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TENSILE STRAIN LIMITS OF BURIED DEFECTS IN PIPELINE GIRTH WELDS

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ABSTRACT

Buried defects, such as lack-of-sidewall fusion defects, are some of the most commonly occurring defects in mechanized girth welds. Although some of the existing ECA (Engineering Critical Assessment) procedures permit the assessment of the significance of buried defects, their application is limited to the nominally elastic applied stress range. The assessment of buried defects is more complex than that of surface-breaking defects. There is much more experimental data on the behavior of surface-breaking defects than buried defects. One simplistic approach is to treat buried defects as surface-breaking defects under a generally accepted assumption that buried defects are less detrimental than surface-breaking defects of the same size.

This paper focuses on the behavior of girth welds containing buried defects subjected to high longitudinal strains. The high longitudinal strains in onshore pipelines may be caused by soil movement such as seismic activity, slope instability, frost heave, mine subsidence, etc. For offshore pipelines, the highest longitudinal strains typically occur during pipe laying operations. The paper describes a strain design methodology based on a crack driving force method that has been previously applied to obtain tensile strain limits of surface-breaking defects. The focus of this paper is the application of the crack driving force methodology to examine the factors affecting the strain limits of girth welds containing buried defects. By using crack driving force relations in conjunction with a constraint-sensitive fracture mechanics approach, tensile strain limits are derived as a function of material grade, defect size, toughness, and pipe wall thickness. The paper concludes with the comparison of strain limits between buried and surface-breaking defects.

KEYWORDS: *Pipeline, strain-based design, strain limit, girth weld, ECA, fitness-for-service, defect acceptance criteria, buried defect, finite element analysis*

INTRODUCTION

Pipeline girth welds may experience high longitudinal strains. For onshore pipelines, the high longitudinal strain may be caused by soil movement, such as seismic activity, slope instability, frost heave, mine subsidence, etc. For offshore pipelines, the highest longitudinal strain typically occurs during pipe laying operation. One of the most extreme cases is the pipe laying by reeling, in which the longitudinal strains can be as high as 2-3%. There are no generally accepted industry standards that provide tensile strain limits of girth welds. The tensile strain limits of girth welds containing welding defects are much more sensitive to the variations of material properties and geometric imperfections than the stress limits. Most ECA codes are stress-based and cannot be used if the longitudinal strain is greater than approximately 0.5%. A start-of-art review of strain-based design of pipelines with focus on girth welds tensile strain limits is given by Wang and Horsley [1].

One of the most commonly occurring defects in mechanized girth welds is the lack-of-sidewall fusion defects. They most often occur deep within the weld, and are treated as buried defects in ECA codes, unless re-characterized as surface-breaking defects under certain circumstances by defect interaction rules. It is generally believed that buried defects are less detrimental than surface-breaking defects of the same size.

Consequently, it is often accepted that buried defects may be conservatively treated as surface-breaking defects. However, this is not universally true among several established ECA procedures. Even within the domain of stress-based design (generally defined as longitudinal strain less than 0.5%), there is a significant variation in the treatment of buried defects. A paper recently published by Wang, et al, demonstrates the inconsistent, and potentially erroneous, treatment of buried defect among established ECA codes [2]. That paper also provided a comparison of various existing codes and standards in dealing with buried defects. It is important to recognize that the inconsistent treatment of buried defects at the low longitudinal strain warrants more research and development work. The current work, although primarily focuses on high longitudinal strain loading, should be helpful in developing consistent ECA procedures for buried defects under low strain conditions.

This paper describes the development and application of a methodology for the assessment of buried flaws in pipeline girth welds subjected to strain based loading conditions. It is based on the concept of predicting failure at the point where the applied CTOD driving force is equal to the apparent CTOD toughness (material's resistance).

OVERVIEW OF THE TECHNICAL APPROACH

To determine the strain limits of girth welds, it is necessary to postulate a failure criterion. In the current work, a failure event is assumed to occur when the driving force is equal to material's resistance to such failure. In the fracture mechanics approach employed in this work, the strain limit is reached when the crack driving force reaches the material's fracture toughness. Further clarifications on the terminology are given below.

1. The term "fracture" refers to a failure event that introduces new free surfaces to the material or structure. For instance, the separation of materials in the vicinity of a weld due to the longitudinal loads is broadly referred to as a fracture. The event of material separation may be a brittle or ductile (including ductile initiation, crack growth, and final failure) from a metallurgical viewpoint.
2. The crack driving force refers to a force that motivates the material separation or fracture in the context given above. In general, the crack driving force can be represented by a number of phenomenological or analytical parameters, such as stress intensity factor K_I, J-integral, crack tip opening displacement (CTOD), or even crack mouth opening displacement (CMOD).
3. The fracture resistance is synonymous with fracture toughness. It may be represented by a number of parameters similar to the crack driving force. The fracture resistance can represent material's resistance to crack initiation, tearing, or ductile growth. The fracture resistance or fracture toughness is typically obtained through destructive testing, such as the standard CTOD test or wide plate test.

