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FRACTURE ANALYSIS FOR PIPELINE GIRTH WELDS IN HIGH STRAIN APPLICATIONS

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ABSTRACT

Over the last several years, Pacific Gas & Electric Company (PG&E) has designed and installed seismic upgrades at several locations where their transmission pipelines cross active fault zones. As part of the process of evaluating the seismic upgrade designs, PG&E commissioned SSD, Inc. (SSD) and Berkeley Engineering And Research, Inc. (BEAR) to perform buried pipe deformation and fracture assessments of the pipeline fault crossings to develop capacity estimates for compressive wrinkling and girth weld tensile fracture. This paper describes the elastic-plastic fracture analysis used to determine girth weld tensile fracture capacity and the relatively simple equations derived that have wide application for high toughness pipe and weld material. The equations have the form:

$$\varepsilon(\%) = \alpha \cdot S_f \cdot \left(\frac{D}{2c}\right)^{0.5} \tag{1}$$

where the S_f is flow stress, D is pipe diameter, $2c$ is flaw length and α is a function of a/t where the a is flaw depth and t is the pipe wall thickness. The tension strain capacity depends on girth weld material toughness, flow stress and the length and depth of flaws that may exist in or near a girth weld. The analysis method used is based on the interaction of ductile tearing and elastic plastic fracture. Crack tip opening displacement (CTOD) is used to characterize material toughness. The derived equations can be used to predict allowable tension strain for X-60 and X-65 pipe with diameters ranging from 10 to 36 inches (273 to 914 mm) and for weld flaw depths of up to 1/3rd of wall thickness. Adequately tough pipe girth welds containing flaws can be shown to have safe tension strain capacities above 4%.

INTRODUCTION

Over the last several years, PG&E has designed and installed seismic upgrades at several locations where their transmission pipelines cross active fault zones. As part of the process of evaluating the seismic upgrade designs, PG&E has commissioned SSD to perform buried pipe deformation analysis of the pipeline fault crossings as a means to develop estimates of the amount of fault offset required to damage the pipelines either due to compressive wrinkling of the pipe wall or due to tensile fracture at pipeline girth welds. The seismic evaluation procedure involves a comparison of computed pipe compression and tension strain demands resulting from the fault offset to appropriate compression and tension strain capacities. On several of these seismic upgrade projects, BEAR was engaged as a sub-consultant to perform fracture mechanics calculations required to develop the tension strain capacities applicable to the pipeline girth welds. The tension strain capacity depends on the toughness of the pipeline girth welds (usually expressed in terms of crack-tip-opening-displacement (CTOD), and the length and depth of flaws that may exist in/near the girth weld).

As part of a recent fault crossing project, PG&E had a series of ten (10) CTOD tests performed on exemplar girth welds fabricated per PG&E Weld Specification #BW/52-2/G, which is a semi-automatic GMAW welding procedure. The CTOD test results indicated that the girth welds had a very high toughness with a mean CTOD of 39 mils (0.99 mm) and a lower bound CTOD of 20 mils (0.51 mm). During the construction phase of the same project, PG&E implemented a sophisticated automatic ultrasonic (AUT) inspection procedure capable of reliably detecting very small girth weld flaws. The sizing accuracy of this procedure is ±0.04 inches (±1 mm) in the through-wall (depth) and length directions. The procedure is expected to be able to detect a 0.015 inch (0.4 mm) deep defect provided that it is at least 0.5 inches (13 mm) long. A report prepared by PG&E's Technical and Ecological Services (TES) group indicated that the flaws measured in field welds for a high strain design application were all small. Based on the combination of very high toughness provided by the semi-automatic welding procedure and the ability to provide a very tight inspection for girth weld flaws using the AUT inspection procedure, PG&E asked SSD and BEAR to extend previous studies to perform fracture mechanics calculations aimed at developing guidelines for allowable tension strains for welds made and inspected using these procedures. This paper summarizes this work effort.

MEASURED FLAW SIZES

The measured flaw sizes from the inspected girth welds made for a high strain design application are given in Table 1. The mean and maximum flaw lengths (2*c*) are 0.175 and 0.637 inches (4.45 and 16.2 mm), respectively. The mean and maximum flaw depths (*a*) are 0.032 inches (0.81 mm) and 0.159 inches (4.0 mm), respectively. Rather than taking the worst flaw depth in combination with the worst flaw length or computing allowable tension strains for every row in the table, the measured flaw depth and length combinations were combined into a single parameter, the Stress Intensity Factor (K_I) as described in Appendix A. The mean and maximum Stress Intensities (K_I) are 18.4 and 42.6 ksi-in$^{0.5}$ (639 and 1,481 MPa-mm$^{0.5}$), respectively. Unfortunately, a statistical assessment of the data in terms of K_I (or CTOD) varies to such an extent that the minimum and maximum values are approximately 3 to 4 standard deviations larger than the mean. Note, data where the flaw depth, *a*, exceeded the flaw length, 2*c*, were discarded as the K_I (or CTOD) solutions are invalid in this range (this occurred for 3 of the 43 samples). The large variation in the data above the average indicates that there is insufficient data to characterize weld flaw size with a normal distribution or there are mechanical reasons driving the statistical distribution. The maximum flaw depth is 0.159 inches or 4 mm (noted in red in Table 1) for a ½ inch (12.7 mm) thick weld made with 6 layers.

