

A SYSTEMATIC APPROACH FOR EVALUATING DENT SEVERITY IN A LIQUID TRANSMISSION PIPELINE SYSTEM

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ABSTRACT

An API 579 Level 3 assessment was performed to determine the stresses in a 2% dent in a 20-inch x 0.406-inch pipeline. The intent was to determine the stress concentration factor (SCF) in the dent with a finite element model using geometry data provided from an in-line inspection caliper run. In addition to the analytically-derived SCF, data were also evaluated from a recent experimental study involving a plain dent subjected to cyclic pressure conditions with a profile comparable to the dent in question. This sample was cycled at a stress range of 70% SMYS and failed after 10,163 cycles had been applied. Using the DOE-B mean fatigue curve, combined with the experimental fatigue life, the resulting SCF factor was derived to be 4.20. This value is within 1% of the calculated FEA-based SCF and served to confirm the technical validity of the SCF. The operator provided historical pressure data covering a 12-month period and a rainflow count analysis was performed on the data. Using this data, along with the API X' design fatigue curve, the estimated remaining life was determined for the dent in question and conservatively estimated to be 65 years. This paper provides details on the analysis methodology and associated results, discussions on the empirically-derived SCF with its use in validating the analytical SCF, and application of the results to estimate the remaining life of the pipeline system. It is the intent of the authors to provide the pipeline industry with a systemic approach for evaluating dent severity using caliper and operating pressure history data.

INTRODUCTION

Today's in-line caliper inspection technology provides operators with relatively accurate data that can be used to evaluate the severity of geometrically-related anomalies such as dents, wrinkles, and ovality in pipelines bends. This data, when coupled with numerical analysis methods, can be used to calculate stresses considering loads such as internal pressure. A useful technique is to calculate SCFs for each anomaly detected by the ILI run. When this exercise is done for an entire pipeline system, the relative severity of the anomalies can be compared as an integral part of an integrity management program.

In addition to calculating stresses using numerical methods, numerous experimental studies have been conducted over the past 30 years with many of these focused on plain dents. An optimized solution is achieved when analytically-derived SCFs are validated using experimental results. This paper provides findings from a study conducted to perform a fitness for service assessment of a dented pipeline using actual in-line caliper inspection. An SCF was calculated for the dent and validated using results from a recent experimental study focused on determining the fatigue life of plain dents subjected to cyclic pressure conditions. This combination of analytically and experimentally-derived SCFs was used to estimate the remaining life

of the given dent using actual pressure data from the pipeline in question. The sections that follow provide details on the analysis methods and results that were achieved using the ILI data. Also included are the experimental findings from a recent dent study and the results of the fitness for service assessment.

ANALYSIS METHODS AND RESULTS

The primary focus of the study was to use finite element analysis (FEA) to evaluate the severity of the dent in question. This was accomplished by calculating a stress concentration factor that was then verified using recent experimental fatigue data. The sections that follow provide details on the FEA work as well as the validation effort using the empirically-derived SCF.

Finite Element Analysis

To construct the finite element model of the dented region, SES used geometry data provided from an in-line caliper tool inspection run with a portion of the file being shown in Figure 1. The basic features of the finite element model are listed below with the layout shown in Figure 2.

- Element dimensions are approximately 0.5-inch x 0.5-inch
- 31,560 nodes and 31,440 elements
- 20-inch OD x 0.406-inch wall thickness
- Pipe length modeled: 10.92 feet
- Elastic material properties
- Plane strain boundary conditions on ends of pipe (cf. Figure 3)
- Internal pressure of 406 psi applied to pipe to generate a nominal hoop stress of 10,000 psi

Figure 4 and Figure 5 are contour plots showing the maximum principal and von Mises stresses in the FEA model, respectively. Note that the calculated SCFs are 4.36 and 4.24 for these two stress state conditions, respectively. Figure 6 shows the maximum principal stress as a function of axial position.

Validating the SCF

After the finite element analysis was completed, empirical data acquired from a recent study involving plain dents was evaluated and compared to the FEA results. The intent was to extract stress intensity factors (SIF) from the experimental results and compare to the FEA-based SCFs. The dents are from a current PRCI study evaluating the fatigue life of plain dents, as well as dents in girth and seam welds. The dents of interest had an initial dent depth of 15% of the pipe's outside diameter and were introduced into 24-inch x 0.311-inch, Grade X52 pipe material.

The dents in this particular pipe material were cycled from 10% to 80% SMYS until failure occurred. This corresponds to a stress range of 36,400 psi. The profile of these experimental dents are compared to the actual 2% dent profile from the ILI data used in the FEA as shown in Figure 7. As noted, the curvature associated with the experimental dent profiles are more severe than the FEA data set. Also included in this figure are the cycles to failure and the calculated SIFs for each dent, as well as the final dent depths measured after the dents had been pressure cycled to failure. Note that the dent severity, which started out as 15% of the pipe's outer diameter, was eventually reduced to a level on the order of 2.65% at ambient pressure. This is typical for pipes having relatively large diameter to wall thickness (D/t) ratios (i.e. D/t ratios greater than 50).

