**Tensile Strain Capacity of Energy Pipelines with Flawed Girth Welds**

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**1- Introduction**

Steel pipelines have proven to be the efficient method for the transportation of oil and natural gas from remote regions like sub-Arctic region of North America to the place of consumption. These pipelines are often subjected to excessive bending, tensile loading and high longitudinal strains due to temperature fluctuations, temperature gradients between the installation and operating temperatures, internal pressure and unfavourable geotechnical conditions. The latter include slope instability, seismic activity or discontinuous permafrost which causes differential settlement of the pipeline due to the freezing and thawing cycle of the permafrost. Among many other reasons which may possibly lead to the failure of a pipeline such as mechanical damage, third party encroachment, dents, longitudinal cracks, corrosion, severe wrinkles and buckling, fatigue, the loss of containment capability due to the presence of girth weld flaws is a long-standing issue in the strain based design of pipelines. In the presence of girth weld flaws, pressurized pipelines exhibit a reduction in their tensile strain capacity under tensile axial and bending loads.

In addition to the aforementioned causes of tensile loading, another occasion where the pipes experience tensile strain is the cold bending procedure. Cold bends are applied on site using cold bending machines, at locations where it is necessary to adjust the vertical or horizontal orientation of the pipe according to changing terrain conditions. Sen et al [1], [2] conducted experimental studies about the buckling of cold bend pipes at the University of Alberta. In these experimental studies it was observed that cold bend pipes may fail on the tension side due to excessive tensile strains in form of a sudden burst.

**2- Literature Review**

**3- Problem Statement**

Girth welds are locations of a line pipe with a relatively high likelihood of failure due to tensile forces. These tensile forces are usually due to geotechnical phenomena like slope instabilities or seismic activity. Also freeze and thaw cycle of the permafrost in arctic regions applies tensile forces on the pipes buried in the ground. One of the major reasons for the tendency of line pipes to failure is a potential risk of flaws in the girth welds which join pieces of line pipes. Since these pieces are joined on site using manual welding methods, the presence of flaws in the girth weld is unavoidable. In addition to the effect of flaws in the girth weld also the decrease in the material properties of the base metal due to heat affected zones around the girth weld cause a tendency to failure and loss of containment capability of the line pipe. Extensive research in the field of strain based design showed that the size of the girth flaw (particularly the length and depth) has a significant effect on the tensile strain capacity of the pipe. Experimental studies of this effect lead to closed form equations for the prediction of the tensile strain capacity of a pipe as a function of yield strength /ultimate strength ratio (Y/T), CTOD toughness, flaw length and flaw depth. These equations (Eq. (1), (2)) are included in the CSA code for pipeline systems operation (CSA Z662). On the other hand most of the experiments in this field consist of curved wide plate tests which don’t take the effect of internal pressure into account. Another drawback of the equations currently in the CSA code is that they are only applicable to pipes with steel grade of X65 and higher. In addition to the equations of the CSA code, different equations have been proposed in the literature, which take the effect of internal pressure into consideration [1], [2]. However none of these proposed equations are designed to predict the strain capacity of vintage pipes. To date research in the field of pipeline structures has primarily been focused on the compressive strain capacity of pipes [3]. As a matter of fact there was not enough experimental research to investigate the tensile strain capacity of pipes under various load combinations and for different pipe dimensions. Therefore there exists a necessity to investigate the strain response of pipes with X52 steel grade and to create a model of this response. In the scope of this research project we are investigating this strain behaviour in the presence of internal pressure on pipes with grade X52. As stated in the beginning of this section there are various conditions than may cause tensile strains on a buried energy pipe. In this research project we are dealing with two conditions which make the presence of tensile strains critical for a line pipe:

1) Flaws in the girth welds.

2) Change of wall thickness and material properties due to cold bending.

