Evaluation, Repair and Rehabilitation of Pipelines Conference and Exhibition
October 31-November 3, 2011
Houston Marriott West Loop, Houston, Texas, USA

Using Full-Scale Destructive Testing Methods to Evaluate the Mechanical Integrity of High Pressure Pipelines

Chris Alexander
Stress Engineering Services, Inc.
Houston, Texas

Brent Vyvial
Stress Engineering Services, Inc.
Houston, Texas

ABSTRACT

Evaluating the mechanical integrity of pipelines involves a variety of tool and skill sets. Over the past several years there has been an increased interest in assessing the performance of vintage pipeline systems and specifically evaluating the effects of existing defects on future performance. Examples of defects include girth and seam welds, corrosion, dents, and wrinkle bends. While lessons learned from prior experience and analysis are critical, the role of testing in the evaluation process is receiving focused attention.

This paper includes detailed discussions on how testing has been used over the past several decades to help pipeline companies assess the integrity of their pipeline systems. Specific emphasis is placed on helping the reader better understand what testing techniques are most appropriate and determining how to interpret and correlate the results into useful information for operating safe pipelines. Case studies will be presented that include studies on involving burst and pressure cycle testing, assessment of composite repairs, and evaluating the integrity of branch connections. The primary focus of this paper is to present how the testing work can be used as an essential element for developing a comprehensive Engineering-Based Integrity Management Program.

INTRODUCTION

At the core of integrity management is the need to ensure the safe operation of pipeline systems. There are obviously numerous means for addressing the needs associated with this central requirement, several of which include studying historical trends and failure patterns, numerical modeling, and full-scale testing. From a statistical standpoint, as the age of a given pipeline increases the likelihood for deterioration of the system also increases. As a result, the importance of understanding the present and future behavior of an aging pipeline becomes even more critical.

Over the past several years there has been an increased interest in pipeline operators requesting that full-scale testing be performed to predict future performance of pipeline materials and existing anomalies such as dents in welds, wrinkle bends, crack-like flaws in seam welds, and vintage girth welds. The central driver behind this trend is that operators need to assess the integrity of their pipeline system in a manner than cannot be achieved using an analysis-only approach. The consequence of failure for transmission pipelines is too high to risk the potential for errors and possible lack of conservatism in a numerical model. In a similar manner, analyses methods that are overly-conservative will generate unnecessary remediation activities. This is likely to create other problems such as over-digging and not focusing on the major problems in a line.

A well-organized testing program can provide significant insights into the performance of a pipeline, both present and future. As part of this effort, readers are encouraged to consider the following benefits in pursuing testing as a means for evaluating mechanical integrity.

- It is possible to organize a testing program that represents future service conditions for a pipeline. As an example, one can apply pressure cycles to a given sample to represent 20 years of future service prior to performing a burst test on a known flaw. In this manner, the testing organization is able to provide the operator with a snapshot of how their pipe material might perform at some future date.
- Most analyses required some consideration of a range of input variables, typically involving material properties and behavior. Because of the potential for variability at the input level, one must bound analysis problems to ensure that both the upper and lower bound responses have been captured. This invariably leads to reduced confidence in results. If one is to integrate selected tests into a study of this type, the overall uncertainty of the analysis work is reduced and greater confidence in predicting the behavior of the pipe is achieved when using numerical models.
- Testing can also be used to validate numerical models and improve confidence in analysis results. Typically, several well-design tests can accompany a wide range of analysis models.

The purpose of this paper is to provide guidance for the pipeline industry in how testing, primarily full-scale destructive, can be used to enhance and improve integrity management. The organization of this paper includes discussions on testing methods, types of testing, case studies based on prior work, integrating analysis and testing results, and lastly a discussion on guidance in using testing as part of an engineering-based integrity management program.

TYPES AND METHODS OF TESTING

In order to discuss the value in testing it is obviously important to consider types of testing and how they are used to evaluate pipeline performance. The sections that follow include discussions on the following types of tests:

- Burst tests
- Cyclic pressure testing
- Bend testing
- Simulated damage creation

Discussions include how the tests are performed (i.e. testing methods) and what is learned in performing each test. On occasion different tests are combined to better represent actual service conditions. An example is to subject a pipeline test sample to cyclic pressures for a specified number of cycles (e.g. number of cycles representing a 20 year service life) prior to performing a burst test. This in effect provides a snapshot of the future burst capacity of the pipeline corresponding to the designated future service period.

