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EVALUATING THE EFFECTS OF OVALITY ON THE INTEGRITY OF PIPE BENDS

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ABSTRACT

This paper provides details on a study performed for a liquids pipeline operator to evaluate the effects of ovality on the mechanical integrity of pipe bends in their 16-inch pipe system. Prior to this study, a caliper tool was run that indicated unacceptable ovality was present in the bends relative to the requirements set forth in ASME B31.4. An engineering investigation was performed based on the methodology of API 579 Fitness for Service. This standard provides guidance on evaluating defects using a multi-level assessment approach (Levels 1, 2, and 3) that rewards rigorous evaluation efforts by reducing the required design margins. Therefore, an extensive evaluation was performed that involved making field measurements of the bends in the ditch. Using these ovality measurements, calculations were performed using the closed-form equations in API 579 for Level 2 assessment. The ovality of several of the bends in the field was deemed unacceptable based on in-field measurements. Consequently, a Level 3 assessment was completed using finite element analysis (FEA). The results of this more rigorous analysis, coupled with more favorable design margins, resulted in this particular bend being acceptable. A tool was developed to permit a general assessment of pipe bends having ovality and was validated by performing a full-scale burst test.

INTRODUCTION

An assessment was performed to evaluate the effects of ovality on the mechanical integrity of bends used in the 16-inch pipeline system. The impetus for the study was geometry data collected by an in-line inspection caliper run that indicated the presence of unacceptable levels of ovality in the 5Ds induction bends in the pipeline. The first assessment activity included making in-field measurements of the bends. The measured data were used as input for a series of calculations based on Level 2 closed-form solutions provided in the API 579 Fitness for Service document.

While two of the five measured bends were classified as acceptable per the API 579 Level 2 assessment, the other three measurements required a Level 3 assessment using finite element analysis. With the more rigorous Level 3 assessment, the remaining three bends were classified as acceptable. Confident in the approach employed using guidance from API 579, a generic tool was developed to permit evaluation of ovality in the 5D 16-inch x 0.375-inch, Grade X52 bends. Integration of this tool in the pipeline company's integrity management program alleviates the need for performing individual assessments of future measured bends due to the general nature of the tool.

The subsequent sections of this paper provide details on the following subjects:

- Field measurements and how data were collected for input into the Level 2 and 3 assessments.
- Details on the Level 2 assessment including the development of a MathCAD sheet specifically designed to integrate the API 579 closed-form equations for ovality assessment.
- Background on the initial finite element model constructed to evaluate bends that had significant ovality (i.e. 10.9%) that required a Level 3 FEA.
- Discussions on the development of a generic ovality assessment tool, integrating both the maximum ovality and ovality ratio relating ovality at the center to the ends of the bend.
- Results associated with full-scale burst testing of the 45 degree 5D pipe bend removed service.
- Metallurgical investigation of the failure.
- Closing sections including Discussion and Conclusions that provide general assessments of the study's results and findings relative to the pipeline company's integrity management program.

FIELD MEASUREMENTS

Prior to making the field measurements, the details provided in API 579 on evaluating ovality were reviewed. From what was observed in API 579, it was obvious that a minimum of 24 diameter measurements were required, or a measurement every 15 degrees circumferentially. Additionally, API 579 indicated that the measurements should evaluate how the ovality changed as one moved along the axis of the pipeline. In other words, how did the ovality change relative to the center of the bend, as opposed to the ends of the bend? As a result, five (5) sets of diameter measurements were made for every bend. These measurements were spaced evenly along the axis, or length, of the bend.

Figure 1 shows the data sheet that was used to record the following information:

- Pipe diameters at specified locations
- Wall thickness measurements made using a hand-held UT meter
- Length of extrados
- Chord measurements for determining degree of bend using geometric and trigonometric relations.

Figure 2 shows pipe diameter measurements being made on one of the pipe bends.

API 579 LEVEL 2 ASSESSMENT (CLOSED-FORM)

In evaluating the effects of ovality on the mechanical integrity of the 5D bends, the API 579 document was used. Part 8, *Assessment of Weld Misalignment and Shell Distortion*, was used from API 579. Listed below are sections on how this chapter from API 579 was used to conduct the three levels of assessment.

Background

Per Section 8.2.5.1 of API 579, Level 1 assessment procedures are based on the criteria in the original construction code (e.g. ASME B31.4 for the problem at hand). If these criteria are not completely defined by the original construction code and are not in the original owner-user design specification, a Level 2 or Level 3 assessment may be performed. Level 1 Assessment procedures should not be used if the component is in cyclic service.

API 579 provides a comprehensive series of equations for conducting the Level 2 assessment that can be programmed into a tool such as MathCAD. A Level 3 assessment may be performed where the Level 1 and 2 methods do not generate acceptable operating or design conditions. There are no guarantees that a Level 3 assessment will generate acceptable design conditions; however, API 579 rewards the more rigorous efforts associated with a Level 3 assessment by reducing the design margins in comparison to the Levels 1 and 2 assessment methods. For the discussion at hand, a non-linear stress analysis was utilized to perform the Level 3 assessment (cf. API 359 Section 8.4.4.3). Details on the stress analysis conducted using finite element methods are provided in a following section of this paper.

API 579 Level 2 Assessment Results

Measurements were made on bends in the field and used as input into the Level 2 MathCAD spreadsheet. An example output of the calculations performed using the November 2007 Dig #2 bend measurements are provided in Figure 3 and 4. Of the three bends that were measured in November 2007, two of the three bends passed the Level 2 assessment; however, the Remaining Strength Factor (RSF) for Dig #1 was deemed unacceptable. As a result, this particular bend required that a Level 3 assessment be performed.

Comments on the API 579 Level 2 Assessment Efforts

After the first round of analyses using the Level 2 assessment tool was completed, it was apparent that due to the design limits associated with this assessment level, that some of the measured bends had ovality levels that required the completion of a finite element based Level 3 assessment.