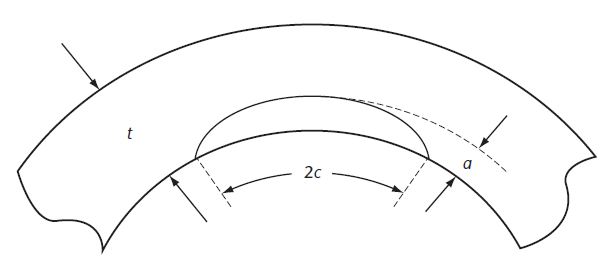
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Figure 1: Definition of a surface flaw according to CSA Z662-11

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**4-Objectives and Specific Aims**

The main objective of this research is to identify the structural behaviour of pipes under tensile strain and to define failure criteria due to tensile strain. In the scope of this research the strain response of X52 vintage pipes with girth weld flaws under tensile forces and internal pressure is analyzed experimentally and numerically. Also previous experimental studies carried out by Sen et al [1], [2] are revisited in order to analyze and verify them numerically and to define tensile failure criteria. Different mathematical descriptions of the tensile strain capacity of pipes are available in the literature in form of prediction equations. Some of these are incorporated in the CSA code for Pipeline Systems Operation (CSA Z662). However there is no well established method for predicting the tensile strain capacity under internal pressure and the current equations in the CSA code don’t consider the effect of internal pressure on . Also none of the currently available methods for tensile strain capacity prediction are applicable to vintage pipes with steel grade X52. The current equations in the literature assume a steel grade of X65 or higher. These conditions make it necessary to investigate the strain response of X52 pipes under internal pressure.

**4-1 Analysis of Pipe Failure due to Tensile Strain**

Pipes may undergo tensile strain due to a variety of reasons (see section 1). These strains can be detrimental if they exceed the tensile strain capacity of the pipe. It is crucial to develop an alarm mechanism which informs the pipeline operators when there is a danger of pipeline failure due to excessive tensile strain. This alarm mechanism should be based on criteria that define the likelihood of a pipe failure. In this research project we are concerned with defining failure criteria which consider the effect of internal pressure on the strain capacity of pipes. Also we are aiming to define new predict methods for the failure due to tensile strain. We are analyzing the effect of internal pressure on the tensile strain capacity from two different view points. Firstly, we are conducting full scale tests in which we load vintage girth welded pipes with tensile forces and internal pressure in the presence of a flaw in the heat affected zone of the girth weld. By varying the amount of pressure and the flaw size we are analyzing the effect of these parameters on the tensile strain capacity of the pipe. The second view point is the analysis of cold bend pipe failure at the tension side. Our studies showed that the occurrence of this mode of failure of a cold bend highly depends on the amount of applied internal pressure.

**4-1-1 Full Scale Experiments with X52 pipe**

In the scope of this experimental project a total of 8 full scale experiments are planned to be carried out. Each experiment has a different combination of girth weld flaw size and internal pressure. The parameters which define the flaw size are the flaw length to pipe wall thickness ratio and the flaw depth to pipe wall thickness ratio . According to the CSA code the allowable ranges for and are and . For and the flaw size is negligible according to the CSA code. Based on this information two different flaw depths and two different flaw lengths are tested which gives us 4 different flaw size possibilities. The third variable internal pressure is also tested at 2 different levels. With the addition of the internal pressure as the third variable a total of 8 different test configurations result each having a different combination of flaw depth, flaw length and internal pressure.

**4-1-2 Investigation of the Tension Side Fracture of Cold Bends**

Cold bending is applied in order to change the direction of a pipeline in a horizontal or vertical plane. This can be necessary to conform with the terrain conditions. Cold bending is done on site using cold bending machines. In the process of cold bending the material properties of the tension and compression side can be affected differently since the compression side (intrados) of the pipe can be loaded beyond the yield stress in compression whereas the tension side (extrados) can be loaded beyond yield stress in tension. In case of the occurrence of local buckling in form of a wrinkle at the compression side, the wrinkled part of the cold bend experiences high tensile strains is more likely to fail due to tensile strain than the tension side. However, experimental studies carried out by Sen et al [1], [2] demonstrated that failure of a cold bend at the tension side can occur earlier than compressive failure under certain loading configurations.

In the scope of this research project, the load case and pipe geometry combination which lead to the tension side fracture of a cold bend in the experimental studies of Sen et al is simulated using finite element analysis. The objective of this simulation is to verify the outcome of the experimental studies of Sen et al and to obtain a better understanding of the conditions which lead to the tension side fracture of a cold bend pipe. Furthermore the numerical analysis of the strain distribution at the tension side of a cold bend for different load cases enables us to define failure criteria for the tension side failure mode of a cold bend pipe.