MAXIMUM ALLOWABLE STRAIN

Using the lower bound CTOD toughness, 20 mils (0.5 mm), together with different defect depths provides a basis for calculating the maximum allowable strain, based on fracture or plastic instability using fracture mechanics principals. The procedure developed for calculating tension strain limits as a function of weld flaw size and toughness is summarized in Appendix A. This procedure was applied to un-pressurized pipe to compute maximum allowable strain for assumed flaw depths (*a*) equal to 1/3, 1/4, and 1/6 of the wall thickness (*t*) as a function of flaw length (2*c*) for outer pipe diameters (*D*) ranging from 10.75 to 36 inches (273 to 914 mm), diameter-to-thickness (*D/t*) ratios of 40 and 60, and pipe grades of X-60 (with API 5L minimum specified yield strength (Sy) and ultimate tensile strength (Su) of 60 and 75 ksi (414 and 517 MPa), respectively) and X-65 (with API 5L minimum specified yield and ultimate strengths of 65 and 77 ksi (448 and 531 MPa), respectively). Figures 1 and 2 present the results for X-60 and X-65 pipes for *a/t*=1/3 while Figures 3 and 4 present the corresponding results for *a/t*=1/6. Because flaws tend to grow towards a 2:1 shape (i.e., *c* = *a*), strain values were calculated for flaw lengths down to *2c* = *2a*, where *a* is the assumed maximum flaw depth, *t/3, t/4* or *t/6*. Note that higher allowable stresses/strains can be obtained by increasing the number of weld layers through the pipe wall thickness hence decreasing the likely flaw size. This analysis assumes the flaws are connected to a surface (i.e., the pipe I.D. or O.D.) with a depth of *a* and a length of *2c*. Subsurface flaws can be evaluated with this procedure by first determining equivalent depths and lengths per the most recent version of API 1104 [1].

Examination of Figs. 1 through 4 and evaluation of various manipulations of the strain results for each *a/t* ratio considered lead to the observation that a smooth regression can be developed for a given flaw depth if the allowable strains were normalized by product of the flow stress (equal to the average of the yield and ultimate stresses) and the square root of the pipe diameter. For an internal pressure of zero, the form of regression in terms of the flow stress (S_f), the pipe diameter (*D*), and the flaw length 2*c* is as follows:

$$\varepsilon(\%) = \alpha \cdot S_f \cdot \left[\frac{D}{2c}\right]^{0.5} \tag{2}$$

where the term "α" decreases with increasing flaw depth. Based on a regression performed for *a/t* ratios of 1/3, 1/4 and 1/6, α can be shown to vary as a quadratic function of *a/t* as follows:

$$\begin{aligned}\alpha = \alpha\left(\frac{a}{t}\right) = 0.024904 \cdot \left[\frac{a}{t}\right]^2 \\ - 0.020641 \cdot \left[\frac{a}{t}\right] \\ + 0.007420\end{aligned} \tag{3}$$

Figure 5 shows a scatter diagram comparing the zero internal pressure strain results calculated by fracture analysis with the results from the above regression model strain function including the quadratic α variation with *a/t* (a total of 180 individual data points are compared). Figure 6 shows the error between regression model and the fracture calculations. The maximum absolute error is less than 0.0125 percent strain over the range of variables considered.

The effect of internal pressures of up to 2400 psi (16,547 kPa) have also been considered as an additional step in this evaluation. In general, allowable strain decreases slightly with increasing pressure, passes through a minimum and then increases significantly. For a crack length of 2*c/t* = 2/3, the maximum decrease in allowable strain due to pressure is 0.3% (relative to the strain value computed with zero pressure). For 2*c/t* = 16.667, the maximum decrease due to pressure is approximately 10% (of the strain value computed with zero pressure). The pressure effect "modifier" is approximately linear between these values of 2*c/t* and varies with the third power of crack depth (decreasing dramatically with more shallow cracks). Thus, a simple pressure effect "modifier" for pressures in the range from 0 to 2400 psi (16,547 kPa) has been derived as a function of *a, 2c* and *t*: $\{1 - 0.1875 \cdot (2c/t) \cdot (a/t)^3\}$. The resulting error in the derived pressure effect "modifier" is less than 1.5% relative to the minimum strain values determined using the equations given in Appendix A.

ALLOWABLE STRAIN FORMULA

Based on the range of diameters (10-inch to 36-inch or 273 to 914 mm), steel grades (X-60 and X-65), *D/t* ratios (40 and 60) considered, the final derived regression formula for allowable strain, including a modifier term "γ" that considers internal pressures ranging from 0 to 2400 psi (16,547 kPa) is as follows:

$$\varepsilon(\%) = \alpha\left(\frac{a}{t}\right) \cdot S_f \cdot \left[\frac{D}{2c}\right]^{0.5} \cdot \gamma\left(\frac{c}{t}, \frac{a}{t}\right) \quad (4)$$

where:

$$\alpha = \alpha\left(\frac{a}{t}\right) = 0.024904 \cdot \left[\frac{a}{t}\right]^2 - 0.020641 \cdot \left[\frac{a}{t}\right] + 0.007420 \quad (5)$$

and:

$$\gamma\left(\frac{2c}{t}, \frac{a}{t}\right) = 1 - 0.1875 \cdot \frac{2c}{t} \cdot \left[\frac{a}{t}\right]^3 \quad (6)$$

where $\varepsilon(\%)$ is strain in percent and S_f is the flow stress (average of the material yield and ultimate stresses, in ksi), D is the pipe diameter (inches), $2c$ is the flaw length (inches) and a/t is the ratio of the flaw depth (a) to the pipe wall thickness (t). This formula applies for welds fabricated per PG&E Weld Specification #BW/52-2/G with a flaw depth "a" between 0 and 1/3 of the wall thickness.

