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Influence of pipe steel heterogeneity of the upper bound tensile strain capacity of pipeline girth welds: A validation study

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ABSTRACT

The strain capacity of flawed girth welds is influenced by the constitutive properties of the connected pipes. Although most defect assessment procedures assume equal properties for both pipes, line pipe steel standards recognize significant variability. A recent theoretical framework provides an upper bound equation of tensile strain capacity based on pipe steel heterogeneity (and regardless of weld properties). This paper validates the equation using 64 curved wide plate test results. A strain capacity prediction method adjusted for heterogeneity is developed, allowing to adopt existing strain capacity equations for welds connecting homogeneous pipes. Its applicability to pressurized pipelines is discussed.

1. Introduction

Strain based design is gaining relevance as many new or planned pipelines face global plastic deformations due to the challenging nature of their environment (e.g. arctic onshore, deepwater offshore). Various procedures have been recently developed for the strain based assessment of girth weld flaws. Most procedures are fracture mechanics based, such as the generic strain-based failure assessment diagram [1–3] and strain capacity equations specifically developed for girth welds using finite element analysis [4–6]. Alternatively, empirical strain capacity equations deserve attention [7]. There is no consensus so far regarding these procedures since the introduction of different assumptions and validity boundaries for each procedure inhibits straightforward comparisons.

Recognized in all current strain based flaw assessments is the importance of actual (rather than minimum specified) mechanical properties of all materials involved. This includes pipe steel, weld metal, and heat affected zones [8]. In particular, pipe stress–strain properties, weld strength mismatch and ductile tearing resistance of the flawed microstructure have received strong attention [9]. Variations in these properties may significantly affect strain capacity. For instance, the potential significance of slight constitutive variations has recently been illustrated in Ref. [10] where, for a specific case study, changes of merely 1 ksi (6.89 MPa) in pipe steel strength (by shifting the entire stress–strain curve) could alter the tensile strain capacity around a factor two.

From the abovementioned list of material properties, effects of weld strength mismatch and ductile tearing resistance are not treated in depth in this paper. Instead, further focus goes to pipe stress–strain behavior. Notwithstanding the recognized importance of actual material properties, it is common practice to assume an equal constitutive behavior for the line pipe steels at either side of a girth weld. This assumption does not hold for field weldments since line pipe steel specifications

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Nomenclature

CMOD	crack mouth opening displacement (CMOD)
CWP	curved wide plate
e	engineering strain (–)
E	Young's modulus (MPa)
e_m	uniform elongation (–)
e_{max}	tensile strain capacity (–)
e_r	remote strain (–)
GSC	gross section collapse
HAZ	heat-affected zone
LVDT	linear variable differential transformer
n	strain hardening exponent (–)
NSC	net section collapse
r	remote strain ratio at failure (–)
R_m	ultimate tensile strength (MPa)
$R_{p0.2}$	0.2% proof stress, used as a measure for yield strength (MPa)
s	engineering stress (MPa)
t	wall thickness (mm)
UF	unstable fracture
Y/T	yield-to-tensile ratio, $R_{p0.2}/R_m$ (–)
ΔR_m	pipe ultimate tensile strength heterogeneity (MPa)
$\Delta R_{p0.2}$	pipe yield strength heterogeneity (MPa)
Δs	pipe steel heterogeneity (MPa)
ε	true strain (–)
σ	true stress (MPa)
$\sigma_{0.2}$	true 0.2% proof stress (MPa)
–	dimensionless quantity

allow for considerable variations in strength (e.g. 150 MPa for the yield strength of API 5L grades X60 to X100 [11]). These variations are inherent to the mass production of high-strength low-alloy (HSLA) line pipe steels using advanced micro-alloying strategies and, very often, thermo-mechanically controlled (TMCP) rolling processes. Published large data sets of stress–strain properties [12,13] enable the statistical analysis of differences between the strength levels of two girth welded pipes ('pipe steel heterogeneity'). For instance, assuming a random normal distribution, the probability of welding pipes with yield strengths differing by 40 MPa or more is around 25% [14].

To the authors' knowledge, pipe steel heterogeneity is recognized as a factor affecting strain capacity since 1994 [15]. The reason is that slight pipe strength differences strongly alter the strain distribution in the vicinity of the girth weld. This is illustrated in Fig. 1 [16], which plots the strain distribution in a Curved Wide Plate (CWP) specimen. A CWP test is an intermediate scale uniaxial test on a pipeline section containing a girth weld at mid-length, which is usually damaged (e.g. by the presence of a weld flaw, weld corrosion or machined notch) or modified to simulate so. For instance, weld flaws are commonly represented by machined notches [17] and blunt corrosion damage can be geometrically imitated by milling or spark erosion [18]. The specimen shown in Fig. 1 (containing a notched weld) samples two pipes of different strength: 22 MPa difference in yield strength – further expressed as 0.2% proof stress $R_{p0.2}$ – and 37 MPa difference in ultimate tensile

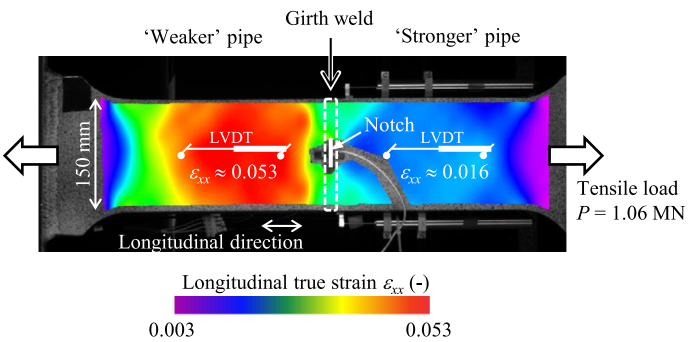

Fig. 1. Under global plastic deformation, differences in the stress–strain properties of girth welded pipes create a strongly non-uniform strain distribution [16].