

## **GIRTH WELD FAILURE IN A LARGE DIAMETER GAS TRANSMISSION PIPELINE**

**Ron Scrivner**

Stress Engineering Services, Inc.  
Houston, Texas  
[ron.scrivner@stress.com](mailto:ron.scrivner@stress.com)

**Butch Exley**

Williams Gas Pipeline  
Houston, Texas  
[butch.d.exley@williams.com](mailto:butch.d.exley@williams.com)

**Chris Alexander**

Stress Engineering Services, Inc.  
Houston, Texas  
[chris.alexander@stress.com](mailto:chris.alexander@stress.com)

### **ABSTRACT**

There have been several recent weld failures either during the initial post construction hydrostatic tests, or immediately following construction. Girth welds typically do not fail as a result of internal hoop loads without the contribution of loads due to out side forces. External loading should be considered during design, welding procedure development, construction, and pipeline operations. This paper presents one example where a girth weld failed as a result of preexisting 1940's weld imperfections and recent, 1980's, external loading. This analysis of the girth weld failure in the 30-inch pipeline included an initial failure analysis, a fracture mechanics analysis, and a finite element analysis that integrated the pipe-soil interaction, as well as localized stresses associated with weld imperfections. A critical part of this study was to evaluate how changes in soil conditions associated with a drought followed by soil saturation associated with rainfall, contributed to lack of local support and increased overburden loads associated with the saturated soil.

The failure analysis of the ruptured girth weld and surrounding pipe concluded that the failure of the girth weld was caused by increased bending loads imposed on the pipeline after recent construction activities, and that the fracture initiated at a lack-of-penetration/fusion imperfection that was 20¼-inches long and 0.110 inches deep. A coupled investigation using finite element and fracture mechanics analyses verified numerically that with reduced-strength soil, stresses were generated in the girth weld of sufficient magnitude to cause a fracture. Temperature, terrain, and fatigue were considered, but were not deemed to significant enough to affect the stresses or other conditions that resulted in the failure.

The overriding observation of this study is that no single factor contributed to the failure that occurred. Rather, the girth weld failure was the result of weld imperfections that generated elevated stresses due to excessive loads imparted to the pipe due to settlement associated with non-compact backfill associated with excavation work. Had the pipe not displaced vertically due to localized soil conditions, it is unlikely that the pipeline would have failed. The recent excavation activities were adequate for normal soil conditions; however, dry soil at the time of construction resulted in lack of compaction and excessive moisture just prior to the failure that generated in differential settlement and heavy overburden, combined with lack of penetration imperfection in the girth weld in question, resulted in generating excessive bending stresses that contributed to the eventual failure of the pipeline.

### **INTRODUCTION**

There have been several recent high profile girth weld failures during or immediately following construction [1]. These failures have been investigated and it has been concluded that welding imperfections were the metallurgical cause. As with any failure, the imperfections interact with stress causing a failure. API 1104 Appendix A requires an analysis of the anticipated stresses during both construction and operation. When a metallurgical failure analysis is performed and defects, based on both workmanship standards or Alternate Acceptance Standards (for example API 1104 Appendix A), are associated with the failure the analysis must consider stresses if the root cause is to be understood.

- Lifting before the weld is complete [2]
- Construction activities including lifting lowering, and/or backfilling
- Normal operations for example:
  - changes in soil conditions (drought or heavy rain)
  - pipeline maintenance (i.e. heavy equipment working over the pipeline, or excavating the pipeline)
- Abnormal operations (i.e. subsidence due to mining, flooding, or earthquake)
- Thermal and/or residual stresses as a result of welding

This paper presents the results of a study performed by the authors, for a major gas transmission company, of a failure that occurred in-service early 2008 in a 30-in nominal outside diameter gas transmission pipeline. A section 6½-ft long of the failed pipe was removed from the line and was provided by for analysis. The pipeline was constructed in the late 1940's with 0.325-in. wall, Grade X52 line pipe. The pipeline had been in service without other incidences due to girth weld failure since constructed. The sample included the complete ruptured girth weld and sections of pipe from up-stream and down-stream of the failure. Pressure at the time of the failure was reported to be 730 psig, or 64.8% of the specified minimum yield strength (SMYS) of the pipe. The pipe split circumferentially across approximately one-half of the pipe circumference.

The details provided in this report address three specific phases of study.

- Metallurgical failure analysis
- Finite element analysis
  - Local model to evaluate stress concentrations in the girth weld
  - Global model to determine tensile and bending stresses generated as a result of pipe-soil interactions
- Fracture mechanics analysis

Figure 1 is a flowchart showing how the various stages of this study are integrated to determine if conditions were present at the time of the incident that could have produced the failure in the girth weld. Expanding on the above bulleted phases of study, the metallurgical analysis was initially performed. As with most failure investigations, this work involved determining the metallurgical cause of the failure and identifying what potential environmental and loading conditions were present. The next phase of work involved using finite element analysis to determine stresses in the girth weld due to welding imperfections. Additionally, the finite element work calculated stresses that were present in the pipeline near the region of the failure due to local changes in soil strength associated with backfilled soil following excavation for recoating activities. The work in this phase of study proved to be extremely important for evaluating a range of plausible soil conditions with reduced properties at the time of the incident and calculating the resulting range of axial tension forces and bending moments. Note in Figure 1 how the global finite element model is used to determine the section forces and moments in the vicinity of the girth weld. These values are used as input into local finite element model in order to calculate the magnitude of stresses that will occur in the girth weld based on internal pressure and displacement of the pipeline due to soil settlement.

While the finite element models were used to determine section forces and moments as well as local stresses in the girth weld, the fracture mechanics models were used to determine the conclusive evidence determining if conditions were present at the time of the incident that could have produced the failure in the girth weld that consequently leaked.

The remaining sections of this report provide details on the work performed to complete this study. This includes the failure analysis investigation, finite element analysis modeling work, and the fracture mechanics analysis. A discussion section is also provided that presents how all elements of the study support the conclusion that the failure resulted from several contributors including stress concentrations in the girth weld combined with elevated bending loads generated by settlement due to reduced soil strength associated prior excavation activities.

## FAILURE ANALYSIS INVESTIGATION

A failure analysis was conducted on the girth weld failure in the pipeline. The investigation was based on an examination of the failed components. The results presented in this section support the conclusion that the girth weld failure incident was the result of increased bending loads caused by local soil settlement in conjunction with excessive stresses in the girth weld due to welding imperfections.

## Background

Following an in-service pipeline rupture that occurred early 2008 a section of failed pipe from the line was removed. The authors were then contracted by the operator to analyze this failure. We were provided an approximately 6½-ft long section of the 30-in. nominal outside diameter (OD) by 0.325-in. wall, Grade X52 line pipe (Figure 2). The sample included the complete ruptured girth weld and sections of pipe from up-stream and down-stream of the failure. Pressure at the time of the failure was reported to be 730 psig, or 64.8% of the specified minimum yield strength (SMYS) of the pipe. The pipe split circumferentially around approximately one-half of the pipe circumference.

The pipeline was originally constructed in the late 1940's with American Petroleum Institute (API) 5LX pipe. It was joined by girth welds in the field using the shielded metal arc welding (SMAW) process. During the summer of 2007, this section of pipeline had been excavated, stripped of its old coating, sand-blasted, and recoated with liquid epoxy. There was no reported maintenance activity on this section of pipeline prior to the work in 2007.

## Visual Examination

The pipe received by SES had split circumferentially at the time of the rupture and the fracture was open to a maximum width of about 1.25 in. The OD was measured as 29.95 inches. The ovality of the pipe was also measured at 2 in. and 24 in. both up-stream and down-stream from the failed weld. Dimensions are summarized in Table 1. Ovality was calculated using the following relation.

$$\text{Percent Ovality} = \left( \frac{\text{OD}_{\text{maximum}} - \text{OD}_{\text{minimum}}}{\text{OD}_{\text{nominal}}} \right) \cdot 100$$

The resulting ovality measurements were:

- Up-stream pipe 24-in. from girth weld = 4.3%
- Up-stream pipe 2-in. from girth weld = 2.0%
- Down-stream pipe 24-in. from girth weld = 2.2%
- Down-stream pipe 2-in. from girth weld = 2.6%

The bend in the pipeline at the failed girth weld (i.e., deviation from a straight line) was measured. A maximum deviation of 1.5 in. was measured at 155 deg (at about 5:00 o'clock and with 12:00 o'clock being the top of the pipe), as depicted in Sketch 1. The pipe had split circumferentially for about 46 in., most of which was in the girth weld or heat affected zone (HAZ). The fracture stopped at both ends shortly after entering the base material of the pipe. Examination revealed a lack of penetration/fusion (LP) in the root pass of the weld.

## Mechanical Testing

A sample of material from both sections of the pipe (one on either side of the girth weld) was subjected to destructive testing. Test results showed that yield and tensile strengths of the up-stream pipe are 52,600 psi and 82,000 psi, respectively. Similarly, yield and tensile strengths of the down-stream pipe are 56,500 psi and 80,400 psi, respectively. These values are shown in Table 2 and were all within the limits specified by API 5LX at the time the pipe was manufactured. Charpy toughness was obtained for each pipe sample and is presented in Table 3.

## Metallographic Examination

The fracture was first viewed with low-power magnification (less than 35X) using a stereoscope. This examination identified a 20¼-in. long welding imperfection, specifically a LP. The LP was 0.110 in. at its deepest location as shown in Figure 3. Shown in Figure 4 is a cross-section of the weld, again revealing the LP both on the fracture side of the weld root bead and the opposite side.

