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Tensile Strain Capacity of Energy Pipelines with Flawed Girth Welds

Literature Review

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1. Executive Summary:

In the presence of girth weld flaws, pressurized pipelines exhibit a reduction in their tensile strain capacity under tensile axial and bending loads. Research conducted to understand this reduction is based on wide plate tests with prefabricated flaws. In addition, the objective of the recent research in this area has been to test the tensile strain capacity of high strength steels of grades X80 and higher. The results of this research has culminated in equations in the Canadian standards association code of practice CSA Z662.07 to predict the tensile strain capacity with a warning indicating that they are based on wide plate tests and do not include the effect of internal pressure. In addition, they only apply to modern high strength steel pipelines with high toughness. However, recent research on X80 pipelines have shown that tests conducted on wide plate tests dramatically over predict the tensile strain capacity of welded pipeline steel compared to the combined effect of internal pressure and axial tensile or bending stress.

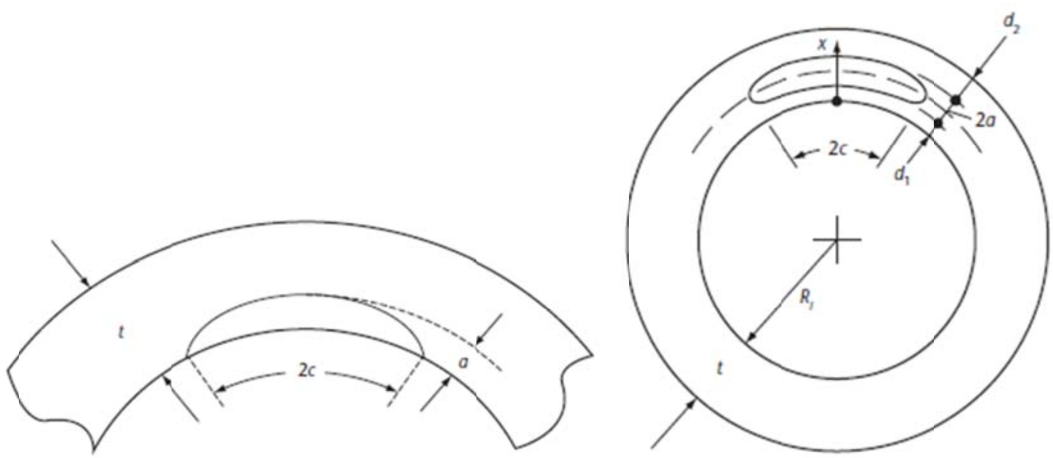
Enbridge Pipelines Inc. has initiated a research project to be conducted at the University of Alberta with the purpose of investigating the tensile strain capacity of vintage X52 pipe under the effect of both internal pressure and axial tensile and/or bending stresses. A 90m of cutout of Enbridge NPS 12 Norman Wells Pipe will be used for this research. Full scale testing of pressurized pipes along with ancillary testing to understand the mechanical properties of vintage pipe in combination with numerical modeling will be conducted. The ultimate goal is to provide a confident assessment of Norman Wells X52 pipe and to predict its behaviour under bending stresses due to soil movements. The results of this research will augment the current Canadian standards with recommendations for X52 pressurized pipes.

The first task in the research proposed by Enbridge Pipelines Inc. and the University of Alberta was to conduct a literature review to understand the state of knowledge of the effect of the internal pressure on the tensile strain capacity of pipelines with flawed girth welds. This document provides an account of the literature that was reviewed. It was found that there is a consensus in the literature that the internal pressure causes a reduction in the tensile strain capacity of flawed girth welds in comparison to the results obtained from wide plate tests. In addition, only one source in the literature has provided an equation to account for this reduction in the tensile strain capacity. However, the equation is based on modern high strength steels. Thus, there is a dire need to conduct the proposed experimental research to obtain appropriate equations that are useful for vintage pipes.