Figure 8 provides two photographs taken after all testing had been completed and the dents had leaked. The center of each crack was located approximately 1.25 inches from the center of the dent. Interestingly, this location is very near the one-half dent depth region. In reviewing the data plotted in Figure 6, it is noted that the maximum principal stress at this location is 27.9 ksi, which corresponds to a stress concentration factor of 2.79. This value is confirmed by the empirically-derived SIFs using the cycles to failure and the DOE B-mean curve [1] that resulted in an average SIF of 2.50 for the six tested dents (cf. see data listed in Figure 7). Although Stress Engineering has performed numerous finite element studies that were validated using experimental results, with these six particular dents this was not done.

Consider the results for Sample #7 listed in Figure 7 that was cycled to failure with a pressure range from of 70% SMYS for 21,103 cycles before a failure developed in the form of a thru-wall longitudinally-oriented fatigue crack. Using this experimental fatigue cycle number and the applied nominal stress range, it is possible to calculate an SIF. Note once again that for this particular discuss the SCF is a value derived from analytical methods (e.g. finite element), while the SIF is an empirically-derived value based on experimental fatigue results.

From previous research the DOE-B mean fatigue curve has proved useful in estimating the experimental cycles to failure for dented pipes. Listed below are the specific steps involved in the calculation process used to determine the empirically-derived SIF including data for Sample #7 described above.

1. Use an S-N fatigue curve to determine the stress range for a specified number of cycles to failure. Equation 1 below uses the DOE-B curve to calculate the stress range for a given cycles to failure of 21,103 cycles. In this equation N is the number of cycles to failure and $\Delta\sigma$ is the stress range in units of ksi. In this problem the known is the cycle number and the unknown is the stress range (i.e. solve for the stress range).

$$N = 2.343E15 \cdot \left[\frac{\Delta\sigma}{0.145} \right]^{-4} \quad (1)$$

2. Using N equal to 21,103 from the fatigue test results, the resulting stress range is calculated to be 83.7 ksi by manipulating Equation 1 to solve for the stress range ($\Delta\sigma$) as shown below.

$$\Delta\sigma = 0.145 \cdot \ln \left(\left[\frac{N}{2.343E15} \right]^{1/4} \right) \quad (2)$$

3. Once the stress range is determined using Equation 2, the SIF for the dent is calculated by dividing the 83.7 ksi stress range by the hoop stress range of 36,400 psi (70% SMYS for Grade X52 pipe). The resulting SCF is 2.30.

As noted in the previous section, the SCF based on the FEA model was 4.36 (cf. maximum principal stress state). When one considers that the empirically-derived SIF for an equivalent dent depth was only 2.30, an adjustment to the analytically-derived value was in order. The solution was to evaluate the location where fatigue cracks initiate in actual plain dents. Experience has shown that fatigue cracks initiate on the shoulder of plain dents in a region nearest to the half-depth of the dent (as shown in Figure 8). Using the calculated maximum principal stresses from the FEA model at the dent half-depth (and location where the fatigue cracks are most likely to develop) the SCF is 2.79 as shown in Figure 6. As a point of reference, note that the average calculated SIF for all six dents in the PRCI study was 2.50 using the approach listed above.

The 2.50 SIF value is within approximately 10% of the calculated FEA-based SCF and serves to confirm the technical validity of the analytically-derived SCF at ½ the depth of the dent that was calculated using the actual dent geometry.

APPLICATION OF RESULTS

SES used the pressure cycle data to estimate the remaining life of the dented region of the pipeline. The CRUNCH software package [1] was used to perform a rainflow count analysis on the pressure spectrum. The purpose in completing this exercise is to convert the random pressure cycle data into a meaningful format that permits the generation of a single equivalent pressure cycle data value using Miner's Rule for an assumed pressure range. The steps involved in this process are as follows.

1. Use CRUNCH to convert the raw pressure spectrum data into a file format that counts the number of pressure cycles for a given set of pressure range bins (e.g. 25 psi, 75 psi, etc.). An example pressure data set id provided in Figure 9.
2. Use the pressure bin data calculated in Step #1 to make a histogram plot as shown in Figure 10.
3. Using Miner's Rule, calculate a single equivalent pressure cycle value for an assumed pressure range. Figure 11 shows results for the provided data set. As noted in this figure, the resulting number of cycles for a "mid range" selected pressure range of 350 psi was calculated to be 1,887 annual cycles assuming the 37day pressure profile. This selection of this pressure range is not critical to the calculated results, but is necessary to provide the Miner's Rule sum. In the spreadsheet shown in Figure 11 the number of design cycles remains similar, even when this pressure range is changed. Note that the exponent employed for the Miner's Rule sum is 3.74, which is the same value used in the API X' curve [3].
4. See the example equation provided below showing how Miner's Rule is used to combine numbers of pressure cycles for different pressure ranges as listed in Figure 11.

$$N_{350} = N_{25} \left[\frac{350 \text{ psi}}{25 \text{ psi}} \right]^{-3.74} + N_{75} \left[\frac{350 \text{ psi}}{75 \text{ psi}} \right]^{-3.74} + \dots \quad (3)$$

5. Using an assumed S-N design fatigue curve (e.g. the API X' curve used in this study), calculate the design cycles for the assumed pressure range (e.g. 350 psi) and the calculated dent

SCF (e.g. 2.79). Note that the SCF has been multiplied by the hoop stress range, which results in a single design fatigue life, which was 122,565 cycles considering the API X' design fatigue curve.