The general approach here is to correlate the crack driving force with various material, defect geometry, and loading parameters. The strain limits are obtained by equating the crack driving force to the material resistance.

CRACK DRIVING FORCE RELATIONS

Factors Affecting Crack Driving Force

The crack driving force is influenced by a large number of factors. They include, but are not limited to the following:

- pipe size
    - diameter
    - wall thickness
- defect size
    - defect height
    - defect length
    - defect depth (for buried defects)
- defect location (weld metal or HAZ)
- material properties
    - strain hardening rate (Y/T ratio),
    - uniform strain (i.e., strain at ultimate tensile strength, or UTS)
    - weld strength mismatch
- weld geometric features
    - weld cap height
    - weld bevel geometry
    - high-low misalignment
    - undercut
- loading mode,
    - uniaxial versus multiaxial loading
    - bending versus tension

It is not possible to examine all the above factors. The focus of this work is those factors that: (1) have the greatest impact on the tensile strain limits and (2) can be controlled in field welding and inspection practice. A number of assumptions are made to capture the most influential factors and still make the problem tractable.

Basic Assumptions

Due to the large number of parameters affecting the tensile strain limits of girth welds, the following assumptions are made to reduce the analysis matrix to a manageable level.

1. There is no strength undermatching in the welds. Only the base metal property is of interest here. The weld joint is conservatively treated as having uniform tensile properties of the base metal. The weld bevel geometry has no influence on crack driving force when the weld joint is assumed to have uniform tensile properties.
2. The defect location (weld metal or HAZ) has no influence on crack driving force when the weld joint is assumed to have uniform tensile properties. However,

the defect location will affect the selection of material's fracture toughness.

3. The weld cap height is conservatively assumed as zero.
4. The buried defects have a defect height of either 3 mm (one weld pass height) or 6 mm (two weld pass height).
5. In was found in the prior work [3,4] that the pipe diameter has negligible effects on tensile strain limits when the defect length is small and the pipe diameter is greater than certain size (16-inch from previous work). The pipe diameter is not a variable in this work.

The assumption Nos. 1 and 2 were made (1) to reduce the number of analysis cases to a manageable level and (2) to establish baseline solutions that provide reasonable yet conservative estimates of girth weld strain limits. Since most field girth welds in a pipeline designed for strain based loading will have overmatching weld metal, these assumptions should produce conservative estimations of tensile strain limits. The results of this work are not applicable to girth welds with undermatching weld tensile properties. The effects of high-low misalignment and undercut are not covered in this work. The remaining significant variables are:

- Pipe wall thickness
- Defect depth relative to pipe surface
- Defect height
- Defect length
- Base metal *Y*/*T* ratio
- Base metal uniform strain
- Toughness

Further Assumptions on Material Properties

Both FE analysis and experimental tests have shown that high strain hardening rate (low *Y*/*T* ratio) increases the tensile strain limits of girth welds. Generally speaking, the higher the pipe grade, the lower the strain hardening rate and uniform strain. Using the API 5L minimum yield and tensile requirements as the baseline, generic relations among pipe grade, *Y*/*T* ratio, and uniform strain are established.

The stress strain curve is assumed to obey the CSA Z662 [5] relation,

$$\varepsilon = \frac{\sigma}{E} + \left(0.005 - \frac{X_g}{E}\right)\left(\frac{\sigma}{X_g}\right)^n \tag{1}$$

where σ and ε are the stress and strain, respectively, E is elastic modulus, X_g is the pipe grade or yield stress at 0.5% strain, and n is the strain hardening exponent. This stress strain relation has a continuous yield (no Lűders extension). One of the useful features of this relation is that the strain is always 0.5% when the stress is at the pipe grade level ($\sigma = X_g$).

The uniform strain, ε_T, is related to the strain hardening exponent by,

$$\varepsilon_T = 2/n. \tag{2}$$

The above relation is based on the observation of a wide range of linepipe materials and is believed to be reasonable. For a given pipe grade, one can use the minimum specified values for yield and tensile per API 5L. These yield and tensile values, together with Eqs. (1) and (2), completely define the full stress strain curve.

Equations (1) and (2) provide a convenient and reasonable way of constructing full stress strain curves for different grades of linepipe materials. They capture the essential relationship between pipe grade and the material's strain hardening capacity. The actual material tensile properties are almost certainly different from the exact form of Eqs. (1) and (2). For instance, Lűders extension is sometimes observed in the stress strain curves of linepipe materials and girth welds. The crack driving force at high strains is influenced by the overall strain hardening behavior as well as the extent of the Lűders extension. It is believed that Eqs. (1) and (2) provide good approximations of the actual material response in the context of material's tolerance to high strains.