Burst Tests

As the name implies, burst tests involve taking a test sample all the way to failure due to pressure overload. The benefit in doing so is to determine the ultimate pressure capacity of a given piece of pipe. Of equal importance is to determine the reduction in strength associated with given defects such as a crack-like flaw in a seam weld or a plain dent with corrosion.

Prior to going to failure, it is often beneficial to perform pressure holds at levels corresponding to the operating pressure of the pipeline as well as the pressure associated with the specified minimum yield strength (SMYS). Strain gages are also useful for providing strain in a given section of the pipe such as corrosion or a dent and are often used to measure strain in pipe samples ultimately taken to failure.

Pressure Cycle Fatigue Testing

Over the years the author has performed hundreds of pressure cycle tests. Often the purpose in testing has been to destructively test via fatigue known pipeline defects or flaws. Another trend that has been frequent as of late is the use of pressure cycling to introduce cumulative damage prior to actually performing a burst test. This is a useful and powerful technique for providing an operator with an understanding about how a pipeline might perform at some future date. A case study is provided in this paper; however, the basic elements associated with this “pre-burst” fatigue study include the following steps.

1. Estimate the number of pressure cycles expected in a given period of time (e.g. 20 years) as well as the associated pressure ranges.
2. Use a rainflow counting technique to determine a single equivalent pressure range (details provided in discussion below) using actual pressure data from a compressor or pump station. Both cycle counting (e.g., rain-flow) and a damage rule (e.g., Miner’s Rule) are required to define a single equivalent pressure range.
3. If the testing is not intended to be destructive, but rather representative of future pressure service, determine the appropriate number of cycles to apply to the sample. Several options exist
    a. Number of cycles based on actual expected conditions.
    b. To account for the standard deviations in fatigue test results, multiply the expected number of actual cycles by a factor. Typical factors range from 10 to 20, where latter is the basis for the fatigue design curves in Section VIII, Division 2 of the ASME Boiler & Pressure Code. The safety factors on cycle number are typically associated with high-strain low cycle conditions, whereas the safety factor on stress amplitude refers to the high-cycle regime.
4. Apply the selected cyclic pressure conditions to the test pipe. It is possible to accelerate the rate of testing using a larger pressure range (i.e. reduce time required to complete tests). Miner’s Rule can then be used to correlate the applied number of cycles to account for different pressure ranges. As a point of reference, using a 4^{th} order relationship between stress and cycles to failure, a single cycle at DP=100% MAOP is equivalent to 16 cycles at DP=50% MAOP.

A rainflow counting technique is useful for developing a single pressure range based on actual pressure history. **Figure 1** provides data from a prior study where the operator provided historical pressure data for a one year period. These data were used as input into a rainflow counting package to generate the histogram shown in **Figure 2**. From the collected pressure range bins and associated frequencies, a single equivalent pressure range was determined using Miner’s Rule for DP=1,104 psi (7.6 MPa). **Figure 2** shows results associated with the development of the histogram and the single equivalent pressure range. The random nature of the actual pressure data can be converted into a single equivalent pressure range that can then be applied to the pipe sample during testing. Consider the table provided in **Figure 2**. a 4th order relationship is assumed between stress and cycles as expressed in the following relation based on Miner's Rule.

$$N_{\Delta P} = N_{1104}\left[\frac{1104\,psi}{\Delta P}\right]^4 \tag{1}$$

In this equation *N* is the number of respective cycles and *ΔP* is the applied pressure range in units of psi. For each pressure range captured from the rain-flow counting exercise (and shown in the histogram in **Figure 2**) a new equivalent cycle number is generated for the 1,104 psi (7.6 MPa) operating pressure condition. As noted in this table, the sum of all resulting cycles generates a single equivalent pressure cycle. Therefore, from the random pressure data presented in **Figure 1**, a single equivalent cycle number of 69 is generated assuming an alternating pressure of 1,104 psi (7.6 MPa) as presented in the table in **Figure 2**.