6. Using the calculated fatigue life results from Step #4 and the annual cycle count from Step #3, the estimated remaining design life in "years" of the pipeline can be calculated (e.g. 65 years in this particular case).

Figure 11 shows the difference in results between the design fatigue lives calculated using the API X' and the DOE-B curves. It is the authors' opinion that the DOE-B mean cycles to failure curve is well-suited for calculating empirical data (i.e. cycles to failure), while the design margin associated with the API X' design curve makes it better-suited for establishing a remaining life based on design conditions. A design margin for fatigue on the order of 20 is appropriate based on the methods of the ASME Boiler & Pressure Vessel Code [4]. In comparing the DOE-B mean fatigue life of 1335742 cycles to API X' design fatigue life of 122,565 cycles, a ratio of 25.3 results. Although conservative, this design margin is on the order of what is appropriate. Whereas the design margin between the DOE-B mean and design curves is only 2.3; a value that is unacceptably low for alternating stresses that exist in dents.

While the estimated number of cycles to failure is primarily a function of the stress range in the dented region of the pipe, the remaining years of service is determined based on the assumed pressure cycle conditions. A more aggressive pressure cycle condition will result in a shorter remaining life. Provided below in Table 1 are results using the respective pressure data considering two different stress concentration factors and three different periods of time. As noted in this table, if one considers for instance only the pressure cycle condition prior to June 18, 2009 for the SCF = 2.79 the estimated remaining life is 3,011 years; however, if one considers the more aggressive pressure cycle condition since June 18, 2009 the estimated remaining life is reduced to 65 years.

CONCLUSIONS

This paper has summarized findings from a study to evaluate stresses in a 2% dent in a 20-inch x 0.406-inch Pipeline. A finite element model of the dented region was constructed using data from an ILI caliper tool run. A maximum SCF was calculated to be 4.24 using the analysis results, although an SCF on the order of 2.79 seems more appropriate based on the results generated from the testing program. This latter value is also consistent with the empirically-derived SIFs calculated using data from the ongoing PRCI dent study.

Historical pressure cycle data for a one year period was used to estimate the remaining life using the API X' curve for the given 2% dent. Using the SCF of 2.79, the estimated remaining life ranges from 65 years for the more aggressive cycle condition (June 18, 2009 to July 25, 2009), whereas using the pressure cycle data prior to this date the estimated remaining life is 3,011 years.

FINAL COMMENTS AND CONSIDERATIONS

A final series of cautionary comments are provided in relation to estimating the future performance of the damaged pipeline. First, no detailed consideration of prior cyclic pressure service has been made in this assessment. This is unlikely to be an issue for this particular pipeline and if the prior data is consistent with the pressure cycle data prior June 2009, one can conclude that the cumulative damage in the dent is likely to be insignificant. A second comment concerns the assumed accuracy of the ILI data. It is the authors' observation that in-line inspection tools can under-predict the severity of dent profiles. In reviewing the data plotted in Figure 7, the experimental data demonstrate a sharper profile than observed with the ILI geometry. The differences that exist between the experimental and analytical data are not sufficient to dismiss the accuracy of the assumed geometry. Finally, it is essential that no cracks be present in the dented region of the pipe as it will significantly reduce the remaining life of the dent when considering cyclic pressure.

REFERENCES

1. Offshore Installations: Guidance on Design and Construction, ISBN 0 11 411457 9, Publication 1984.
2. CRUNCH USER'S GUIDE by Marshall L. Buhl, Jr., National Wind Technology Center, National Renewable Energy Laboratory, Golden, Colorado, revised on October 15, 2003 for version 2.9.
3. API RP 2A, *Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms*, American Petroleum Institute, 01-Jul-1993.
4. *Criteria of the ASME Boiler & Pressure Vessel Code for Design by Analysis in Sections III and VIII, Division 2*, The American Society of Mechanical Engineers, New York, 1969.

