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Structural integrity of corroded girth welds in vintage steel pipelines

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ABSTRACT

Girth welds of old steel pipelines and their surrounding heat affected zones are susceptible to corrosion attack. The resulting reduction in wall thickness may reduce the axial load or internal pressure bearing capacity to an unsafe level. Since standards provide limited guidance on weld corrosion assessment, the authors have executed an extensive experimental program to evaluate the axial load bearing capacity of corroded girth welds. To this end, curved wide plate tests have been executed and were analyzed by means of 3D digital image correlation. This paper discusses key influence factors related to weld geometry and material (strength and toughness). Then, the results are used to develop an assessment approach, based on Annex G of BS 7910:2013 and modified to account for the elastic–plastic stress–strain concentration resulting from weld misalignment.

1. Introduction

When 'vintage' (say, older than 40 years) steel pipelines for fossil fuel transmission are inspected, circumferential metal loss due to corrosion may be detected in girth welds and their adjacent heat affected zones (HAZs). Such metal loss follows from the potentially suboptimal application of field coatings which were, at their time of installation, not considered as a critical factor. In addition, corrosion may be triggered by sensitive microstructures and/or chemistries associated with the weldment [1,2].

Local metal loss reduces the load bearing capacity of a pipeline. On the one hand, when the predominant loading component is internal pressure, structural integrity depends on the depth a and axial length L of metal loss (Fig. 1). There are well established procedures to assess the severity of corrosion damage in the body of vintage pipes, for instance the 'modified ASME B31G' equation [3]. This semi-empirical equation expresses burst pressure p_{max} or maximum hoop stress $\sigma_{h,max}$ as follows (D and B representing pipe outer diameter and wall thickness, respectively):

$$p_{\max}\frac{D}{2B} = \sigma_{h,\max} = \sigma_f\left(\frac{1-0.85\frac{a}{B}}{1-\frac{0.85}{M}\frac{a}{B}}\right) \quad (1)$$

with σ_f a so-called flow stress equal to SMYS + 69 MPa, SMYS being the pipe steel's specified minimum yield strength. The addition of 69 MPa conservatively accounts for the beneficial effect of strain hardening on load bearing capacity. Using an extensive test database, Leis et al. [4] have shown that a more objective – but potentially non-conservative – value for flow stress would be the ultimate tensile, rather than the yield strength of the pipe metal. Coming back to Eq. (1), 0.85 is an empirical correction factor for non-rectangular metal loss geometry and M is a dimensionless 'Folias factor' accounting for stress concentrations in the presence of a notch ($M \geqslant 1$) due to bulging [5]. M reflects an effect of finite corrosion length L. Eq. (1) is valid for $a/B \leqslant 0.8$ (an empirical limit) and allows for the potential presence of an axial stress σ_a equal to $\sigma_h/2$, which could be induced by internal pressure due to end cap effects. Martin et al. [6] observed that the collapse based modified ASME B31G equation can be applied to (blunt) corrosion in brittle materials. In their test database, pipeline steels having a Charpy transition temperature of as high as +40 °C were covered.

On the other hand, when the predominant loading component is axial stress (resulting from external factors such as ground movement), the severity of metal loss is governed by its depth a and circumferential arc length $2c$. In such case, the axial plastic collapse stress is commonly predicted using a criterion developed by Kastner et al. [7]:

$$\sigma_{a,\max} = \sigma_f\cdot\frac{\left(1-\frac{a}{B}\right)\left(\pi-\frac{2ca}{DB}\right)}{\left(1-\frac{a}{B}\right)\pi+2\frac{a}{B}\sin\left(\frac{2c}{D}\right)} \quad (2)$$

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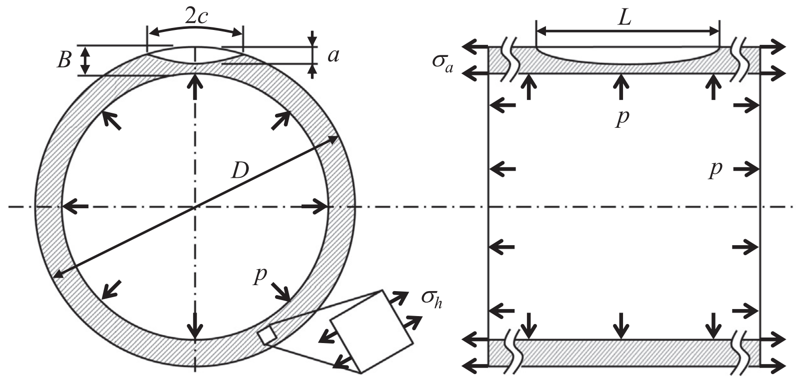

Fig. 1. Definition of symbols related to geometry (pipe, corrosion damage) and load state.

