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Structural integrity analysis of axially cracked pipelines using conventional and constraint-modified failure assessment diagrams

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Abstract

This study explores applications of the failure assessment diagram (FAD) methodology to predict the failure behaviour for high pressure pipelines with planar defects having different geometries (i.e., crack depth and crack length). One purpose of this investigation is to assess the capability of FAD procedures in integrity analyses of high pressure pipelines with varying crack configurations. Another purpose is to address the effectiveness of constraint-based FADs to predict burst pressure of low-constraint cracked pipelines. Full scale burst testing of end-capped pipe specimens with axial surface flaws provide the data needed to compare the failure predictions derived from the FAD procedures. The analyses reveal that the degree of agreement between predicted pressures and experimentally measured values depends rather markedly on the crack size for the tested pipes. Moreover, the analyses also show a possible weak dependence of the predicted pressures on the constraint-based correction scheme. Overall, the results validate the use of FAD-based methodologies for defect assessments of axially cracked pipelines.

Keywords: FAD procedure; Axial flaws; Burst pressure; Pipelines; Constraint; *J*–*Q* approach

1. Introduction

Fracture assessment procedures for pressurized components play a key role in design, fabrication and safe operation of pressure vessels, piping systems and storage tanks. In particular, accurate predictions of the failure pressure in damaged oil and gas pipelines remain essential for the safety assessment of high pressure piping systems, including onshore and offshore facilities. As the pipeline infrastructure ages, robust procedures for integrity analyses become central to specifying critical flaw sizes which enter directly into procedures for repair decisions and life-extension programmes 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. Current codes and standards for oil and gas pipelines provide rules for welding, inspection and testing of transmission pipelines (see, for example, API 1104 [1], CSA Z662 [2]). While these codes provide simplified acceptance criteria for fabrication defects (such as slag inclusions and porosity in weldments) based upon workmanship standards and fracture toughness testing, they do not specifically address fitness-for-service assessments of crack-like defects that form during in-service operation.

Fracture mechanics-based approaches, also referred to as engineering critical assessment procedures, provide a means for constructing a correlation of crack size with applied loading as measured by the linear elastic stress intensity factor, K, or the elastic–plastic parameter defined by the J-integral and its corresponding value of the crack tip opening displacement, CTOD (see further details on these fracture parameters in Anderson [3]). Further developments in the engineering critical assessment methodology include the effects of plasticity on crack tip loading by adopting the concept of failure assessment diagrams (FADs) to evaluate the severity of crack-like flaws. A key feature of FAD-based approaches is the introduction of a concise framework to explicitly address the potential interaction between stress-controlled cleavage

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fracture and plastic collapse to predict structural failure. The methodology thus provides a highly effective, albeit conservative, acceptance criterion for cracked structural components which relates the operating conditions with a critical applied load or critical crack size. Several flaw assessment procedures based upon the FAD concept, such as the R6 methodology [4], BS 7910 [5], SINTAP [6], API 579 [7] and ASME Code Section XI [8], among others, are now well established and widely employed to analyze the significance of defects in terms of assessment of structural integrity.

The FAD methodology defines a two-criteria assessment curve which incorporates a coupling relationship between crack-tip loading (K, J or CTOD) describing the fracture conditions and a limit-load solution describing plastic collapse of the remaining crack ligament. The key to this approach 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 failure locus then suffices to provide geometry-independent predictions. However, structural defects in pressurized piping systems are very often 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.) [9–11]. These crack configurations generally develop low levels of crack-tip stress triaxiality (associated with the predominant tensile loading which develops in pressurized piping systems) thereby contrasting sharply to conditions present in deeply cracked specimens under bending. Moreover, high grade pipeline steels currently used exhibit much higher cleavage fracture resistance compared to older, lower grade pipeline steels; under increased loading, these materials develop extensive plastic deformation at the crack tip prior to fracture. Consequently, assessments of defects in low constraint structural components based upon conventional FAD equations may be unduly conservative and overly pessimistic. While such conservatism represents an extra factor of safety, excessive pessimism in defect assessments can lead to unwarranted repairs or replacement of in-service pipelines at great operational costs.

The technological importance of fracture behaviour for low-constraint cracked structures prompted the development of more refined defect assessment procedures capable of including effects of constraint variations on cleavage fracture toughness. These approaches advocate the use of geometry dependent fracture toughness values so that crack-tip constraint in the test specimen closely matches the crack-tip constraint for the structural component. In particular, Ainsworth and O'Dowd [12] and Ainsworth [13] proposed a constraint-based correction to the FAD procedure which reflects the strong role of constraint on correlations of cleavage toughness data for varying crack configurations and loading modes (tension vs. bending). The approach builds upon the constraint-based Q methodology [14,15] to correct measured toughness values using low constraint fracture specimens thereby modifying the shape of the FAD assessment line. The predictive procedure for defect assessments thus becomes a function of structural constraint which should remove or alleviate the inherent conservatism of the FAD philosophy.

This study explores applications of the FAD methodology to predict the failure pressure for high pressure pipelines with planar defects having different geometries (i.e., crack depth and crack length). One purpose of this investigation is to assess the capability of FAD procedures in integrity analyses of high pressure pipelines with varying crack configurations. Specifically, the present work compares the burst pressure predictions for two widely used FAD procedures: BS 7910 [5] and API 579 [7]. Another purpose is to address the effectiveness of the Q-based correction for the influence of constraint on the FAD curves and, consequently, on failure predictions. Full scale burst testing of end-capped pipe specimens with axial surface flaws provides the data needed to compare the failure predictions derived from the utilized FAD procedures. The analyses reveal that the degree of agreement between predicted pressures and experimentally measured values for both FAD procedures depends rather markedly on the crack size for the tested pipes. Our exploratory application presented here provides a representative set of results which provide further support for using the FAD methodology in defect assessments of pressurized pipes with axial flaws.

2. Overview of the FAD methodology

It is widely recognized that brittle fracture and plastic collapse caused by overloading are competing failure modes in cracked structural components made of materials with sufficient toughness. Early work by Dowling and Townley [16] and Harrison et al. [17] to address the potential interaction between fracture and plastic collapse introduced the concept of a two-criteria failure assessment diagram (most often referred to as FAD) to describe the mechanical integrity of flawed components. In the FAD methodology, a roughly geometry and material independent failure line is constructed based upon a relationship between the normalized crack-tip loading, K_r, and the normalized applied (remote) loading, L_r, in the form

$$K_r = f(L_r), \tag{1}$$

where

$$K_r = \frac{K_I(P,a)}{K_{mat}} \tag{2}$$

and

$$L_r = \frac{P}{P_L(a,\sigma_{ys})}. \tag{3}$$

Here P is the applied (remote) load, a is the crack size, K_I is the elastic stress intensity factor, K_{mat} is the material's fracture toughness, σ_{ys} is the yield stress and P_L is the value