Table 1 Pipe grade and associated lower bound, middle level, and upper bound strain hardening rates and uniform strains

Grade		API Min. Yield		API Min. Tensile		API Min. Requirements, Lower Bound *Y*/*T*			Middle *Y*/*T*			Upper Bound *Y*/*T*		
(ksi)	(MPa)	(ksi)	(MPa)	(ksi)	(MPa)	*Y*/*T*	Strain Hardening Exponent, *n*	Uniform Strain	*Y*/*T*	Strain Hardening Exponent, *n*	Uniform Strain	*Y*/*T*	Strain Hardening Exponent, *n*	Uniform Strain
52	359	52	359	66	455	0.788	15.38	13.0%	0.841	19.88	10.1%	0.894	27.95	7.2%
60	414	60	414	75	517	0.800	16.43	12.2%	0.850	21.19	9.4%	0.900	29.70	6.7%
65	448	65	448	77	531	0.844	20.84	9.6%	0.883	26.72	7.5%	0.922	37.33	5.4%
70	483	70	483	82	565	0.854	22.16	9.0%	0.890	28.33	7.0%	0.927	39.42	5.1%
80	552	80	552	90	621	0.889	28.69	7.0%	0.917	36.44	5.5%	0.944	50.32	4.0%

It is recognized that the actual *Y*/*T* ratio of a pipe material can be different from that computed using the API 5L minimum requirements. Since the strain limits are reduced with increasing *Y*/*T* ratio, a non-conservative prediction may result if the actual *Y*/*T* ratio is higher than that from the API 5L minimum requirements. Therefore, for each pipe grade an upper bound and a middle level *Y*/*T* ratio was computed and listed in Table 1. The lower bound *Y*/*T* ratio is computed from API 5L minimum yield and tensile requirements. The upper bound *Y*/*T* ratio is taken as the average of the lower bound *Y*/*T* ratio and unity. The middle level *Y*/*T* ratio is the averaged value of lower bound and upper bound *Y*/*T* ratios. The *Y*/*T* ratio, strain hardening exponent, and uniform strains for each grade of pipe with three assumed *Y*/*T* ratios are given in Table 1. For each pipe grade, the UTS for three levels of *Y*/*T* ratios were set to the same value as the API minimum requirement. The upper bound and middle level *Y*/*T* ratios were achieved by increasing the yield stress levels.

The actual yield and ultimate tensile strength of linepipes are most often higher than the API specified minimum values. As far as developing crack driving force relations beyond the elastic strain range, the strain hardening capacity is much more influential than the absolute magnitudes of the yield and ultimate tensile strength. Therefore, the reasonable *Y*/*T* ratio assumed in the current analysis is adequate for the purpose of defining strain limits, although the assumed absolute values of yield and UTS may be lower than the actual materials. It is believed that the middle level Y/T ratio is a good approximation to actual materials encountered in present-day construction. However, the upper bound values can exist in some cases. As the purpose of this work is to establish generally applicable strain design baseline, not case-specific design, the middle level Y/T ratio was selected for all analysis cases.

OVERVIEW OF FINITE ELEMENT ANALYSIS

Finite Element Model

Three-dimensional FE models simulating a section of pipe with a planar buried defect were generated. Due to the symmetry conditions, one quarter of the pipe is represented by the FE model to simulate the full pipe behavior. The location and the size of the buried defects are defined by defect depth, defect length, and defect height, as shown in Figure 1.

The shape of the buried defects is either elliptical or rectangular as shown in Figure 2 and Figure 3. To accommodate the meshing requirements, the end of the rectangular defects is not perfectly squared. However, its effects on strain limits should be minimal as the length of this end section is much smaller than the overall length of the defect.

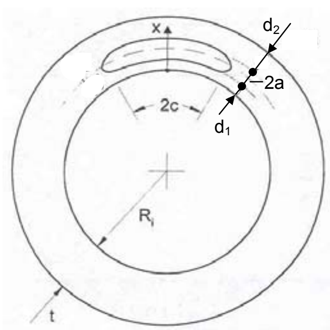

Figure 1 Definition of the defect location and size: 2c being the ***defect length***, 2a being the ***defect height***, and d_1 being the ***defect depth*** (always measured from ID)

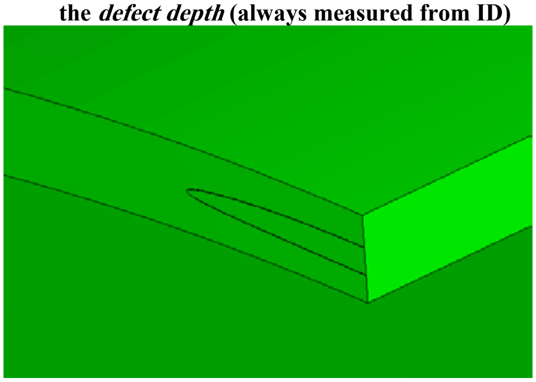

Figure 2 The profile of a buried elliptical defect of a 30-inch (762.0-mm) OD 3/8-inch (9.525 mm) W.T. pipe with a defect of 3-mm height, 3-mm depth, and 50-mm length

