Load bearing capacity of corroded girth welds in vintage pipelines below the ductile-to-brittle transition temperature

by Prof. Stijn Hertelé[1], Dr Koen Van Minnebruggen[1], Kaveh Samadian[1], Prof. Wim De Waele[1], and Paul Roovers[2]

1 Ghent University, Dept. EEMMeCS, Soete Laboratory, Zwijnaarde, Belgium

2 Fluxys Belgium SA, Brussels, Belgium

Technology for Future and Ageing Pipelines Conference

Het Pand, Gent, Belgium

11-12 April, 2018

Organized by

Lab. Soete

and Tiratsoo Technical

and supported by

Clarion Technical Conferences

The European Pipeline Research Group

PRCI

and

Pigging Products & Services Association

Load bearing capacity of corroded girth welds in vintage pipelines below the ductile-to-brittle transition temperature

GIRTH WELDS IN VINTAGE PIPELINES (older than 40 years) are susceptible to corrosion as the field joint coatings deteriorate. The resulting reduction in wall thickness might reduce the axial load or internal pressure bearing capacity to an unsafe level. The toughness of the girth welds in vintage pipelines might be low in comparison to modern pipelines. Standards such as ASME B31G provide limited guidance on how to assess girth weld corrosion. Previous investigations produced an extensive database of mechanical tests of girth welds showing metal loss. Results led to a workmanship criterion of 20% allowable wall thickness reduction and a plastic collapse based ECA methodology for prediction of load bearing capacity. The ductile-to-brittle transition temperatures of the tested welds, however, were too low to provide statements for brittle failure. This paper describes a new experimental programme in which welds were tested below their transition temperature. Test results indicate that both the workmanship criterion and the collapse based ECA methodology retain validity in brittle scenarios, provided the weld is free of natural workmanship flaws.

Introduction

The Belgian gas transmission pipeline grid was strongly expanded after the discovery of the Dutch Groningen gas field in the 1960s. When these vintage pipelines are inspected by an intelligent pig, it is not excluded that circumferential metal loss in the girth weld and adjacent to the girth welds is detected. It is a fact that girth weld coating (applied in the field) is done in less favourable conditions than pipe coating applied in the mill.

There are different approaches to deal with the integrity assurance of girth welds showing metal loss, four of which are highlighted below.

- It may practically be decided that the pipe section containing the corroded girth weld is to be cut out when the corrosion in the girth weld area is deeper than the level of the adjacent pipes. This is, arguably, a very conservative approach which may be economically undesirable.

- As a result of the publication of ASME B31G-2009 there is a possibility to apply flow-stress based criteria such as B31.G, modified B31.G or RSTRENG effective area “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.” [1]. The applicability hereof is hampered by the absence of concrete quantifications of these requirements.

- The report of EPRG project 177/2014 [2] collected a test database which led to the suggestion of a workmanship criterion for allowable (girth or long seam) weld metal loss in vintage pipelines. The criterion, further referred to as the “20% rule”, suggests that 20% metal loss is allowable in the girth weld, irrespective of toughness, provided it is free of adjacent natural flaws. Hereby, allowability relates to the pipe’s ability to reach a remote axial stress level equal to SMYS. The criterion is backed by six independent test programs, producing a large database of around 200 component scale test results on vintage pipeline welds (including low toughness welds and undermatched welds), and supported by numerical parametric studies performed by Leis et al. [3]. An example database, generated by Soete Laboratory (Ghent University), is depicted in Figure 1 [4]. The database comprises 34 medium wide plate tests (one having a naturally corroded weld, the other ones containing machined metal loss). Hereby, a (mm) is the depth of metal loss, B (mm) is the wall thickness (average of both welded pipes), W (mm) is the width of the specimen’s net section, $2c$ is the circumferential arc length of the metal loss region, and M_T represents the tensile strength mismatch of the girth weld (values higher than unity representing overmatch). Notably, the sound use of the 20% rule is uncertain for contemporary pipeline girth welds given the likelihood of limited work hardening compared to vintage material.

- Reference [4] has explored the predictive ability of a plastic collapse assessment using BS7910. The axial load bearing capacity of girth welds showing metal loss could be accurately calculated when actual material properties were input. This involved taking weld ultimate tensile strength for flow stress (as suggested by Leis et al. in [3]) and replacing the (elastic) BS7910 correction for weld misalignment by a relaxed (elastic-plastic) stress concentration factor.