API 579 LEVEL 3 ASSESSMENT (FINITE ELEMENT)

The finite element analysis work served a critical role in the evaluating the integrity of the pipe bends. As discussed previously, the API 579 Level 2 assessment utilizes a series of closed-form equations based on shell theory. One of the original three digs had ovality levels that were identified as unacceptable according to the Level 2 calculations. As a result, a Level 3 evaluation was conducted using finite element methods. Once this work was done, It was suggested that a series of finite element models be parametrically analyzed for the purpose of developing a generic tool for evaluating a range of ovality levels for the 16-nch diameter pipeline. The concept behind this approach was that once this tool was developed, the pipeline company could perform assessments as required and not require a Level 3 finite element model for every conceivable ovality condition.

The follow sections of this paper provide details on the finite element modeling effort that was conducted to develop the general-purpose ovality tool. A subsequent section, *Development of the Ovality Assessment Tool*, specifically discusses the tool and its use. The ABAQUS version 6.5 general-purpose finite element code was used for all analysis work.

Local and Global Finite Element Models

Ovality levels measured for Digs #2 and #3 were deemed acceptable per the API 579 Level 2 assessment procedure; however, Dig #1 had significant ovality (10.9%) that required an evaluation using Level 3 assessment methods. The Dig #1 bend was evaluated using FEA with elastic-plastic material properties. A detailed finite element model of the Dig #1 5D bend was made using the field measurements. The sections that follow provide details on the analysis methods and results associated with the first round of analysis work.

Results are presented for the following finite element models:

- Global finite element model considering pressure and thermal loads
- Local finite element model used to capture stresses in bend considering pressure and loading from global FEA model
- Parametric FEA model results used to generate the ovality assessment tool.

Global Finite Element Model

The global finite element model was used to compute stresses generated during the normal operation of the pipeline, as well as determining forces and moments imparted to the pipe bend locally. The model considered an internal pressure of 1,400 psi, an operating temperature of 160°F (temperature differential of 90°F relative to assumed ambient conditions of 70°F), and buried pipe conditions with soil spring constants of 500 lbs per inch per linear inch.

Figure 5 shows the von Mises stress distribution considering both internal pressure and temperature loads. As noted, the maximum von Mises stress is 42.1 ksi. An additional series of models were analyzed by separating (i.e. de-coupling) the effects of temperature and pressure. The maximum axial stresses calculated for the pressure-only and temperature-only cases were 14.7 ksi and 21.2 ksi, respectively. The results for this set of analyses are shown in Figure 6. It should be noted that all calculated stresses are based on elastic material properties. For the global model no attempt was made to integrate plasticity, although as one can see all of the calculated stresses are below the specified minimum yield strength of 52 ksi for the Grade X52 pipe material, so there is no reason to account for plasticity. Table 1 provides the forces and moments that were extracted from the global FEA model and used as input into the local shell model.

Local Finite Element Model

The geometry for Dig #1 (November 2007) was used to create the geometry for the local finite element model. Loading included internal pressure on the internal surface of the shell elements, as well as load calculated from the global FEA model (and presented previously in Table 1). A uniform wall thickness of 0.340 inches was used in the model.

Figure 7 and Figure 8 are contour plots showing the von Mises stresses and maximum principal strains at design conditions, respectively. Of particular note is the fact that the maximum stress and strain occur at the intrados[1] of the bend. This is consistent with equations based on the Lorentz formulation that demonstrate that the maximum and minimum stress states occur at the intrados and extrados of a bend, respectively. Another observation, although not integrated into this particular model, is that the thinner section of a

[1] The *intrados* is the inside arc of the bend, while the *extrados* is the outside arc.

bend typically occurs on the extrados due to thinning during forming. Due to the localized thinning, it is likely that this section of the bend will have the maximum stress, an observation that was confirmed by the full-scale burst test performed for this study. In terms of determining what impact wall thinning has on the pressure capacity of a bend, the change in failure pressure is directly related to variations in wall thickness can be used for estimation purposes. As the wall thickness is decreased, the pressure capacity of the bend can be expected to decrease as well.

Parametric Finite Element Model

Once the global and local finite element models were analyzed, a parametric study was performed to evaluate the pressure capacity of bends having a range of ovality levels. The intent in conducting the parametric study was development of the general ovality assessment tool. While greater details on this tool are provided in the following section, *Development of the Ovality Assessment Tool*, the intent in this discussion is to provide technical details on the analysis models that were used.

Provided in Table 2 is the matrix of load cases that were included in the parametric study. Figure 9 accompanies this table in providing details on the referenced geometry. Of particular note are the following variable ranges:

- Center ovality from 0.0 to 25.0 percent
- Ovality ratios ranging from 1.0 to 5.0 where this ratio corresponds to the center ovality divided by the ovality at the ends of the bend

DEVELOPMENT OF THE OVALITY ASSESSMENT TOOL

An ovality calculator was developed using finite element models. The purpose of this calculator was to take the field measurements from each pipeline bend and provide the design pressure based on the finite element calculated plastic analysis collapse load. Provided below is a brief description on how the tool was developed and how it is used to calculate a design pressure for a given ovality level.

Development of the Ovality Calculator

Based on the range of measurements made of the bends, finite element models were fabricated that included ovality levels at the center of the bends ranging from 0 to 25 percent. An additional expression was also considered, hereafter referred to as the *ovality ratio*. The ovality ratio is an expression calculated by dividing the <u>ovality at any given location</u> (typically at the ends) along the length of the bend by the <u>ovality at the center</u> of the bends. The range of ovality ratios considered in this study is from 1.0 to 5.0. A total of 16 finite element models were constructed in order to integrate the range of center ovality levels and the ovality ratios at the ends of the bend. From these models 16 different collapse loads were calculated that were each multiplied by the 0.6 design margin to calculate the respective design pressures.

To develop a calculator for calculating design pressure as a function of both center ovality and the ovality ratio at the ends of the bend, numerical curve fit expressions were generated as shown in Figure 10. An interpolation scheme was then generated to permit the calculation of a single design pressure value for any combination of center ovality and ovality ratio.