## Discussion on Failure Analysis

Metallurgical examination of the failed pipeline joint revealed a welding imperfection in the root pass which was a maximum of 0.110 in. deep and 20¼-in. long. This imperfection was located near the 8:00 o'clock position when looking down-stream. The joint failure was initiated at this imperfection, followed the girth weld and its HAZ for most of its length, and then terminated in the pipe material. The fracture exhibited some ductility for its entire length. When the

advancing fracture moved into the base material, the fracture mode became tearing shear and was halted. There was no sign of fatigue in the fracture.

Longitudinal forces acting on the girth weld resulting from internal pressure could have been as high as one-half that of the hoop stress, or 32.4% of SMYS, assuming that no imperfections existed. Mechanical testing showed that the pipe met the SMYS required by API 5LX, and with a 20-in. imperfection penetrating one-third of the wall thickness, there was sufficient cross-section available to support the load created by internal pressure. This conclusion is supported by the fact that this weld carried the service load without incident for more than 55 years.

SES concluded that the failure was the result of a combination of axial and excessive bending loads, based on several observations including:

- Deformation present opposite the fracture
- Fracture orientation
- The observed ovality
- The fracture extended almost exactly half of pipe circumference
- The fracture ended in tearing shear in the base material outside the HAZ

Had there been sufficient longitudinal loading to initiate a rupture, the failure would have parted the pipeline. It is also more than coincidence that the pipeline was cleaned and recoated within the last year. This activity was also conducted during a dry season, which would result in difficulties with soil compaction and therefore uneven support of the pipeline following construction. It was also reported that significant rainfall had occurred well after construction and shortly before the rupture. This moisture would have had an impact on soil consolidation and likely contributed to increased stresses on the pipeline. The logical conclusion regarding this incident is that the joint failure was the result of increased bending loads in conjunction with reduced strength of the girth weld due to welding imperfections. This is further supported by the ovality measured in the region of the failure, which is a result of bending stresses. Many failures, and this one is no exception, are a direct result of several factors that combine to generate unacceptable conditions.

### Closing Comments on Failure Analysis

The following conclusions were developed based on findings associated with the metallurgical failure analysis.

1. Visual and metallographic examination of the failure indicated that the pipe rupture initiated at a deep, 0.110-in. welding imperfection, specifically, a lack of penetration/fusion (LP) in the root pass of the weld. This LP extended about 20¼ in. around the girth weld.
2. It is believed that excavation and recoating activities conducted in 2007 on this section of pipeline reduced the support provided by the surrounding soil, which resulted in axial tension and excessive bending stress on the joint that led to its failure.

### FINITE ELEMENT ANALYSIS

The purpose of this phase of the program is to evaluate the stresses in the girth weld and determine if conditions were present that could have resulted in failure of the pipeline. Tasks associated with this effort include numerically modeling the pipe-soil interaction, evaluating local stresses in the vicinity of the weld, and using fracture

mechanics to determine if a pre-existing flaw could have resulted in the failure.

After the failure analysis was performed, numerical modeling was used to evaluate the potential conditions in the pipeline at the time of the failure. Two major observations were made that influenced the path forward for the numerical modeling efforts. First, lack of penetration imperfections existed in the girth weld and that these anomalies generated stress concentration factors. Secondly, that excessive bending stresses generated the resulting failure. Therefore, using these observations two finite element models were constructed. A local model to calculate the local stress concentration factor due to the girth weld imperfections associated with combinations of tension and bending loads. A second global finite element model to evaluate the pipe-soil interaction and calculate what forces and bending moments could have been present in the vicinity of the girth weld at the time of the incident. Of particular interest in this latter model was the reduced soil properties associated with backfill material and how loss of support increased local axial tension forces and bending moments acting on the girth weld.

The primary focus of this phase of work was to determine the magnitude of axial stresses in the vicinity of the girth weld. As a final follow-on activity, fracture mechanics calculations were performed to determine the likelihood for crack propagation in the girth weld.

### Local Finite Element Model

The purpose of the local finite element model was to determine the elevated stresses in the vicinity of the girth weld due to welding imperfections. The sections that follow provide specific details on the analysis methodology and corresponding results.

**Analysis Methodology** Using the geometry of the girth weld from the failure analysis investigation, measurements were made for the purpose of constructing the local finite element model. Figure 5 shows the geometry of the weld profile used to create the finite element model. A relatively fine mesh was used in the vicinity of the ID lack of penetration to capture elevated stresses.

The configuration for the local model was axisymmetric elements with asymmetric loading. This axisymmetric configuration essentially means that one plane of elements can be used to represent the full geometry for a cylindrical geometry (i.e. no variation in the geometry as a function of circumference). Asymmetric loads are those that are by definition not symmetric relative to the pipe axis. The application of a transverse load used to generate a bending stress in the pipe, as shown in Figure 6, is a typical asymmetric load. From a numerical standpoint, it is possible to model a detailed section of a pipe using a relatively small number of elements (e.g. 15,000) where a full three-dimensional model would likely require several orders of magnitude more elements.

Referring once again to Figure 6, the end of the pipe was fixed in all degrees of freedoms as one would load a cantilever beam. Pressure was applied on all internal surfaces of the pipe including the crack. Uniform tension was applied to the open end elements of the pipe as a distributed load. A bending moment was applied via a shear load at the open end of the model. A total of 25 load cases were analyzed, and bending moments ranging from 0 to 100% of the yield moment were applied along with axial tension loads ranging from 0 to 100% of the yield tension force. For all load cases an internal pressure of 811.2 psi was used. Stresses were extracted from these 25 models and used to

generate plots showing stress as function of the applied bending and tension loads. These resulting stresses were the basis for evaluating what stresses existed in the vicinity of the girth weld and were used to the calculated section forces and bending moments from the global model.

### Global Finite Element Model

Once the local finite element model work was complete, the next phase of work focused on calculating section forces and moments in the vicinity of the weld considering global pipe loading. Of particular interest in performing the global finite element model was the terrain of the pipeline and the soil properties. During the recoating work in 2007, soil was excavated along the pipeline including the area around the girth weld in question. In the process of backfilling the soil, it appears that proper compaction was not achieved and the resulting soil did not have the same properties as the undisturbed soil. Figure 11 is a sketch provided showing the overall layout for the pipeline. Of particular importance is the 66 feet of soil that was excavated in early 2008. It is this region of soil that was modeled using degenerated soil properties that are reflective of what would happen if the soil were not properly back-filled and compacted following excavation.

In addition to the sketch, survey data was provided that included the coordinates of the pipeline in three-dimensional space. Additionally, the survey data included the level of soil cover on the pipeline. Figure 12 is a plot showing the topography of the pipeline in two-dimensional space that includes the position of the pipeline (**RED** curve), as well as the elevation of the natural ground that provides the depth of soil cover (**BLUE** curve). Also included in this figure is the position of the girth weld relative to the topography of the pipeline.

The soil properties surrounding the pipeline were based on actual measurements, as well as estimates for the soil used for the backfill during the excavation work. Table 4 provides the measured soil properties that include the soil unit weight (density) and well as the soil stiffness. Note that soil densities are presented for both dry and wet soil conditions, which are important for the distributed soil loading on top of the pipeline. In terms of the soil stiffness, the spring constants are provided that include the axial, lateral, and vertical directions (uplift on top of pipe and bearing on bottom of pipe). Two sets of data are included for the residual subgrade soil as well as the backfill properties.

One final comment is warranted prior to discussing details on the global finite element model. During the preliminary investigations it was conducted that the pipeline displaced approximately 1 inch vertically in the vicinity of the girth weld. During the course of the analysis, this displacement was considered as a point of reference to evaluate if the models had been set up correctly, and more importantly if soil properties with reasonable stiffness values were used.

Having studied the conditions of the soil and terrain in the vicinity of the girth weld, work on the global finite element model was initiated. The sections that follow provide specific details on the ABAQUS two-dimensional planar model that included the geometry of the pipeline, stiffness of the soil (including the reduced properties of the soil associated with the excavation activities), and the distributed load associated with the top soil. Results are presented that include the section forces and moments in the vicinity of the girth weld, as well as the overall axial stress in the pipeline.

**Analysis Methodology** Based on the geometry of the pipeline, soil, and terrain, it was determined that a two-dimensional planar model would accurately capture the response of the pipeline to the internal pressure and distributed loading conditions and the surrounding soil. Recognizing that the replaced soil had a stiffness that was less than the nominal residual subgrade, it was necessary that the model permit the integration of this condition including both the differences in soil stiffness and density.

**Geometry for Global Model** Figure 13 shows the geometry for the global finite element model. The pipe was modeled using the ABAQUS *PIPE21* beam element that permits the integration of internal pressure loading. The soil was modeled using the ABAQUS pipe-soil interaction elements. These elements permit the inclusion of soil stiffness in all directions, including axial, transverse (which was not used in this planar model), and vertical (uplift and bearing). In order to use the soil properties provided (cf. Table 4), it was necessary to convert the spring values provided in lbs per cubic foot (pcf) to the ABAQUS soil spring interaction elements that require linear displacement spring in units of lbs per inch. The equations below are used to make the necessary conversions for the axial and vertical springs.

$$k_{\text{axial}} = \pi D L K_{\text{axial}}$$

$$k_{\text{vert}} = D L K_{\text{vert}}$$

where:

$k_{\text{axial}}$  = Axial spring stiffness (lbs/in)

$k_{\text{vert}}$  = Vertical spring stiffness (lbs/in)

$D$  = Pipe outside diameter (inches)

$L$  = Axial length (assumed to be 1 inch for a unit length condition)

$K_{\text{axial}}$  = Terracon-provided axial soil springs (pcf)

$K_{\text{vert}}$  = Terracon-provided vertical soil springs (pcf)

Provided below are the converted spring constants.