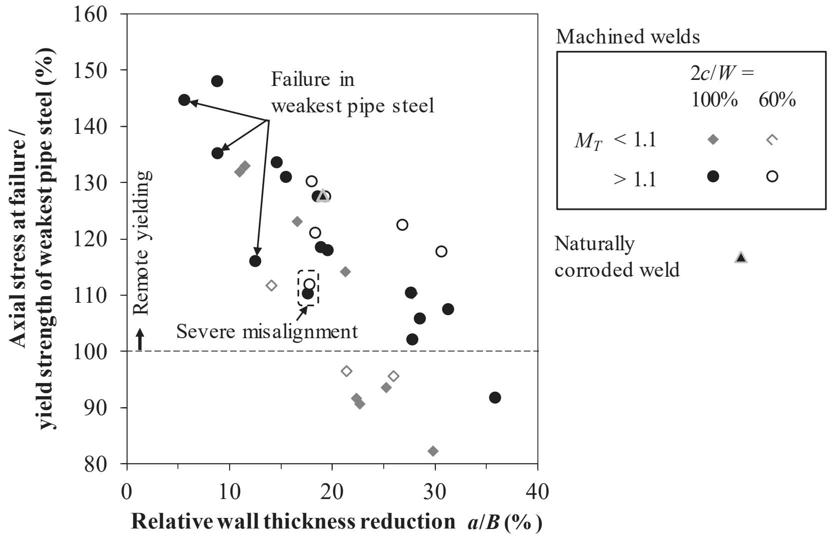

Figure 1: Published results database of load bearing capacity tests performed at Soete Laboratory, Ghent University [4].

The 20% metal loss criterion provides an interesting balance between avoidance of overconservatism (e.g., compared to the first option above) and simplicity in use (e.g., compared to the fourth option above). The absence of toughness requirements strongly adds to its practical applicability, yet is associated with the bold statement that plastic collapse occurs irrespective of the level of toughness. Experimental studies to support this statement are limited, but exist. For instance, Martin et al. [5] stated that methods such as modified B31G are applicable in materials with a transition temperature of +40°C. Nonetheless, current practical implementations of the 20% rule tend to cautiously adopt a toughness criterion. For instance, Fluxys only applies the criterion on its pipelines installed after 1983 (for which minimum Charpy V-notch values were specified). Prior to 1983, there was a weld requirement of 28 J (1/1) based on U-notched rather than V-notched Charpy specimens. This requirement cannot be linked to common CVN criteria leading to plastic collapse (such as EPRG's 30/40 J min./ave. criterion for the assessment of girth weld defects [6]). For pipelines installed before 1983, Fluxys currently reverts to the first (and most conservative) of four abovementioned approaches.

This paper introduces newly generated experimental data to support the applicability of the 20% allowable metal loss criterion in scenarios of low CVN toughness. To this end, medium wide plate (MWP) tests have been performed on welds obtained from the Belgian gas grid, at a sufficiently low test temperature to trigger brittle fracture. The paper is structured as follows. Section 2 discusses the characteristics of the tested material and the methodology of the experimental programme. Results are provided and discussed in Section 3. Section 4 reflects on factors of conservatism of wide plate testing with respect to pipelines subjected to internal pressure. Section 5 finally concludes.

Experimental programme

This section summarizes the materials and methods applied for the test programme to investigate girth weld metal loss acceptability in scenarios of brittle fracture. Attention is given to small scale material characterization and the procedure for medium wide plate (MWP) testing at low temperature.

Material characteristics

Four girth welds were extracted from the Belgian gas pipeline grid by Fluxys Belgium SA. In experimental work previously reported in references [4, 8], these welds were denoted as W7-W10. Their corresponding pipelines were constructed in 1969 (W7, W8) and 1973 (W9, W10), and comprise API 5L grade X60 UOE pipes having a nominal outer diameter of 914 mm (36") and a nominal wall thickness of 10.2 mm (W7, W9) or 12.2 mm (W8, W10). The material was selected from a larger stock of excavated girth welds, motivated by their relatively lower Charpy V-notch values compared to the other available material.

Tensile properties of the pipe steels and weld metals are conform to vintage pipe material that was used in the period of installation. Summarized,

- the pipe steels are generally characterized by continuous ('round house') yielding and show strong work hardening, Y/T ranging between 0.66 and 0.75 (based on full thickness longitudinally oriented specimens). All weld metal (round bar) tensile testing indicates Y/T ratios between 0.74 and 0.87, generally showing a discontinuous yielding onset.
- the high degrees of work hardening are associated with high levels of ductility, uniform elongation ranging between 10.2%–16.6% (base metal), and between 7.0%–11.1% (weld metal).
- weld strength overmatch is high, ranging between 17%–50% (based on yield strength) and 8.8%–28.1% (based on ultimate tensile strength).

Each girth weld has been Charpy V-notch (CVN) tested (L-T oriented specimens with respect to the pipe axis) at four temperatures (+20° C, 0 °C, -40 °C and -60 °C) with the notch either at the weld metal centre (WMC) or in the 50% heat-affected zone / fusion line (HAZ/FL) region. Three repeat tests were performed for each configuration. Limited wall thickness and/or the occurrence of weld misalignment inhibited the extraction of full size Charpy specimens from welds W7, W9 and partially W10. Where necessary, ¾ subsize specimens (having a thickness of 7.5 mm) were sampled and associated impact energies have been converted into full size equivalents.

The rationale for the chosen temperatures for Charpy characterization is as follows. In a previous project, the welds were Charpy tested at 0° and 20 °C. The remaining material allowed for characterizations at two additional temperatures. A first CVN test series for this project was performed at -40° C. Should these tests have indicated brittle behaviour, the MWP tests would have been executed at -40° C and a second CVN test series would have taken place at -20° C for additional characterization. However, transitional behaviour was observed and it was decided to perform the final CVN test run at -60 °C. The tests specimens at -60 °C were near to fully brittle, showing shear area percentages of less than 27%. Hereby, WMC material was clearly more brittle than HAZ/FL material, showing %SA consistently below 13%. Impact energy data (Figure 2; full size equivalent values) reveal similar observations, WMC notched specimens failing at less than 20 J for -60 °C. Minimum and average impact energies are summarized in Table 1.

