Proceedings of the Seventeenth (2007) International Offshore and Polar Engineering Conference
Lisbon, Portugal, July 1-6, 2007

ISBN 978-1-880653-68-5; ISBN 1-880653-68-0(Set); ISSN 1098-6189 (Set)

Strain Based Design of High Strength Pipelines

Yong-Yi Wang, Ming Liu, and David Rudland
Engineering Mechanics Corporation of Columbus
Columbus, OH, USA
David Horsley
BP Exploration and Production Technology
Calgary, Alberta, Canada

ABSTRACT

Tensile rupture is one of the limit states in strain-based design of pipelines. The tensile strain capacity of a pipeline is controlled by the strain capacity of the girth welds. Factors affecting the tensile strain capacity of girth welds are numerous. A few dominant factors are material's strain hardening capacity, toughness (including transition temperature and tearing resistance), and the existence of weld defects. The girth weld tensile strain capacities of an X70 and an X100 linepipe were studied in this work. Extensive material property characterization was performed, including a variety of small scale testing, such as tensile, Charpy, and standard CTOD toughness. The same welds were tested in mini-wide plate configuration under tension at room temperature and cold temperatures as low as -27°C. The mini-wide plate specimens were extensively analyzed numerically. Attempts were made to correlate small scale tests results and the tensile strain capacity measured from the mini-wide plates. The correlation used a set of closed form equations that were developed previously on the basis of the crack driving force approach and the concept of apparent toughness. Reasonably good correlation was observed for both X70 and X100 girth welds. When measured by safety factors on the predicted strain limits (safety factor ≡ measured strain limit / predicted strain limit), the coefficient of variation was in the range of 0.20-0.25. Certain limitations in using small-scale specimen test results to predict large scale tensile strain limits were also observed.

KEYWORDS: strain-based design, tensile strain limits, girth welds, ECA, fracture mechanics, pipeline

INTRODUCTION

One of the limit states in the strain-based design of pipelines is the tensile strain capacity. Girth welds tend to be the weakest link in the tensile strain capacity due to the existence of weld defects and metallurgical and/or mechanical property changes from welding thermal cycles. The term "girth weld" here broadly refers to the entire weld region, including the deposited weld metal, fusion boundary, and the heat-affect zone (HAZ). Certain base metal (pipe material) properties are a critical part of the girth weld strain capacity; as they affect the metallurgical and mechanical properties of the weld region. For instance, the chemical composition of the base metal may play a critical role in the propensity of HAZ hydrogen cracking, particularly in older and high carbon materials. In modern high strength pipelines, HAZ softening and weld metal cracking may occur, both of which can have a significant impact on the tensile strain capacity of the pipeline. In this paper tensile strain limits of X70 and X100 girth welds are experimentally measured by mini-wide plate tests. The test results are analyzed numerically and the tensile strain limits are correlated with small-scale test data.

EXISTING TOOLS FOR DETERMINING TENSILE STRAIN CAPACITY

Wide Plate Testing

Existing data that provides evidence of tensile failure strains for pipeline girth welds primarily comes from wide plate tests. At the present time, wide plate testing is one of the most recognized tools for strain-based design. The test specimen is a curved piece of pipe with a nominal gauge width of 200 to 450 mm and is loaded in longitudinal tension. The specimen typically has a girth weld with a machined or fatigue sharpened notch at the mid-length along the weld. The strain across the weld is monitored while the specimen is pulled longitudinally until failure. Most of the wide plate tests were done at the University of Gent in early years. Tests have also been performed at C-FER, JFE, and Nippon Steel Corporation in recent years. Wide plate testing has been used as a tool for material and weld procedure qualification (Hukle et al., 2005). It has also been used for project-specific design validation. A large database of the failure strains of girth welds has been established from wide plate tests (Denys et al., 2002). Wide plate testing has provided industry with valuable data on weld properties, material requirements, and weld defect tolerance.

Extension of Stress-Based Design Procedures for Strain-Based Design

DNV OS-F101 (2000) provides broad guidance on girth weld defect acceptance criteria for longitudinal strain ranging from elastic to plastic. The standard stipulates that an ECA (Engineering Critical Assessment) should be performed in accordance with the Level 3 procedure of BS 7910 (1999) for high strain applications. The Level 3 BS 7910 procedure is a stress-based approach in the form of failure assessment diagram (FAD). The FAD relies on the existence of a limit load (or plastic collapse load). While the limit load is a good measure of a structure's load bearing capacity, it is a poor measure of the strain capacity. When the material response is in the plastic range, a small change in stress can result in a large change in strain. The FAD approach can work reasonably well if material has strong strain hardening capacity, such as certain lower grade materials used in offshore applications. Modern high-strength linepipe materials (API X70 and above) typically exhibit low strain hardening. The strain hardening capacity of the corresponding high strength girth weld metal can be even lower. Consequently assessment results of the FAD approach can be quite insensitive to the strain level for these materials.