Development of a Physics-based Approach for the Prediction of Strain Capacity of Welded Pipelines

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ABSTRACT

Various industry efforts are underway to develop or improve methods to address design of pipelines for harsh arctic or seismically active regions. The design challenges associated with these regions involve multiple limit states that require characterization of load from large ground deformations, as well as material capacity. The focus of this paper is the development of a physics-based approach to characterize the strain capacity of a welded pipeline for the tensile limit state. Full-scale pressurized pipe tests and three dimensional (3D) finite element analyses (FEA) were conducted to develop the limit states. An experimental program was conducted to measure the strain capacity of full-scale pressurized pipes and provide validation to the physics-based approach. In addition to full-scale tests, round bar tensile and single edge notched tension (SENT) specimens were employed in the experimental program to characterize the weld properties. Multiple measures were taken to account for the influence of natural material variability on the full-scale test results to facilitate validation of the physics based approach. The measures included the use of gas metal arc welding (GMAW) mechanized welding procedure and the production of additional welds to characterize material variability around the circumference of the welded pipes and across multiple welds. Finite element analysis (FEA) based parametric study was conducted to model both fracture and plastic collapse failure mechanisms observed in full-scale tests. The parametric study shows that in addition to fracture toughness and overmatch, misalignment may also significantly affect strain capacity due to transition in failure mode from plastic collapse to ductile tearing. The study illustrates a need to incorporate the observed effect of these parameters in experimental programs designed to characterize strain capacity for development of next generation fracture assessment procedures.

KEY WORDS: Pipeline strain capacity, Fracture mechanics, Strain-based design, Pipeline girth welds, Fracture toughness, Single Edge Notch Tension Specimen (SENT), Misalignment.

INTRODUCTION

The oil and gas industry has moved towards development of resources in remote regions with seismically active zones and arctic climates. Pipelines operating in seismic or permafrost regions may be subjected to large plastic strains caused by ground movements. Traditional stress based design may not be cost effective in such harsh environments. Consequently, strain-based design guidelines for qualification of welded pipelines subjected to large deformations are needed to facilitate future developments in arctic and seismically active regions.

In recent years, ExxonMobil has undertaken a comprehensive experimental and numerical program to develop insights into the characterization and prediction of tensile strain capacity of welded pipelines. The program focused on three main objectives:

1. Experimentally determine the applicability of crack tip opening displacement (CTOD) based fracture parameter and use of R-curves for strain capacity prediction
2. Determine appropriate small scale specimens to measure weld toughness properties for use in the prediction and performance of pressurized welded pipe, and
3. Develop and validate a numerical methodology for prediction of tensile strain capacity of welded pipe

A summary of work published by ExxonMobil as part of objectives 1 and 3 is provided below.

ExxonMobil developed an unloading compliance technique [Gioielli, Minnaar, Macia and Kan, 2007] to measure crack extension during full-pipe testing. The method enabled the quantification of CTOD as a function of applied strain. Furthermore, numerical analysis by Minnaar, Gioielli, Macia, Bardi and Biery (2007) established a method to determine toughness resistance curves (R-curves) from full-scale experimental responses. This work has shown that the R-curve behavior of pipe without welds is not influenced by internal pressure. This finding provided the motivation to develop a small scale specimen to measure material toughness in the absence of pressure. Furthermore, it was shown that a CTOD based fracture parameter correctly predicts strain capacity under large deformation conditions, if a CTOD-based R-curve is used in a tearing analysis. Tearing analysis uses a tangency criterion between applied driving force curve (driving force vs. crack growth) and the measured R-curve to determine the failure strain (strain capacity). This approach successfully predicted the effect of pressure on crack driving force and the reduction of strain capacity due to pressure.

Kibey, Minnaar, Issa, Gioielli (2008) conducted large parametric studies and investigated the effect of geometric factors such as wall thickness (WT), misalignment, flaw size, pipe diameter etc. on tensile strain capacity of welded pipelines and showed that misalignment may have a strong impact on tensile strain capacity of welded pipelines. The parametric study also showed that strain capacity is strongly influenced...