Based on the Charpy data, it was decided to execute MWP tests at a targeted temperature of -60 °C, anticipating that this temperature would result in brittle failure.

Table 1: CVN impact energy data of the tested welds at -60 °C.

	CVN impact energy at -60°C (full size equivalent) min./ave. of 3 repeat tests (J)	
Weld	WMC	HAZ/FL
W7	12 / 15	33 / 37
W8	12 / 15	21 / 25
W9	11 / 14	20 / 27
W10	10 / 12	19 / 22

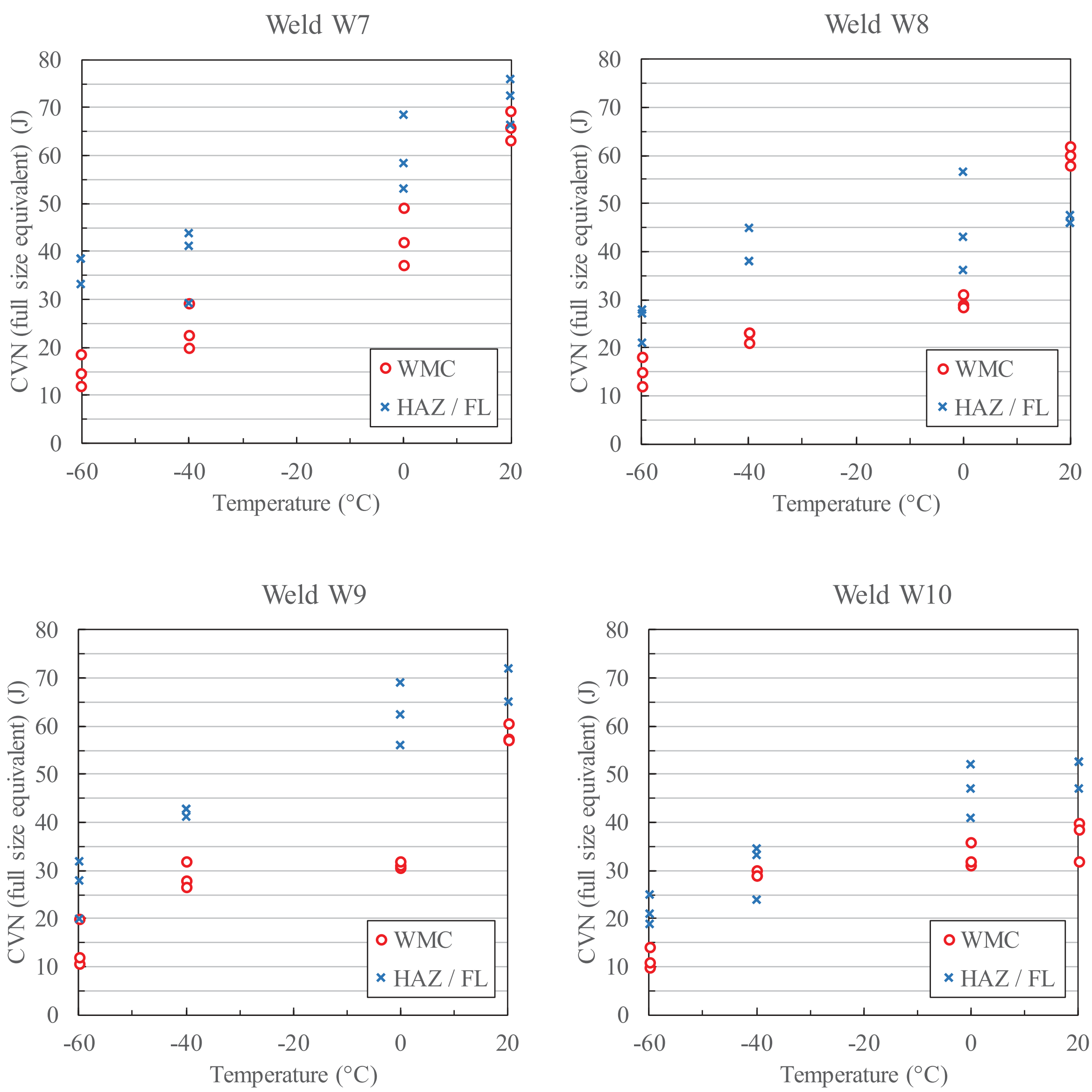

Figure 2: Charpy V-notch transition curves (in terms of impact energy, full size equivalent) of the tested welds.

Medium wide plate (MWP) testing

Medium wide plate tests have been performed on all four girth welds. A MWP test is a uniaxial tensile test on an unflattened (i.e. curved) welded pipe section containing the girth weld at mid-length. The geometry of a MWP specimen is shown in Figure 3(a). To apply the tensile load, two end blocks were welded to the specimen shoulders and the assembly was mounted in Soete Laboratory's 2.5 MN universal servo-hydraulic test machine. Testing was performed at an initial crosshead speed of 1.50 mm/min, which was increased to 3.00 mm/min after the clear occurrence of a gross section (pipe metal) yielding phenomenon. The deformation rate was sufficiently small to ensure quasi-static loading conditions.