Table 2 summarizes the allowable tension strains computed using this formula by setting the flaw length equal to the minimum permissible value for computation (i.e., $2c$=$2a$) over the range of D and steel grades considered. Table 3 provides the tension strains computed for each pipe diameter for X-60 and X-65 grade pipe using the maximum measured defect length ($2c$=0.637 inches or 16.2 mm).

It should be noted that allowable strain increases with increasing material yield and ultimate strength. Thus, a conservative analysis can be performed using the specified minimum material strength values. Furthermore, the analysis method is conservative for the typical case of weld metal yield strengths equal to or greater than the pipe yield strength.

In summary, the derived regression formula given above provides a simple method to determine allowable strain that is far simpler than fracture analysis and just as accurate. Furthermore, the data and assessment indicate PG&E can consider inspection based only on flaw length. The allowable strain values determined using the above equations do not contain a capacity reduction factor.

LIMITATIONS

The procedures used herein to develop the tension strain capacities are applicable to welds fabricated per PG&E Weld Specification #BW/52-2/G containing a surface flaw with a depth "a" between 0 and 1/3 of the wall thickness and assume a CTOD value greater than or equal to 20 mils (0.5 mm) and that the material yield and ultimate strengths satisfy the API 5L minimum values. The allowable strain formula includes a modifying factor that accounts for the maximum possible reductions in strain capacity for pressure (0 to 2400 psi or 16,547 kPa).

The instability solutions used in the analysis are based on lower bound test data (see Appendix A) to provide some conservatism. However, no safety factors are included in the analysis, nor adjustments for crack size detection error. Users must account for these factors based on their particular situation.

The stress strain curve for the subject material must be well behaved (i.e., yield strength greater than 70% and less than 85% of the ultimate strength) in that it can be characterized by an elastic-perfectly plastic approximation based on a flow stress equal to the average of the yield and ultimate stress values. A new method subsequently developed to the work described herein more accurately characterizes strain hardening; the material stress strain relation can be approximated by a much more flexible Ramberg-Osgood relationship.

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APPENDIX A: TENSILE STRAIN CAPACITY FOR PIPELINE GIRTH WELDS

A.1 THEORY AND PROCEDURE

The most appropriate demand-capacity measure for tensile fracture is longitudinal tensile strain. By considering the toughness properties of the weld material and probable crack sizes in the pipeline girth welds, the maximum allowable bending and axial loads and associated strains can be estimated.

The approach used here follows the methodology described in British Standard PD 6493:1991, Level 2 [2] for the interaction relation between fast fracture and plastic instability. The interaction relation is referred to as a Failure Assessment Diagram (FAD) which takes into account both secondary stresses such as welding residual stresses and instability of the remaining ligament. More accurate elastic plastic solutions are substituted for fast fracture and plastic instability to significantly improve the PD 6493 method and eliminate its primary drawbacks: (1) fracture based on flat plate solutions and (2) inconsistent instability models that do not include pipe bending and tension.

S_r is the ratio of applied stress in the remaining ligament to the flow stress, or in the case of bending, the applied moment divided by the limit moment. K_r is the ratio of the applied elastic stress intensity factor (or $CTOD^{1/2}$) to the critical material stress intensity factor (or $CTOD_{mat}^{1/2}$):

$$S_r = \frac{\sigma}{\sigma_f} \quad \text{or} \quad S_r = \frac{M}{M_o} \tag{7}$$

$$K_r = (\delta_r)^{1/2} = \left(\frac{\delta_I}{\delta_{mat}}\right)^{1/2} \tag{8}$$

where σ is the net section stress, σ_f is the flow stress (taken as the average of the yield and ultimate stress values), M is the applied moment, M_o is the limit moment, δ_{mat} is the critical material CTOD (crack-tip-opening-displacement) and δ_I is the applied elastic CTOD:

$$\delta_I = \frac{(Y\sigma)^2 \pi a}{\sigma_y E} \tag{9}$$

where a is the crack depth, E is the modulus of elasticity, and σ_y is the yield stress. The stress intensity magnification factor, Y, is defined by the general expression form used to define the stress intensity factor:

$$K_I = \sigma \sqrt{\pi a}\; Y \tag{10}$$

The interaction expression relating K_r and S_r and defining the Level 2 FAD limit curve [2] is:

$$K_r = S_r \left(\frac{8}{\pi^2} \ln \sec\left(\frac{\pi}{2} S_r\right)\right)^{-1/2} \tag{11}$$

If a point lies within the FAD curve, the assumed flaw size and applied stress/strain are acceptable. If a point lies outside the FAD curve, the assumed flaw size and applied stress/strain are not acceptable. The previous equations can be used to determine K_r, S_r and the allowable applied stress or moment.

Secondary stresses, such as welding residual stresses (WRS) can be included in this formulation. However, for strain values above twice the yield strain, it has been shown by other researchers that the effects of secondary stresses are insignificant at high strains [2,3]. One of the intents of the Level 2 and 3 assessment methods in the British Code is to take advantage of elastic/plastic analysis results to more accurately determine the applied stress and strains. Thus, WRS's are not considered.