Using the mathematical expressions displayed in Figure 10, an EXCEL spreadsheet was programmed to calculate a design pressure considering the following variables:

- Center ovality (percent)
- Ovality ratio on each end of bend (non-dimensional)
- Actual yield strength of pipe material (psi)

The final design pressure is calculated by averaging the design pressures on each end of the bend. The effects of other factors not considered here that could increase design pressure include:

- Increase in yield strength
- Increasing wall thickness at intrados from 0.340 inches to 0.420 inches
- Increasing wall thickness of overall bend from 0.340 inches to 0.430 inches

An increase in each of these factors will act to increase the design pressure.

Listed below are the basic steps involved in using the ovality assessment tool once actual field measurements have been made.

1. Calculate ovality at center of pipe bend $(D_{max} – D_{min}) / D_{nom}$
2. Calculate ovality at both ends at the tangent lines
3. Calculate the ovality ratio (OR) for both ends of the bend
4. Use the FEA-based chart to determine the Lower Bound Collapse Load (LBCL) from the ovality measurements at both ends
5. Determine, based on the desired level of conservatism, the final LBCL
    a. Maximum OR
    b. Minimum OR
    c. Average of the above two
6. Calculate the Design Pressure as 0.6*LBCL

The programmed EXCEL spreadsheet automates Steps #4 through #6, generating a single design pressure for the pipe bend.

Example Problem Using the Ovality Calculator

An example problem is provided using the ovality calculator. The following input data were used in calculating the design pressure for a 16-inch x 0.340-inch, Grade X52 pipe bend:

- Center ovality of 11.3 percent
- Ovality ratio on end A of the bend: 7.23
- Ovality ratio on end B of the bend: 1.61
- Yield strength of 52,000 psi

Figure 11 shows the EXCEL sheet used to compute the design stress for this particular bend seen in the field. As noted in this figure, the relative severity of the ovality limits the design pressure to 1,427 psi. Also presented in this figure is the 72% SMYS pressure of 1,591 psi (MOP, where MOP is defined as 72% SMYS for a liquid pipeline). The design pressure of 1,427 psi is only 90% MOP for this particular pipe, and therefore this ovality level would be deemed unacceptable if the operator wanted to continue operation based on the methods presented in this study.

TEST METHODS AND RESULTS

A full-scale burst test was performed using a 45 degree 5D bend removed from the 16-inch NPS pipeline. The sections that follow provide details on the test set-up and results obtained during the burst test.

Sample Preparation

The test sample was a 16-inch OD x 0.375-inch w.t., Grade X52 45 degree 5D bend. Before testing, measurements were taken. Several noteworthy observations are made in viewing the measured data:

- The calculated ovality at the center of the bend was 3.04 percent ((D_{max} – D_{min}) / D_{nom}). It is likely that in the field the actual ovality would be greater than this value due to compression loads generated by lateral expansion of the pipe due to the elevated operating temperatures.
- The maximum and minimum ovality ratios at the ends of the bend using the measured data are 4.61 and 2.75, respectively.
- It is clear from the wall thickness measurements that the process of induction bending the pipe caused increased and decreased thicknesses at the intrados and extrados, respectively. Of particular note is the thinnest wall measurement of 0.331 inches measured at the center of the bend at the intrados. This value is 88.3 percent of the nominal 0.375 inch wall thickness.

End caps were welded to the sample and strain gages were applied to the sample at the designated locations. Bi-axial strain gages were used to measure hoop and axial strain during the test. The sample was then placed in the burst pit and the pressure lines and instrumentation were connected.

Test Results

The pipe failed at an internal pressure of 3,513 psi in the center of the bend at the extrados. Hoop and axial strains were measured during testing using strain gages (data not included in this paper). A close-up photograph of the burst failure is shown in Figure 12. The calculated circumferential failure strain in the pipe was 7.4% based on post-failure measurement of the circumferential elongation at the *fish mouth* opening.

The failure occurred on the extrados of the bend in the approximate center of the fitting along its radius. The wall thickness of the bend was measured prior to testing and the minimum value was 0.331 inches and observed along the extrados of the bend. The burst formed a longitudinal ductile tear with a typical "fish mouth" shape. Closer examination of the fracture following burst testing showed that there was a significant reduction in the wall thickness, or necking, along the fracture due to yielding as shown in Figure 13. The center of the fracture alternated between shear and a cup-and-cone fracture that formed a saw tooth shaped edge. There was no sign of any imperfections seen along the fracture. The fracture propagated as tearing shear from the ends, in both directions, of the overload section and then terminated.

DISCUSSION

One of the primary purposes of conducting the full-scale burst test was to validate the numerical models and specifically the ovality assessment tool that was developed. The test sample burst at a pressure of 3,513 psi. If this burst pressure value is multiplied by 0.6, the safe design pressure based on full-scale testing is 2,107 psi. Using the measurements taken from the burst test sample prior to failure, the ovality calculator shows a safe design pressure 2,063 psi. These calculated values are within 2 percent of one another, confirming that the ovality assessment tool is functioning as intended. The other important point from this correlation is that the ovality present in the burst sample did not pose a serious integrity threat to the pipeline system of which it is a part.

Another point of discussion concerns the effects of altering different variables on the plastic collapse pressure for the pipe bend. If one considers the geometry associated with Dig #1 (November 2007) and a uniform wall thickness in the bend of 0.340 inches, the following variables alter the calculated limit load pressures as noted. Included in parentheses are either the reductions or increases in collapse pressure. These results are provided graphically in the bar chart shown in Figure 14. Note that collapse pressure used in this context is not collapse due to external pressure, but failure due to plastic overload caused by increased pressure (i.e. burst pressure of the bend).

- Original pipe bend geometry: 2,553 psi
- With capped end pressure end load: 2,081 psi (0.82)
- Thicker intrados of 0.420 inches: 2,872 psi (1.12)
- Thicker pipe bend thickness of 0.430 inches: 3,466 psi (1.35)
- Addition of composite material (0.50 inches): 4,552 psi (1.78)

The design pressures for each respective case are calculated by multiplying the above values by the 0.60 design margin.