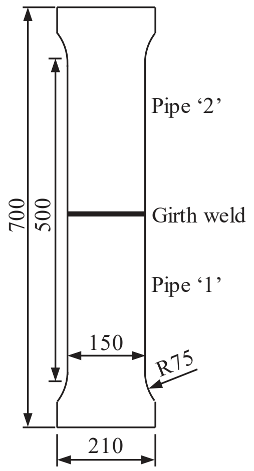

Figure 3: (a) Geometry and nominal dimensions of a Medium Wide Plate specimen. (b) Cooled specimen, insulated by means of Rockwool. White cables indicate the presence of thermocouples to monitor weld temperature during testing.

Specimens were cooled by means of ethanol, which was circulated through cooling pads attached to the outer diameter surfaces of the specimen (one pad at each side of the weld). Temperature was monitored by means of K-type thermocouples that were spot-welded to the girth weld region. Heat loss to the environment was reduced to an acceptable level, by covering the specimen with Rockwool (Figure 3b). Note that there was a tendency for weld temperature to increase as the tests proceeded, due to the development of plasticity. Anticipating this tendency, each specimen was initially cooled down to a temperature around -65 °C. All specimens had a temperature below -60 °C at the onset of base metal yielding and around -60°C at fracture (notwithstanding one specimen which had a temperature of -52 °C at the end of testing).

Corrosion metal loss was simulated by artificially machining part of the girth weld from the cap side. A 20 mm diameter spherical mill has been used in sequential passes longitudinal to the girth weld direction, aiming to cover the entire weld cap and 5 mm at either side of the weld cap (Figure 4). As a result, not only the weld but also the adjacent HAZs have been reduced in wall thickness. All welds were machined over the entire specimen width. Milling was performed by means of a devoted program implemented into a CNC milling machine. Its automatic implementation is based on tactile profile measurements adjacent to the weld, which were converted into best fitting circles to describe the pipe curvature. Weld hi-lo misalignment (potentially variable over the specimen width) was calculated by linear interpolation of profile measurements across the weld and accounted for in the milling process. Specimens were firmly clamped during machining to avoid distortion due to redistribution of residual stress.

After machining, the profile of the damaged weld cap was measured along three trajectories, equally divided over the specimen width. This allowed to quantify wall thickness reduction (a, mm), which was defined as the height difference between the deepest machined point and the 'lower' pipe of the misaligned weld (average of three paths). All MWP specimens had a targeted wall thickness reduction of a/B = 20% (relative to the average pipe wall thickness B). The CNC milling procedure produced smooth metal loss regions, wall thickness reduction being exceptionally close to this target (average: 20.0%; standard deviation: 1.0%).

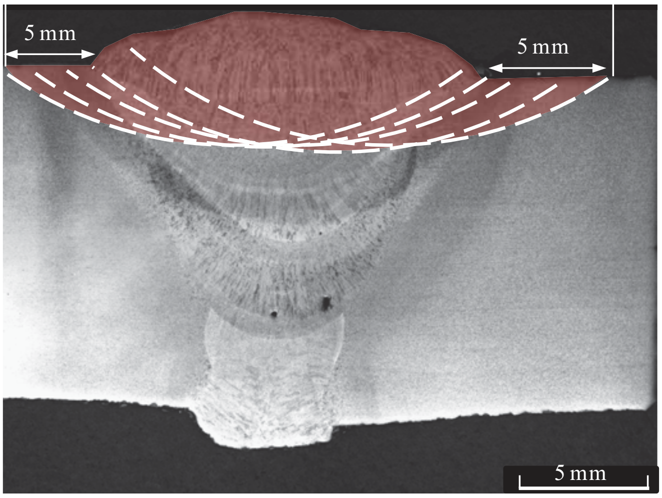

Figure 4: Schematic representation of simulated corrosion damage. Five milling passes are shown; more passes were actually applied to obtain a smooth metal loss profile.

The mechanical response of the MWP specimens was documented in terms of tensile load P (or, when divided by the average cross section of both plates, the longitudinal gross stress s), and the displacement of a clip gauge traversing the weld at a height of 2.5 mm above the outer pipe surface, having an initial gauge length of 30 mm. The 'weld strain' e_{weld} is defined as this displacement, divided by the initial gauge length and expressed as a percentage.

Test interpretation consisted of three aspects. The maximum longitudinal stress level s_{max} (further referred to as the 'failure stress') is the primary assessment criterion. This failure stress is expressed in relative terms as corresponding to 100% when its value equals the (actual) yield strength of the weakest pipe in the weld assembly. Metal loss is considered acceptable if the relative failure stress exceeds 100%. This performance requirement is a translation of the criterion that weld corrosion damage should not prohibit the weldment's possibility to attain gross section yielding.

