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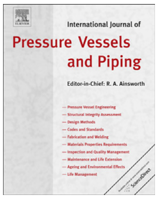

A numerical investigation of constraint effects in circumferentially cracked pipes and fracture specimens including ductile tearing

Diego F.B. Sarzosa, Claudio Ruggieri*

Department of Naval Architecture and Ocean Engineering, University of São Paulo, São Paulo SP 05508–900, Brazil

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ABSTRACT

This work addresses a two-parameter description of crack-tip fields in bend and tensile fracture specimens incorporating the evolution of near-tip stresses following stable crack growth with increased values of the crack driving force as characterized by J. The primary objective of this study is twofold. First, the present investigation broadens current understanding on the role of constraint and test conditions in defect assessment procedures for pipeline girth welds using SE(T) and SE(B) specimens. Second, the work addresses the potential coupled effects of geometry and ductile tearing on crack-tip constraint as characterized by the J–Q theory which enables more accurate correlations of crack growth resistance behavior in conventional fracture specimens. Plane-strain and 3-D finite element computations including stationary and growth analyses are conducted for 3P SE(B) and clamped SE(T) specimens having different notch depth (a) to specimen width (W) ratio in the range $0.1 \leq a/W \leq 0.5$. Additional 3-D finite element analyses are also performed for circumferentially cracked pipes with a surface flaw having different crack depth (a) over pipe wall thickness (t) ratios and fixed crack length. A computational cell methodology to model Mode I crack extension in ductile materials is utilized to describe the evolution of J with the accompanying evolving near-tip opening stresses. Laboratory testing of an API 5L X70 steel at room temperature using standard, deeply cracked C(T) specimens is used to measure the crack growth resistance curve for the material and to calibrate the key cell parameter defined by the initial void fraction, f_0. A key result emerging from this study is that shallow crack SE(B) specimens can accurately and conservatively produce crack growth resistance curves that describe well the measuring toughness capacity of circumferentially cracked pipes under remote bending. The present results provide additional understanding of the effects of constraint on crack growth which contributes to further evaluation of crack growth resistance properties in pipeline steels using SE(T) and SE(B) specimens while, at the same time, eliminating some restrictions against the use of shallow cracked bend specimens in defect assessment procedures.

1. Introduction

Substantial progress has been made in recent years in fitness-for-service (FFS) procedures applicable to defect assessments and life-extension programs of critical engineering structures. These methodologies, also referred to as Engineering Critical Assessment (ECA) procedures, provide a concise framework to correlate crack size with applied loading in terms of failure assessment diagrams (FAD) to evaluate the severity of crack-like flaws [1–3]. A key feature of these approaches lies in the use of fracture toughness data measured from deeply cracked specimens tested under bend loading to guarantee high levels of stress triaxiality which drive the fracture process. Under such conditions, a single geometry-independent failure locus then suffices to provide highly effective, albeit conservative, acceptance criteria for cracked structural components. Several flaw assessment methodologies based upon the FAD concept, such as the R6 procedure [4], BS7910 [5], API 579 [6] and SINTAP [7], among others, are now well established and widely employed to analyze the significance of defects in terms of assessment of structural integrity.

Most structural defects are very often part-through surface cracks that form during fabrication or during in-service operation (*e.g.*, blunt corrosion, slag and nonmetallic inclusions, weld cracks, dents at weld seams, etc.) [8]. These crack configurations develop low levels of crack-tip stress triaxiality which contrast sharply to

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* Corresponding author.
E-mail addresses: claudio.ruggieri@usp.br, claudio.ruggieri@gmail.com (C. Ruggieri).

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conditions present in deeply cracked specimens. Structural components falling into this category include girth welds made in field conditions for high pressure piping systems and steel catenary risers (SCRs). In particular, as the offshore infrastructure moves into deeper waters, SCRs become more attractive due to their relative low cost, larger diameter and much larger structural capacity when compared to flexible risers. More efficient and faster installation methods are now available which employ the pipe reeling process and allow welding and inspection to be conducted at onshore fabrication facilities (see, *e.g.*, [9,10]). The welded pipe is coiled around a large diameter reel on a vessel and then unreeled, straightened and finally deployed to the sea floor. Undetected crack-like defects in girth welds for these structures are therefore subjected to strong tensile fields associated with large plastic strains which often lead to significant ductile crack extension of a subcritical flaw thereby increasing its size. ECA procedures applicable to reeled pipes [11] rely on the direct application of crack growth resistance ($J - \Delta a$) curves (also often termed *R*-curves) measured using small, laboratory specimens to specify acceptable flaw sizes. Consequently, the transferability of experimentally measured fracture resistance data to these structural piping components, including pipe girth welds, remains essential in accurate predictions of the in-service residual strength and remaining life.