CONCLUSIONS

This paper has provided detailed documentation on a study conducted to evaluate the effects of ovality on the integrity of pipe bends. Measurements were made on five (5) individual bend locations. Actual field measurements were used to perform calculations to determine if any loss of integrity existed due to ovality on the bends.

The basis of the evaluation was the API 579 Fitness for Service document that has a specific section with guidance for evaluating ovality in a pipe bends. While several of the bends could be evaluated using the closed-form equations provided as part of the API 579 Level 2 assessment, some of the bends have greater ovality required a more rigorous evaluation, Level 3, involving finite element analysis. Due to the potential for having to individually evaluate the ovality levels in numerous bends, a series of parametric FEA models were analyzed for the purpose of developing a general-purpose ovality assessment tool. This tool permitted the pipeline operator to evaluate ovality levels up to 25%, with a factor of 5 in differences of ovality between the center and ends of the bend.

A final phase of this program included a full-scale test of a bend removed from the field (16-inch x 0.375-inch, Grade X52 45° pipe bend). This line has a Maximum Operating Pressure (MOP) of 1,440 psi. End caps were welded to the pipe sample that was pressurized to burst where it failed at a pressure of 3,513 psi. This pressure level is 1.44 times the Specified Minimum Yield Strength (SMYS) pressure and 2.44 times the MOP. The design pressure determined for the tested pipe bend using the ovality assessment tool was within 2 percent of the design pressure based on the burst failure pressure of the test sample, confirming the validity of the ovality tool and the methodology used to develop it.

REFERENCES

[1] API 579-1 ASME FFS-1 2007 Fitness for Service (API 579 Second Edition), API/ASME Fitness-For-Service Joint Committee, The American Society of Mechanical Engineers, Three Park Avenue, New York.

[2] American Society of Mechanical Engineers, *Liquid Transportation System for* Hydrocarbons, *Liquid Petroleum Gas, Anhydrous Ammonia and Alcohols*, ASME B31.4, New York, New York, 2003 edition.

[3] Harvey, John F., *Theory and Design of Pressure Vessels* (Second Edition), Van Nostrand Reinhold, New York, 1991, pages 52-56.

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Date	
Location	
Crew members	

Pipe information including nominal diameter, wall thickness, grade, operating pressure, and type and degree of bend:

Outside Diameter (inches)	16					
Wall Thickness (inches)						
Measurement	**General**	**Location 1 (0.0L)**	**Location 2 (0.25L)**	**Location 3 (0.50L)**	**Location 4 (0.75L)**	**Location 5 (1.0L)**
General measurements						
Extradus Length, L						
Radii, R_n						
Chord length, C_{inside}						
Chord length, C_{mean}						
Chord length, $C_{outside}$						
Chord height, h						
Diameter measurements (inches)						
Diameter, 0 degrees						
Diameter, 15 degrees						
Diameter, 30 degrees						
Diameter, 45 degrees						
Diameter, 60 degrees						
Diameter, 75 degrees						
Diameter, 90 degrees						
Diameter, 105 degrees						
Diameter, 120 degrees						
Diameter, 135 degrees						
Diameter, 150 degrees						
Diameter, 165 degrees						
Ovality Level						
Ovality Ratio						
Wall thickness measurements						
Wall thickness, 0 degrees						
Wall thickness, 90 degrees						
Wall thickness, 180 degrees						
Wall thickness, 270 degrees						
Extra notes and comments						

Figure 1 – Project data sheet used for recording ovality in the field

Figure 2 – **Measuring diameter of bend using calipers**
(that this is done in two planes in order to locate the minimum radius in both planes)

8.4.3.3 Out of Roundnees - Cylindrical Shells and Pipe Elbows

STEP 1- Determine values for the following variables based on the type of out-of-roundness:

$\theta := 0 \cdot deg$	Angle for the major axis of out-of-round to where the stress is computed
$C_s := 0.5$	factor to account for the severity of the out-of-roundness, use Cs=0.5 for a purely oval shape Cs=0.1 for shapes which significantly deviate from an oval shape.
$D_m := 16 \cdot in$	mean diameter
$D_o := 16 \cdot in$	outside diameter of pipe bend corrected for LOSS and FCA as applicable
$D_{max} := 16.1875 in$	maximum [pipe] outside diameter corrected for LOSS and FCA as applicable
$D_{min} := 15.563 in$	minimum [pipe] outside diameter corrected for LOSS and FCA as applicable
$E_y := 28 \times 10^6 \cdot psi$	Young's modulus
$FCA := 0.0 \cdot in$	Future corrosion allowance
$LOSS := 0.0 \cdot in$	amount of uniform metal loss away from the local metal loss location at thetime of the assessment.
$t_{nom} := .500 in$	nonimal or furnished thickness of the component adjusted for mill undertolerance as applicable.
$t_{rd} := .500 in$	uniform thickness away from the local metal loss location established by thickness measurements at the time of assessment.
$\upsilon := 0.3$	Poisson ratio
$L_f := 1.00$	Lozentz factor (Annex A, paragraph, A.5.5.)
$P := 1440 psi$	Internal or external design pressure
$SMYS := 52000 psi$	Pipe yield strength
$f_{wm} := 0.2$	Weld misalignment factor
$f_d := 0.72$	Design factor
$RSF_a := 0.9$	Allowable remaining strenght factor from Table 2.3 - Recommended Allowable Remaining Strength Factor Based on the Design Code
$S_a := f_d \cdot SMYS$	Allowable stress
$H_f := 1.5$	Factor dependant on whether the induced stress from the shape deviation is categorized as a primary or secondary stress (see Annex B1); Hf = 3.0 if the stress is secondary and Hf = 1.5 if the stress is primary.