Cyclic stresses and crack growth are also neglected in this analysis. They can be shown to be insignificant using the evaluation criteria given in Appendix A of API Standard 1104, Standard for Welding Pipelines and Related Facilities [1]:

$$S^* = N_1 (\Delta \sigma_1)^3 + N_2 (\Delta \sigma_2)^3 + \ldots + N_k (\Delta \sigma_k)^3 \tag{12}$$

where N_i is the number of cycles at the ith cyclic stress level, σ_i (units of ksi) and S^* is the spectrum severity. Cyclic stresses are not considered to be significant if S^* is less than 4 x 10^7.

A.2 TENSILE STRAIN CAPACITY

Yield and ultimate stresses corresponding to the minimum values specified per API 5L have been assumed for the analysis. The fracture analysis was performed as a function of toughness based on a minimum CTOD value of 20 mils.

The crack depths considered ranged from 1/6 to 1/3 of the wall thickness. The stress intensity magnification factor used in the analysis is that given in [4] for an internal circumferential crack in a pipe:

$$Y = Q^{-1/2} + \begin{pmatrix} 0.02 + \zeta\,(0.0103 + 0.00617\,\zeta\,) \\ +\,0.0036\,(1 + 0.7\,\zeta\,)(R/t - 5\,)^{0.7} \end{pmatrix} Q^{3/2} \tag{13}$$

$$\zeta = \frac{a}{t}\left(\frac{a}{2c}\right) \qquad Q = 1 + 1.464\left(\frac{a}{2c}\right)^{1.65}$$

where a is the crack depth, $2c$ is the crack length and R is the mean pipe radius. This solution was developed for pipes with radius to thickness ratios up to 20. However, the data used to develop the relation appears to be relatively insensitive to the R/t ratio and the solution is commonly cited for general use without restriction [5].

To determine S_r an estimate of limit moment is required. A lower bound approximation for the limit moment of a pipe with axial loading and a circumferential flaw is given in reference [6]:

$$M_o = 2\,\sigma_f\,R^2\,t\,\left(2 \sin \beta - (a/t) \sin \theta\right)$$

$$\beta = \frac{\pi}{2}\left[\,1 - (\theta/\pi\,)(a/t) - (\,\sigma_t\,/\,\sigma_f\,)\,\right] \tag{14}$$

$$\theta = c/R$$

where R and t are the pipe mean radius and thickness, a and c are the crack depth and half length, and σ_t is the applied axial load divided by the pipe cross sectional area. The limit moments for design and analysis are determined as a fraction of M_o. It would be desirable to account for axial load and hoop stress separately. Unfortunately, the limit moment expression for combined moment and axial loading is based on tests where the axial loading is provided by pressure [7]. The effects of axial force and hoop stress are both included and cannot be separated in the present approach.

In a deformation demand-capacity analysis, a limit strain is simpler to use than a combination of limit moments and axial loads. Unfortunately, a limit strain can only be determined analytically for two cases: (1) pure moment loading (no pressure or axial loads), and (2) moment and pressure loading, with the axial stress equal to half the hoop stress due to pressure (i.e., pressure vessel conditions). Assuming elastic, perfectly plastic deformation, the applied moment can be related to the size of the plastic regions [7]:

$$M = 2\,\lambda\,\sigma_f\;t\,R^2\left(\frac{\varphi}{\sin\varphi} + \cos\varphi\right)$$

$$\lambda = \left(1 - 0.75\;\alpha^2\right)^{1/2} \tag{15}$$

$$\alpha = \frac{\sigma_h}{\sigma_f}$$

where the effective stress is assumed to equal the flow stress, σ_h is the hoop stress due to pressure, and φ is the angle from the neutral axis to the plastic zone as defined in Reference [6]. The axial strain at the elastic/plastic interface can be shown to equal [6]:

$$\varepsilon_{it} = \frac{\sigma_f}{E}\left(\frac{\alpha}{2} + \lambda - v\,\alpha\right) \tag{16}$$

on the moment-tensile side of the pipe and:

$$\varepsilon_{ic} = \frac{\sigma_f}{E}\left(\frac{\alpha}{2} - \lambda - v\,\alpha\right) \tag{17}$$

on the moment-compression side where, v is Poisson's ratio and ε_{it} and ε_{ic} are axial strains at the elastic/plastic interface on the moment tension and compression sides, respectively. The strain at the centerline is equal to the average axial strain and can be shown to equal:

$$\varepsilon_{ave} = \frac{\alpha\,\sigma_f}{E}\left(\frac{1}{2} - v\right) \tag{18}$$

Note that ε_{ave} is equal to zero for zero pressure ($\alpha = \sigma_h/\sigma_f = 0$). Assuming plane sections remain plane, the strain at the outer most fibers on the moment-tension side of the pipe is:

$$\varepsilon = \varepsilon_{ave} + \frac{\varepsilon_{it} - \varepsilon_{ave}}{\sin\varphi} \tag{19}$$

where ε is the limit strain at the outermost fiber.

