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Strain-based Design—Advances in Prediction Methods of Tensile Strain Capacity

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In recent years, ExxonMobil has undertaken a comprehensive experimental and numerical program to characterize tensile strain capacity of welded pipelines under different operational, geometric and material property conditions. Key parameters affecting tensile strain capacity have been identified through sensitivity studies and used in a large-scale FEA-based parametric study to develop closed-form tensile strain capacity equations for different limit states. A key parameter affecting tensile strain capacity of welded pipelines is the tearing resistance (CTOD R-curve). Small-scale testing techniques have been developed to characterize the tearing resistance (R-curve) of full-scale pipelines using single edge notched tension (SENT) specimens. Experimental and numerical results have shown that the SENT R-curves closely match the full-scale test R-curves. The generalized tensile strain capacity equations have been validated against 20 full-scale tests for pipe grades X65 to X80 grades. The equations correctly predict the observed failure mode in the full-scale tests as well as the tensile strain capacity. Simplified, conservative tensile strain capacity equations with fewer parameters have been developed by making reasonable assumptions for several key parameters. The generalized and simplified tensile strain capacity equations can form the basis of a multi-tier engineering critical assessment (ECA) procedure for strain-based design of welded pipelines.

INTRODUCTION

Pipelines operating in arctic and seismically active regions may be subjected to large ground movement that can lead to large plastic deformation in the pipelines. Deepwater flowline may also experience large lateral displacement in start-up and shut-down operations due to thermal and pressure variations. Traditional allowable stress design methods address scenarios where the global response is mainly elastic and may not be sufficient for design of pipelines experiencing large strains in challenging arctic and seismic conditions. There is a need to develop methods for pipeline design beyond yield, commonly termed strain-based design. These methods facilitate prediction of the tensile strain capacity of pipelines from a given set of geometry and material properties. This paper presents an overview of the tensile strain capacity prediction methodology recently developed by ExxonMobil. This methodology includes: An FEA-based tensile strain capacity prediction approach addressing all relevant limit states (ductile tearing and plastic collapse), closed-form, generalized tensile strain capacity equations for relevant limit states, and small-scale SENT testing procedure for tearing resistance measurement of full-scale welded pipes.

In recent years, increasing attention has been given to development of strain-based design methodologies for welded pipelines (Linkens, Formby and Ainsworth, 2000; Wang, Rudland, Denys and Horsley, 2002; Wang, Cheng and Horsley, 2004; Wang, Liu, Horsley and Zhou, 2006; Mohr, Gordon and Smith, 2004; Liu and Wang, 2007; Tyson, Shen and Roy, 2007; Østby and Hellesvik, 2007; Sandvik, Østby and Thaulow, 2008). These and other studies have served to gain understanding of the effect of various factors on strain capacity. For example, Wang, Rudland, Denys and Horsley (2002) and Wang, Liu, Horsley and Zhou (2006) related strain capacity to the following parameters: flaw depth, flaw length, yield-to-tensile (Y/T) ratio, weld overmatch, apparent crack-tip opening displacement (CTOD) toughness and weld cap height. Sandvik, Østby and Thaulow (2008) correlated tensile strain capacity of plain pipes to defect size, material strain hardening and biaxial loading.

ExxonMobil has undertaken a comprehensive experimental and numerical program to develop insights into characterization of the tensile strain capacity of welded pipelines. The program was conducted in various phases, including full-scale test development, prediction methodology, small-scale testing development and validation. A summary of published literature describing these phases appears below.

Details of large-scale testing techniques using unloading compliance to measure crack growth were published in the First Strain-based Design Symposium held at the 2007 ISOPE Conference in Lisbon. The testing program described the use of full-scale pressurized pipe tests to measure strain capacity and the use of curved wide plate tests (CWPT) to study weld performance and tearing resistance behavior (R-curve) (Gioielli, Minnaar, Macia and Kan, 2007; Fairchild, Cheng, Ford, Minnaar, Biery, Kumar and Nissley, 2007; Kibey, Minnaar, Issa and Gioielli, 2008; Lillig, 2008; Fairchild, Crawford, Cheng, Macia, Nissley, Ford, Lillig and Sleigh, 2008; Gioielli, Cheng, Minnaar and Fairchild, 2008; Kan, Weir, Zhang, Lillig, Barbas, Macia and Biery, 2008). The experimental results showed that internal pressure does not significantly influence the full-scale plain pipe tearing resistance (R-curve).

Numerical analysis by Minnaar, Gioielli, Macia, Bardi, Biery and Kan (2007) showed that pressure significantly influences crack growth driving force but does not affect the material resistance to crack growth (R-curve). Their work also showed that tangency of full-scale R-curves and full-scale pipe driving force can be used to estimate the tensile strain capacity of pipes. Kibey,

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KEY WORDS: Pipeline tensile strain capacity, fracture mechanics, strain-based design, tearing resistance, full-scale pipeline tensile test, model validation, single edge notched tension (SENT) specimen.