Figure 3 – Page 1 of the Level 2 assessment sheet for Dig #2

STEP 2- Determine the wall thickness to be used in the assessment

$t_c := t_{rd} - FCA$ $\qquad$ $t_c = 0.5in$

STEP 3- Determine the circumferential membrane stress using the thickness from STEP 2

$Y_{B31} := 0.4$ $\qquad$ (Section A.8 Nomenclature)

$E := 1.0$ $\qquad$ Weld joint efficiency

This calculation based on methods outlined in Section A.5.5 - Pipe Bends Subject to Internal Pressure.

$$\sigma_m := \frac{P \cdot L_f}{E} \cdot \left(\frac{D_m}{2 \cdot t_c} - Y_{B31} \right) \qquad \sigma_m = 22464psi$$

STEP 4- Determine the ratio of the induced circumferential bending stress to the circumferen membrane stress at the circumferential position of interest (max value at $\theta = 0, \pi/2$)

Note: The ovality of this field bend is considered "Global" as the ovality at the ends of the bend are at least equal to 50% of the mid-elbow (or mid-bend) region. For conservatism, the maximum level of ovality, which happened to occur in the bend, is used in the calculation.

4) Global Out-Of-Roundness Of an Elbow Or Pipe Bend (no limitation on bend radius)

$$R := \frac{D_m - t_c}{2}$$

R is the mean radius of the cylinder (mid-wall)

$$R_b := \frac{\frac{3 \cdot R \cdot \cos(2 \cdot \theta)}{t_c \cdot L_f} \cdot \left(\frac{D_{max} - D_{min}}{D_o} \right)}{1 + 3.64 \left(\frac{P \cdot R}{E_y \cdot t_c} \right) \cdot \left(\frac{R}{t_c} \right)^2}$$

$$Ovality := \frac{D_{max} - D_{min}}{D_o}$$

$Ovality = 3.903\%$

STEP 5- Determine the remaining strength factor

$R_{bs} := R_b$ $\qquad$ $\sigma_{ms} := f_{wm} \cdot \sigma_m$

$$RSF := \min\left[\left[\frac{H_f \cdot S_a}{\sigma_m \cdot (1 + R_b) + \sigma_{ms} \cdot (1 + R_{bs})} \right], 1.0 \right]$$

$RSF = 1$

STEP 6- Evaluate the results by comparing RSF to RSF_a (RSF_a = 0.9 per Table 2.3)

Summary := if[[((RSF < RSF_a))], "UNACCEPTABLE", "Acceptable per Level 2"]

Summary = "Acceptable per Level 2"

Figure 4 – Page 2 of the Level 2 assessment sheet for Dig #2

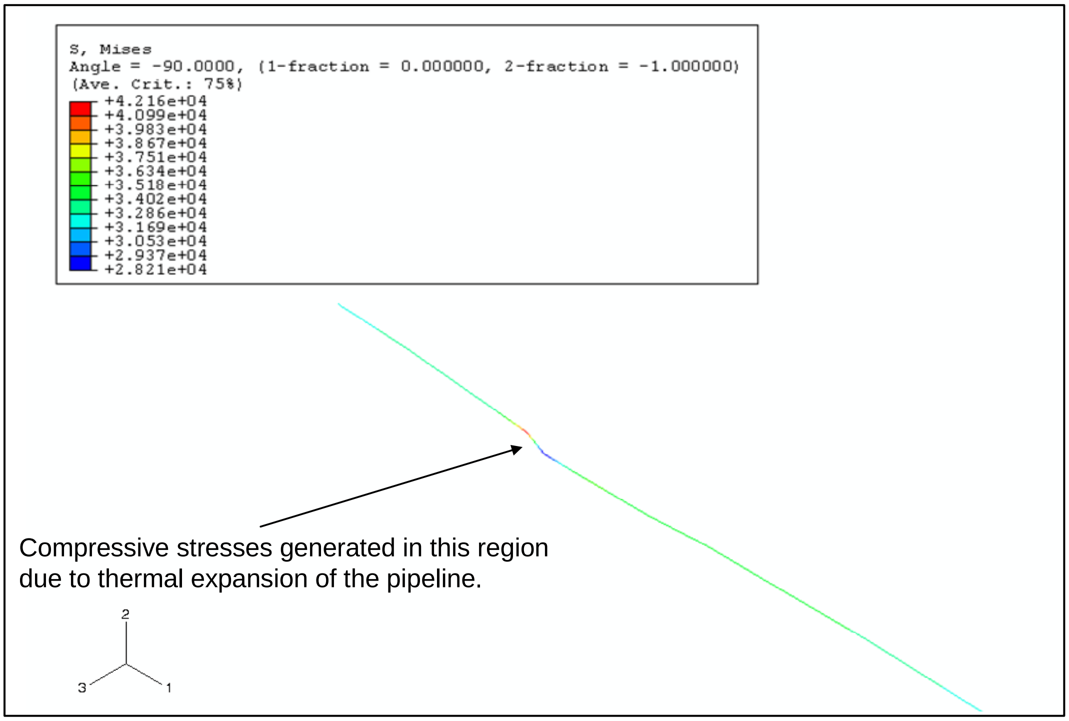
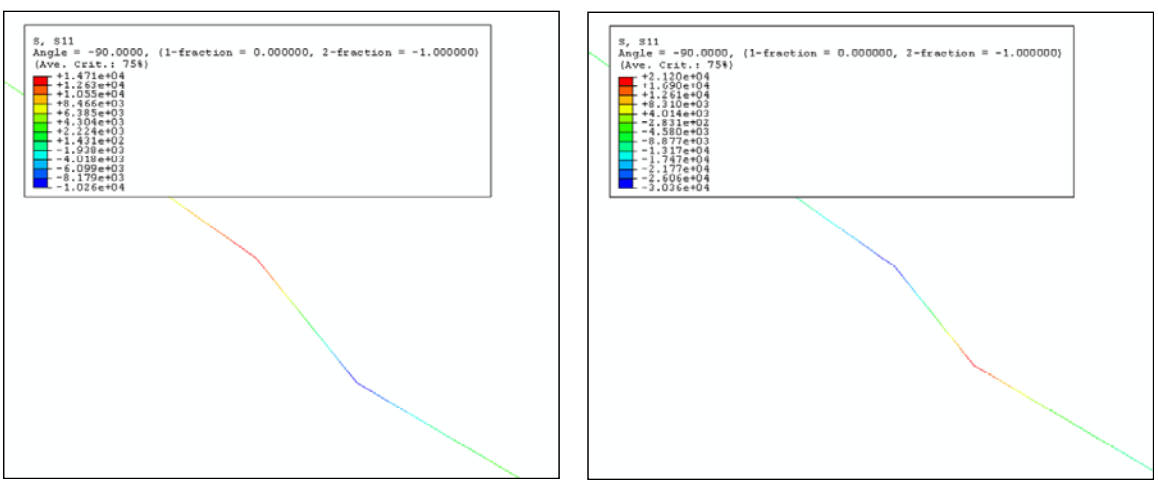


