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Numerical modeling of ductile crack extension in high pressure pipelines with longitudinal flaws

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ABSTRACT

This study examines the applicability of a micromechanics approach based upon the computational cell methodology incorporating the Gurson–Tvergaard (GT) model and the CTOA criterion to describe ductile crack extension of longitudinal crack-like defects in high pressure pipeline steels. A central focus is to gain additional insight into the effectiveness and limitations of both approaches to describe crack growth response and to predict the burst pressure for the tested cracked pipes. A verification study conducted on burst testing of large-diameter, precracked pipe specimens with varying crack depth to thickness ratio (a/t) shows the potential predictive capability of the cell approach even though both the GT model and the CTOA criterion appear to depend on defect geometry. Overall, the results presented here lend additional support for further developments in the cell methodology as a valid engineering tool for integrity assessments of pipelines with axial defects.

1. Introduction

Defect assessment procedures for high pressure piping systems play a key role in fitness-for-service analyses of oil and gas transmission pipelines, including onshore and offshore facilities. Common causes of failures in oil and gas transmission infrastructure derive primarily from crack-like surface flaws (either internal or external) that form during fabrication (slag and nonmetallic inclusions, weld cracks, lack of fusion, etc.) or during in-service operation (blunt corrosion, fatigue, stress corrosion cracking—SCC, dents at weld seams, etc.) [1–3]. As the pipeline infrastructure ages, robust procedures for integrity assessments become central to specifying critical flaw sizes which enter directly into procedures for repair decisions and life-extension programs of in-service structural components. Perhaps more importantly, these procedures must ensure fail-safe operations which avoid costly leaks and ruptures due to material failure to comply with the current stringent environment-based regulations.

A number of structural integrity procedures focus on axial flaws as these defects are subjected to high stresses due to internal pressure. Conventional failure criteria for longitudinal crack-like defects in pipelines are derived based upon a simple fracture mechanics analysis for planar or crack-like flaws. Such procedures are calibrated by extensive burst testing of pipes containing machined cracks conducted on low-to-moderate strength structural steels (API Grades X52 and X60) [4–6]. While these acceptance criteria for linepipe defects clearly simplify integrity analyses of in-service piping components, they essentially reflect a limit-load solution for a blunted axial crack in a pressurized vessel or pipe. Moreover, these integrity assessment procedures assume failure criteria which do not necessarily reflect the actual failure mechanism (such as, for example, stable crack growth prior to final failure) nor do they address specific requirements for high grade pipe steels currently used. For these cases, failure assessments may be overly conservative or provide significant scatter in their predictions, which lead to unnecessary repair or replacement of in-service pipelines at great operational costs [7].

Pressurized cracked pipelines made of high grade, high toughness steels often undergo significant stable crack growth prior to material failure. Under sustained ductile tearing of a macroscopic crack, large increases in the load-carrying (pressure) capacity for the flawed piping component are possible beyond the limits given by the pressure values at yielding of the remaining crack ligament. Simplified engineering approaches for defect assessments, such as the R6 [8], BS7910 [9], API579 [10] and SINTAP [11] methodologies, incorporate ductile tearing effects to evaluate the severity of crack-like flaws in structural components, including piping systems, in terms of the J-integral fracture parameter [12,13] to characterize the significant increase in toughness over the first few millimeters of stable crack extension (Δa). These methods, also referred to as engineering critical

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