Table 1 - Design Life as a Function of Operating Period and Stress Concentration Factor
(Miner's Rule assessment uses exponent of 3.74 from the API RP2A X' curve)

SCF = 2.79			SCF = 4.24		
All year (7/25/08 - 7/25/09)	Last 37 days (6/18/09 - 7/25/09)	Year minus last 37 days (7/25/08 - 6/17/09)	All year (7/25/08 - 7/25/09)	Last 37 days (6/18/09 - 7/25/09)	Year minus last 37 days (7/25/08 - 6/17/09)
306 years	65 years	3,011 years	64 years	14 years	629 years

DENT PROFILE - WC 504719															
Distance ft.	Channel #1	Channel #2	Channel #3	Channel #4	Channel #5	Channel #6	Channel #7	Channel #8	Channel #9	Channel #10	Channel #11	Channel #12	Channel #13	Channel #14	Channel #15
504713.65	-0.026	-0.031	-0.027	-0.031	-0.025	-0.034	-0.036	-0.043	-0.039	-0.037	-0.028	-0.030	-0.025	-0.022	-0.022
504713.66	-0.026	-0.031	-0.027	-0.031	-0.025	-0.032	-0.036	-0.043	-0.039	-0.039	-0.028	-0.030	-0.027	-0.022	-0.022
504713.67	-0.026	-0.029	-0.027	-0.031	-0.025	-0.032	-0.036	-0.043	-0.039	-0.039	-0.028	-0.030	-0.027	-0.022	-0.022
504713.68	-0.026	-0.031	-0.027	-0.031	-0.025	-0.032	-0.036	-0.043	-0.039	-0.039	-0.028	-0.030	-0.027	-0.022	-0.022
504713.68	-0.026	-0.031	-0.027	-0.031	-0.025	-0.032	-0.036	-0.043	-0.039	-0.039	-0.028	-0.030	-0.027	-0.022	-0.022
504713.69	-0.026	-0.031	-0.027	-0.031	-0.025	-0.032	-0.036	-0.043	-0.039	-0.037	-0.028	-0.030	-0.027	-0.022	-0.022
504713.70	-0.026	-0.031	-0.027	-0.031	-0.025	-0.032	-0.036	-0.043	-0.039	-0.037	-0.028	-0.030	-0.027	-0.022	-0.022
504713.71	-0.026	-0.031	-0.029	-0.031	-0.025	-0.032	-0.036	-0.043	-0.039	-0.039	-0.030	-0.030	-0.027	-0.022	-0.022
504713.72	-0.026	-0.031	-0.029	-0.031	-0.025	-0.032	-0.036	-0.043	-0.039	-0.037	-0.030	-0.030	-0.027	-0.024	-0.020
504713.73	-0.026	-0.031	-0.029	-0.029	-0.027	-0.032	-0.036	-0.045	-0.039	-0.037	-0.030	-0.030	-0.027	-0.024	-0.020
504713.73	-0.026	-0.031	-0.029	-0.029	-0.025	-0.032	-0.036	-0.045	-0.039	-0.037	-0.030	-0.030	-0.027	-0.024	-0.022
504713.74	-0.026	-0.031	-0.029	-0.029	-0.025	-0.032	-0.036	-0.043	-0.039	-0.037	-0.030	-0.030	-0.025	-0.024	-0.022
504713.75	-0.026	-0.031	-0.029	-0.029	-0.025	-0.032	-0.036	-0.043	-0.039	-0.037	-0.030	-0.030	-0.025	-0.024	-0.022
504713.76	-0.028	-0.031	-0.027	-0.029	-0.025	-0.034	-0.036	-0.043	-0.039	-0.037	-0.030	-0.030	-0.025	-0.024	-0.022
504713.77	-0.028	-0.031	-0.027	-0.029	-0.025	-0.034	-0.036	-0.043	-0.041	-0.037	-0.030	-0.030	-0.025	-0.024	-0.024
504713.78	-0.028	-0.031	-0.027	-0.029	-0.025	-0.034	-0.036	-0.043	-0.041	-0.037	-0.030	-0.030	-0.025	-0.024	-0.024
504713.79	-0.028	-0.031	-0.027	-0.029	-0.023	-0.034	-0.034	-0.041	-0.043	-0.037	-0.030	-0.032	-0.025	-0.022	-0.026
504713.80	-0.028	-0.031	-0.027	-0.029	-0.023	-0.034	-0.034	-0.041	-0.041	-0.037	-0.030	-0.032	-0.025	-0.022	-0.024
504713.81	-0.028	-0.031	-0.027	-0.029	-0.023	-0.034	-0.034	-0.043	-0.041	-0.039	-0.030	-0.032	-0.025	-0.024	-0.024
504713.82	-0.028	-0.031	-0.027	-0.029	-0.023	-0.034	-0.034	-0.043	-0.041	-0.039	-0.030	-0.032	-0.025	-0.024	-0.024
504713.83	-0.026	-0.031	-0.027	-0.029	-0.023	-0.032	-0.034	-0.043	-0.041	-0.039	-0.030	-0.032	-0.025	-0.024	-0.022
504713.83	-0.026	-0.031	-0.027	-0.029	-0.023	-0.032	-0.034	-0.043	-0.039	-0.039	-0.030	-0.032	-0.025	-0.024	-0.022
504713.84	-0.026	-0.031	-0.027	-0.029	-0.023	-0.032	-0.034	-0.043	-0.039	-0.039	-0.030	-0.032	-0.025	-0.024	-0.022
504713.85	-0.026	-0.031	-0.027	-0.027	-0.023	-0.032	-0.034	-0.043	-0.039	-0.039	-0.030	-0.032	-0.025	-0.024	-0.022
504713.86	-0.026	-0.031	-0.025	-0.027	-0.023	-0.030	-0.034	-0.043	-0.039	-0.039	-0.030	-0.032	-0.025	-0.024	-0.020
504713.87	-0.026	-0.031	-0.025	-0.027	-0.023	-0.030	-0.034	-0.043	-0.039	-0.039	-0.030	-0.032	-0.025	-0.024	-0.020
504713.88	-0.026	-0.031	-0.025	-0.027	-0.023	-0.030	-0.034	-0.041	-0.039	-0.039	-0.030	-0.030	-0.025	-0.024	-0.020
504713.88	-0.026	-0.031	-0.025	-0.027	-0.023	-0.030	-0.034	-0.041	-0.039	-0.039	-0.030	-0.030	-0.025	-0.024	-0.020
504713.89	-0.026	-0.031	-0.025	-0.027	-0.023	-0.030	-0.034	-0.041	-0.039	-0.039	-0.030	-0.030	-0.025	-0.024	-0.020
504713.90	-0.026	-0.031	-0.025	-0.025	-0.023	-0.028	-0.034	-0.041	-0.039	-0.039	-0.030	-0.030	-0.025	-0.024	-0.020