- Residual subgrade soil
  - Vertical direction: 1350 lbs/in
  - Axial direction: 4241 lbs/in
- Backfill soil
  - Vertical direction: 150 lbs/in
  - Axial direction: 471 lbs/in

For the global finite element model, there are basically two load cases based on whether the soil properties are for wet or dry soil conditions. From a modeling standpoint, the fundamental difference between these two load cases involves the density of the soil and the resulting distributed load on top of the pipe. The depth of cover on top of the pipeline is assumed to be 5.7 feet. Provided below are the soil densities used in the two finite element models.

- DRY case model
  - Residual subgrade soil density of 95 pcf (113 lbs/in distributed load)
  - Backfill soil density of 90 pcf (107 lbs/in distributed load)
- WET case model
  - Residual subgrade soil density of 120 pcf (143 lbs/in distributed load)
  - Backfill soil density of 115 pcf (137 lbs/in distributed load)

An internal pressure of 811 psi was included in the model. The carbon steel pipe material was modeled elastically with an elastic modulus of 30 million psi and a density of 0.281 lbs/in<sup>3</sup>. A mentioned

previously, the vertical displacement of the pipe near the girth weld was monitored and compared to the target value of 1 inch.

**Analysis Results** The finite element models were analyzed and results were post-processed. The primary focus of this phase of work was to calculate the sections forces and moments in the vicinity of the girth weld. Table 5 provides the calculated section forces and moments from the finite element models. Included in this table are the percentages of the calculated values relative to the percentage of yield values. As noted a minimal increase in the calculated values results for the wet soil condition. The calculated force and moment are used as input in determining the maximum stress in the girth weld.

Figure 14 and Figure 15 are collections of contour plots for the dry and wet load cases respectively. Included in these plots are the following variables:

- Axial stress on top and bottom of the pipe
- Section force
- Section moment
- Vertical displacement

What is important to note in all of these contour plots is that the maximum values occur in the vicinity of the girth weld. With the reduced soil properties in this region of the models, based on actual conditions, as expected the resulting pipe deflection generated elevated stress conditions in the girth weld. A point of emphasis is that the resulting section forces and bending moments associated with the calculated displacement correspond almost exactly to the pre-analysis estimated vertical displacement of 1 inch.

## FRACTURE MECHANICS STUDY

A crack assessment was performed on the 30-inch x 0.325-inch, Grade X52 pipe material. The modeled crack sizes include an ID lack-of penetration/fusion imperfection 20¼-in. long and 0.110 in. deep, similar to what was found from the failure analysis. This crack analysis focuses on determining stresses that predict failure in modeled cracks in the 30-inch pipeline. The fracture mechanics analysis is a static analysis that follows API RP 579, "Fitness for Service." Cracks were modeled circumferentially on the ID, adjacent to the girth weld.

### Material Properties

The pipeline material is API 5L, X52 and material testing showed the actual yield and ultimate strengths to be in excess of these minimum values as shown in Table 7. The minimum values from the testing were used in the analysis along with an assumed modulus of elasticity of 29,500 ksi and a Poisson's ratio of 0.3. The material toughness was acquired from the HAZ region near the fusion line of the weld. This region adjacent to the weld was generally where the crack progressed. The CTOD tests were conducted at 10 C, which is near the upper shelf based on the Charpy results. The resulting CTOD values were 0.18, 0.20, and 0.22 mm (7.1, 7.9, and 8.7 mils). The minimum value was used in the analysis. The summary of the results of the three tests is shown in Table 6.

### Loading

Concerns about burying and subsequent stresses that may have developed were discussed in the previous analysis. The limiting tensile stress that would cause failure was determined based on loading, the crack, and pipe geometry and the material properties. To account for the stress field that may be present following welding, models were run with yield-magnitude residual stress. Additionally, a residual stress value of 16 ksi, or 30% of the yield stress, was analyzed to examine

the effect of a lower residual stress. A lower residual stress could come from either post-weld heat treatment or from stress relaxation over time.

## Methodology

Calculations to determine crack growth were implemented using Signal Fitness for Service, Version 3.0, from Quest Reliability, LLC. The assessment procedure employed in this study is a general assessment procedure based on a single fracture toughness value, typically CTOD ( $\delta$ ) or  $K_{IC}$ , which may be associated with limited ductile tearing. While safety factors can be included through input variables, no inherent safety factors are included in the method. The limiting value of a parameter such as flaw size, applied stress, or fracture toughness, can be altered to determine the maximum allowable value permissible on the failure assessment diagram (FAD).

This procedure uses fracture mechanics principles to establish a FAD that assesses the tendency of material failure due to both fracture and plastic collapse. An assessment line is plotted on the diagram and calculations for a crack provide the coordinates of an assessment point. If this assessment point lies on or outside the assessment line, the crack is considered to be unacceptable. If the assessment point lies within the area bounded by the axes and the assessment line, the crack is acceptable (see Figure 16). The vertical axis of the FAD is a ratio of the applied conditions, in fracture mechanics terms, to the conditions required to cause fracture, measured in the same terms. The horizontal axis is the ratio of the applied stress to that required to cause plastic collapse. For Level 2, this definition is

$$L_r = \frac{\sigma_{ref}}{\sigma_y} \quad (1)$$

where  $\sigma_{ref}$  is the calculated local reference stress and  $\sigma_y$  is the yield stress of the material.

## Results and Discussion

The results of the analysis demonstrate that it is possible for crack in the girth weld to propagate when the pipe is subjected to axial stresses below the yield strength of the pipe material. For the 20 inch long by 0.11 inch deep crack, the range of axial stresses leading to failure are between 32 and 46 ksi for residual stresses equal to 52 and 16 ksi, respectively. The finite element analysis results demonstrate that stresses of sufficient magnitude (i.e. greater than 46 ksi) were present to produce the level of crack propagation calculated using the fracture mechanics model.

The results of the analysis are summarized in Table 8. The table gives the axial stress that is predicted to cause failure of the specified cracks. Two crack lengths were examined, a 20 inch long crack similar to what was observed from the metallurgical evaluation and a 2-inch long crack. In comparison to stresses associated with the 20-inch crack, the 2-inch long crack increases the axial stress required for failure from 4 ksi (53 – 49 ksi) to 14 ksi (34 – 20 ksi) for crack depths of 0.06 and 0.14 inches, respectively. A graph showing the variation in axial stress as a function of crack depth is given in Figure 17 for the 20-inch cracks.

Modeling a high residual stress case (with the residual stress equal to the yield of the material), reduces the allowable axial stress. For the 20 inch long by 0.11 inch deep crack, the axial stress is 32 and 46 ksi for residual stresses equal to 52 and 16 ksi, respectively.

The axial stress at a girth weld in a pipeline can be amplified from a variety of geometrical sources. If the two welded pipes have slightly different thicknesses there will be a stress concentration in the weld region. If the fit-up is not exact, there may be local hi-low offsets or eccentricities at the weld. It was mentioned in reference 1 that ovality was present in the pipeline, a fact that is not too surprising for this high a D/t ratio. Ovality is often a result when bending unrestrained pipe having D/t ratios similar to the pipe in question (D/t = 92). Predictions of geometrical SCF values can be found in several sources [3, 4, and 5] and can reduce the axial stresses tabulated in Table 9.

The analysis modeled the limiting axial stress based on the crack geometry with a sharp crack front. The root pass weld was imperfect and original construction activities or years of operations may have initiated the crack front. Cracks initiate and grow typically through either cyclic loading or elevated static loads. Lack of fusion at the root of the weld will create a stress concentration, but it will not create a sharp crack without additional dislocation movement in the grains. Recognizing that gas pipelines are not typically subject to cyclic pressure conditions and that the observed failure occurred in the vicinity of recent excavation activities, it can be concluded that the cause of elevated stresses in the vicinity of the girth weld were due to general movements of the pipeline due to environmental conditions associated with the surrounding soil.

## DISCUSSION

The primary purpose of this study was to determine if conditions existed in the 30-inch pipeline that could have generated the resulting crack propagation. Previous sections of this report have independently provided details on the calculated results based on the local finite element model to calculate local stresses in the girth weld, global finite element model to evaluate pipe-soil interactions, and a fracture mechanics evaluation to determine the minimum stress state required to produce crack propagation.

From the global finite element model, the section forces and moments for the wet case were calculated to be 420,000 lbs (26.4% yield) and 1.4 million in-lbs (11.7% yield), respectively. Figure 18 plots the maximum axial stress from the local axisymmetric finite element model where results are plotted as functions of applied axial tension values and bending moments. As noted, using the loading conditions for the wet case the resulting maximum axial stress in the weld is approximately 54 ksi.

The calculated stress in the girth weld is compared to the minimum axial stress required to cause crack propagation based on the fracture mechanics calculations. Assuming that a residual stress on the order of 16 ksi exists in the weld, it is reasonable to assume that the axial stress required to cause a failure is 46 ksi. In reviewing the above data, it clear that with an axial stress of 54 ksi in the girth weld, the potential for developing stresses in the vicinity of the weld of sufficient magnitude to cause a failure seems probable.

Several other factors were not considered in this study. One included the effects of temperature fluctuations on stresses in the pipeline. The operating temperatures in the region of interest can be assumed to be steady-state. Additionally, the ambient conditions of the surrounding soil are unlikely to vary enough where thermal expansion of the pipeline would be an issue. For these reasons, no attempt was made to model or calculate stresses generated by thermal expansion of the pipeline. Additionally, in modeling the loading on the pipeline,

only axial and vertical motions were considered. No attempt was made to evaluate the transverse displacement of the pipeline. It is believed that any additional lateral movement would only increase the stresses presented herein; therefore, one can conclude that the calculated stresses as presented are indeed conservative and represent a lower bound condition.