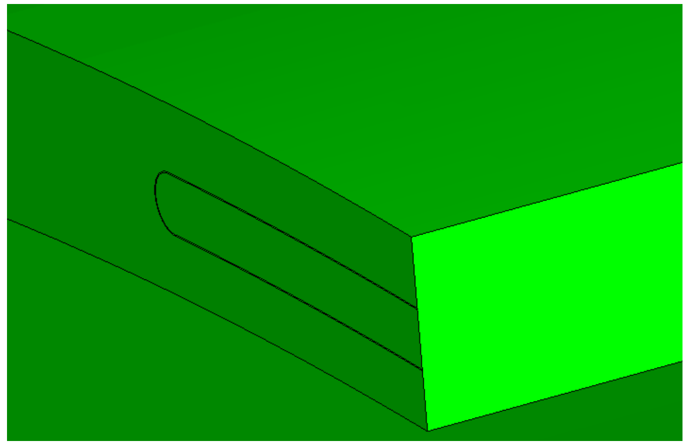

Figure 3 The profile of a buried rectangular defect of a 30-inch (762.0-mm) OD 3/8-inch (9.525 mm) W.T. pipe with a defect of 3-mm height, 3-mm depth, and 50-mm length

Analysis Procedures

Symmetric boundary conditions were imposed on the symmetry planes. Uniform remote axial displacement was applied as the primary loading. All the analyses used a large-strain large-displacement formulation as implemented in ABAQUS® version 6.3-1.

Analysis Matrix

Pipe Grade

The range of pipe grades analyzed was X52, X60, X65, X70, and X80. For all grades, the middle level Y/T ratios were assumed.

Pipe Wall Thickness

The pipe wall thickness was 6.35 mm (0.250 inch), 9.525 mm (0.375 inch), 12.7 mm (0.500 inch), and 19.05 mm (0.750 inch).

Defect Depth, Length, and Height

The defect depth ranged from 1.5 mm to 6.0 mm, most were either 3 mm or 6 mm. The defect lengths were 12.5 mm, 25 mm, 50 mm, and 75 mm. The defect height was either 3 mm or 6 mm. The relative defect heights (defect height over wall thickness) were 0.47, 0.31, 0.24, and 0.16.

Pipe Diameter

The pipe diameter was fixed at 30 inch (762 mm).

Shape of Buried Defect

Both elliptical and rectangular buried defects were analyzed.

Data Reduction and Presentation

Automated data processing routines were developed to systematically extract and analyze the data. The most fundamental output from the analysis is the relation between crack driving force (measured in CTOD) and the remote longitudinal strain. The remote longitudinal strain is synonymously called axial strain. The crack driving force was computed directly from the crack tip deformation profile at the deepest point of the defect using the customary 45° line interception technique. The remote longitudinal strain was read from strains on the elements close to the longitudinal end of the model remote from the cracked plane.

The relation between crack driving force and longitudinal strain was converted and consolidated in various forms to facilitate understanding and comparison. These forms are given in the following sections.

ANALYSIS RESULTS

Understanding the Crack Driving Force

A series of equivalent plastic strain contours focusing on the cracked region are given in Figure 4, Figure 5, Figure 6, and Figure 7. These contours represent the intensity of plastic deformation in the vicinity of the crack under almost identical remote longitudinal strain condition (1.5% strain). The relative differences among these contours reflect the effects of various physical parameters, such as wall thickness, defect length, and defect shape.

The effects of wall thickness on the local strain concentration are shown in Figure 4 and Figure 5 for pipes with the same flaw dimension and material properties, but different wall thickness. The thin-walled pipe (Figure 5) has much higher strain concentration than the thick-walled pipe.

The effect of defect length is shown by comparing Figure 4 and Figure 6. The 50-mm long defect (Figure 6) has higher strain concentration than the 25-mm long defect (Figure 4). The effect of defect shape is shown by comparing Figure 4 and Figure 7. The pipe with rectangular defect (Figure 7) has higher strain concentration than the pipe with elliptical defect (Figure 4).

