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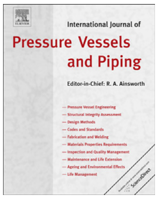

Blunt defect assessment in the framework of the failure assessment diagram

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ABSTRACT

In order to reduce over-conservatism in fitness-for-service assessment procedures, experimental evidence and recent analytical developments recognise the importance of considering the actual shape of non-sharp flaws and/or the real geometric constraint conditions at the crack tip. This paper addresses the effect of blunt defects on the structural integrity assessment of reactor pressure vessel (RPV) and pipeline steels. Parametric studies for compact tension specimens with various notch root radii are performed using finite element analysis. The notch fracture toughness, the resistance to the onset of ductile cracking and the *J*-integral, quantifying the notch driving force, are evaluated. A stress-modified fracture strain model is used as a virtual testing method. The results are analyzed in the framework of the failure assessment diagram (FAD), showing that the existing shape of the FAD is also suitable for assessments of blunt defects and how the concepts introduced can be used to reduce the conservatism in defect assessment, define margins on failure and indicate when plastic collapse is the dominant failure mechanism.

1. Introduction

There exist many situations in engineering applications in which detected defects are not sharp [1–3]. However, it is common practice to simplify and re-characterise these defects into shapes more amenable to analysis. Current assessment procedures such as API579-1 [4], R6 [5] and BS7910 [6] usually treat defects as infinitely sharp cracks, both because they can be treated by well-known approaches like linear elastic fracture mechanics (LEFM) or elastic plastic fracture mechanics (EPFM) and also because this assumption represents the worst case scenario, thus being conservative from a fitness-for-service (FFS) point of view.

The material resistance to fracture is usually described by critical stress intensity factor (SIF), crack tip opening displacement (CTOD) or *J*-integral values. A considerable amount of published work recognises the benefit of using an apparent/effective fracture toughness in FFS assessments [7–10]. Constraint, that is, the level of triaxial state of stress, is usually related to the capacity to absorb more energy by accommodating plastic deformation. The local stress and strain fields surrounding a non-sharp defect are known to be less severe than those at the tip of a sharp crack, thus exhibiting a reduced constraint condition. The initiation and propagation of damage under these conditions will occur at higher values of applied J and higher J-R curves will be typically measured experimentally. Thus, in FFS calculations, this increased toughness implies that the conditions for repair or replacement of a component containing a non-sharp defect could be relaxed.

A number of authors have tested components containing non-sharp defects to evaluate the effective fracture toughness for a variety of materials and notch geometries. Both cleavage fracture [11,12] and ductile tearing [13–16] as well as the influence of the notch geometry on the mechanisms triggering fracture have been reported in the literature [8,17,18].

The evaluation of the effective fracture toughness for a given material requires extensive experimental testing for the component of interest and for different notch/defect geometries. Thus, it is expensive and time-consuming. Different approaches making use of minimum experimental information may be needed to reduce the number of tests. In this context, several authors [19–23] have proposed and validated different procedures to include the effect of

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Nomenclature

a	crack length
a_o	initial crack length
Δa	average crack growth
B	specimen thickness
E	elastic modulus
F^{Kr}	reserve factor on K_r
$F^{Kr(crack)}$	reserve factor on K_r for a sharp crack
$F^{Kr(\rho)}$	reserve factor on K_r for a blunt defect
J	J-integral
J_{el}	elastic J-integral
J_{el}^{crack}	J value evaluated elastically for a sharp crack
J_{el}^{ρ}	J value evaluated elastically for a blunt defect
J_{IC}^{crack}	J value at 0.2 mm crack growth for a sharp crack
J_{IC}^{ρ}	J value at 0.2 mm crack growth for a blunt defect; effective fracture toughness
$\Delta\varepsilon_e{}^p$	incremental equivalent plastic strain
K_I	mode I stress intensity factor
K_{mat}	fracture toughness
P	applied load
P_{max}	maximum load
P_L	(plastic) limit load of a structure containing defects
W	specimen width
α, β, γ	material constants, see Eq. (5)
ε_f	fracture strain
σ_{flow}	flow stress
σ_u	ultimate tensile stress
$\sigma_{0.2}$	0.2% proof stress
σ_e	von Mises effective stress
σ_h	negative hydrostatic (mean normal) stress
σ_h/σ_e	stress triaxiality
σ_e, σ_m	equivalent stress and hydrostatic stress
σ_1, σ_2, σ_3	principal stresses, see Eq. (4)
ν	Poisson's ratio
ω, $\Delta\omega$	accumulated damage and incremental damage respectively