## INDUSTRY IMPLICATIONS

Similarly, it well known that girth welds in transmission pipeline seldom fail due to hoops stresses alone even during testing to more than 100% of SMYS and the failures that do occur are the result of combined loading from outside forces. Understanding the stresses that result in failures are as important as understanding the welding imperfections that initiate fracture. This knowledge can be applied to both construction and operation of pipeline to better assure a safe pipeline infrastructure. This information can also be applied to the development of alternate acceptance criteria for welding procedure development.

## CONCLUSIONS

This report has provided details on the comprehensive investigation conducted by the authors to evaluate the pipeline failure that occurred in the 30-inch x 0.325-inch, Grade X52 line pipe that ruptured early 2008. The work performed by the authors involved an initial failure analysis based on examination of the failed girth weld. Additional efforts involved a fracture mechanics analysis and a finite element analyses to determine localized stresses in the girth weld.

The primary focus of the study was to determine if conditions existed in the vicinity of the pipe girth weld that could have produced the observed failure. Using reduced soil strength values that resulted from recent excavation activities, a vertical displacement of 1 inch was calculated at the location of the girth weld. This displacement is consistent with the pre-analysis projections and was used to confirm the accuracy of the calculated results. The maximum axial stress corresponding to this condition was calculated to be 54 ksi. The fracture mechanics calculation verified that any stress exceeding 46 ksi was sufficient to cause failure of the girth weld. Therefore, the results of this study demonstrate that conditions were present that could have caused the observed failure.

The overriding observation of this study is that no single factor contributed to the failure that occurred. Rather, the girth weld failure was the result of weld imperfections that generated elevated stresses due to excessive loads imparted to the pipe due to settlement associated with non-compact backfill associated with excavation work. Had the pipe not displaced vertically due to soil localized conditions, it is unlikely that the pipeline would have failed. Like many failures that occur, this incident was the direct result of combined factors that included localized girth weld lack of fusion imperfections and reduced soil properties produced by recent re-coating excavation activities in the vicinity of a sag bend during a drought. After the soil was saturated by rain, the local soil properties were reduced enough that elevated bending stresses were generated in the girth weld. It is likely that the excavation construction practices would have been adequate for normal soil conditions; however, lack of compaction followed by elevated moisture conditions, combined with elevated stresses in the girth weld, caused a leak to occur in the 30-inch gas pipeline.

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3. Connelly, L.M., and Zettlemoyer, N., "Stress Concentrations at Girth Welds of Tubulars with Axial Wall Misalignment," Proceedings of the 5th International Symposium of Tubular Structures, Nottingham, U.K., August 1993.
4. Buitrago, J., and Zettlemoyer, N., "Fatigue Design of Critical Girth Welds for Deepwater Applications," OMAE 98-2004, Lisbon, Portugal, July 6-9, 1998.
5. Det Norske Veritas Recommended Practice C203, "Fatigue Design of Offshore Steel Structures," April, 2008.

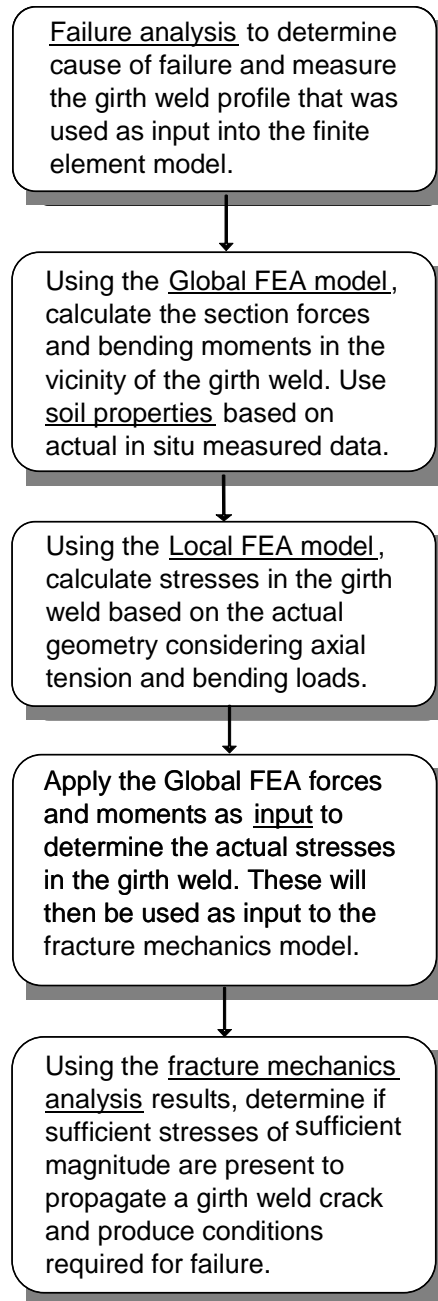
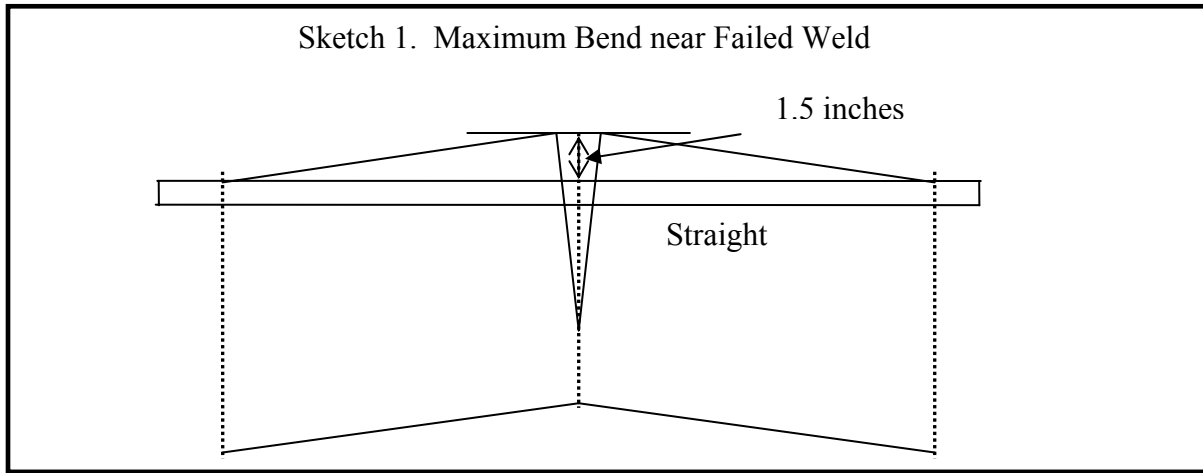
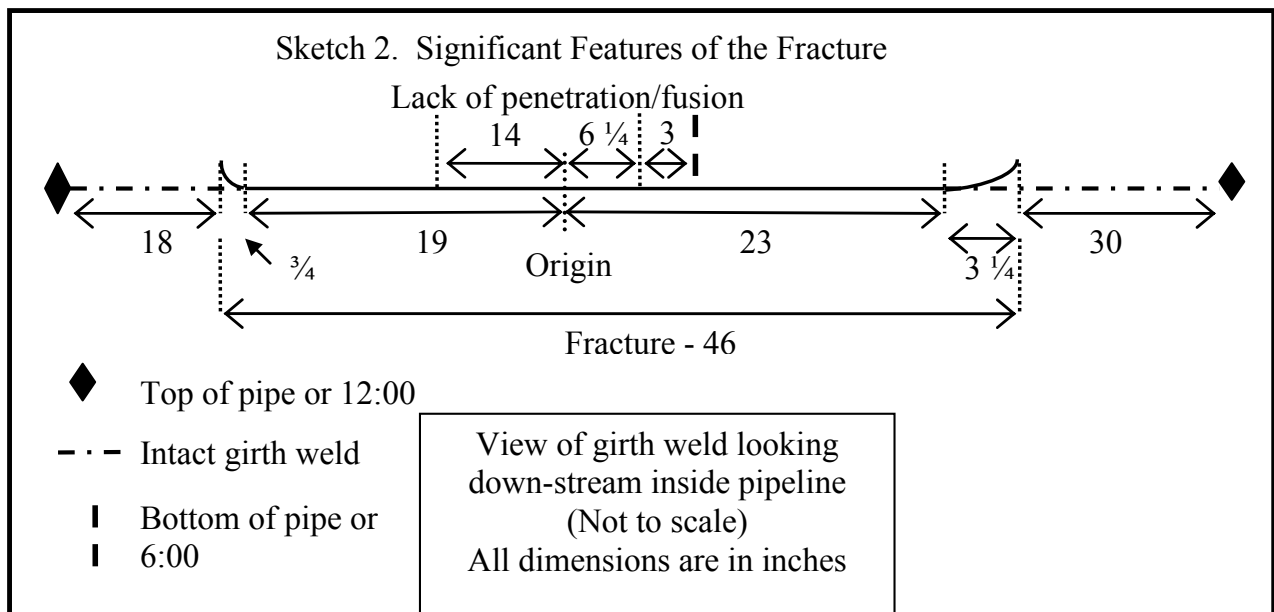