Figure 5 – von Mises stress in global model considering all loads



Axial Stress for Pressure Only Load Case
$S11_{max}$ = 14.7 ksi

Axial Stress for Temperature Only Load Case
$S11_{max}$ = 21.2 ksi

Figure 6 – Axial stresses in global model considering independent loading

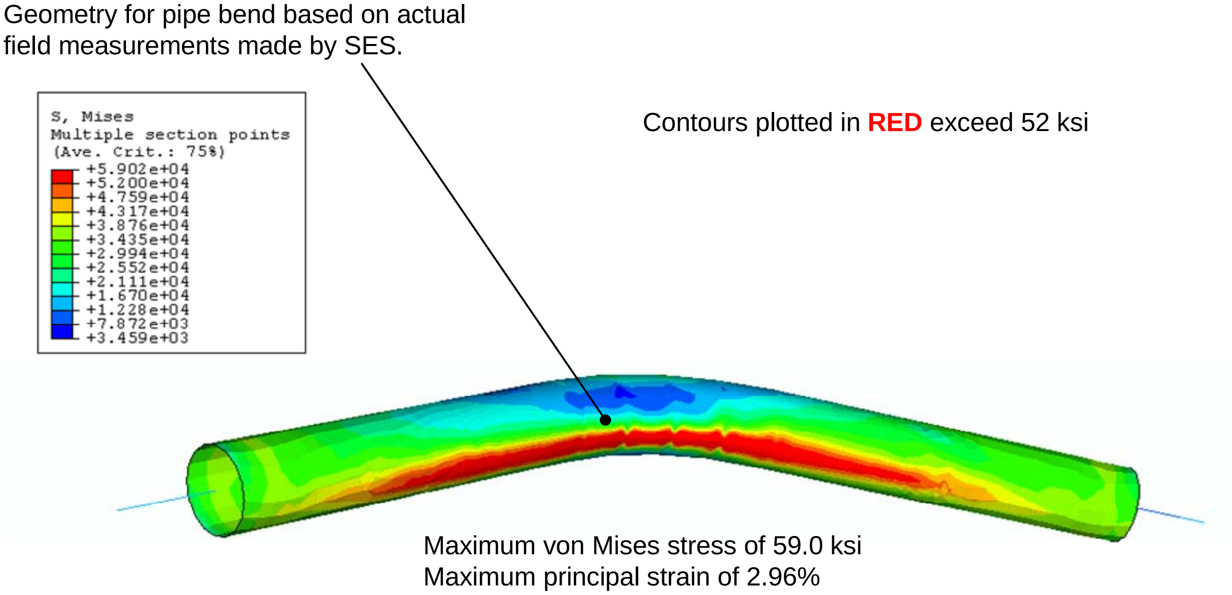


Figure 7 – Von Mises stress state at design conditions (1,440 psi and 160F)

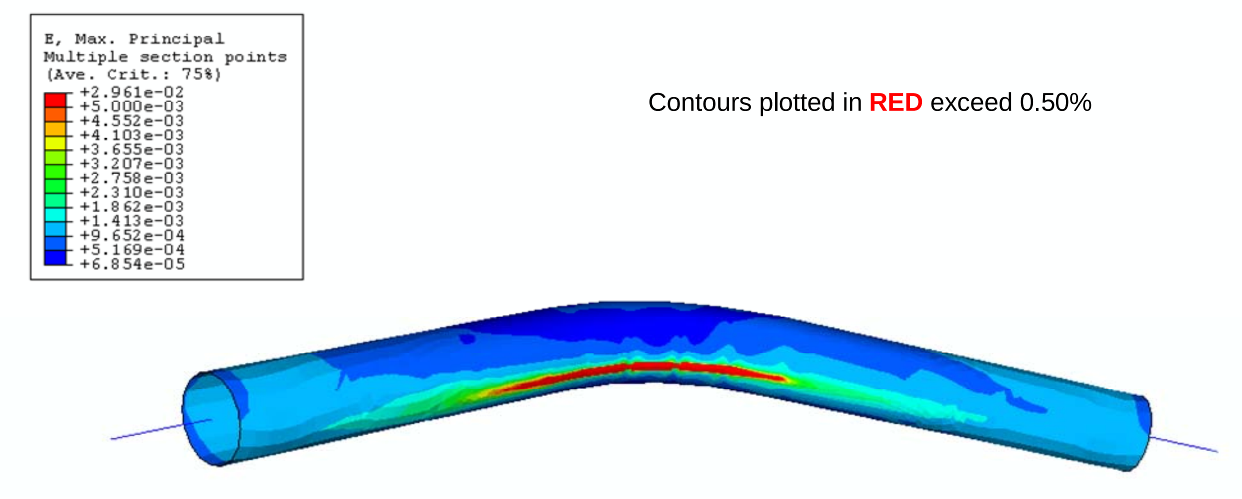
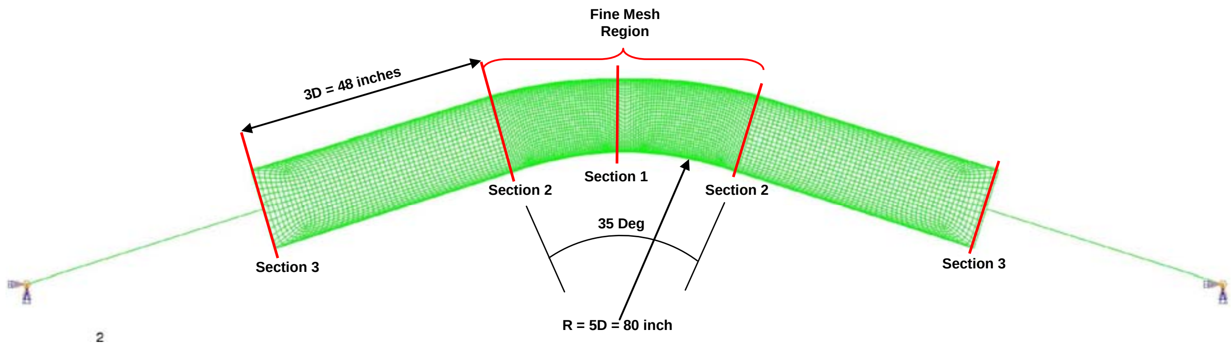