Figure 1 – Portion of geometry raw data for dented region of pipeline
(Matrix dimensions: 1,315 rows by 40 columns)

**Note: Model built to mid-wall OD (19.594 in)*

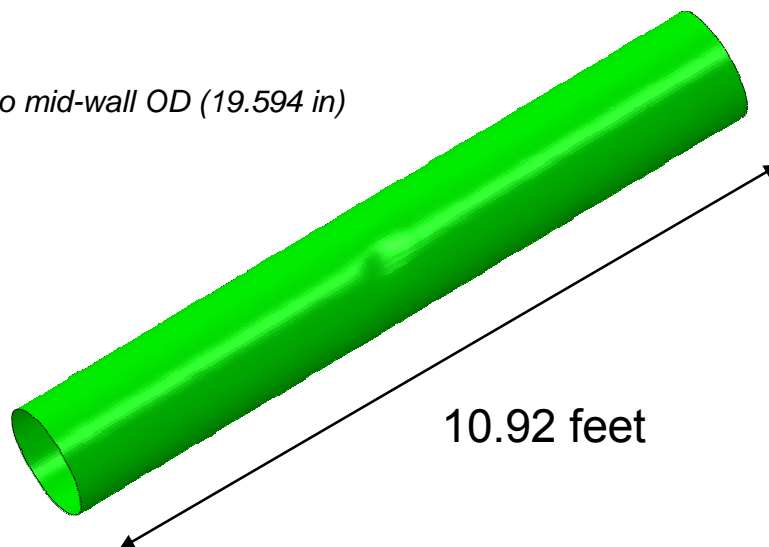
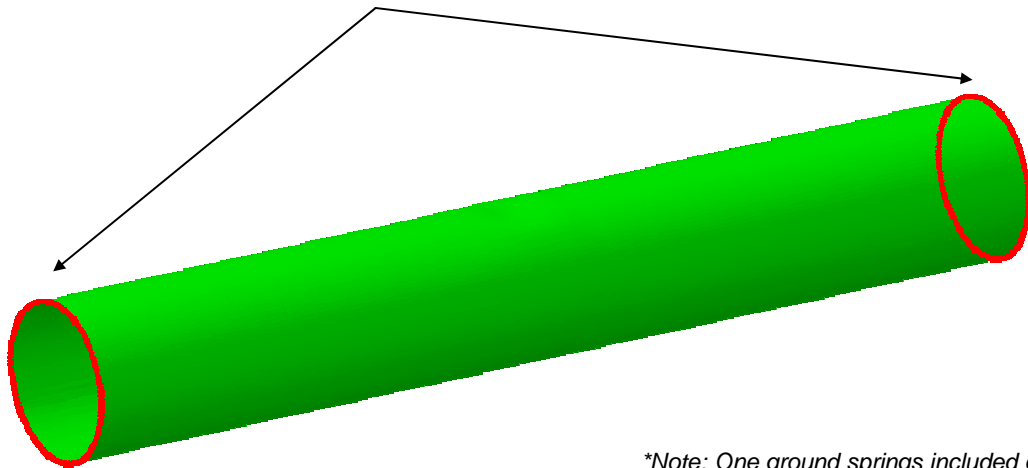