Figure 1 – Flow chart showing stages of the numerical analysis



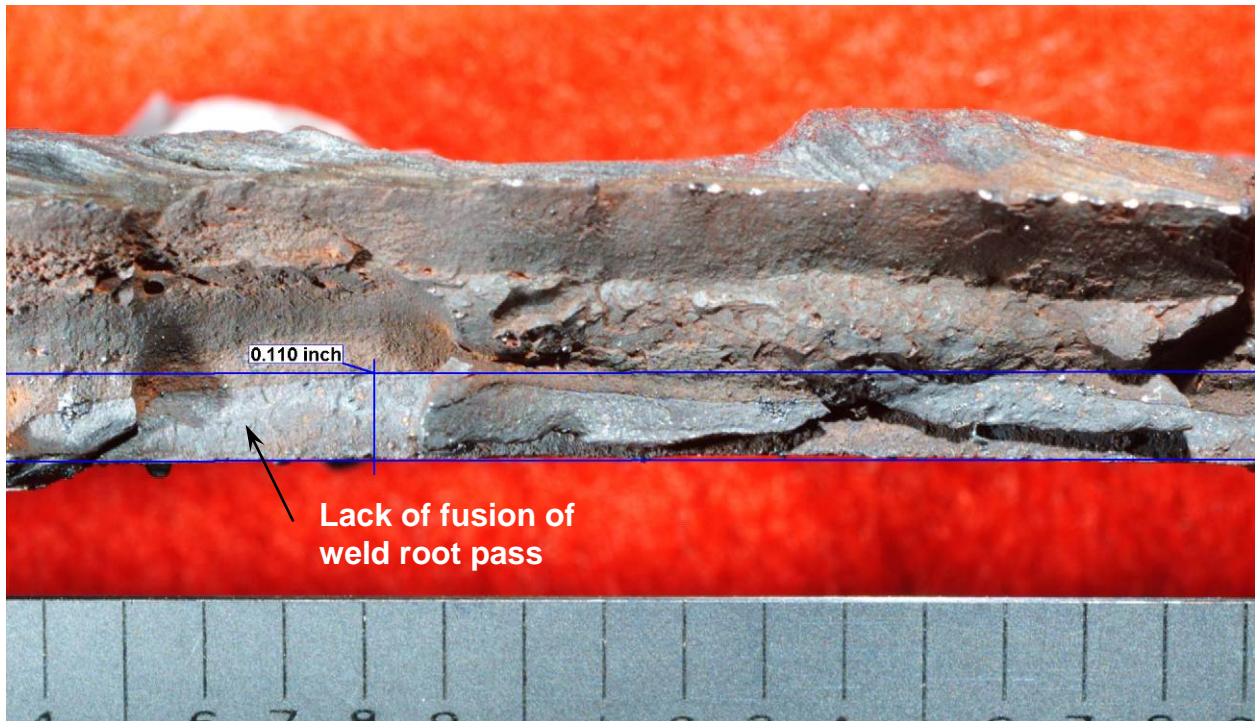
Sketch 2 shows the relative locations of the significant features including the origin, the area of LP and the ends of the fracture.



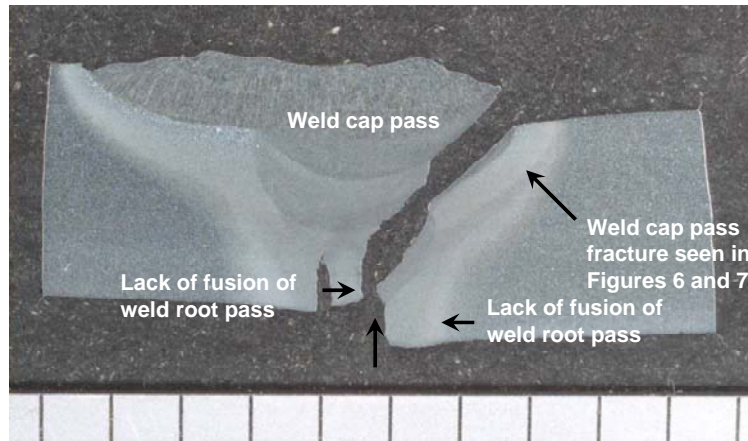




**Figure 2 – Photograph and two sketches showing ruptured pipe section as received**  
(Arrow (circled) indicates direction of flow)

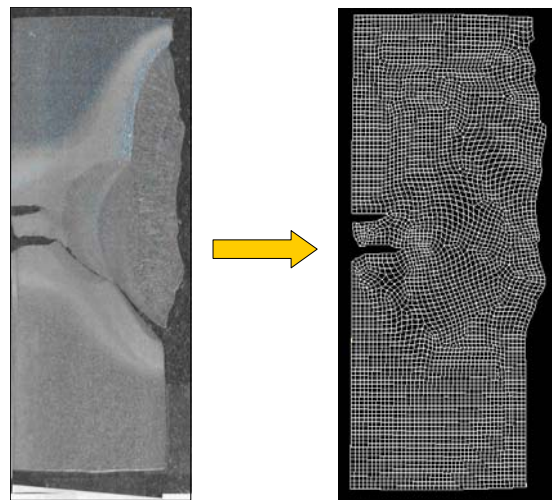


**Figure 3 - Photomicrograph of fracture origin and depth of LP**  
(Scale divisions are in inches)

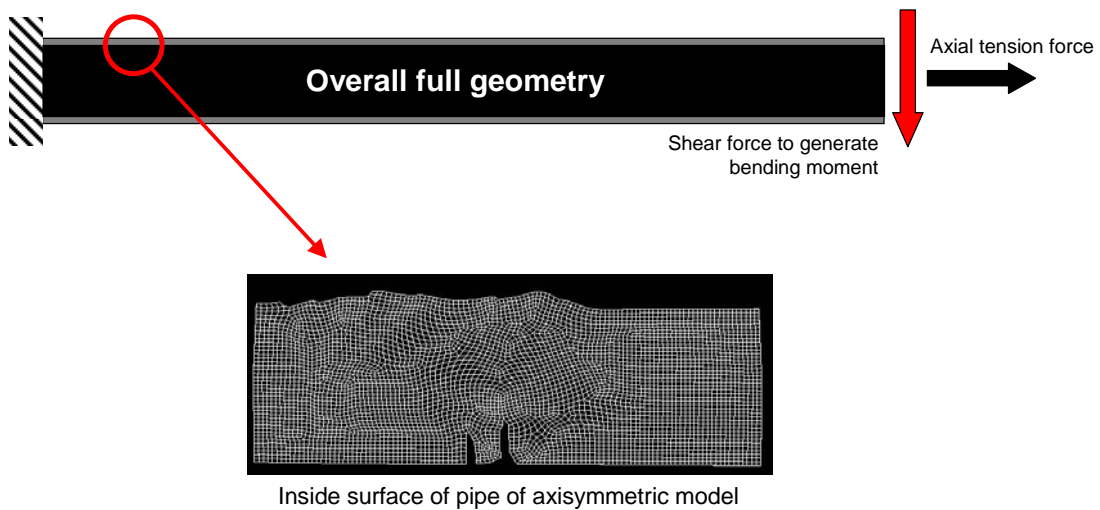


**Figure 4 - Photomacrograph girth weld cross-section at fracture origin showing lack of fusion between the root and bevel land.**

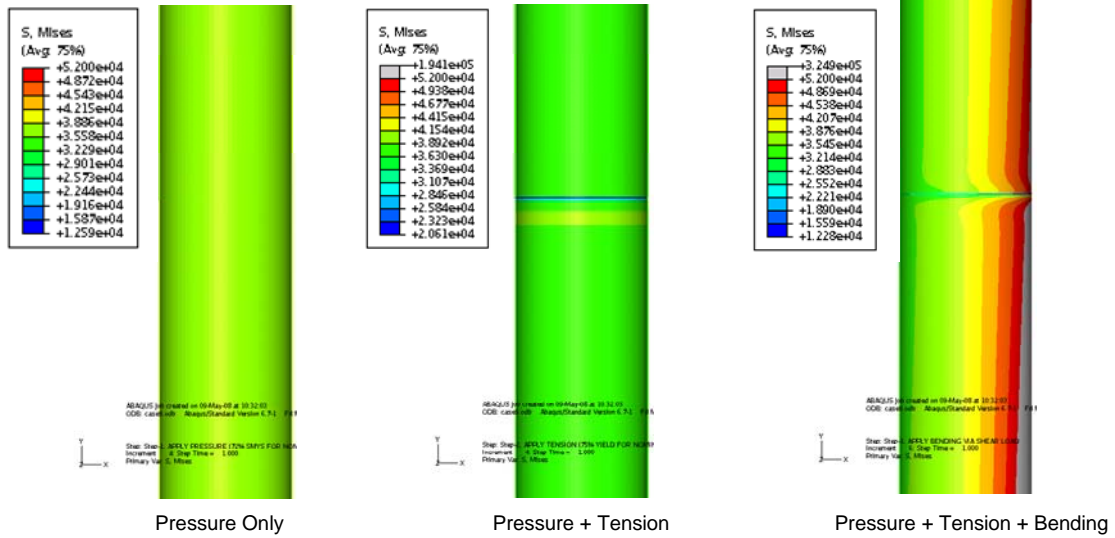
(Scale divisions are 0.10 inch. Etchant: 2% Nital)