In the calculation of relative failure stress, pipe yield strengths have been corrected for the test temperature, noting that small scale base metal tensile tests were executed at room temperature. Hereto, the following equation was adopted from BS7910 [9]:

$$\sigma_{y,low\ temperature} = \sigma_{y,room\ temperature} + \frac{10^5}{491+1.8T} - 189 \qquad (1)$$

where σ_y represents yield strength (taken here as $R_{t0.5}$) expressed in MPa, and T is temperature expressed in °C. It is easily confirmed that 20 °C yields a zero correction, and strength increases with decreasing temperature. For instance, a test temperature of -65 °C gives rise to a yield strength increase of 78 MPa. Notably, Østby et al. [10] have evaluated Eq. (1) against experimental data obtained from (albeit contemporary) HSLA pipe steels, weld metals and heat-affected zones. Their finding was that Eq. (1) tends to overestimate the increase of yield strength at low temperature. This statement was confirmed in an experimental programme at Ghent University, performed within the scope of a different project. Overpredictions of base metal yield strength are conservative within the context of interpreting weld metal loss acceptability.

A second interpretation is the failure mode of the tests. The nature of fracture was checked by means of post mortem visual inspection. Fracture surfaces were additionally screened for indications of natural weld flaws, which may decrease the failure stress.

Finally, weld strain e_{weld} versus longitudinal stress records have been used to interpret the deformation behaviour of the weld. Weld strain provides information on the level of plasticity that can be achieved by the weld prior to failure.

3. Results and discussion

Figure 5 plots an example trajectory of relative longitudinal stress and temperature as a function of weld strain, up to failure. Figures like this allow to conclude that the test temperature was sufficiently low (below/around -60 °C), and that the acceptability criterion for metal loss is met (relative failure stress of 128%, which is higher than 100%).

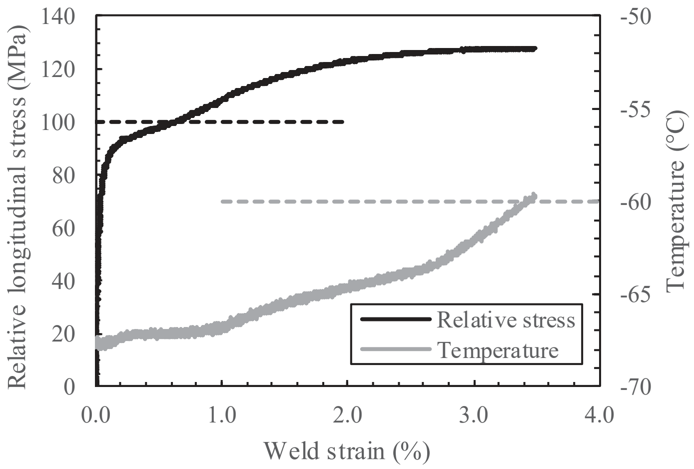

Figure 5: Example test result, depicting relative longitudinal stress and weld temperature as a function of weld strain.

Figure 6 plots the relative failure stresses as a function of relative wall thickness reduction (red solid markers). As a reference, Soete Laboratory's previous database of tests at room temperature (Figure 1) is replicated (black markers). The horizontal dashed line represents the lower bound for acceptability of girth weld corrosion as put forward in section 2.2. Clearly, the load bearing capacities of specimens tested at low temperature fall within the cloud of data points for specimens tested at room temperature (which failed by plastic collapse). All nine low temperature tests failed at a longitudinal stress level exceeding the yield strength (corrected for low temperature) of the weakest pipe metal. In other words, gross section yielding was attained for all specimens. The lowest observed relative failure stress is 107.7% (specimen having a wall thickness reduction 20.9%). Hence, a workmanship criterion of 20% allowable wall thickness reduction would yield safe predictions for the low temperature test database.

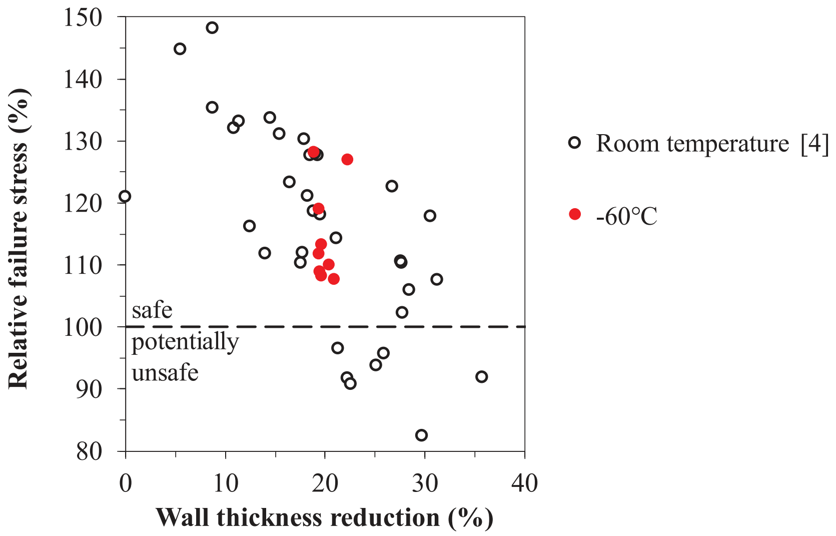

Figure 6: The newly obtained test results at low temperature are located within the scatter band of test results at room temperature.