Figure 2 – Geometry of finite element model including dented region

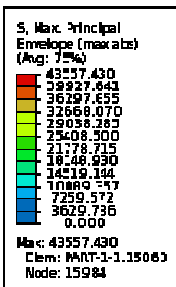
Symmetry Boundary Conditions on each Pipe End



**Note: One ground springs included on each pipe end to restrain rigid body motion*

Figure 3 – FEA model boundary conditions

Legend units in psi



$$SCF_{MP} = \frac{43557}{10000} = 4.36$$

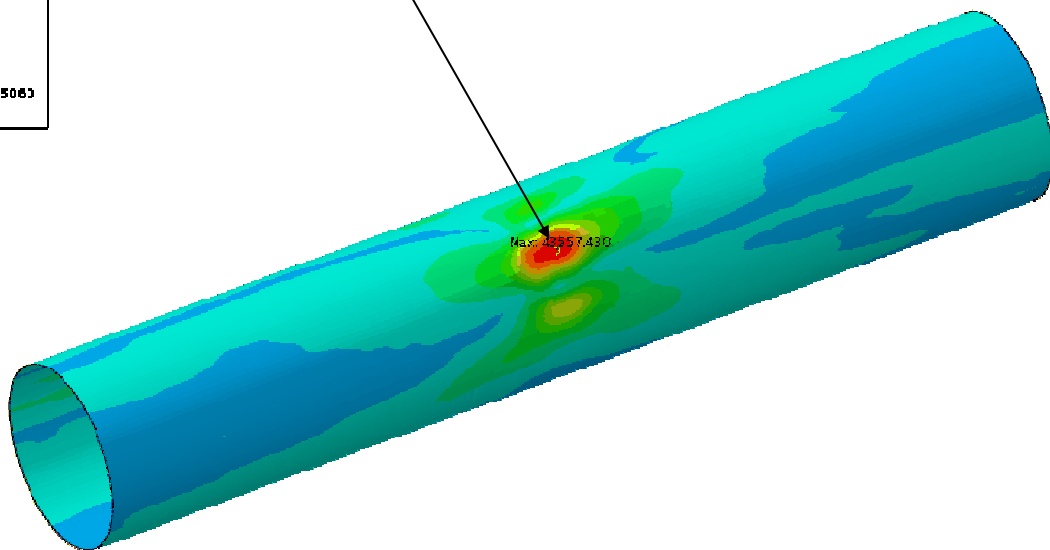
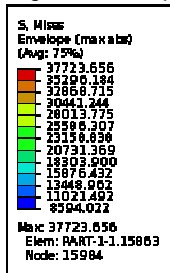