2. Literature Review

2.1 Weld Defects Classification and CSA Z662.07:

The Canadian Standard Association Code of Practice CSA Z662.07 classifies possible weld defects as surface breaking or buried (Figure 1). Surface breaking defects are those that resemble a crack that is connected to the surface of the pipe, while buried defects are those that are not connected to the surface of the pipe (Figure 1). According to Z662.07, in the absence of any experimental data, the critical tensile strain of the pipe material can be calculated based on two equations (Equation C4 and Equation C5) as functions of the defect parameters given in Figure 1 and the material properties (toughness, yield and ultimate tensile strengths) of the pipe material. These equations were developed based on the extensive experimental work conducted by Wang et al. [21,22,18,19,20] on curved wide plates (CWP) with prefabricated defects. However, the code specifies high values for toughness as a limitation to using these equations, indicating that these equations were developed for modern steel pipelines. In addition, the code specifically warns that the effect of the internal and/or external pressure on the longitudinal strain capacity is not considered in the equations and experienced judgement needs to be used or testing needs to be conducted to verify the behaviour under the effect of pressure. Thus, in order to understand the longitudinal tensile strain capacity of Enbridge X52 vintage pipeline it is imperative to conduct full scale experiments and toughness tests for a possible range of defects under the effect of both internal pressure and longitudinal bending and/or axial tensile loading.



(a) (b)

Figure 1. Classification of weld defects according to CSA Z662.07 (a) Figure C3 from CSA Z662.07: Surface breaking defects and (b) Figure C4 from CSA Z662.07: buried defect

2.2 Research Conducted on Strain Capacity of Pipelines Using CWP:

Due to the difficulty associated with full scale testing of pressurized pipes, full scale tests have usually been conducted on curved wide plates (CWP) with prefabricated flaws or defects. Wang et al. (2002) [24] calculated the strain capacity of girth welds containing surface breaking welding defects by numerical analysis. They verified their numerical analysis results with an experimental program on CWP tests designed to develop strain design guidelines for a limited range of applicability. In their study, they compared finite element analysis (FEA) results with the experimental results of the full scale bend test and the tensile loading experiments of CWP performed by the University of Waterloo and the welding institute of Canada and published by Pick et al. and Glover et al. [13,6,5]. They utilized the finite element analysis software ABAQUS to model different defect depths, defect lengths, pipe toughness and weld strength mismatch levels. They concluded that the crack defect size is the most influential parameter for the girth weld strain capacity. The parametric equations developed by this study can be useful to understand the effect of defect size and mismatch level on the strain limit of girth welds. However, equations developed using CWP tests cannot predict the tensile strain capacity in the presence of axial loading combined with internal pipeline pressure.

Wang et al. (2011) [16] discussed the overview of tensile strain capacity prediction methodology recently developed by ExxonMobil. The methodology includes: An FEA-based tensile strain capacity prediction approach addressing all relevant limit states (ductile tearing and plastic collapse) from which a closed-form generalized tensile strain capacity equations can be derived that accounts for the relevant limit states, and small-scale Single-Edge Notch Tensile (SENT) testing procedure for tearing resistance measurement of full-scale welded pipes.

2.3 Research Conducted on Strain Capacity of Pressurized Pipelines:

While CWP tests can be useful to understand weld tearing resistance behaviour, recent studies suggest that full scale pressurized pipe tests are required to accurately measure the strain capacity of buried pipelines. Different numerical studies show that the internal pressure significantly affects the crack growth driving force but it does not influence the material resistance to crack growth (Minnar et al, 2007 [11]). Using both an experimental and a numerical approach, Cheng et al. (2009) [1] suggested that the Single-Edge Notch Tensile (SENT) test can be used to obtain the toughness material curves (R-curve) to characterize the behaviour of the material. The obtained curves are similar to those obtained from full scale pipes testing.