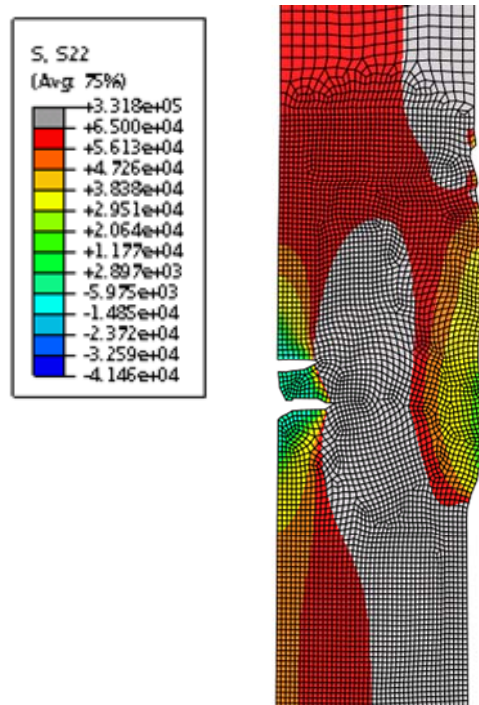
**Figure 5 – Weld profile used to create geometry for FEA model**



**Figure 6 – Axisymmetric model with asymmetric loading**



**Figure 7 – von Mises stresses for Case 9**  
(units for plotted stress contours are in psi)



**Figure 8 – Axial stresses for Case 9 considering pressure, tension, and bending**  
(units for plotted stress contours are in psi)

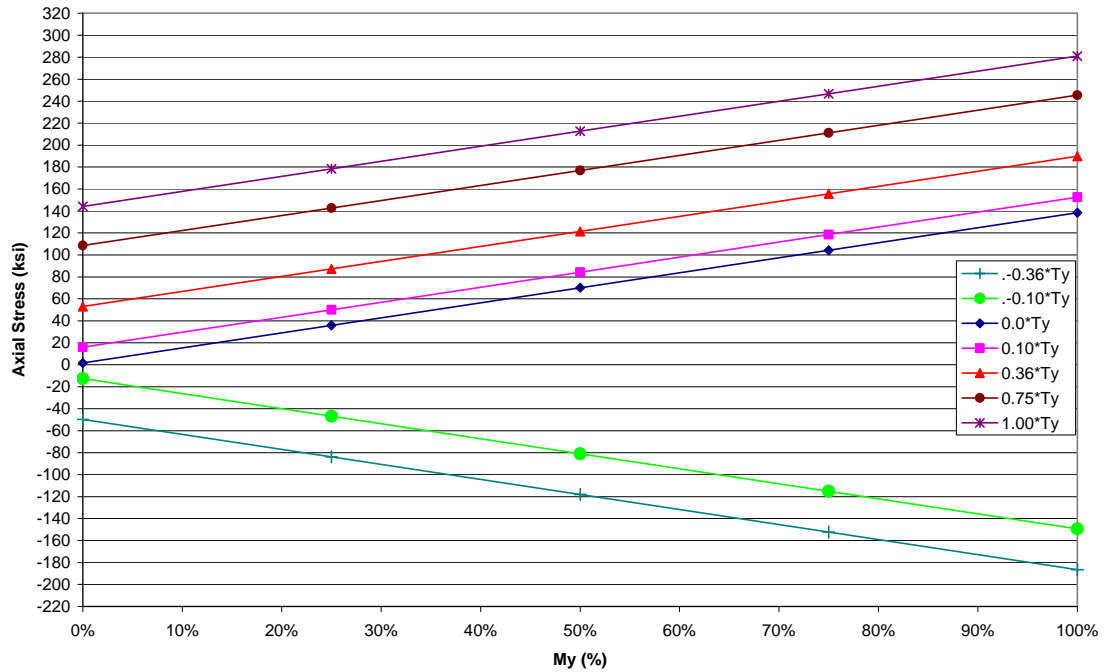


Figure 9 – Axial stress as a function of applied tension and bending loads

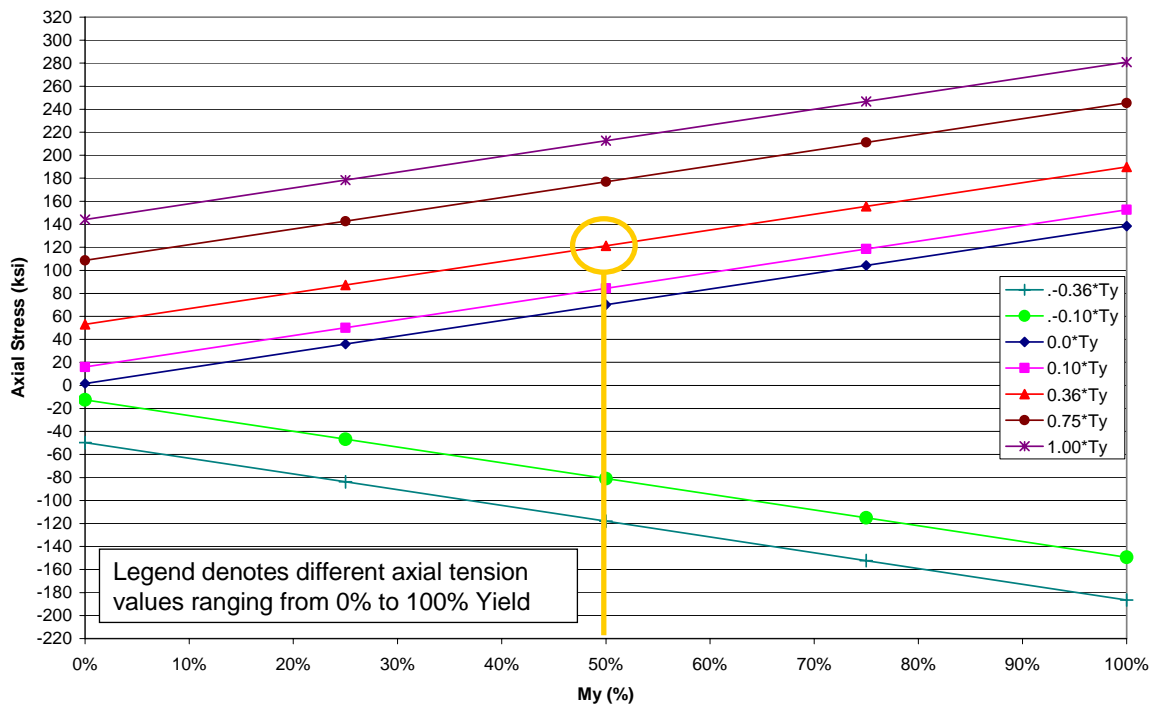


Figure 10 – Plot showing resulting axial stress of 120 ksi for 50% $M_{yield}$  and 36% $T_{yield}$