Fractography indicates that all fracture surfaces were brittle. Fracture surfaces of two specimens indicated the presence of small embedded natural weld flaws, which are acceptable by workmanship (sizes below 9.0 mm long by 2.9 mm deep). For these specimens, chevron marks indicate that fractures initiated from the natural weld flaws. It is noteworthy that the presence of small natural weld flaws did not inhibit both specimens' ability to fail beyond pipe metal yielding. As an example, Figure 7 shows a brittle fracture that initiated from a group of porosities.

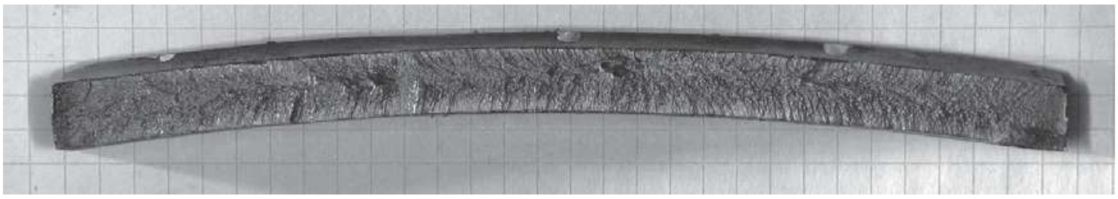

Figure 7: Example fracture surface, indicating brittle fracture originating from a weld porosity.

A consequence of brittle fracture is the inability of the weld metal to fully exhibit its ductility. This is reflected in Figure 8, depicting weld strain values at maximum load as a function of the minimum CVN energy of the weldment (including weld metal and HAZ) at -60 °C. Plotted for the sake of comparison are the weld strains at failure of the MWP test database at room temperature. Although the strain at failure of the welds is less at -60°C than at room temperature, brittle material behaviour did not inhibit the occurrence of plasticity within the welds, which can be associated with a weld strain level of 0.5%.

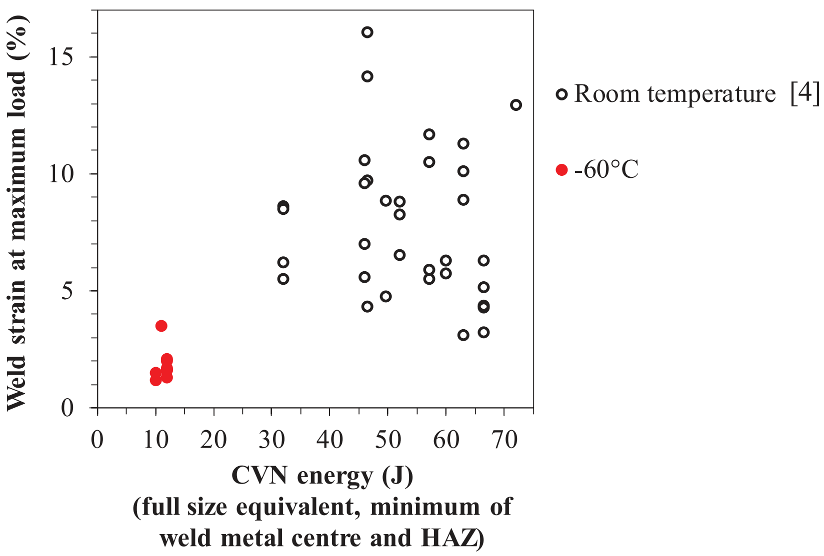

Figure 8: Brittle fracture did not inhibit the occurrence of plasticity within the welds (associated with a weld strain of 0.5%).

Given the observed effect of toughness on weld strain at failure, it is worthwhile checking whether corrosion assessment methods (which assume plastic collapse) can predict the failure of the tested specimens. In references [4, 7], Ghent University's previous tests at room temperature were compared against a plastic collapse assessment stipulated by the latest edition of BS7910 (2013 + A1:2015) [9], and also informed by ASME B31G [1]. The assessment adopts the reference stress approach, which predicts plastic collapse as soon as the structure's limit load is attained. This limit load depends on geometrical characteristics (in particular: metal loss depth, weld misalignment) and material strength, translated into an assumed flow stress. BS7910 adopts the Willoughby and Davey limit load solution for tension loaded plates [11]. A minor modification was proposed in the description of effects weld misalignment effects, which are estimated in an overly conservative manner by BS7910. This modification reduces the level of conservatism and was theoretically motivated by the fact that the BS7910 correction for weld misalignment is based on linear elastic behaviour, and this correction could be relaxed by implementing an elastic-plastic stress concentration factor instead.

Multiple definitions exist for flow stress, two of which deserve particular attention:

- **SMYS + 69 MPa**. This definition is adopted in the ASME B31G corrosion assessment criterion, and is known to yield conservative results for vintage pipe, due to its high strain hardening characteristics. This conservatism was confirmed in Ghent University's MWP dataset at room temperature [4]. Notably, the ASME B31G definition is less conservative for vintage pipe than other standardized flow stress values (e.g., average of SMYS and SMTS (BS7910), or a predefined percentage of SMYS (CSA Z662)). Hence, conservatism of plastic collapse predictions using the ASME B31G definition of flow stress implies conservatism when using the BS7910 and CSA Z662 definitions of flow stress.
- **The *actual, ultimate* tensile strength (R_m or UTS) of the damaged material (being the weld metal in this case).** Leis et al. [3] indicated this definition to produce accurate (rather than conservative) predictions of plastic collapse load. In other words, conservative and non-conservative predictions may occur. This statement was also confirmed for Ghent University's MWP dataset at room temperature [4].