**4-2 Assessment of the sensitivity of tensile strain capacity prediction equations to different geometric and material parameters.**

Different geometric parameters and material properties effect the tensile strain capacity of a pipe at different levels. Since our project consists of a limited number of full scale tests, it is not possible to test the effect of all parameters experimentally. Therefore it is necessary to narrow down the focus of the project to the most significant parameters effecting the tensile strain capacity. In order to achieve this, the sensitivity of the current CSA equations as well as other proposed equations in the literature should be analyzed with respect to changing magnitudes of different parameters.

**4-3 Identification of the Tensile Strain Capacity of the X52 Pipes in the Presence of Internal Pressure and Girth Weld Flaws**

In each experiment the longitudinal and hoop direction strains are measured with strain gauges at critical locations of the pipe. In addition to that, digital image correlation is used to obtain the strain field of the pipe. The results of these measurements are used to define the tensile strain capacity of each specimen. There are different options to define the tensile strain capacity of a full scale specimen according to the test results:

**Option 1:** In the literature the tensile strain capacity is defined as the average axial strain value at a uniform strain zone far away from the girth weld flaw location. In this case several strain gauges are mounted on this uniform strain zone. The average of these measurements is called the remote strain. The drawback of this method is that it is not easy to estimate a uniform strain zone before the test. Therefore there is a high likelihood that the measured remote strain is not the actual average strain at the uniform strain zone.

**Option 2:** The tensile strain capacity of the pipe can be defined as the axial strain at the uniform strain zone closest to the girth weld flaw as observed in the image correlation data. The advantage of this option is that it is not necessary to estimate the location of the uniform strain zone ahead of the test. Since the painted area for the image correlation could be chosen arbitrarily large, this method offers high flexibility in terms of the area of interest for the remote strain.

**Option 3:** As an alternative to defining the tensile strain capacity as a single number for each test specimen, the critical strain profile could be defined in the longitudinal direction of the pipe. For this purpose the strain values from the digital image correlation and the strain gauge measurements are used in combination with each other. For the first two tests three measurements can be used to create the strain profile. These measurements are the strain value at the edge of the painted area near the end plate, the strain gauge measurement in the middle of the lower side of the pipe, and a strain measurement at the edge of the painted area around the flaw. A decreasing strain variation can be observed in the direction from the end plates to the flaw. However near the pipe failure the strains at the flaw side start to exceed the strain gauge measurements from the middle part.

**4-4 Comparison between the different tensile strain capacity equations in the literature.**

Several research groups have introduced equations for the prediction of the tensile strain capacity based on full scale tests and finite element analysis. These equations have certain limits of applicability in terms of flaw size limits or material property limits. A common approach is to develop a system whose input consists of flaw dimensions, pipe geometry, material properties and whose output is the tensile strain capacity of the pipe having these geometry and material properties. Our objective is to make a comparison between outputs of each equation in order to have an understanding of their applicability to different scenarios. The following equations are currently available in the literature for the prediction of the tensile strain capacity:

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|  | (1) |
|  | (2) |
|  | (3) |

|  |  |  |
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| Equation (1) |  | Crack-tip opening displacement (CTOD) toughness [mm] |
|  | Ratio of yield strength to tensile strength (Y/T) |
|  | Ratio of flaw length to pipe wall thickness |
|  | Ratio of flaw height to pipe wall thickness |
| Equation (2) |  | Fitted functions of normalized geometry and material parameters |
|  | Girth weld CTOD toughness [mm] |
| Equation (3) |  | Functions of flaw size and pipe material properties |
| a | Flaw depth |
| C | Half flaw length |
| t | Pipe wall thickness |

**5- Methodology and Expected Outcome**

The first step in the analysis of the tensile strain capacity of X52 pipes was to better understand the tensile strain capacity prediction equations currently available in the CSA code. The equations (1) in section 3 has different levels of sensitivity to all the parameters listed in equation (2). In order to quantify these differences full factorial analysis was conducted for equation (1). In , 3 denotes that for each parameter in equation (1) 3 levels of magnitude are selected and 4 denotes that the number of parameters analyzed is 4.

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