In 2009, Sakimoto et al. [14] investigated the influence of internal pressure on the ductile crack initiation and ductile tearing behaviours of pipelines in an experimental study. They also developed a simple method to predict ductile strain initiation and leakage of the pressurized pipe by using the material curves (R-curve) of SENT specimens. They augmented their experimental study with a finite element analysis study and showed that the internal pressure does not affect the material curve. On the other hand, the internal pressure increases the effective opening displacement and leakage by increasing the crack driving force. By comparing their experiments with their numerical study, they concluded that it is possible to predict critical strain on ductile crack initiation and leakage of pressurised pipe by using SENT tests and FEA results.

Recently, Igi et al. (2010, 2011) [8,7] investigated the tensile strain capacity of high strength pipe. X80 pipes with outer diameter of 508 mm and wall thickness of 14.3 mm were tested under full scale tension to understand the influence of internal pressure on the tensile strain capacity. During the test, the load, crack mouth opening displacement and axial elongation were recorded using a load cell, clip gauge and LVDT, respectively. To measure the ductile crack length propagation and the amount of notch displacement, microscopic sectional observation was performed. They also conducted wide plate tests to understand the tensile strain capacity predicted without the internal pressure. The results of their tests concluded that the strain capacity is highly influenced by the internal pressure with approximately 50% tensile strain capacity reduction in the case of the pressurised pipe tests compared to the wide plate test.

They observed that the internal pressure increases the crack driving force due to a dramatic increase in the strains at the flaw site. In addition to the full scale tests, they conducted material toughness tests on and augmented their work with a numerical study using the finite element analysis software ABAQUS. This study described a simplified method to predict the tensile strain capacity of the pressurized pipe by using material data obtained from fracture mechanics tests and finite element analysis.

Kibey et al. (2010) [9] developed closed form, simplified equations for the tensile capacity of X65 and X80 pressurized pipelines and validated the equations by a comprehensive full scale test program conducted by Minnaar et al. and Gioielli et al. [11,3].The main focus of this study was to measure material resistance curves for predicting the tensile strain capacity and to develop and validate finite element analysis methodology to predict tensile strain capacity of pressurized pipelines. They also developed and validated closed form equations to predict tensile strain capacity of pipe by using finite element based parametric studies. The results of this study showed that the equations were validated by the previous experimental study. These equations can be applicable for various flaw sizes, various grades and pipe sizes and they can relate the influence of flaw and pipe geometry parameters to the tensile strain capacity.

The difference between the results of CWP and full scale pipe tests were examined in details by Stephens et al, (2010) [15]. They conducted 16 axial tension tests on full pipe and 10 tests on CWP panels cut from X65 pipes with 12.75 inch diameter. All specimens contained surface breaking notches on the outside surface of the pipe to simulate the girth weld flaws. Half of the full scale tests were conducted using high internal pressure and the other half using low internal pressure. CWP tests were designed for a single girth weld. The results of this study showed that the strain capacity is reduced significantly in the case of the presence of high internal pressure. The reduction of the capacity varies for different yield/tensile strength ration and whether the flaw is in the body pipe or in the heat affected zone. Figure 1 shows the reduction of strain capacity due to the presence of internal pressure. Similar results were obtained through the experimental studies conducted by Gioielli et al (2007) and Qxtby et al (2007) [12,3].

In a review article, Wang et al (2010) [17] discussed the influence of the mechanical properties, weld strength mismatch levels and toughness on the tensile strain capacity. They noted that the scattered test data of material parameters may lead to an imprecise prediction of the actual material response. While a number of tensile strain capacity models are under development, it is difficult to develop and validate the model using these material parameters. Their conclusion was based on analyzing several experimental studies conducted by Gianetto et al. (2010) [2] and Stephens et al. (2010) [15]. Finally they concluded that more equations are required for different categories of flaw size and material parameters.