Figure 8 – Maximum principal strain at design conditions (1,440 psi and 160F)



Section 1 = Highest Ovality Section

Section 2 = Ovality defined by Ovality Ratio

Section 3 = Ovality of 1% (for smooth transition of ovality)

Ovality = $(D_{max} - D_{min}) / D_{nominal}$

Ovality Ratio = Ovality at Section 1 / Ovality at Section 2

Figure 9 – Figure for Table 2 showing parametric FEA geometries

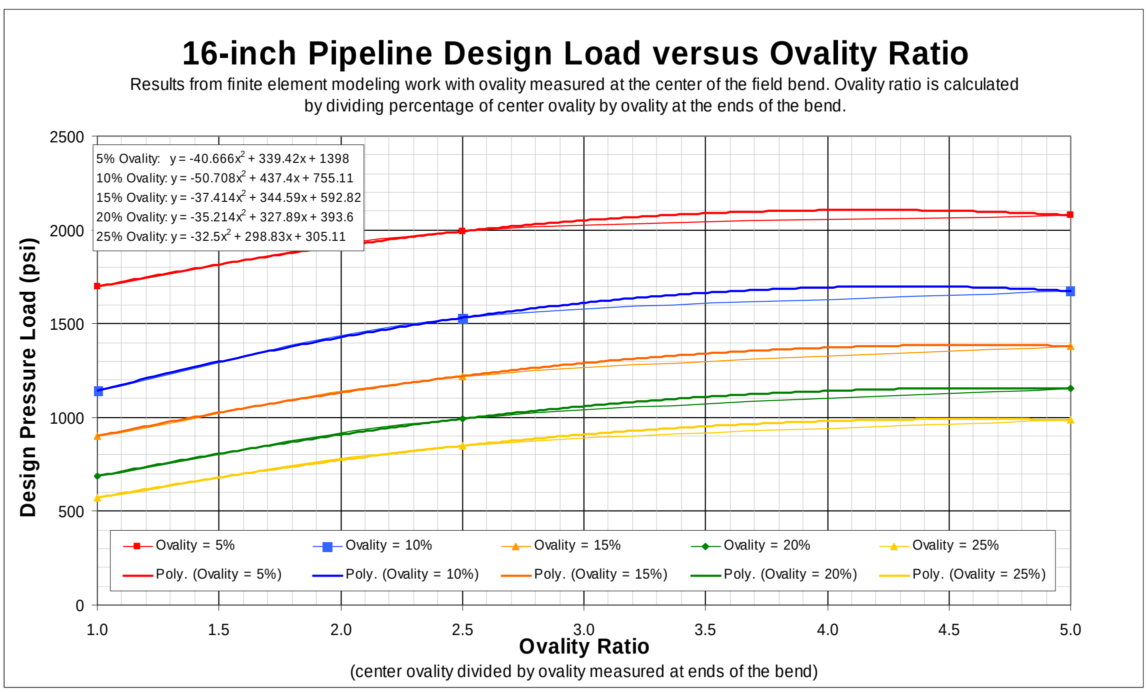


Figure 10 – Curve fits and equations for the design pressure curves
(colored curves represent ovality measured at center of bend, design margin of 0.6 included)

Center Ovality:	11.3	percent
Ovality Ratio A:	7.23	*(Does not use values greater than 5 or less than 1)*
Ovality Ratio B:	1.61	*(Does not use values greater than 5 or less than 1)*
Yield Strength	52,000	psi (model based on Grade X52 pipe)

Calculations for End A (uses Ovality Ratio A)

Center Ovality	x^2	x^1	x^0	P_{below}	P_{above}	P_{design}
0	-40.662	339.42	1398	2078.6	2079	0.0
5	-40.662	339.42	1398	1674.4	2079	0.0
10	-50.708	437.4	755.11	1380.4	1674	1598.0
15	-37.414	344.59	592.82	1152.7	1380	0.0
20	-35.214	327.89	393.6	986.8	1153	0.0
25	-32.5	298.83	305.11	986.8	987	
				End A Design Pressure:	**1598**	**psi**

Calculations for End B (uses Ovality Ratio B)

Center Ovality	x^2	x^1	x^0	P_{below}	P_{above}	P_{design}
0	-40.662	339.42	1398	1839.1	1839	0.0
5	-40.662	339.42	1398	1327.9	1839	0.0
10	-50.708	437.4	755.11	1050.6	1328	1255.8
15	-37.414	344.59	592.82	830.2	1051	0.0
20	-35.214	327.89	393.6	702.0	830	0.0
25	-32.5	298.83	305.11	702.0	702	
				End B Design Pressure:	**1256**	**psi**

Designated Design Pressure: 1427 psi

(based on average of ends A and B)

Other considerations that will modify the Design Pressure		
Effect of Yield Strength	1427	psi
Addition of 0.50-inch Armor Plate Pipe Wrap	2544	psi
Intrados thickness of 0.420 inches	1605	psi
Field bend thickness of 0.430 inches	1937	psi
SMYS for 16-inch x 0.340, Grade X52 pipe	2210	psi
72% SMYS for 16-inch x 0.340, Grade X52 pipe	1591	psi