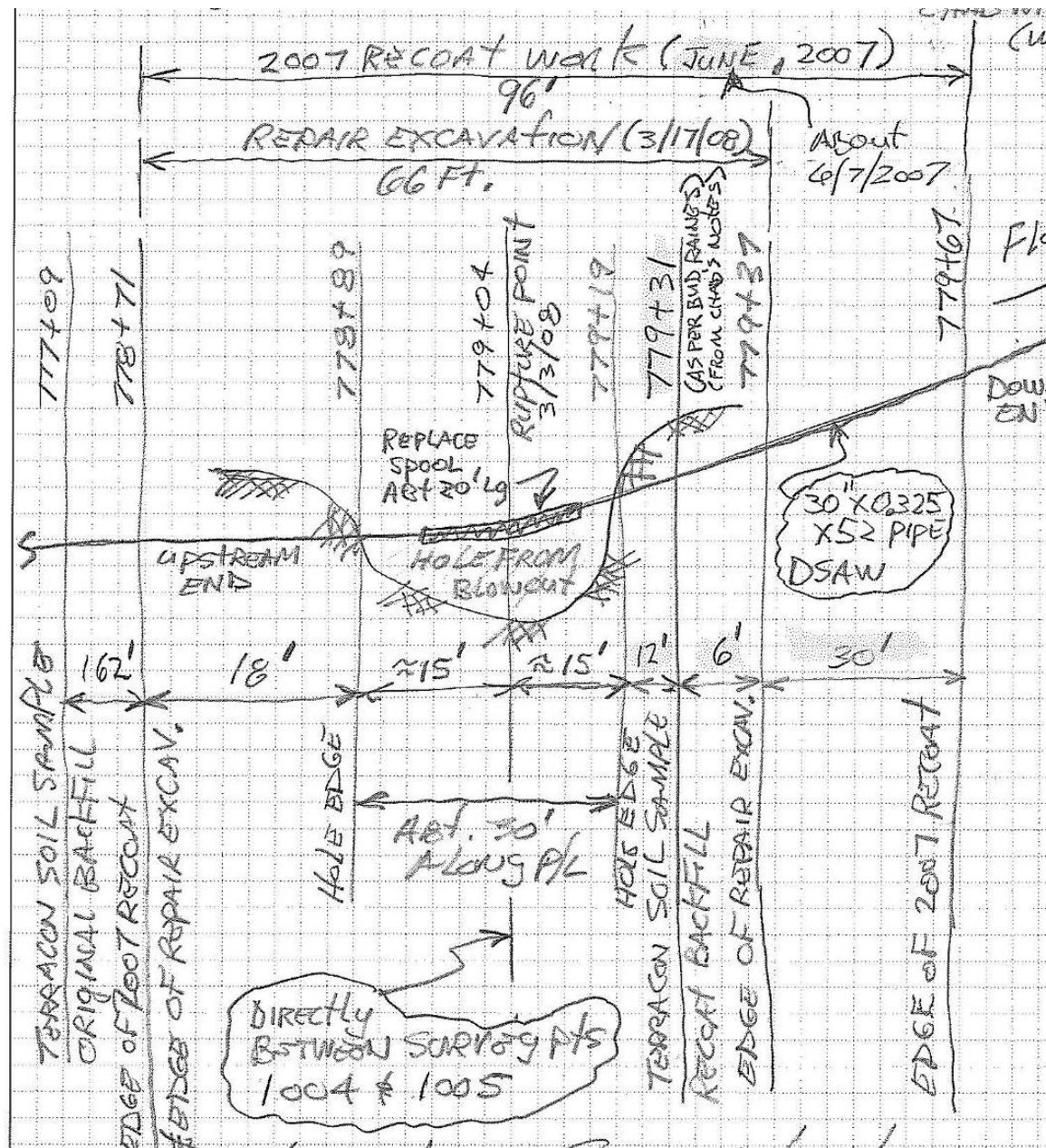
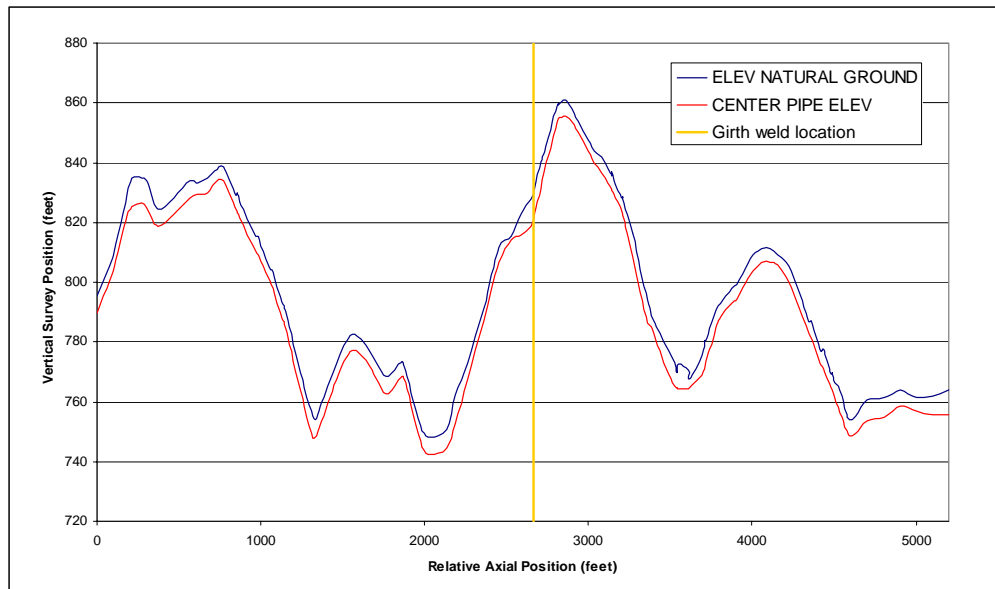
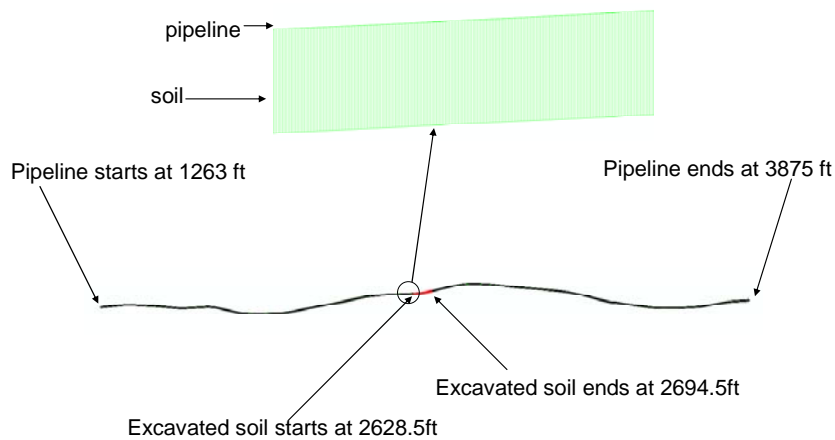


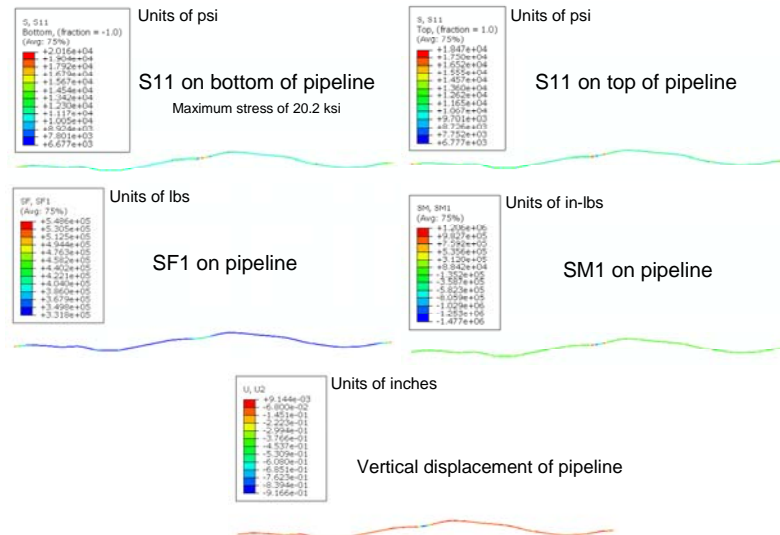
Figure 11 – Sketch showing layout of excavation activities near girth weld



**Figure 12 – Plot showing survey data of pipeline and natural ground**



**Figure 13 – Geometry for the two-dimensional global planar model**



**Figure 14 – Stresses, forces, moments, and displacements for the dry soil case**

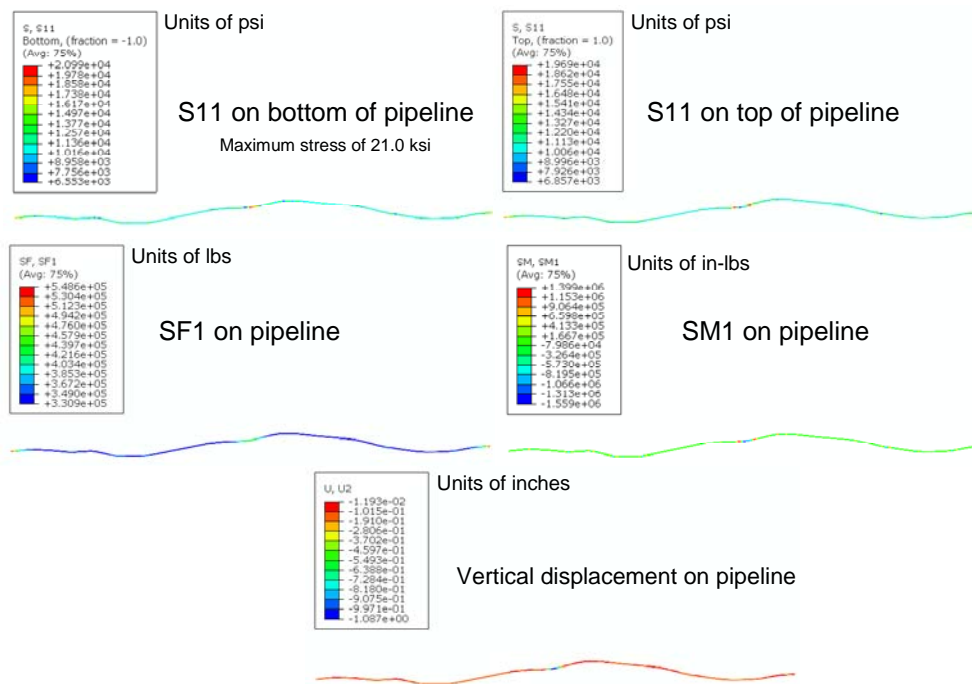


Figure 15 – Stresses, forces, moments, and displacements for the wet soil case

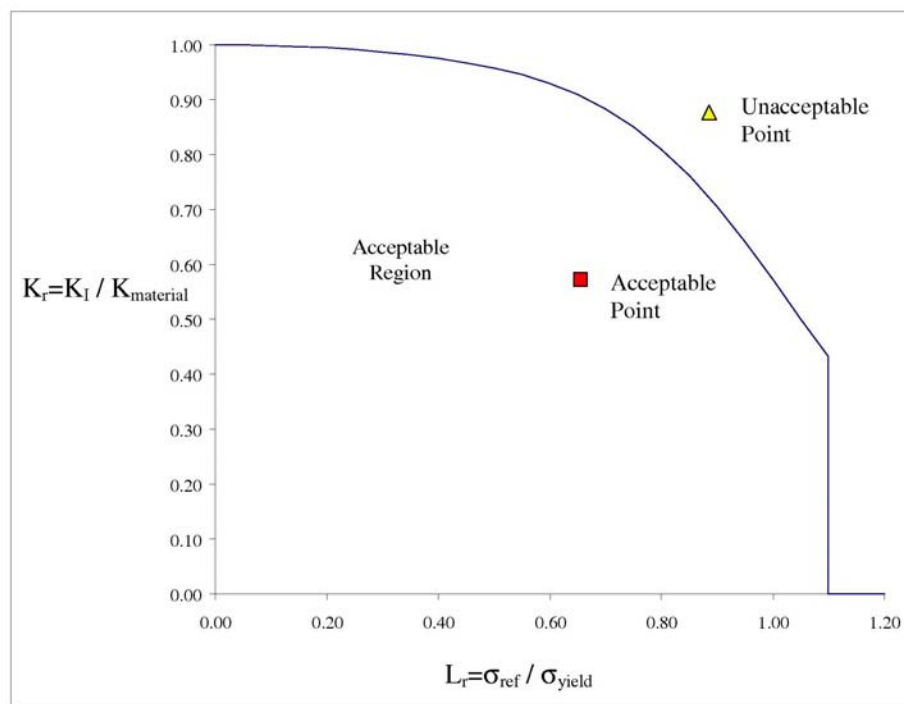


Figure 16 - Example FAD Diagram Showing Acceptable and Unacceptable Regions  
Crack growth continues until FAD limit is reached