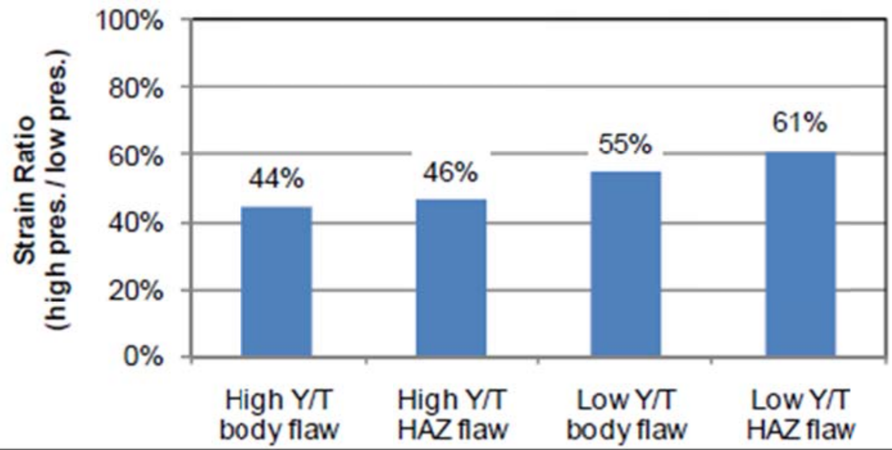


Figure 1: Reduction of tensile strain capacity due to internal pressure (Stephens et al. 2010 [15])

In a more recent report, Wang et al. [23] conducted 24 full scale tests on X65 electric-resistance welded (ERW) pipes to measure the effect of different parameters, in particular the internal pressure on the tensile strain capacity of flawed girth welds. Their report introduces a pressure effect factor designed to find the tensile strain capacity of flawed girth welded pipes with internal pressure. They concluded that the tensile strain capacity of pipes without internal pressure are in the range of 1.5 to 2.5 higher than the tensile strain capacity of pipes with internal pressure. The pressure factor introduced by Wang et al. is a result of their long track record of experiments and numerical analyses on high strength steel pipes. One aspect of our work will be to evaluate the developed equations with the vintage X52 Normal Wells Pipeline.

Not only does the internal pressure reduce the tensile strain capacity of pipes containing defects, but it also reduces the tensile strain capacity of plain pipes. In 2010, Zhu et al. [25] theoretically investigated the effect of axial tensile strain on the plastic yield load carrying capacity of pipelines subjected to internal pressure. The results of this study showed that yield pressure, yield hoop and axial stresses are functions of the tensile strain, Poison’s ratio, Young’s modulus and the yield strength. Their theoretical approach showed that internal pressure is the dominant load in the pipe and that the hoop stress is the maximum principal stress. They concluded that the internal pressure may reduce the yield loading capacity of the pipe leading to an unexpected premature pipeline failure.

The studies conducted on tensile strain capacity indicated that the internal pressure causes a reduction in the expected resistance to tensile loading. However, this behaviour was only examined in high strength pipes of grades X80 and X65. Similar studies are required for vintage pipe. We are proposing to conduct similar full scale tests on a 90 m cut-out of Enbridge X52 pipes to understand their tensile strain capacity in combination with the internal pressure. Single-Edge Notch Tension (SENT) tests will be conducted to understand the tearing behaviour of the material. Full scale tests will be compared with finite element analysis results to characterize the strain behaviour in the vicinity of the weld flaws.

The current established tensile capacity equations in CSA Z662.07 are designed to evaluate the tensile strain capacity of modern pipe with CTOD toughness greater than 0.1mm. Vintage pipelines, however, are known to have a much lower toughness than those applicable to the CSA Z662.07 design equations. Accordingly, a methodology should be generated to evaluate the tensile capacity of vintage pipelines as a function of their material properties, geometry and loading conditions. This methodology can be established through a combination of full scale testing, ancillary testing, finite element analysis and parametric studies. Generating this methodology for Enbridge's Norman Wells Pipeline specifically will allow for accurate prediction and a full understanding of the effects of slope movements on the tensile capacity of this pipeline.

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