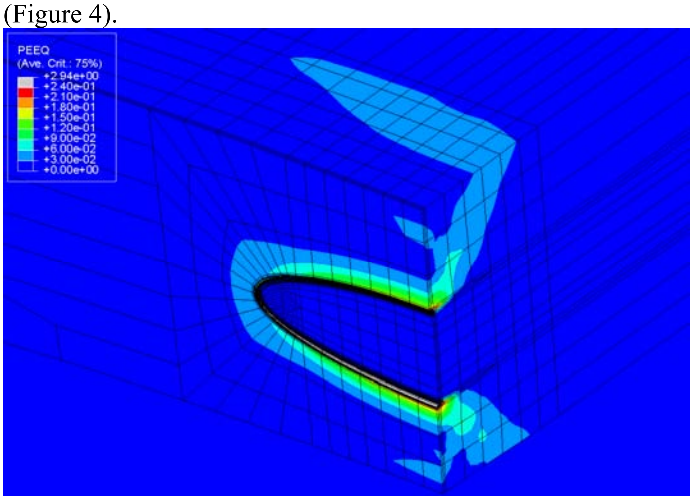

Figure 4 **Equivalent plastic strain contour of a 30-inch (762.0-mm) OD 0.75-inch (19.05 mm) W.T. pipe with an elliptical defect (defect height=6 mm, defect depth=6 mm, and defect length=25 mm) at a remote axial strain of 1.50%.**

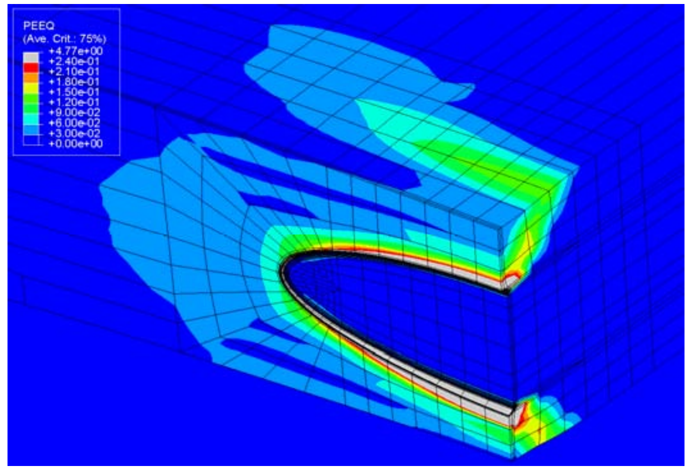

Figure 5 **Equivalent plastic strain contour of a 30-inch (762.0-mm) OD 0.50-inch (12.70 mm) W.T. pipe with an elliptical defect (defect height=6 mm, defect depth=3 mm, and defect length=25 mm) at a remote axial strain of 1.50%.**

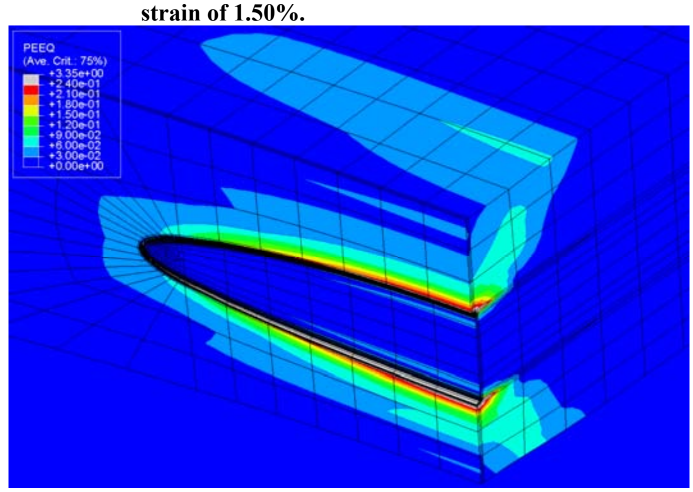

Figure 6 **Equivalent plastic strain contour of a 30-inch (762.0-mm) OD 0.75-inch (19.05 mm) W.T. pipe with an elliptical defect (defect height=6 mm, defect depth=6 mm, and defect length=50 mm) at a remote axial strain of 1.50%.**

The crack driving force (measured in CTOD) is a fundamental parameter representing the magnitude of the driving force imparted on the defect. It, for instance, provides indication of the intensity of the plastic deformation around the defect. The plastic deformation reflects the driving force experienced by the material around the defect. Figure 8 gives the crack driving force versus longitudinal strain relations for the cases depicted in Figure 4, Figure 5, Figure 6, and Figure 7. It can be seen that the crack driving force relations correctly rank the relative impact of various geometric parameters, as evident from the equivalent plastic strain contours.