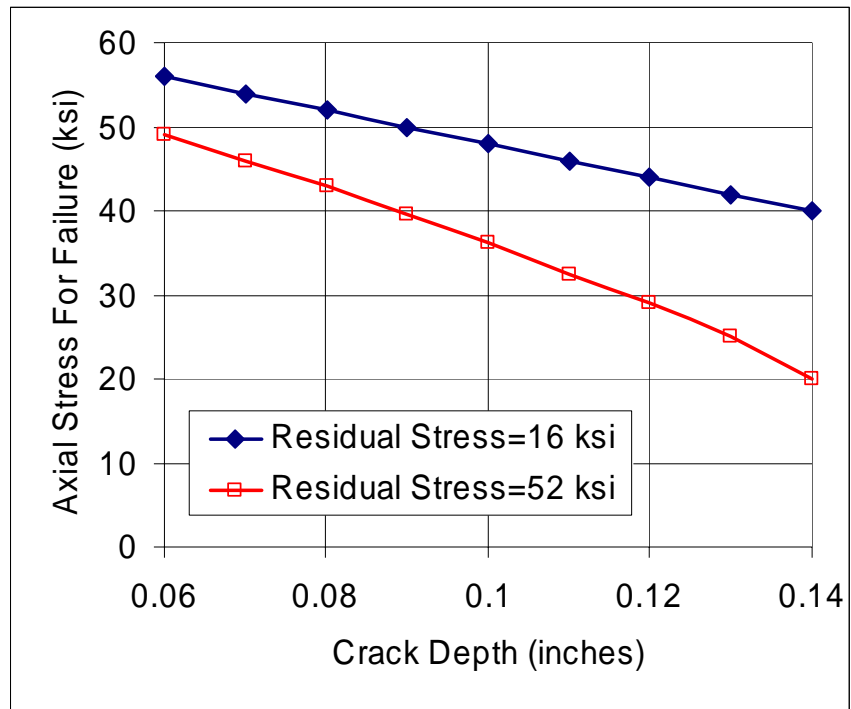


Figure 17 - Axial Stress Required to Cause Failure of a 20-inch Long, ID Surface Crack.

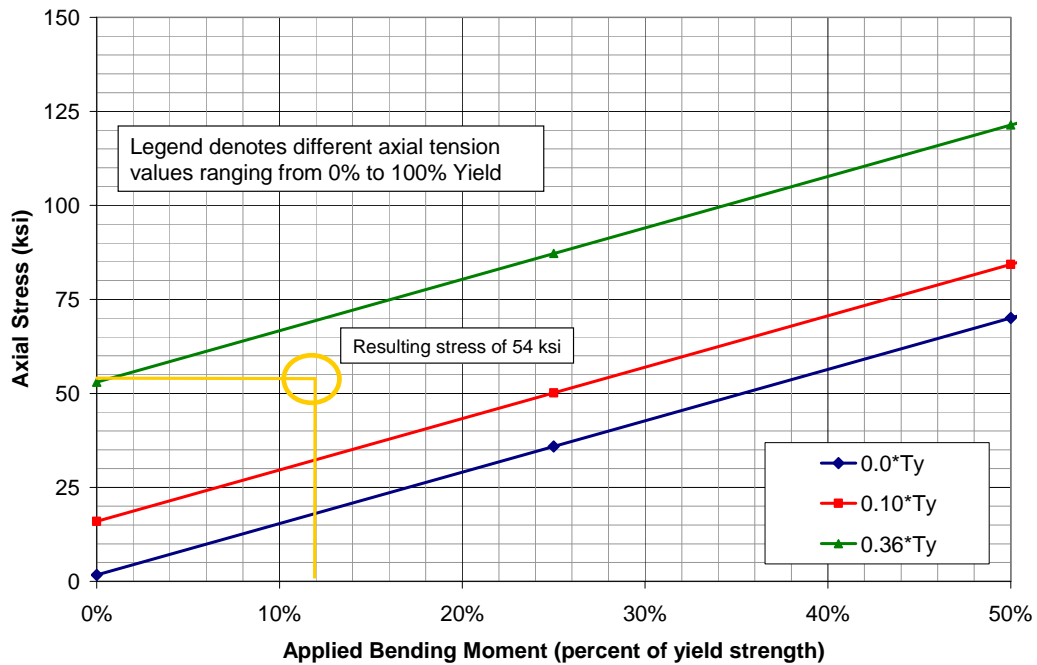


Figure 18 – Maximum axial stress as function of tensile force and bending moment (data acquired from local finite element model at girth weld location)



**Table 1 - Diameter Measurements of Pipe as Received**

Location (deg)	Up-Stream Pipe		Down-Stream Pipe	
	24 in.*	4 in.*	4 in.*	24 in.*
0-180	29.24	29.77	29.95	29.56
15-195	29.31	29.66	29.88	29.59
30-210	29.67	29.75	29.79	29.81
45-225	30.06	29.81	29.77	29.99
60-240	30.46	29.83	29.73	30.12
75-255	30.47	29.80	29.69	30.13
90-270	30.32	29.80	29.67	30.24
105-285	30.29	30.02	29.91	30.33
120-300	30.14	30.26	30.22	30.29
135-315	29.86	30.24	30.33	30.09
150-330	29.36	30.17	30.23	29.78
165-345	29.17	29.89	30.04	29.60

\* Axial distance from failed girth weld

**Table 2 - Results of Tensile Testing of Pipe Material**

Sample	Yield (psi)	Tensile (psi)	Elongation (%)
Up-stream	52,600	82,000	29
Down-stream	56,500	80,400	33
API 5L minimum requirements	52,000 min.	66,000 min.	25 min.

Note: Testing performed in accordance with API 5L

**Table 3 – Mechanical Test Results (Pipe A: 657:08 and Pipe B: 658:08)**

CHARPY IMPACT TEST RESULTS ASTM E23 TYPE: A SIZE: 10mm x 6.67mm (2/3 Size)					
SPECIMEN NO:	TEST TEMP.	NOTCH LOCATION	FT. LBS.	% SHEAR	LAT. EXP (MILS)
Transverse 657-08					
#1	0°F	BASE	21	99	34
#2		"	21	99	37
#3		"	20	99	36
#1		BASE	19	60	36
#2		"	21	60	42
#3		"	21	60	42
#1	@ +50°F	BASE	18	60	42
#2		"	17	50	30
#3		"	20	60	40
#1	@ +25°F		8	30	17
#2			8	30	18
#3			8.5	30	18
#1	@ +15°F		7	30	11
#2			8	30	17
#3			8	30	17
Transverse 658-08					
#1	F	BASE	24	99	38
#2		"	25	99	40
#3		"	22	99	36
#1	F	BASE	19	60	36
#2		"	20	60	36
#3		"	18	60	36
#1	@ 50°F		13	40	23
#2			13	40	20
#3			10	40	19
#1	@ 25°F		7	30	16
#2			8	30	18
#3			9	30	18
#1	@ 15°F		7	20	38
#2			7	20	40
#3			8	20	14

Soil Type	Table 4 – Soil Strength Parameters from Terracon						
	Friction Angle (degrees)	Unit Weight (pcf)		Soil Springs (pcf)			Vertical Bearing
		Dry	Wet	Axial	Lateral	Vertical Uplift	
Residual subgrade	32	95	120	45	45	4	45
Backfill	24	90	115	5	5	4	5

**Table 5 – Section Forces and Moments from Global Model**

Cases	Axial force (lbs)	Bending moment (inch-lbs)	U2 (inches)
<b>Dry Case</b> (Base soil density of 95 pcf)	410,000 (25.7% Yield)	1,200,000 (10.0% Yield)	0.92
<b>Wet Case</b> (Base soil density of 120 pcf)	420,000 (26.4% Yield)	1,400,000 (11.7% Yield)	1.09

**Table 6 – CTDO Testing Results**

CTOD Test - BS 7448 Part 2							
	Location	Geometry	Orientation	Test Temp [°C]	Delta [mm]	Fracture Mode	Comments
001:Heat Affected Zone	HAZ	Bx2B	T-T	10	0.18	M	Nil
002:Heat Affected Zone	HAZ	Bx2B	T-T	10	0.20	M	Nil
003:Heat Affected Zone	HAZ	Bx2B	T-T	10	0.22	M	Nil

**Table 7 - Results from Mechanical Testing of Pipe Material**

Sample	Yield (psi)	Tensile (psi)	Elongation (%)
Up-stream	52,600	82,000	29
Down-stream	56,500	80,400	33
API 5L minimum requirements	52,000 min.	66,000 min.	25 min.

**Table 8 - Values for the Axial Stress that Causes Failure of the Pipeline**  
(ID, Circumferential Surface Cracks)

Crack Length inches	Crack Depth inches	Residual Stress=17.3 ksi	Residual Stress=52 ksi
2 inches	0.06	60 ksi	53 ksi
	0.07	58	50
	0.08	56	48
	0.09	55	45
	0.1	54	43
	0.11	53	41
	0.12	51	39
	0.13	50	37
	0.14	49	34
20 inches	0.06	56 ksi	49 ksi
	0.07	54	46
	0.08	52	43
	0.09	50	39
	0.1	48	36
	0.11	46	32
	0.12	44	29
	0.13	42	25
	0.14	40	20

Note: The values in **bold** correspond to data for the actual measured lack of fusion at the root of the weld.