Abbreviations

ASTM	American Society for Testing and Materials
CTOD	crack tip opening displacement
C(T)	compact tension
EPFM	elastic-plastic fracture mechanics
FAD	failure assessment diagram
FE	finite element
FFS	fitness-for-service
LEFM	linear elastic fracture mechanics
LLD	load-line displacement
MPC	multi-point constraint
N-SIF	notch stress intensity factor
SIF	stress intensity factor

the geometry on both the driving force and the constraint conditions at the defect. Most of these approaches consider small-scale yielding conditions and use LEFM or EPFM to evaluate the notch driving force (e.g., N-SIF, notch J-integral) and an additional parameter (e.g., Q- or T-stress) which defines the constraint condition in the process zone. These procedures are usually called global approaches.

An alternative framework for effective fracture toughness assessment is the application of failure models, often referred to as local approaches. Local approaches couple the loading history (stress-strain) near the crack-tip region with micro-structural features of the fracture mechanism [24]. The parameters depend only on the material and not on the geometry, and this leads to better transferability from specimens to structures than single- and two-parameter fracture mechanics methods [25]. Several models based on local approaches have been applied with considerable success for the fracture initiation mechanism given by cleavage fracture or ductile tearing. In this study, due to the high ductility of the materials under analysis, ductile tearing is considered to be the principal mechanism for fracture.

The most commonly used models for ductile fracture are the Beremin ductile model [26], the Gurson-Tvergaard-Needleman [27–29] and Rousselier [30] models. These models consider the effects of void nucleation and growth on the material stress-strain behaviour, and thus are usually called 'micromechanical models for ductile failure'. Although of some physical meaning, the number of independent parameters and the difficulty in their determination make the use of these models cumbersome for practical engineering applications.

There is another type of ductile model, usually referred to as a phenomenological model, which involves fewer parameters and is of simpler implementation. Due to the fact that stress triaxiality has a strong influence on void growth and therefore on the strain to fracture [31–35], phenomenological models correlate stress triaxiality with the critical strain to fracture. Such models have been researched by McClintock [31], Rice and Tracey [32], Hancock and Mackenzie [33,34] and Hancock and Brown [35], and further developed based on the concept of a stress-modified critical strain [36,37]. From this concept, more recently, a simple method to simulate ductile failure using a finite element (FE) technique has been proposed which is called a stress-modified fracture strain model [38,39]. This has been extensively applied to components containing defects, showing good agreement with test results including those from sharp cracks and blunt defects [39–43].

In this work, finite element ductile fracture simulations using the stress-modified fracture strain model are performed to evaluate the effect of notch radius. The varying severity of the stress fields due to the presence of the notch and the implications of the different constraint levels due to notch acuity are analyzed within the framework of the failure assessment diagram (FAD). Compact tension, C(T), specimens with a wide range of notch root radii are modeled using FEA and ductile damage simulation to construct resistance curves (J-R curves) for four different materials, showing different fracture criteria and tensile properties. Effective fracture toughness values are obtained from the J-R curves and the applied elastic J and the limit load, representing the notch driving force, are derived and assessed on the FAD. Section 2 reviews the FAD assessment. Section 3 briefly explains the damage model and the simulation technique and summarises the material properties used in this work. The different geometries of C(T) specimens and FE analysis details are described in Section 4. Results are presented and discussed in Section 5. The benefits from considering the blunt shape of defects are also discussed by means of showing the effect on reserve factor relative to that for a sharp defect. The work is concluded in Section 6.