Table 1 Flaw Inspection Data

$2c$ (in)	a (in)	K_I ksi-in^{05}
0.060	0.055	23.5
0.099	0.030	20.1
0.079	0.064	25.6
0.259	0.016	15.8
0.059	0.058	24.1
0.055	0.012	13.3
0.373	0.004	7.7
0.259	0.159	42.6
0.139	0.039	23.2
0.339	0.009	11.9
0.100	0.050	24.5
0.179	0.038	23.5
0.320	0.018	16.7
0.074	0.014	14.2
0.174	0.005	8.9
0.353	0.004	8.0
0.637	0.010	12.8
0.079	0.061	25.1
0.099	0.041	22.7
0.159	0.027	20.0
0.055	0.029	18.4
0.074	0.043	22.1
0.313	0.006	9.5
0.074	0.035	20.6
0.473	0.010	12.8
0.358	0.009	11.6
0.099	0.045	23.4
0.099	0.042	22.9
0.080	0.054	24.1
0.279	0.014	14.6
0.220	0.012	13.8
0.080	0.046	22.9
0.254	0.006	10.0
0.114	0.013	14.1
0.094	0.012	13.6
0.079	0.078	28.0
0.034	0.021	15.2
0.219	0.020	17.3
0.054	0.033	19.3
0.034	0.029	17.1

Note: 1 inch = 25.4 mm and 1 ksi-in^{05} = 34.757 MPa-mm$^{0.5}$

Table 2 Allowable Tension Strains for Pipe Diameters of 10 to 36 inches (273 to 914 mm) and Flaw Length $2c = 2a$

Steel Grade	D/t Ratio	a/t Ratio	Strain (%)
X-60	40	1/3	1.72
X-65	40	1/3	1.81
X-60	60	1/3	2.11
X-65	60	1/3	2.22
X-60	40	1/4	2.30
X-65	40	1/4	2.42
X-60	60	1/4	2.82
X-65	60	1/4	2.96
X-60	40	1/6	3.45
X-65	40	1/6	3.63
X-60	60	1/6	4.23
X-65	60	1/6	4.45

Table 3 Allowable Tension Strains Based on Maximum Measured Defect Length ($2c$=0.637 inches = 16.2 mm)

Diameter (inches)	a/t Ratio	X-60 Strain (%)	X-65 Strain (%)
10.75	1/3	0.90	0.95
16	1/3	1.11	1.16
20	1/3	1.24	1.30
24	1/3	1.36	1.43
30	1/3	1.52	1.60
36	1/3	1.67	1.76
10.75	1/4	1.05	1.11
16	1/4	1.28	1.35
20	1/4	1.44	1.51
24	1/4	1.58	1.66
30	1/4	1.76	1.85
36	1/4	1.93	2.03
10.75	1/6	1.29	1.36
16	1/6	1.58	1.66
20	1/6	1.76	1.86
24	1/6	1.93	2.03
30	1/6	2.16	2.27
36	1/6	2.37	2.49

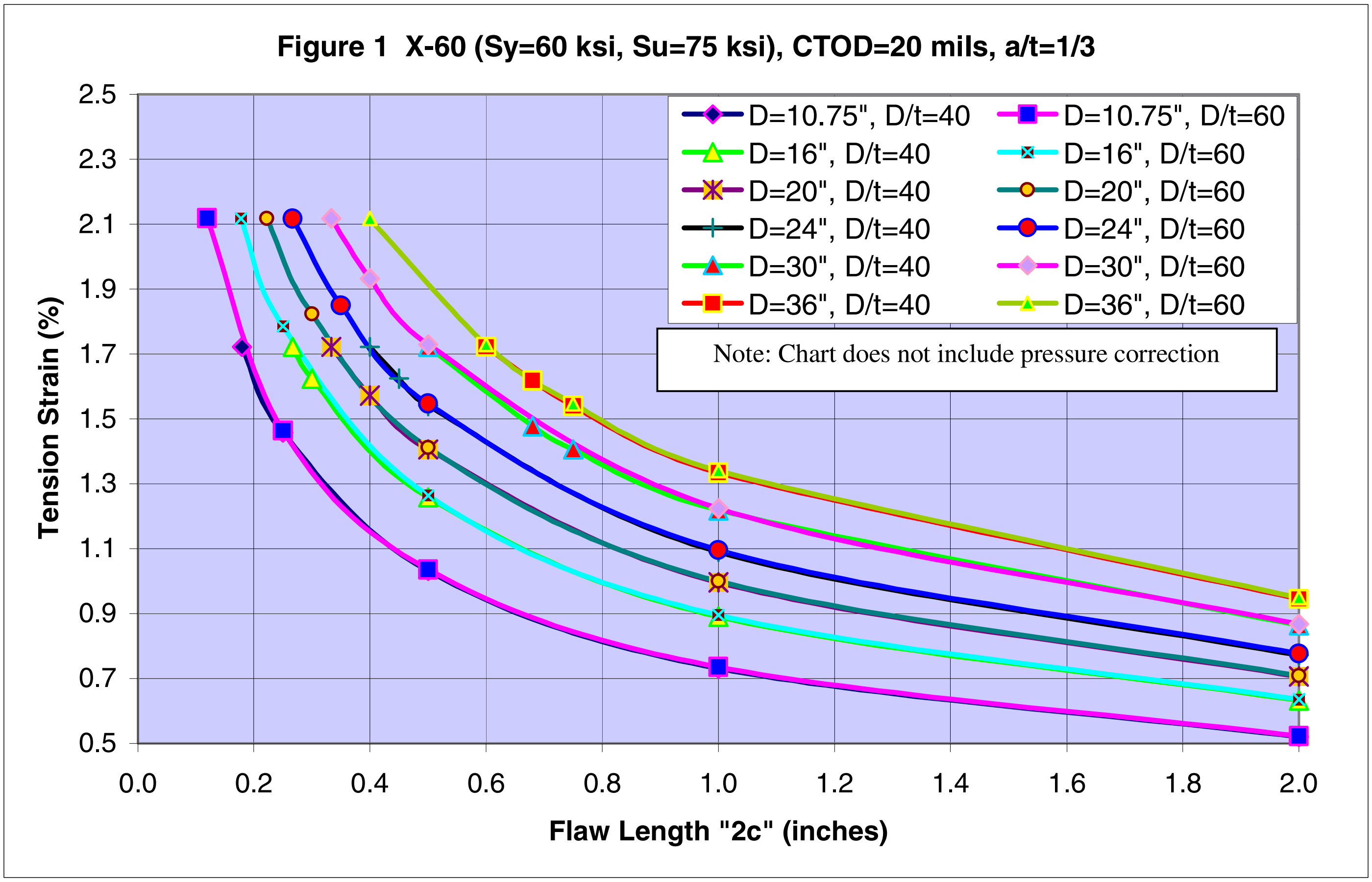
Figure 1 X-60 (Sy=60 ksi, Su=75 ksi), CTOD=20 mils, a/t=1/3
Tension Strain (%)
Flaw Length "2c" (inches)
D=10.75", D/t=40
D=10.75", D/t=60
D=16", D/t=40
D=16", D/t=60
D=20", D/t=40
D=20", D/t=60
D=24", D/t=40
D=24", D/t=60
D=30", D/t=40
D=30", D/t=60
D=36", D/t=40
D=36", D/t=60
Note: Chart does not include pressure correction
2.5
2.3
2.1
1.9
1.7
1.5
1.3
1.1
0.9
0.7
0.5
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0