Figure 4 – Contour plot showing the maximum principal stress state

Legend units in psi



$$SCF_{VM} = \frac{37723}{8888} = 4.24$$

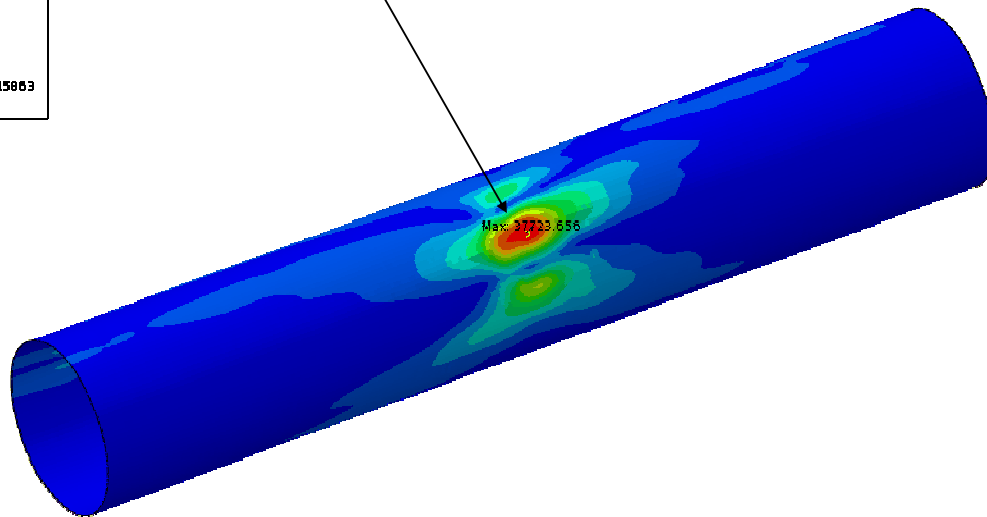


Figure 5 – Contour plot showing von Mises stress state

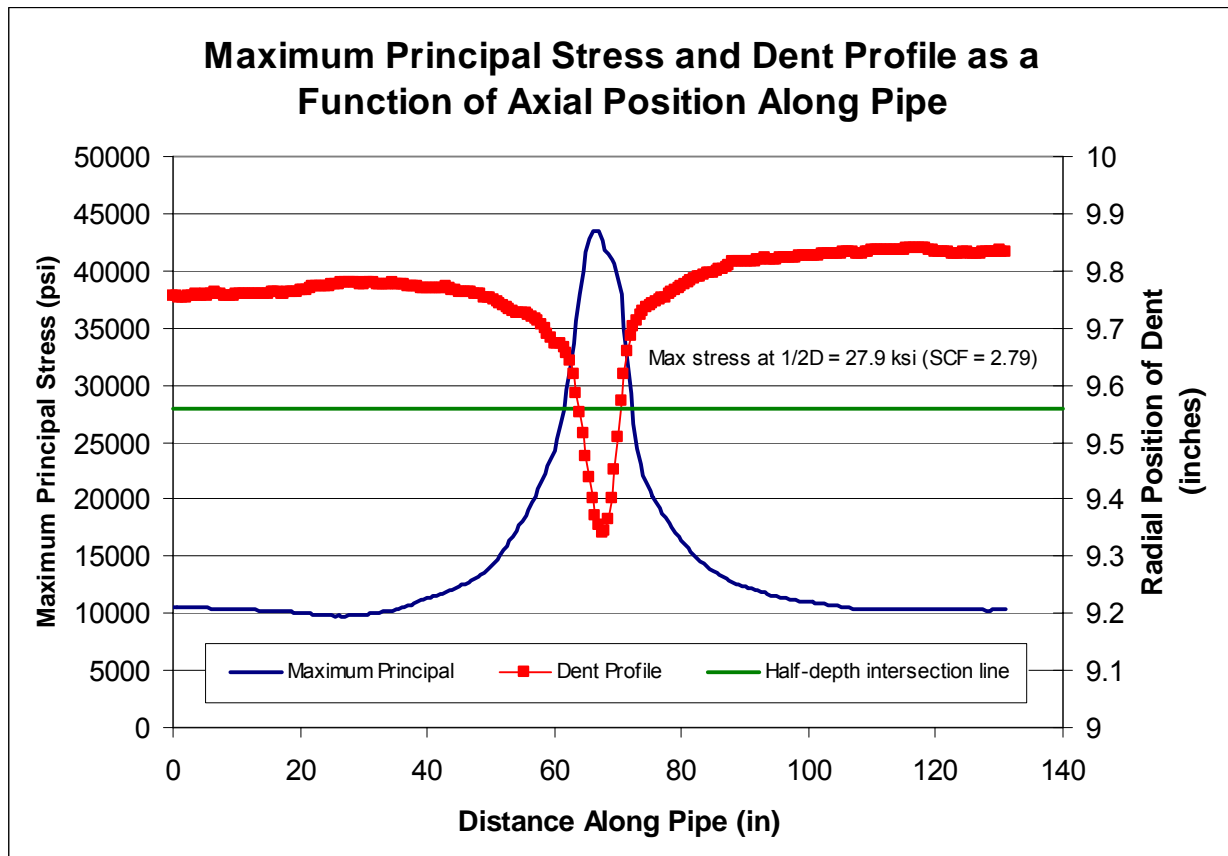


Figure 6 – Calculated stress and dent profile showing maximum stress at dent half-depth