However, experimental testing of fracture specimens to measure resistance curves consistently reveals a significant effect of specimen geometry, crack size (as characterized by the a/W-ratio) and loading mode (tension *vs.* bending, on *R*-curves (see Refs. [12–14] for illustrative toughness data)). For the same material, high constraint configurations, such as deeply cracked bend SE(B) and compact tension C(T) specimens, yield low *R*-curves while shallow-notch bend and predominantly tension loaded configurations develop higher resistance to ductile tearing and larger toughness values at similar amounts of crack growth. This diverse range of ductile fracture behavior under varying constraint conditions has prompted research efforts to incorporate the observed increase in toughness during ductile crack growth in defect assessment procedures of low constraint structures, including circumferentially cracked pipes and cylinders. These approaches rely on the use of single edge notch tension SE(T) specimens under clamp conditions to measure experimental *R*-curves more applicable to high pressure piping systems, including girth welds of marine steel risers. The primary motivation to use clamped SE(T) fracture specimens in defect assessment procedures for this category of structural components is the similarity in crack-tip stress and strain fields driving the fracture process for both crack configurations as reported in previous studies by Nyhus and co-workers [15–17]. Later, Xu et al. [18,19] examined effects of constraint on ductile crack growth resistance for clamped SE(T) and standard, deeply cracked SE(B) fracture specimens to correlate their fracture response with ductile fracture behavior in circumferentially cracked pipes.

These previous research efforts represent a significant advance in engineering applications of constraint-designed SE(T) fracture specimens directly connected to structural integrity assessments of girth welds in reeled SCRs. Most of these results are derived from comparing SE(T) configurations having varying crack sizes with a standard, deeply-cracked SE(B) specimen with $a/W = 0.5$. Here, the evolving levels of crack-tip constraint with increased remote loading in the SE(T) specimens follow closely the corresponding levels of stress triaxiality for a surface cracked pipe under predominantly tensile loading. It remained apparent, however, that a more systematic investigation on the measuring toughness capacity of these specimens beyond the onset of constraint loss is needed to assess the degree of similarity between SE(T) configurations and circumferentially surface cracked pipes. Nevertheless, recent applications of clamped SE(T) fracture specimens to characterize crack growth resistance properties in pipeline steels [20] have been effective in providing larger flaw tolerances and, at the same time, reducing the otherwise excessive conservatism which arises when measuring the material's tearing resistance based on high constraint specimens.

While now utilized effectively in fracture testing of pipeline girth welds, some difficulties associated with SE(T) testing procedures, including fixture and gripping conditions, may raise concerns about the significance and qualification of measured crack growth resistance curves. Such uncertainties in measured fracture toughness may potentially affect tolerable defect sizes obtained from ECA procedures. While slightly more conservative, testing of shallow-crack bend specimens (which is often viewed as a nonconventional SE(B) configuration) may become more attractive due to its simpler testing protocol, laboratory procedures and much smaller loads required to propagate the crack. Consequently, use of smaller specimens which yet guarantee adequate levels of crack-tip constraint to measure the material's fracture toughness emerges as a highly effective alternative.

Motivated by these observations, this article addresses a two-parameter description of crack-tip fields in bend and tensile fracture specimens incorporating the evolution of near-tip stresses following stable crack growth with increased values of the crack driving force as characterized by the *J*-integral. The primary objective of this study is twofold. First, the present investigation broadens current understanding on the role of constraint and test conditions in defect assessment procedures for pipeline girth welds using SE(T) and SE(B) specimens. Second, the work addresses the potential coupled effects of geometry and ductile tearing on crack-tip constraint as characterized by the $J - Q$ theory which enables more accurate correlations of crack growth resistance behavior in conventional fracture specimens. Plane-strain and 3-D finite element computations including stationary and growth analyses are conducted for 3P SE(B) and clamped SE(T) specimens having different notch depth (a) to specimen width (W) ratio in the range $0.1 \leq a/W \leq 0.5$. Additional 3-D finite element analyses are also performed for circumferentially cracked pipes with a surface flaw having different crack depth (a) over pipe wall thickness (t) ratios and fixed crack length. For the growth analyses, the models are loaded to levels of J consistent with a crack growth resistance curve, $J - \Delta a$, representative of a typical pipeline steel. A computational cell methodology to model Mode I crack extension in ductile materials is utilized to describe the evolution of J with the accompanying evolving near-tip opening stresses. Laboratory testing of an API 5L X70 steel at room temperature using standard, deeply cracked C(T) specimens is then used to measure the crack growth resistance curve for the material and to calibrate the key cell parameter defined by the initial void fraction, f_0.

2. Overview of the computational cell model for ductile tearing

This section presents a summary of the cell-based framework to model stable crack growth in ductile materials. Further details of the cell model are found in Refs. [21–23]. Ductile fracture in metals is a process of material failure which incorporates various and simultaneous mechanisms at the microscale level [24]. The commonly observed stages of this process are: a) formation of a free surface at an inclusion or second phase particle by either decohesion or particle cracking; b) growth of a void around the particle by means of increased plastic strains and hydrostatic stresses; and c) coalescence of the growing void with adjacent voids. Experimental observations and computational studies show that the plastic strains for nucleation are small thereby causing only little damage in the material ahead of the crack tip. This feature