Development of Surface Flaw Interaction Rules for Strain-Based Pipelines

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ABSTRACT

Strain capacity prediction is important for strain-based design (SBD) of welded pipelines operating in harsh environments involving discontinuous permafrost, active seismicity, and offshore ice gouging. Current strain capacity prediction models consider only a single flaw; however, potentially multiple defects neighboring one another may exist. As a result, practical engineering tools are needed to assess such cases. In the current paper, it is shown that the existing flaw interaction rules developed for allowable-stress design are not applicable for SBD, which can lead to overly conservative or non-conservative assessment. A combined numerical modeling and experimental testing investigation was performed to develop interaction rules for co-planar surface flaws specific to SBD pipelines. Advanced finite element (FE) modeling was used to simulate flaw interaction and full-scale tests (FSTs) were conducted to study the effects of flaw spacing on pipeline strain capacity. The FE modeling was first validated against the experiments and then used to develop surface flaw interaction rules through a parametric FE study. Using the rules, multiple flaws were converted into an equivalent single flaw resulting in the same pipeline strain capacity.

KEY WORDS: Strain-based design; strain capacity; flaw interaction rule; full-scale tests.

INTRODUCTION

The capability of designing pipelines to safely and economically traverse regions of harsh environmental conditions plays a critical role in the development of remote energy resources. In these regions, pipelines may be potentially subjected to large plastic deformation in the longitudinal direction resulting from environmental loadings, such as earthquake fault rupture, soil liquefaction, frost heave, thaw settlement and ice gouging (Nixon, 1991; Nobahar and Phillips, 2007; Selvadurai, 1993). SBD is one engineering approach intended to deal with these loading conditions and ensure pipeline integrity while sustaining a finite amount of plastic deformation (Macia, 2010).

The ability of a welded pipeline to sustain finite longitudinal tensile plastic deformation while maintaining pressure containment integrity is characterized as tensile strain capacity (TSC). Prediction of TSC of welded pipelines is an important topic for SBD and has been a subject of ExxonMobil research (Minnar, 2007; Kibey, 2008, 2009, 2010; Fairchild, 2011, 2012; Wang, 2009, 2010). The previous studies on TSC prediction were focused on a single surface flaw. However, the occurrence of multiple flaws in a pipe girth weld is not uncommon and mainly results from pipeline construction (welding). The effects of multiple interacting flaws on TSC have not been completely understood. An overly conservative prediction of TSC in the presence of multiple flaws can increase unnecessary weld rejection and repair rate. On the other hand, a non-conservative prediction increases the risk of potential pipeline failure under the design environmental loading conditions. Accurate and reliable prediction of TSC in the presence of multiple flaws is beneficial to efficient pipeline fabrication through engineering critical assessment and to fitness for service (FFS) assessments.

A conventional approach to deal with multiple flaws in a pipeline girth weld is to combine them into a single equivalent flaw amendable to analysis in a process known as re-characterization. The re-characterization is typically conducted in accordance with the well-established flaw interaction rules in the industry standards (API1104; API 579/ASME FFS-1; BS7910). These rules were established for stress-based (i.e., allowable stress) pipelines (Leek and Howard, 1996; O’ Donoghue, 1984). After re-characterization, the fracture assessment is conducted based on the re-characterized single flaw. In allowable stress design, the fracture assessment methodology is consistent with the framework of small-scale yielding conditions, i.e. crack driving force is well defined and used for fracture assessment. Flaw interaction under the small-scale yielding conditions can lead to the increase of crack driving force characterized by the stress intensity factor or J-integral (Bezensek and Hancock, 2004; Hasegawa, 2001; Murakami and Nemat-Nasser, 1982). Given that distance between adjacent flaws controls their interaction, the flaw interaction rules for allowable stress design generally define a critical distance for combining them into a single flaw. In SBD, plastic deformation and ductile tearing are within the design scenario. There are two primary tensile limit states for SBD pipelines, fracture (onset of ductile tearing instability) and plastic collapse. The fracture limit state is generally associated with significant crack propagation and localized plastic deformation in crack ligaments conforming to large-scale yielding conditions. Under such large-scale yielding conditions, crack driving force is not well defined and does not fully capture the interaction of plastic deformation fields around the...