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Ductile fracture of pipe-ring notched bend specimens – Micromechanical analysis

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ABSTRACT

Integrity of pipes is typically assessed by testing fracture mechanics specimens, such as compact tensile (CT) or single-edge notched bending (SENB). However, for some pipe dimensions it is not easy or possible to fabricate a specimen conforming to the requirements of standard procedures. A new type of specimen is proposed recently, which can be advantageous for relatively small pipe diameters and axial defects - the pipe ring notch bend specimen - PRNB.

In this work, criteria for failure by ductile fracture of PRNB specimens are determined experimentally and by application of micromechanical analysis. The influence of size of the specimen, as well as size and shape of the stress concentrator, is analysed. The results of this study, along with previous authors' results, lead to the conclusion that the pipe ring specimens can be applied in integrity assessment of pipes with defects. Also, the benefits of their application include much simpler fabrication and the same material history as the pipe itself.

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1. Introduction

Many recent studies have dealt with the analysis of deformation behaviour, failure, integrity assessment and remaining service life of pipelines. Most of them, e.g. [1–3], deal with fracture initiation, i.e. determining the critical loading level for crack growth initiation. The crack growth in pipelines is modelled so far using different techniques, such as cohesive zone model [4], the extended finite element method X-FEM [5] or micromechanical analysis [6]. In addition to fracture, the pipeline components with cracks can also fail by plastic collapse under the exploitation loads; straight pipes are considered in [7], while pipe elbows with different geometries are examined in [8,9]. Both of the failure types are considered in [10], on the pipes with axial surface cracks.

Also, in addition to crack-like defects, blunt volumetric defects (which resemble the shape of local corrosion damages), are also often analysed in the literature, [11–14]. Plastic collapse of the remaining ligament is considered as failure condition in [11,12], typically by tracking the value of von Mises stress. On the other hand, failure by fracture initiation at the position of the defect (bottom of the blunt stress concentrator - machined notch) is analysed in the papers [13,14]. Other approaches for assessment of load carrying capacity of pipes with simulated corrosion defects have also been applied, such as notch frac-

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Nomenclature

a_0	initial crack (or notch) length [mm]
a_f	final crack length [mm]
Δa	crack length increment [mm]
f	porosity or void volume fraction [−]
f^*	damage function or modified void volume fraction [−]
f_0	initial porosity [−]
f_c	critical porosity [−]
f_F	porosity at final fracture [−]
f_u^*	value of damage function at the moment of fracture [−]
f_v	volume fraction of non-metallic inclusions [−]
K	parameter which describes how the load capacity loss develops after the critical porosity has been reached in Gurson-Tvergaard-Needleman (GTN) model [−]
n	hardening exponent [−]
q_1, q_2	constitutive parameters in the GTN model and Complete Gurson model (CGM) [−]
r	void space ratio [−]
R	ring specimen external radius [mm]
S	distance between supports [mm]
W	ring specimen width [mm]
B	ring specimen thickness [mm]
S_{ij}	stress deviator [MPa]
R_f	stress ratio for cyclic loading, i.e. ratio of the minimum and maximum load [−]

Greek symbols

α, β	constants (in the CGM) introduced by Thomason [−]
ε_1, ε_2, ε_3	principal strains [−]
η	plastic correction factor [−]
λ	mean free path between non-metallic inclusions [μm]
σ_1	maximum principal stress [MPa]
σ_m	mean stress [MPa]
σ	current flow stress of the material matrix [MPa]
ϕ	yield function of the GTN model [−]

ture mechanics in [15] or using the sharp pre-crack shape to model the blunt local corrosion damages, [16]. Of course, some of the initial defects can be prevented in the pipe fabrication procedure; quality testing of the welded (seam) pipes is considered in [17].

Experimental determination of fracture toughness of the fabricated pipes is often difficult, because the standard requirements regarding the specimen/crack geometry cannot be fulfilled for all wall thicknesses. For the circumferential cracks, the authors of [6,18] have shown that the SENT specimen (single-edge notched tension specimen) is more adequate for assessment of fracture development in the pipe wall than SENB specimen (single-edge notched bending). Testing of SENB specimen is defined by ASTM 1820 standard [19], while British standard BS 8571 [20] deals with examination of SENT specimen. Another two studies [21,22] also deal with the defects in circumferential direction; the authors of [21] consider determining the stretch zone width (SZW) on the newly proposed compact pipe specimen, while the fracture conditions of these specimens are compared with those for a cracked pipeline in [22].

In this work, a recently proposed testing technique for determining the fracture toughness on defects in axial direction is applied, which includes the use of new pipe-ring notch specimens for bending (PRNB) [23,24], with stress concentrator in the form of fatigue pre-crack or machined notch with root radius = 0.25 mm, Fig. 1. The main aim is to determine the ductile fracture conditions under external loading. These specimens can be easily produced (i.e. cut) from a pipe, which enables a quick and efficient testing. Moreover, the specimen material has undergone the same manufacturing and thermal treatment as the pipe itself.

Some other examples of non-standard specimens containing cracks in axial direction of the pipe can also be found in literature, such as curved compact tension (CCT) specimens examined in [26], or different non-standard configurations for tension and bending shown in [27]. However, they are typically characterised by a relatively complex preparation and/or testing procedure.

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