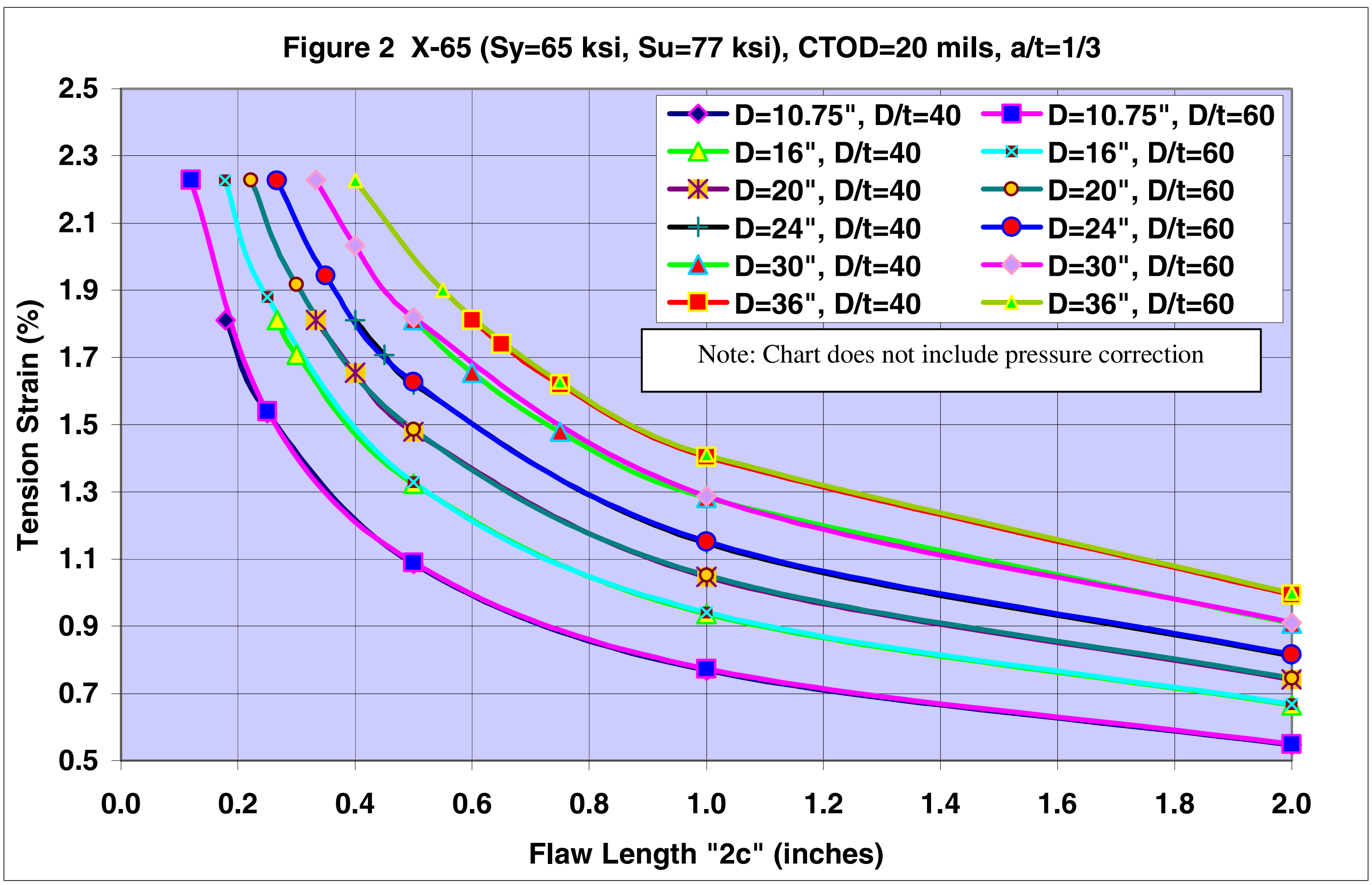
Figure 2 X-65 (Sy=65 ksi, Su=77 ksi), CTOD=20 mils, a/t=1/3
Tension Strain (%)
Flaw Length "2c" (inches)
D=10.75", D/t=40
D=10.75", D/t=60
D=16", D/t=40
D=16", D/t=60
D=20", D/t=40
D=20", D/t=60
D=24", D/t=40
D=24", D/t=60
D=30", D/t=40
D=30", D/t=60
D=36", D/t=40
D=36", D/t=60
Note: Chart does not include pressure correction
2.5
2.3
2.1
1.9
1.7
1.5
1.3
1.1
0.9
0.7
0.5
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0