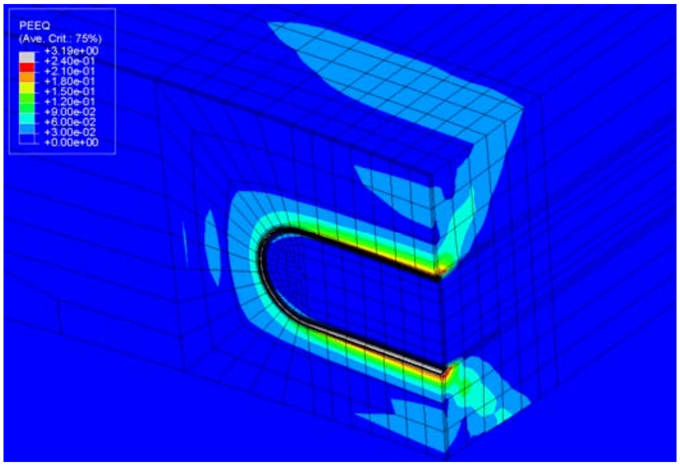

Figure 7 **Equivalent plastic strain contour of a 30-inch (762.0-mm) OD 0.75-inch (19.05 mm) W.T. pipe with a rectangular defect (defect height=6 mm, defect depth=6 mm, and defect length=25 mm) at a remote axial strain of 1.50%.**

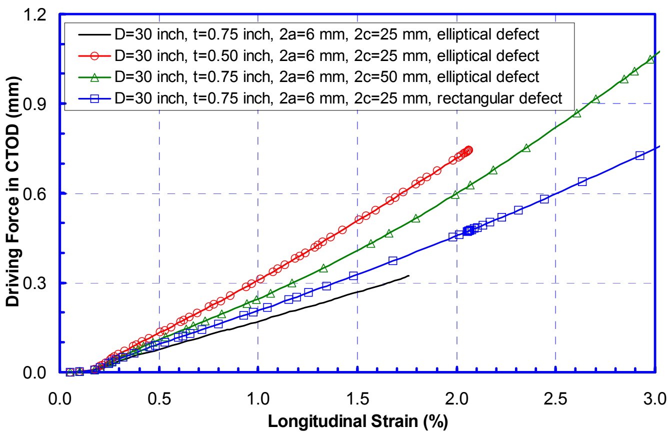

Figure 8 **The relations between crack driving force and longitudinal strain showing the effects of wall thickness, defect length, and defect shape**

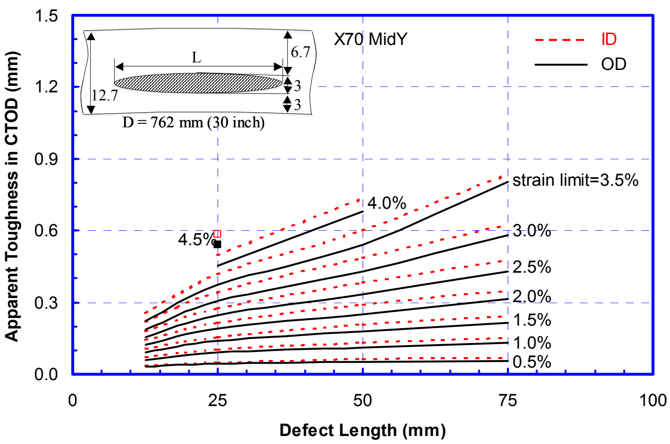

Figure 9 **Relations among three key variables for an X70 material**

To make the vast amount of data more useful, the CTOD driving force versus the remote longitudinal strain relations were converted to a format similar to that of Figure 9. By equating the driving force with the apparent toughness, this new format defines the relationship amongst the three key variables: defect length, toughness, and applied strain. When any two variables are known, the third variable can be determined. The difference between the solid and dashed lines in Figure 9 illustrates the effects of ligament thickness. The thinner ligament, on the ID side in this case, results in higher driving force.

Table 2 **Sample tensile strain limits of a 0.50-inch (12.7-mm) wall thickness pipe with various defect size and material grades**