It is important to mention that, in this study, both flow stresses have been soundly corrected for low temperature, by adding 78 MPa (associated with a temperature of -65 °C according to Eq. 1):

regarding SMYS + 69 MPa: the soundness of this correction for yield strength has been discussed below Eq. (1).
regarding actual weld UTS: literature indicates that the strength correction for low temperature – albeit developed for yield strength – is representative for ultimate tensile strength (i.e., overestimates the actual strength increase). For instance, an empirical model developed in reference [15] (based on test results on S690 steel) predicts increases in ultimate tensile strength (at -65 °C) of merely 56 MPa for a steel having a tensile strength of 600 MPa at room temperature. Notably, an experimental dataset of tensile tests on API 5L grade X80 steel at room and low temperature, obtained at Soete Laboratory and reported in reference [12], indicated an average ultimate tensile strength increase of 0.98 MPa/°C, corresponding with 83 MPa increase at -65 °C relative to room temperature values. This value exceeds the assumed increase of 78 MPa by 5 MPa, which would increase the obtained collapse load predictions by less than 1% of their current value (given that tensile strengths fluctuate around 600 MPa). Such minor discrepancy is considered acceptable.
The abovementioned assessment procedure for plastic collapse has been applied to the newly generated MWP test data at low temperature. Results are plotted in Figure 9 (coloured red), and are complemented by the previously obtained assessment dataset at room temperature (in black). Two datasets are plotted (crosses and diamond markers), each adopting a different flow stress definition. It is seen that:

- the "accurate" flow stress definition of Leis et al. [3], based on actual ultimate tensile strength of the weld, yields representative failure stress predictions. The degree of scatter is comparable to that of the room temperature dataset. This indicates the soundness of applying a plastic collapse based assessment for the coupons tested at low temperature.
- the ASME B31.G definition of flow stress (SMYS + 69 MPa) consistently yields conservative predictions, the degree of conservatism being comparable to that of the room temperature dataset. Assessments using this flow stress definition underestimate the failure stresses by at least 20 % of their actual values. This observation is in line with reference [5].

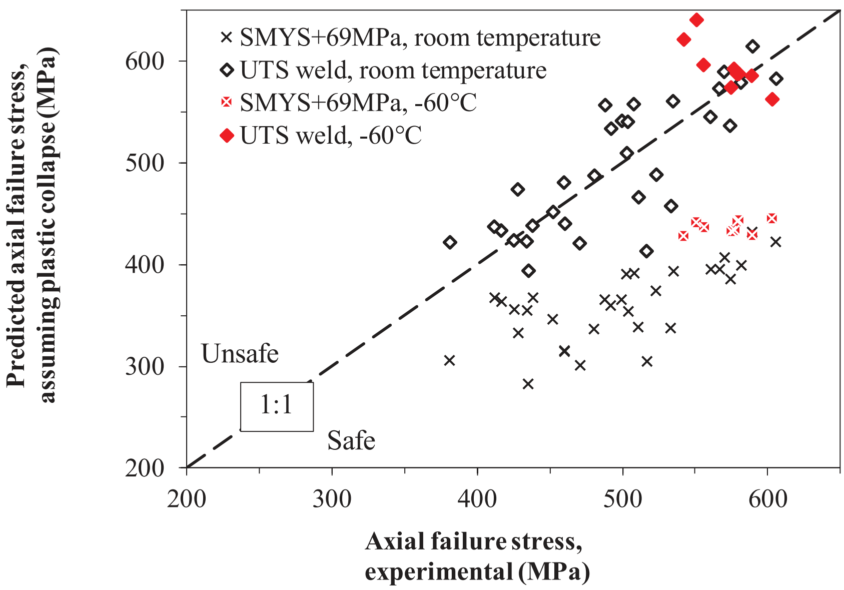

Figure 9: Failure stresses can be accurately predicted by means of a plastic collapse based assessment method (diamond markers), and conservatively predicted when assuming SMYS + 69 MPa as a flow stress (cross markers). The agreement is comparable for tests at room temperature and at -60 °C.

Factors of conservatism with respect to pressurized pipe

With the aim of translating the 20% allowable weld metal loss rule into practice, it is worthwhile listing major factors of conservatism of MWP testing with respect to pressurized pipe, when it comes to the acceptability of girth weld metal loss.

- When corrosion metal loss targets the girth weld, the dimensions of the corroded region are typically much larger in the circumferential direction than in the axial direction. The most severe loading condition with respect to such metal loss profile is uniaxial tension longitudinal to the pipe axis. MWP tests allow to reach the level of yield strength and above in the axial direction. In contrary, the axial stress introduced by internal pressure is half the hoop stress or less (depending on boundary conditions), and this hoop stress is a safety factor below the SMYS of the pipe steel.