Figure 3 X-60 (Sy=60 ksi, Su=75 ksi), CTOD=20 mils, a/t=1/6

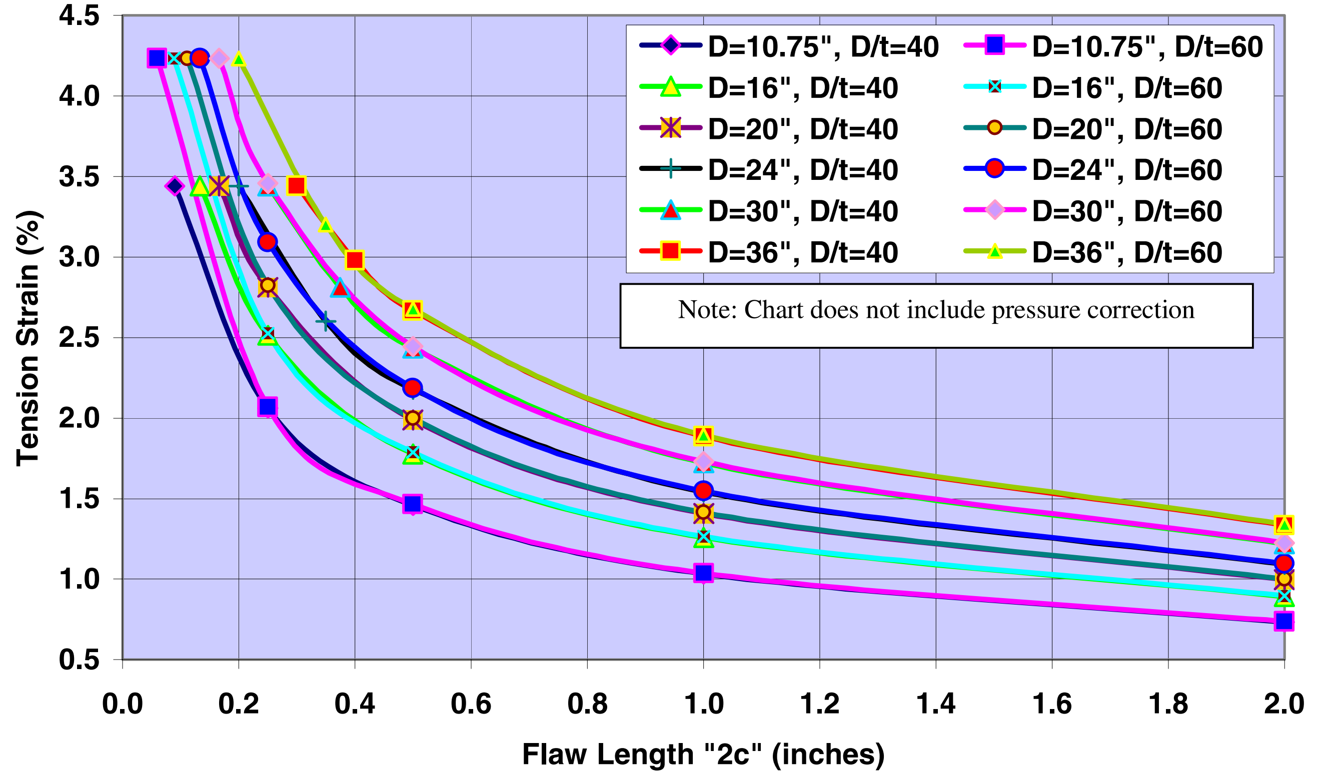

Figure 4 X-65 (Sy=65 ksi, Su=77 ksi), CTOD=20 mils, a/t=1/6

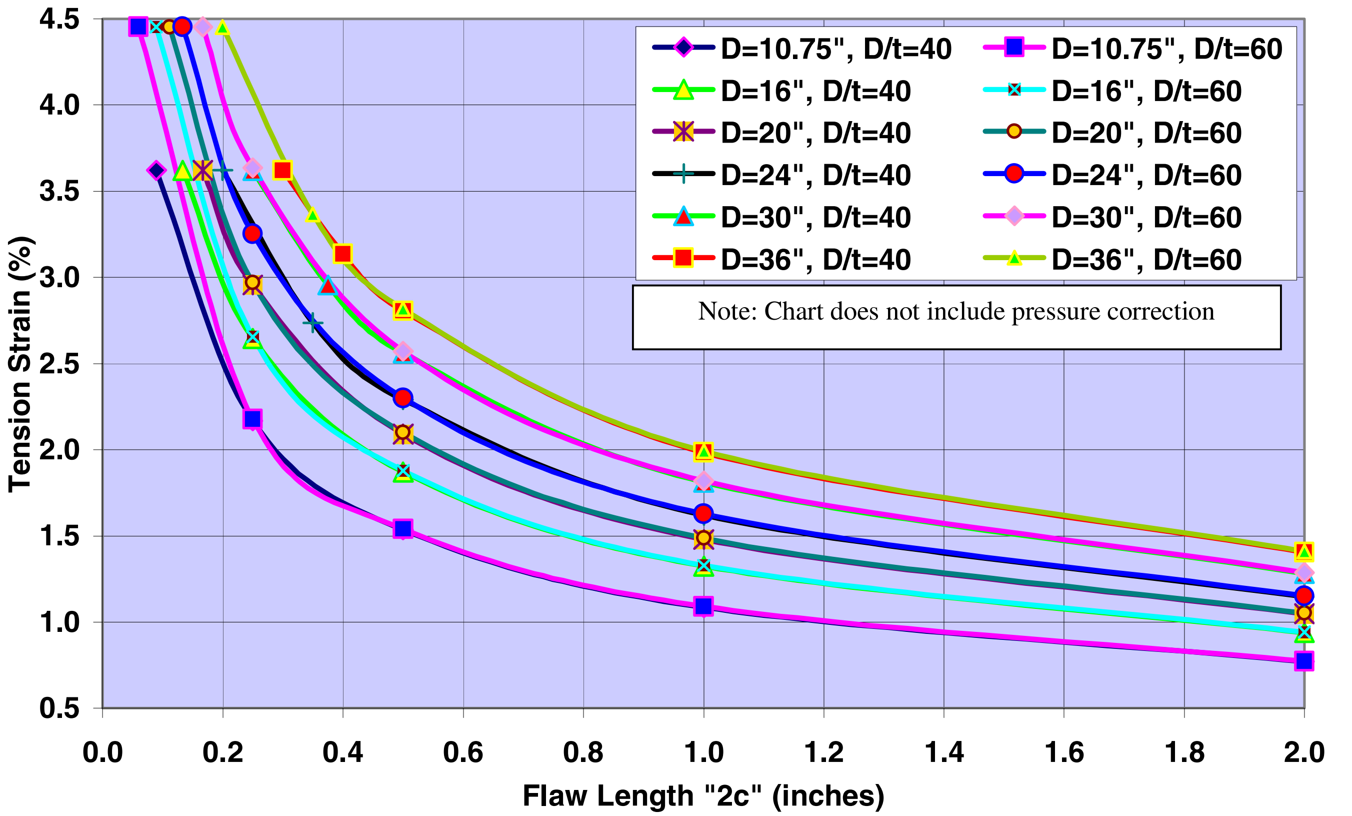