Note: Default model has a thickness of 0.340 inches

Figure 11 – EXCEL spreadsheet ovality calculator with input and output data

Figure 12 – Close-up photograph of burst failure

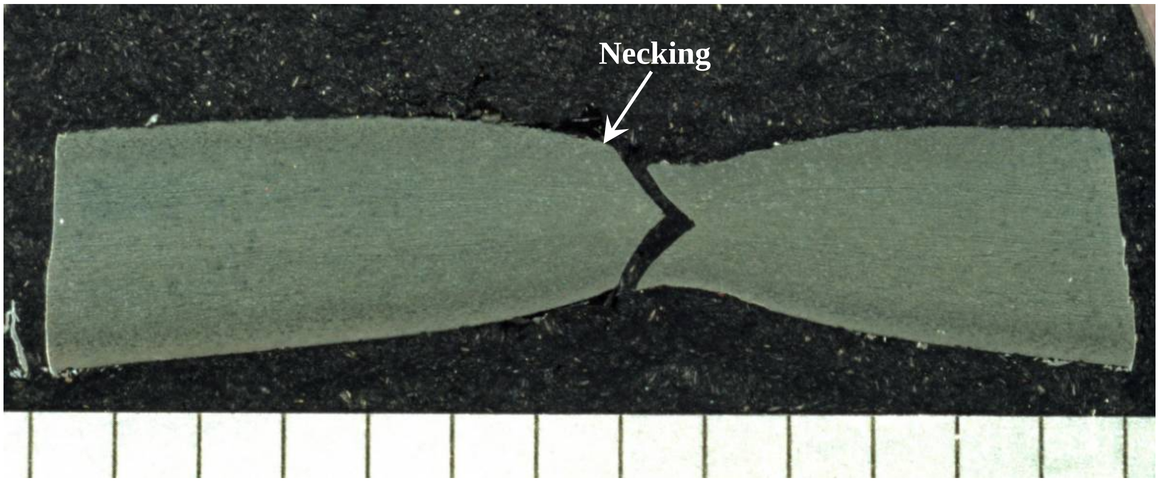


Figure 13 – Photomacrograph of the ductile overload cross-section.
Image shows reduction of cross-section where necking is clearly observed.
Scale divisions are 1/10 inches.

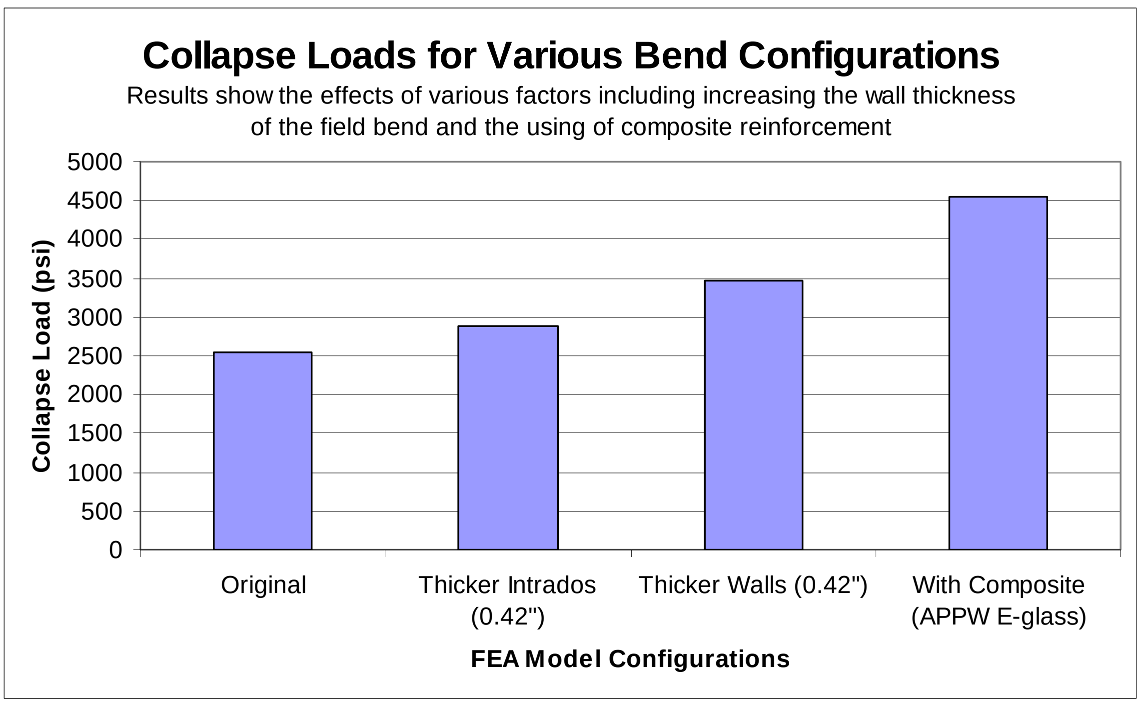


Figure 14 – Effects of different variables on the bend collapse pressure

Table 1 – Global reaction forces and moments

Load	Upstream Node	Downstream Node
FX	-112,579 lbs	-102,522 lbs
FY	12,234 lbs	-51,701 lbs
FZ	-4,314 lbs	9,900 lbs
MX	1,332,070 in-lbs	-1,771,070 in-lbs
MY	346,083 in-lbs	-287,103 in-lbs
MZ	-453 in-lbs	-5,402 in-lbs

Table 2 – Matrix of load cases for parametric FEA study

Ovality	Ovality Ratio (OR)	Section1 (center)	Section2 (Offset to Center)	Section3 (1% ovality at Extreme Ends)
		% Ovality	% Ovality	% Ovality
0	1	0.0	0.0	0.0
5	1	5.0	5.0	1.0
10	1	10.0	10.0	1.0
15	1	15.0	15.0	1.0
20	1	20.0	20.0	1.0
25	1	25.0	25.0	1.0
5	2.5	5.0	2.0	1.0
10	2.5	10.0	4.0	1.0
15	2.5	15.0	6.0	1.0
20	2.5	20.0	8.0	1.0
25	2.5	25.0	10.0	1.0
5	5	5.0	1.0	1.0
10	5	10.0	2.0	1.0
15	5	15.0	3.0	1.0
20	5	20.0	4.0	1.0
25	5	25.0	5.0	1.0