Wall Thickness		Defect Length	Defect Height	Defect Depth	Material Grade		Strain Limit (%) at the Apparent Toughness (mm) Below, Elliptical Defects				Strain Limit (%) at the Apparent Toughness (mm) below, Rectangular Defects			
(inch)	(mm)	(mm)	(mm)	(mm)	(ksi)	(MPa)	0.2	0.3	0.4	0.6	0.2	0.3	0.4	0.6
0.500	12.70	12.5	3.0	3.0	52	359	3.03	4.42	5.60	7.75	2.86	4.13	5.28	6.90
					60	414	2.96	4.29	5.45	7.55	2.78	4.01	5.10	6.70
					65	448	2.81	4.09	5.22	7.35	2.64	3.80	4.85	6.45
					70	483	2.78	4.05	5.18	7.30	2.59	3.75	4.80	6.40
					80	552	2.63	3.80	4.85	6.95	2.45	3.52	4.50	6.05
			6.0	3.0	52	359	1.49	2.10	2.66	3.72				
					60	414	1.45	2.04	2.57	3.60				
					65	448	1.35	1.90	2.39	3.34				
					70	483	1.33	1.87	2.37	3.30				
					80	552	1.22	1.79	2.22	3.14				
		25.0	3.0	3.0	52	359	2.14	3.08	3.92	5.30	1.82	2.63	3.36	4.60
					60	414	2.07	2.96	3.75	4.98	1.76	2.52	3.20	4.34
					65	448	1.92	2.74	3.47	4.71	1.61	2.31	2.93	3.99
					70	483	1.88	2.68	3.39	4.59	1.58	2.25	2.85	3.87
					80	552	1.72	2.45	3.08	4.15	1.43	2.03	2.56	3.45
			6.0	3.0	52	359	0.81	1.14	1.46	2.05	0.67	0.94	1.20	1.69
					60	414	0.79	1.10	1.40	1.96	0.65	0.91	1.15	1.61
					65	448	0.71	1.00	1.27	1.77	0.59	0.82	1.04	1.45
					70	483	0.70	0.98	1.24	1.72	0.58	0.80	1.01	1.40
					80	552	0.64	0.88	1.11	1.54	0.53	0.72	0.90	1.24
		50.0	3.0	3.0	52	359	1.74	2.47	3.13	4.29	1.34	1.94	2.49	3.41
					60	414	1.66	2.30	2.90	3.90	1.28	1.84	2.33	3.15
					65	448	1.49	2.12	2.67	3.62	1.13	1.62	2.05	2.76
					70	483	1.45	2.05	2.59	3.49	1.09	1.56	1.97	2.64
					80	552	1.29	1.82	2.27	3.03	0.95	1.34	1.67	2.19
			6.0	3.0	52	359	0.46	0.63	0.78	1.06	0.36	0.48	0.58	0.77
					60	414	0.45	0.60	0.75	0.98	0.36	0.46	0.56	0.72
					65	448	0.40	0.54	0.65	0.86	0.32	0.40	0.48	0.61
					70	483	0.39	0.51	0.62	0.80	0.32	0.40	0.47	0.59
					80	552	0.37	0.45	0.53	0.67	0.32	0.37	0.42	0.51
		75.0	3.0	3.0	52	359	1.59	2.21	2.77	3.77	1.15	1.65	2.10	2.83
					60	414	1.51	2.09	2.60	3.48	1.09	1.54	1.94	2.56
					65	448	1.33	1.84	2.29	3.05	0.93	1.31	1.64	2.14
					70	483	1.28	1.77	2.20	2.92	0.89	1.25	1.56	2.02
					80	552	1.11	1.52	1.87	2.45	0.76	1.03	1.25	1.57
			6.0	3.0	52	359	0.34	0.45	0.54	0.71	0.27	0.34	0.40	0.50
					60	414	0.34	0.43	0.52	0.66	0.27	0.33	0.39	0.47
					65	448	0.31	0.38	0.44	0.55	0.26	0.30	0.34	0.41
					70	483	0.31	0.38	0.44	0.53	0.26	0.30	0.34	0.40
					80	552	0.31	0.35	0.39	0.46	0.26	0.30	0.33	0.36

Strain Limit as a Function of Material Property, Wall Thickness, and Defect Size

The relations among key variables, similar to those in Figure 9 are further simplified to tabular forms. These tables provide strain limits for several defect geometries at various values of assumed apparent toughness. Table 2 is an example of these tables. There are two lines, corresponding to crack driving force values taken from ID and OD side of a buried defect, in each key variable relation similar to Figure 9. The values of Table 2 were taken from the side with thinner ligament, i.e., lower strain limit to provide conservative estimates of the strain limits. *There are no explicit safety factors built into the table. These results should not be used for undermatching girth welds.*

EFFECTIVE USE OF THE STRAIN LIMITS

The most challenging aspect of using the key variable relations similar to those of Figure 9 and the tabulated strain limits similar to Table 2 is determining the appropriate value of apparent toughness. In the context of this report, the apparent toughness is the toughness measured from specimens with similar constraint conditions as pipeline girth welds. Ideally, the apparent toughness should be determined directly from testing specimens with low constraint conditions. However, there are no codified test standards to measure the toughness of low constraint specimens. A number of research projects are under way with the aim of developing and validating test procedures for low constraint specimens [6,7].

In the absence of test procedure that can be used to measure the apparent toughness, it is useful to estimate the apparent toughness from the large library of CTOD toughness from the standard CTOD specimens (high constraint). For modern linepipe materials and their girth welds, brittle fracture is typically not of a concern under almost all pipeline construction and service conditions. The review of available literature and test data indicates that it is reasonable to assume an apparent toughness in CTOD (low constraint) be 2-3 times of the toughness measured from standard CTOD specimens (high constraint). In a recently published Japan Welding Engineering Society technical report [8], a conversion factor of 2.5 from high constraint to low constraint CTOD toughness is given. However, the magnitude of this "multiplier" may be dependent on materials and fracture processes. For instance, experimental tests have shown that the effect of constraint on ductile failure is small at the point of initiation, but increases with further ductile tearing [9,10]. Relevant experimental tests are necessary if such multipliers are to be used in practice.