Figure 6 Model Strain Error- Unpressurized Pipe

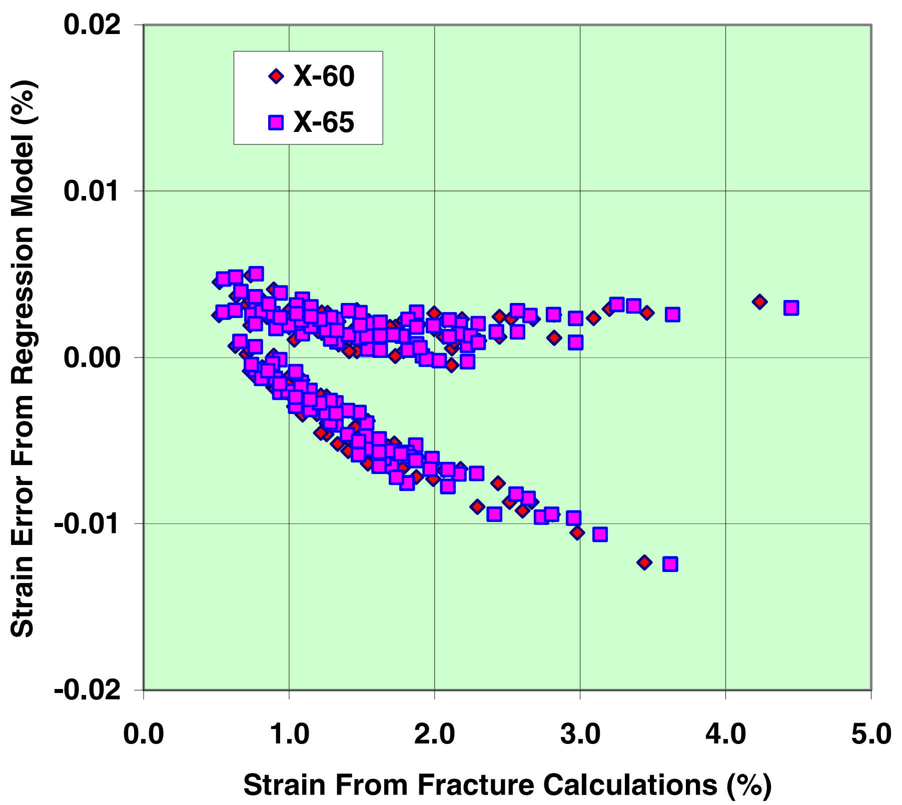

Figure 5 Scatter Diagram for Model vs. Calculated Strain Values - Unpressurized Pipe