This equation has been included in standards such as BS 7910, the British Standard on assessment of flaws in metallic structures [8], both as a reference stress solution for crack-like flaws and for corrosion. Notwithstanding its national character, this standard has established a worldwide reputation and its adoption exceeds British boundaries.

Eqs. (1) and (2) have been developed with the aim to assess metal loss in pipe steel, remote from girth welds. It is noted that their primary focus was on crack-like defects, but their application on uniform pipe metal loss is justified as the equations are based on plastic collapse failure (as opposed to toughness driven failure). A non-brittle homogeneous material within a perfectly cylindrical geometry is assumed. Girth welds, however, may encompass brittle microstructures, exhibit heterogeneous material properties, show geometrical imperfections such as misalignment and may house residual stresses. Guidance on corrosion assessments in the vicinity of a weld is vague. For instance, ASME B31G can be adopted for girth weld corrosion in a pressurized pipeline "provided that the welds are of sound quality, have ductile characteristics and provided workmanship flaws are not present in sufficiently close proximity to interact with the metal loss" [3]. Since these requirements are not quantified, current practice tends to treat girth weld corrosion in vintage pipeline with extreme care. This often results in a large number of unnecessary and expensive pipeline excavation works. Also, ASME B31G cannot be used to assess the effect of the circumferential extent of the corrosion.

Recognizing the abovementioned limitation of standards' advice, a recent literature survey has collected published experimental data on the load bearing capacity of (potentially low toughness) welds showing metal loss [9]. This study, however, concludes that the number of tests performed so far is insufficiently exhaustive to unambiguously judge on the acceptability of weld metal loss. Moreover, not all potential influence factors have been covered with equal detail. In particular, the number of published tests on misaligned welds is very limited. Finally, the literature review attempts to propose a workmanship criterion by suggesting that metal loss extending up to 20% of the structure's wall thickness is acceptable irrespective of toughness (in the absence of sharp defects). However, no attempts are made to predict the actual load bearing capacity of corroded welds within the philosophy of an engineering critical assessment.

In an attempt to better understand the effect of girth weld corrosion on the structural integrity (i.e., load bearing capacity) of vintage pipelines, the authors have carried out a destructive test program on sample welds extracted from the Belgian gas transmission pipeline grid, operated by Fluxys Belgium SA. This paper reports on the results of this program and evaluates an assessment method. It is structured as follows. Section 2 describes the materials and methods used. Section 3 discusses the experimental results. Attention goes to effects of weld specific features (potentially beneficial or adverse) such as weld strength mismatch, toughness and misalignment. Then, Section 4 evaluates an approach for girth weld corrosion assessment, based on Annex G of BS 7910 and supported by the experimental results. Conclusions are provided in Section 5.

2. Materials and methods

Section 2.1 describes the tested materials. Sections 2.2 and 2.3 explain the experimental program, respectively focusing on component and small scale testing.

2.1. Origin of girth welds

Ten girth welds ('W1' to 'W10') were extracted from the Belgian gas pipeline grid (Table 1). Their corresponding pipelines were constructed between 1967 and 1973 and – having successfully operated for at least 40 years – can be categorized as vintage. Different pipe types were covered: seamless, longitudinally seam welded and spirally seam welded. Two API 5L [10] pipe grades

Table 1
Overview of tested girth welds.

Weld	Year of installation	Pipe seam type	API 5L [10] pipe grade	Nominal outer diameter D (mm)	Nominal wall thickness B (mm)	D/B (–)
W1	1967	Seamless	X46	350	6.4	55
W2	1971	Spiral	X60	500	5.6	89
W3	1971	Longitudinal	X60	400	6.5	62
W4	1968	Longitudinal	X60	500	7.2	69
W5	1967	Seamless	X46	350	6.4	55
W6	1971	Spiral	X60	500	5.6	89
W7	1969	Longitudinal	X60	914	10.2	90
W8	1969	Longitudinal	X60	914	12.2	75
W9	1973	Longitudinal	X60	914	10.2	90
W10	1973	Longitudinal	X60	914	12.2	75