Furthermore, it should be cautioned that this multiplier should not be used if maximum load CTOD toughness is obtained from the standard bend tests, unless further analysis is conducted. A maximum load CTOD toughness in many cases violates the necessary conditions that qualify the measured toughness as specimen geometry-independent values. Such conditions restrict the size of crack-tip plastic zone to a small fraction of the overall specimen size at the point when the toughness value is taken. These conditions are enforced in *K*- and *J*-based fracture toughness tests, such as those of ASTM E 399 and E 1820. Further background on the necessity of such conditions may be found in McMeeking and Parks [11] and Shih and German [12]. The CTOD test standards never enforced these so called "specimen size validity" criteria. The practical implication of high CTOD value as given by the maximum load CTOD has become more acute in modern high strength, high toughness, and high Y/T ratio materials. A more through review of the constraint-based fracture mechanics and its implications in the assessment of girth weld defects are given in a separate paper [13].

In summary, the determination of the appropriate value of the apparent toughness is a subject of intensive research activities presently. Both analytical and experimental procedures in determining the apparent toughness are expected to emerge in the near future.

COMPARISON WITH SURFACE BREAKING DEFECTS

The relative longitudinal strain tolerance of surface-breaking and buried defects can be examined by comparing the development of crack driving forces as a function of the longitudinal strain. These crack driving force relations are converted to the key variable relations similar to those of Figure 9. Figure 10 provides such relations for an X70 pipe with a wall thickness of 3/8 inch (9.53 mm). The defect height is fixed at 3 mm in both cases. Assuming an apparent toughness of 0.3 mm and defect length of 27 mm, the strain limit of the surface-breaking defect is 1.0%; whereas the buried defect of the same size can tolerance a strain of 2.0%. If the target strain limit is set at 1.0% (no safety factor included here), the allowable defect length of the surface-breaking defect is 27 mm; whereas the allowable length of the buried defect is 75 mm for the same toughness of 0.3 mm. It is cautioned that the above comparison does not consider the effect of defect re-categorization which is not necessary under most defect interaction rules for the defects of Figure 10. The comparison similar to that of Figure 10 is possible for other wall thickness, pipe grade, and defect size. Our analysis so far has shown that surface-breaking defects are more detrimental to the tolerance to high longitudinal strains than buried defects of the same size.

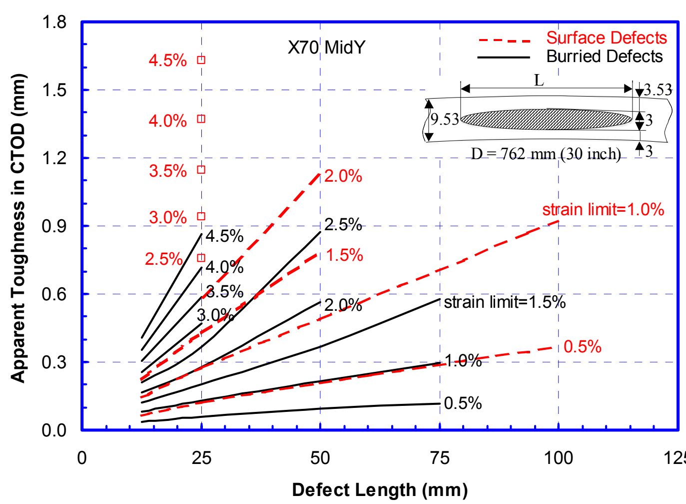

Figure 10 Relations among three key variables for an X70 material with surface-breaking and buried defects of the same size

CONCLUDING REMARKS

A systematic investigation of various factors affecting the tensile strain limits of buried girth weld defects has been conducted. By using the concept of crack driving and apparent toughness, baseline tensile strain limits of buried defect have been established for a wide range of pipe grades, wall thickness, defect size, and material toughness. It should be emphasized that experimental validation of the proposed strain limits is necessary if they were to be used in practice. The results of this work are valuable in that the relative influence of various factors affecting the strain limits of buried girth weld defects has been characterized.

A number of factors that may affect the strain limits of pipeline girth welds were not considered.

- It is known that materials loaded under high strain rate can have higher tensile properties and lower toughness than the same materials loaded under quasi-static conditions. Dynamic loading can increase materials' transition temperature.
- The effects of hoop stress on the longitudinal strain limits were not investigated in this work. On the basis of plastic flow under multiaxial loading and the effects of hydrostatic pressure on the rate of void growth and coalescence, it may be expected that the hoop stress should have an impact on the longitudinal strain limits.

Weld strength mismatch can have a strong influence on the strain limits of girth welds containing planar defects. Some preliminary work has been done for selected materials and defect geometries [14,15].

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