial parameters
Crack compliance method

ABSTRACT

Application of the crack compliance method to the analysis of thin-walled rings with a radial crack has two features: a crack is considered as a concentrated angular compliance and the deformation of all other sections of the rings is calculated as for a curvilinear beam. The latter can be most conveniently found by the method of initial parameters where the values of generalized forces and displacements at the end of some zone are determined as a linear combination of their values at the beginning of the zone. The goal of the study is to derive and apply the method of initial parameters equations taking into account the influence of circumferential stresses on the ring curvature. As far as the authors know, this is the first time that the stress intensity factor has been derived for an elastic thin-walled pipe with a radial crack in a geometrically nonlinear formulation. Here, an increase in pressure leads to a somewhat slowed increase in the stress intensity factor. In addition, a number of problems for dents are considered. The effect of the dent shape on the stress–strain state is analyzed. An expression for the stress intensity factor for a complex defect, a crack emanating from the dent apex, is presented.

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1. Introduction

The modern means of in-line inspection of pipelines allows revealing a large number of cracks and dents. For each of them the operator has to make a justified decision about their acceptability or the kinds and terms of repair. The stress analysis of pipes, including the computation of stress intensity factors for cracks, is an important constituent of such a decision.

There are two problems when analyzing a pipe with a dent under a large internal pressure: the rerounding effect of the pressure and the poorly defined geometry of the dent being a local defect. Dents are characterized not only by the conventional dimensions – depth, width, and length – but also by such a subjective parameter as the smoothness of its contour (sharp, plain, etc.), which complicates the development of general methods for their analysis. In the case of a crack emanating from the dent, the problem formulation becomes more difficult because of the geometrical features of the crack. This makes the standard FEM based analysis a rather inconvenient one.

Thus for cracked dent of complex geometry the more urgent task is the development of simple engineering procedure of SIF calculation rather than graphical presentation of FEA results or construction of simplifying formulas. As example of the later approach we mention a well-known defect assessment manual [1], which provides the corresponding formula. The manual [1] uses Hopkins' solution [2] based on the strip yield model. This in fact is the simplest form [3] of a two-criteria approach and formed the basis for the first version of the well-known R6 document proposed in 1976. Thus, Hopkins'

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0013-7944/$ - see front matter © 2008 Published by Elsevier Ltd.
doi:10.1016/j.engfracmech.2008.03.008

Nomenclature

K_I	stress intensity factor (SIF)
(r, φ)	polar coordinates
R_0	the initial radius of curvature of the ideal ring
$R(\varphi)$	polar radius of the middle surface of the ring
w, u	radial and circumferential displacements
E, ν	Young's modulus and Poisson's ratio
$\vec{n}, \vec{l}$	normal and tangent vectors
θ	rotation angle of the cross-section
$\Delta\theta$, Δu	jumps in rotation angle and displacements in the cracked section
β_i, γ_i	dimensionless values of these jumps in the cracked section for i-loading
a	depth of a crack
$\alpha = a/t$	dimensionless depth of a crack
$Y_i(\alpha)$	dimensionless SIF for i-loading
M	bending moment per unit width of ring
N, Q	circumferential and transverse forces per unit width of ring
N_N	nominal force from internal pressure (as for ideal ring)
N_1	additional force due to the shape imperfection
σ_N, σ_M	intensities of stress from circumferential force and bending moment
$\sigma_q(x)$	distribution of the circumferential stresses in the cracked section due to all outer forces, shape imperfection, residual stress in case of the crack absence
$\bar{\sigma}_q(x)$	dimensionless law of the above stress distribution
q	intensity of these stresses
P	internal pressure
$\bar{p} = \frac{PR_0^3 \cdot 12}{E' t^3}$	dimensionless pressure
$\sigma_P(x)$	the law of the circumferential stress distribution in the thick-walled pipe due to inner pressure (Lame's formula)
$\sigma_P^1(x)$	the sum of the above Lame's stresses and uniform stresses from inner pressure
p_0	intensity of the above stresses
$\sigma_\varphi = PR_0/t$	circumferential stresses in thin-walled pipe
ω	coefficient of the SIF reduction
W	dent depth at the point of the center of the dent
$\Delta\varphi$	angular length of the dent
ψ_1	angle jump at the point of the center of the dent
ψ_2	angle jump at the point which is the transition from the dent to the undistorted part of the pipe
$M_N = \frac{PR_0}{t} Wt$	nominal bending moment for a small dent
N_e	equivalent axial force by Tresca's condition

solution [2] uses both nominal stresses from internal pressure and the original expression for the stress intensity factor (SIF) based on formulas for a strip with a crack under membrane and bending stresses.

The second above mentioned problem, namely the rerounding effect of the pressure action, is a more complicated and a less evident one. This phenomena is exhibited, for example, in decreasing of coefficient of pipe bend flexibility at loading by bending moment due to additional action of internal pressure. As it was said in resent paper [4] "The pressure reduction effect in smooth piping elbows is well known, but little understood". In fact the inner pressure increase the apparent stiffness of the pipe wall and the primary goal of this paper is foremost to draw attention to it in case of the presence of crack.

With respect to thin-walled shells, this problem was thoroughly studied by Calladine [5]. He have shown that small initial, or acquired due to the outer loading, deflections from the ideal cylindrical shell form can be accounted for as some additional distributed loading applied to the cylindrical shell. His method was called the equivalent load method. Practical formulas were obtained only for infinitely long axial imperfections [5] while a 3D analysis of actual defects using the approach was performed in [6]. But Papkovich [7] was the first to obtain a correct solution taking into account the action of internal pressure on the ring. Considering that the imperfection profile can be expressed as a Fourier series, he obtained a geometrically nonlinear analytical solution for displacements and stresses. Note that an identical solution is presented in the well known API 579 Fitness-For-Service Standard [8]. For completeness of presentation, it will be given in this work too.

The proposed below method consider the crack as a concentrated compliance when the jumps in displacements and angles of rotation in the cracked section are linearly related to the values of force and moment in it. The proportionality factors are calculated by integrating SIF over the crack length. This technique has found wide application in linear fracture mechanics, especially for beams, thin-walled shells, and plates. It was suggested for the analysis of elliptic cracks in plates under the name of line spring model by Rice and Levy [9] where the classical Kirchhoff's plate theory was used. Further development was made, in particular, by Delale and Erdogan [10] where an analysis of cracked shells was performed based on Reissner's governing equations.

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