- With the exception of one specimen in the test database of Figure 9, all tested welds were intendedly machined to simulate the occurrence of corrosion metal loss. The result is a uniform degree of metal loss over the girth weld, and complete removal of the weld cap. Such severe degree of material removal is unlikely for real corrosion, which would tend to retain (part) of the weld cap. The strengthening effect of this weld cap is substantial, as shown in reference [4].

- When hoop stress dominates over axial stress (as is the case for pure internal pressure), the detrimental effect of girth weld misalignment will be less pronounced. For instance, BS 7910 suggests to neglect girth weld misalignment when the only stress component acting on the weld is oriented in the hoop direction.

- Whereas operational conditions (maximum allowable operating pressure) are linked to the SMYS of the pipe steel, the acceptability criterion of girth weld metal loss in the MWP tests was based on the ability to attain remote yielding (which is related to the actual yield strength of the pipe steel rather than its SMYS).

Summary and conclusions

Experimental work has been performed to quantify the axial load bearing capacity of girth welds originating from vintage, large diameter X60 steel pipes and showing corrosion-like metal loss. Nine medium wide plate (MWP) tests have been conducted and have been supported by small-scale material characterization. Brittle fractures have been triggered by testing the welds at -60 °C and below. This temperature was chosen on the basis of a Charpy V-notch test program preceding the MWP tests. An intended wall thickness reduction of 20% was closely achieved for all MWP specimens by means of a devoted CNC milling procedure.

Supported by the small-scale characterization of the tested materials, the following conclusions are drawn for the MWP test database:

- The low observed Charpy toughness characteristics at -60 °C (impact energy and percentage shear area) corresponded with brittle fractures in all MWP tests.
- Despite the brittle nature of failure, all MWP specimens could reach a sufficient load level to cause the weakest base metal to yield, thus meeting a weld metal loss acceptability criterion set forward in EPRG report 177/2014 [2]. Hereby, all welds plastically deformed, straining between 1.2% and 3.5% at failure.
- Failure stresses can be accurately predicted by means of a plastic collapse based assessment method, proposed in BS 7910 and slightly modified to account for elastic-plastic weld misalignment effects. Conservative failure stress predictions (underestimating failure stress by at least 20% of the actual value) were achieved by adopting the ASME B31.G definition of flow stress.
- Base metal yielding was not inhibited by the presence of small natural weld flaws in two MWP specimens, out of which brittle fractures initiated.

Referring back to the rationale of this test program, it can be concluded that this report supports the findings of EPRG project 177/2014, and provides additional confidence in the soundness of the 20% allowable metal loss rule in absence of a toughness criterion.

Acknowledgements

The authors would like to acknowledge the assistance of the technical staff of Soete Laboratory.

References

1. ASME B31G, 2012. Manual for determining the remaining strength of corroded pipelines. American Society of Mechanical Engineers, New York, USA.
2. Davis, E., Swankie, T., 2015. Assessment of corrosion associated with the girth or long seam weld in vintage pipelines. DNV-GL report 15640 Issue 1.0, EPRG project 177/2014, 78 p.
3. Leis, B.N., Clark, E.B., Zhu, X.K., Galliher, R.D., 2004. Guidelines for assessing corrosion associated with girth and long-seam welds. Gas Technology Institute, USA, Report GRI-04/0119, 100 p.
4. Hertelé, S., Cosham, A., Roovers, P., 2016. Structural integrity of corroded girth welds in vintage steel pipelines. Engng. Struct. 124, 429-441.
5. Martin, M., Andrews, R., Chauhan, V., 2009, Project #153, The Remaining Strength of Corroded Low Toughness Pipe, GL Industrial Services Ltd. Report 9247 Issue 3.0 (PHSMA DTPH56-05-T-0003)
6. Andrews, R., Denys, R.M., Knauf, G., Zarea, M., 2015. EPRG guidelines on the assessment of defects in transmission pipeline girth welds – Revision 2014. J. Pipeline Engng. 14(1), 9-21.
7. Roovers, P., Swankie, T., Hertelé, S., 2015. Assessment of corrosion associated with the girth or long seam weld in vintage pipelines (EPRG project 177/2014). in: Denys, R. (Ed.), Proc. 1st Ageing Pipelines Conf., Ostend, Belgium.
8. Hertelé, S., Denys, R., Lefevre, T., Roovers, P., 2013. Structural integrity of corroded girth welds. in: Denys, R. (Ed.), Proc. 6th Int. Pipeline Tech. Conf., Ostend, Belgium. Paper S01-01.
9. BS 7910, 2013 (+A1 2015). Guide to methods for assessing the acceptability of flaws in metallic structures. British Standards Institution, London, UK.
10. Østby, E., Hauge, M., Horn, A.M., Akselsen, O.M., 2013. Fracture mechanics design criteria for low temperature applications of steel weldments. in: Proc. 23rd Int. Offshore Polar Engng. Conf. (ISOPE), Anchorage, Alaska, USA.
11. Willoughby, A.A., Davey, T.G., 1989. Plastic collapse at part wall flaws in plates, in: Wei, R.P. (Ed.), Fracture mechanics: perspectives and directions. Proc. 20th Nat. Symp. ASTM STP 1020, Bethlehem, Pennsylvania, USA.
12. Tubex, H., 2015. Stress-strain behaviour of high-strength steels at low temperatures. Ghent University, MSc thesis dissertation.