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Instability analysis of pressurized pipes with longitudinal surface cracks

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ABSTRACT

Recently three of the authors of this paper presented analytical solutions for reference loads of plate geometries with semi-elliptical surface cracks subjected to tension, bending, combined tension-bending and biaxial tension. These solutions were shown to provide more accurate crack driving force estimates than the conventional limit load solutions available in the literature, and the method behind them allowed for a wider application range. Within the present paper a methodology for the fracture analysis of thick-wall pressurized pipes using the R6 assessment method and considering both, biaxial and combined tension-bending loading is developed and validated. The analyses are carried out analytically, and the comparison between the predicted critical loads and experimental burst test failure loads shows satisfying agreement, this way demonstrating the potential of the proposed method.

1. Introduction

The structural assessment of pressurized components is an important issue in many engineering applications, e.g., in the nuclear and oil & gas industry, where the risk of component failure must be minimized because of severe failure consequences [1]. In case of steel components, surface defects (corrosion pits, dents) are the most common flaws at which fatigue cracks develop. These must be considered in component assessment, as their propagation could finally lead to failure [2]. Besides theoretical analyses it is important to perform experimental tests in order to assess the load-carrying capacity of the cracked components. In the case of pressurized components burst tests are carried out in order to evaluate the critical pressure [3].

Common flaw assessment methods [4,5] require the accurate determination of the material fracture resistance. This can be measured following standard test procedures [6] which make use of specimens that are highly constrained to plastic deformation in order to provide lower bound estimates of the fracture resistance.

For elastic–plastic failure analyses, besides the stress intensity factors, limit load solutions of cracked components are needed, which can be found in handbooks [7,8]. These solutions were obtained for different yielding conditions and their accuracy is usually not well known. In order to improve the accuracy, new solutions have been generated based on finite element analyses during the last years. In particular, recent solutions for surface and through-thickness cracks in cylinders under internal pressure are provided in Refs. [9–11].

In Refs. [12,13] three of the authors of the present paper presented analytical parametric solutions for what they call reference loads for tension, bending, combined tension-bending and biaxial tension loading of plates with semi-elliptical surface cracks (see also Ref. [14]). Solutions have been also provided based on stresses, defining what the authors call reference yield stress σ_0. It must be remarked that the reference load is not a limit load, but it is rather an alternative to the limit load and it has been developed in order to obtain a better description of the crack driving force as a function of the applied load. The approach allows a wider application range and the solutions demonstrated to provide more accurate crack driving force estimates compared with the ones based on common limit load solutions, especially in case of large cracks [13]. A brief summary of the basics of the reference load,

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Nomenclature

a	crack depth (Fig. 1)
a_0	initial crack depth assumed or existent in the component
a_c	critical crack depth at failure
c	crack semi-length (Fig. 1)
c_0	initial crack semi-length assumed or existent in the component
c_c	critical crack semi-length
$f(L_r)$	ligament yielding correction function (Eqn. (12))
l	length of the pipe
p	internal pressure
p_c	critical internal pressure, failure pressure
w_j	coefficients of the weight function (Eqn. (2))
A	deepest point of the crack front (semi-elliptical surface cracks)
B	specimen thickness
B_N	specimen net thickness
C	surface points of the crack front (semi-elliptical surface cracks)
C_i,C_{ii}	fitting parameters in the reference yield stress solutions (Eqns. (3)–(5), (7), (8), (14)–(17))
CDF	crack driving force
CMOD	crack mouth opening displacement (R-curve testing)
D_o	nominal outer diameter of the pipe
E	modulus of elasticity
EDM	electric discharge machining
E'	effective modulus of elasticity (E for plane stress; $E/(1-\nu^2)$ for plane strain)
FAD	failure assessment diagram
F_0	reference load
H	distance between grips (Fig. 6)
J	integral
J_e	elastic J-integral (K^2/E')
K	stress intensity factor, K-factor
L_r	ligament yielding parameter (Eqn. (11))
L_r^{max}	localized plastic collapse limit (Eqn. (13))
R-curve	crack resistance curve, in the present paper given as $J-\Delta a$ curve
R_m	ultimate tensile strength
SIF	stress intensity factor
T	wall thickness of the pipe and of plates
W	specimen width (Fig. 6)
α	correction factor for the bending stress component (Eqn. (22))
ε	strain (general notation)
ε_{ref}	reference strain (Eqn. (12))
γ	proportionality factor between bending and membrane stress
λ	biaxial stress ratio (Eqn. (6))
ν	Poisson's ratio
σ	stress (general notation)
σ_a	axial stress (Eqn. (23))
σ_{app}	applied stress
σ_b	bending stress
$\sigma_{b,0}$	reference bending yield stress under pure bending (Eqn. (17))
$\sigma_{biax,0}$	reference yield stress under biaxial tensile loading (Eqn. (5))
σ_j	stress coefficients (Eqn. (1) and Eqn. (2))
σ_{ref}	reference stress (Eqn. (12))
σ_m	membrane stress
σ_m^*	reduced reference tensile yield stress under combined loading (Fig. 3)
σ_0	reference yield stress, general notation (Eqn. (11))
$\sigma_{m,0}$	reference yield stress for tensile loading (Eqn. (3))
σ_x	remote stress in x direction (Fig. 1)
σ_r	radial stress (Eqn. (23))
σ_θ	hoop stress (Eqn. (23))
σ_y	remote stress in y direction (Fig. 1)
σ_Y	yield strength (general), either R_{eL} or $R_{p0.2}$
ξ	coordinate through the wall thickness (Eqns. (1) and (2)), general notation
Δa	stable crack extension

respectively reference yield stress, approach is provided in the Appendix.

Within this study the reference yield stress solutions for plates under biaxial tensile loading have been applied to the assessment of thick-walled pressurized pipes and validated against four burst tests. The use of substitute geometries (plates) for the structural integrity assessment of these pipes was discussed by some of the authors in previous works, in which J-integral analytical estimates for plates were compared to the values calculated by means of finite element simulations on pipes [15,16].

Axial semi-elliptical surface cracks of different size were introduced on the outer surface of the pipe by electric discharge machining (EDM) and subsequent cyclic loading. Component analysis has been conducted analytically, thus giving a straightforward approach and time efficient tool compared to other methods (e.g. finite elements). The analytical procedure demonstrated to yield good predictions (slightly conservative) of the burst pressures.

2. The fracture mechanics approach

2.1. The proposed methodology

In the present study a methodology is developed for predicting the instability of pressurized pipes subjected to complex loading conditions different from uniaxial loading. The principle follows methods such as R6 [4] or SINTAP/FITNET [5]. The stress profile (assumed as two dimensional) is determined for the component without crack. This can be done by finite elements or, as in the present case, analytically. It is then applied to a substitute geometry (a plate or a hollow cylinder) depending on the component to be investigated. Based on the stress profile, which is usually fitted by a polynomial, the K-factor and the limit load or, as proposed by the authors, the reference load is determined for the deepest and the surface points of the crack (points A and C respectively).

The proposed method consists of a number of subsequent steps that will be explained in this section.

2.1.1. Step 1: determination of the stress profile in the component without crack

The stress profiles can be obtained by finite elements or by analytical methods, however, all loading components have to be considered. In the general case this may include the applied service loads such as external forces, moments or pressure, dead weight and inertia loads, thermal stresses, residual stresses (welding residual stresses, press fit stresses, etc.), and stresses due to mechanical resonance. For pressurized components it is important to consider biaxial tension loading as presented in Ref. [15] and in the validation example in this paper.