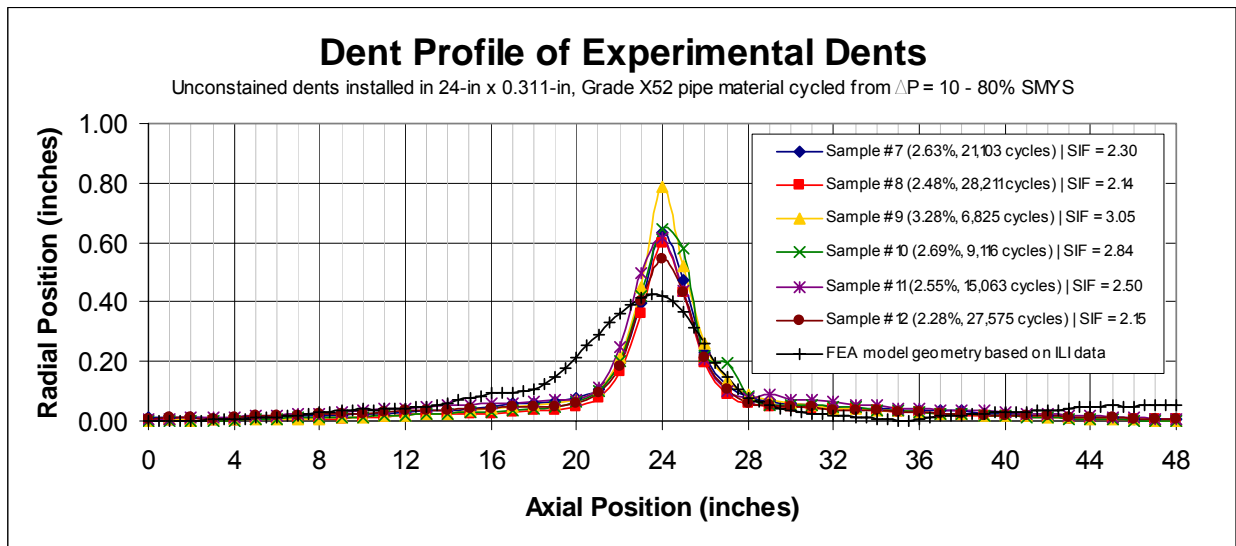


Figure 7 – Analytical versus experimental dent profiles in pipe



Figure 8 – Photographs of dents from PRCI test samples

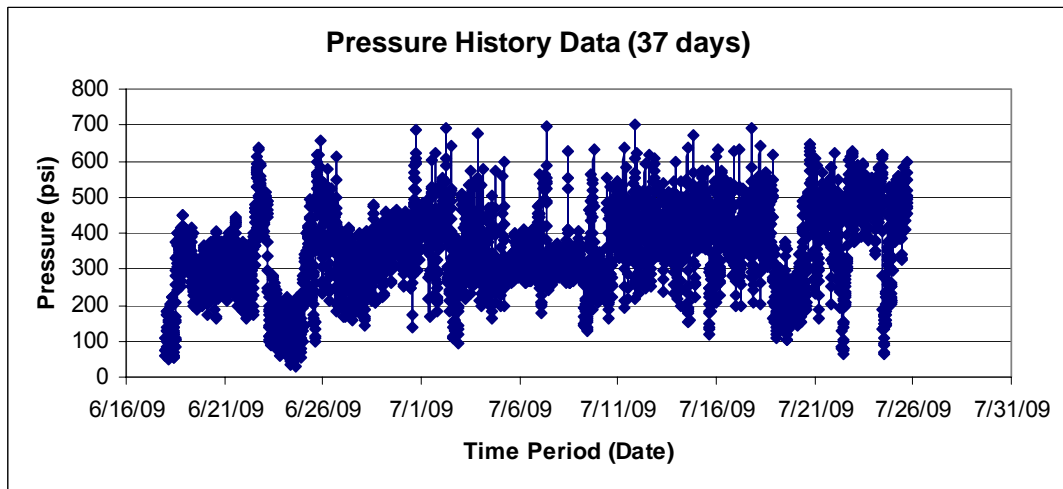


Figure 9 – Historical Pressure History Data for 6/18/09 to 7/25/09
(Last 37 days of the provided pressure cycle data)

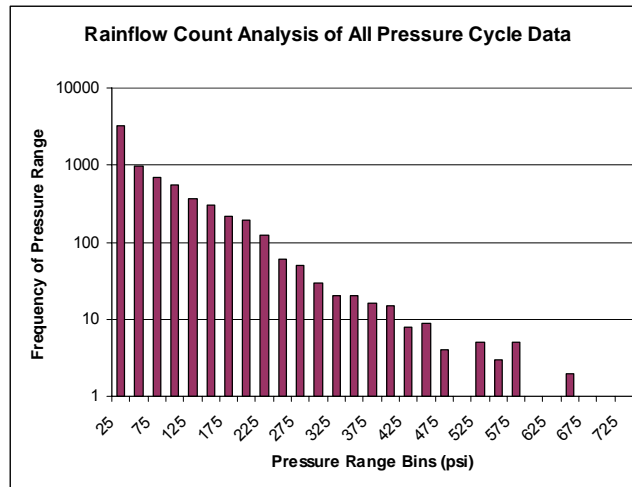


Figure 10 – Pressure cycle histograms for entire period of interest

Data analysis of Shell Pipeline Company 20-inch x 0.406-inch pipe

Dent profile of the 2% dent at ODO 504719

Pipe outside diameter 20 inches

Pipe wall thickness 0.406 inches

Target Pressure Cycle Range (ΔP) 350 psi

Order of S-N curve (exponent) 3.74

MAOP 1440 psi

Hoop stress range at ΔP 8621 psi

Number of equivalent cycles at ΔP 191

Dent stress concentration factor (SCF) 2.79

Mean cycles to failure (DOE-B mean) 3,094,991 cycles

Design life (DOE-B) 1,335,742 cycles

Design life in years (DOE-B) 6983 years

Design life (API X') 122,565 cycles

Design life in years (API X') 65 years

Bin	Frequency	$N_{\text{equivalent}}$
25	332	
50	128	0.1
75	78	0.2
100	57	0.5
125	28	0.6
150	33	1.4
175	26	1.9
200	22	2.7
225	15	2.9
250	4	1.1
275	6	2.4
300	9	5.1
325	8	6.1
350	7	7.0
375	7	9.1
400	9	14.8
425	5	10.3
450	6	15.4
475	3	9.4
500	0	
525	4	18.2
550	2	10.8
575	4	25.6
600	2	15.0
625	1	8.7
650	1	10.1
675	1	11.7
700	0	
725	0	
TOTAL	191	
	1887	

for 37 days

for 1 year

Figure 11 – Data Analysis Showing Calculated Results
(Tabulated data same as histogram plotted in Figure 9)