Bend Testing

Bending is always part of offshore pipeline work, whether it is at the installation level of subsea accounting for issues such as thermal buckling; however, bending can also be an issue for onshore pipelines when considering the effects of terrain, land movement, earthquakes, and mudslides. In addition to introducing bending loads, tests can simultaneously introduce the effects of internal pressure and axial tension or compression.

Because of safety concerns, bending tests often do not involve testing to failure. Rather, bending loads are applied until a plastic collapse condition is reached and the limit state load is defined as the point where the pipe can take no more appreciable loading. Strain gages are typically used in bend testing to provide feedback on the level of strain being introduced into the test sample and identification of the plastic collapse. A case study is presented that provides results for a bend test used to assess the level of reinforcement provided by a corroded pipe section reinforced with composite materials.

Simulated Damage Creation

Although a fair portion of the work recently performed by the author and his firm have involved actual defective pipe materials removed from the field, from time to time efforts are required to simulate damage using laboratory means. Besides the obvious inclusion of applying excessive loads during tests (i.e. pressure, tension, and bending) to introduce failure, the defects most often simulated during testing include corrosion, plain dents, and mechanical damage.

Figure 3 shows the set-up for testing done to generate mechanical damage in 12.75-inch (324 mm) diameter pipe material. To inflict damage a gouge was generated by forcing a back-hoe tooth into the sample that was simultaneously pulled, during which pressure was maintained in the sample at 70% SMYS. **Figure 4** shows the geometry for the three back-hoe teeth as well as a photograph of one of the simulated defects.

CASE STUDIES

The best means for demonstrating the effectiveness of testing to assess mechanical integrity is using case studies. The case studies below provide details on studies done for pipeline operators. An important consideration for the information presented herein is that all of these case study tests were used to convey to government regulators the soundness of the pipeline in question. In effect these tests became part of integrity management program packages.

The discussions that follow for each of the case studies all contain the following items.

1. Purpose of test
2. Type of test
3. Implications of results

Burst to Failure with Pre-cycling Pressure Fatigue Test

As part of their integrity management program (IMP), a gas pipeline operator was required to evaluate a series of issues in their system that included one dent with a small external scratch, another dent that had an internal gouge created by an in-line inspection tool, and another sample that had a dent in a girth weld and had been repaired using Clock Spring 5 years prior to testing. The operator requested that a series of burst tests be conducted on these three pipe sections removed from the main pipeline to evaluate their mechanical integrity.

In addition to burst testing, the client requested that a series of ancillary investigations be conducted to provide insights on the performance of the pipe material. The additional efforts included the following:

- Make detailed measurements of the dent area in order to develop an understanding for how future defects with similar geometries might behave. **Figure 5** shows the dent measurements for one of the test samples.
- Install strain gages in the vicinity of the dents on the two samples with dents. One of the samples was also fitted with a displacement transducer to monitor dent rerounding during pressure testing. **Figure 6** is a photograph showing strain gages installed on one of the samples.
- The test sample that had the Clock Spring repair was pressure cycled approximately 18,000 cycles prior to burst testing to represent 50 years of service (DP = 200 psi (1.38 MPa)).

Each of the three samples was burst tested. Of the two dents without the composite repair, strain was monitored during testing. **Figure 7** shows strain gage readings taken during one of the burst tests. This particular sample failed at 2,291 psi (15.8 MPa) and the maximum strain recorded during testing was at Gage #8, a gage located remote from the dent (a result that confirmed to the operator that there concerns regarding the dent were not warranted). Several photographs from this program are provided in **Figure 8**.

The outcome of this program was important. For one, all of the bursts occurred at pressures exceeding the SMYS pressure for the pipeline and two of the bursts occurred at pressures two times the operating pressure. Secondly, the sample with the Clock Spring was tested at the highest pressure of all tests. The results demonstrated the soundness of the composite repair, even thought it had been in service for several years and subjected to 18,000 pressure cycles before burst testing. This test program met the expectations of the pipeline operator and was used to demonstrate the integrity of the pipe material to pipeline regulators.

Bend Testing Corroded Pipe with Composite Repair

Composite systems are a generally-accepted method for repairing corroded and mechanically-damaged onshore pipelines [1, 2]. The pipeline industry has arrived at this point after more than 15 years of research and investigation. Because the primary method of loading for onshore pipelines is in the circumferential direction due to internal pressure, most composite systems have been designed and developed to provide hoop strength reinforcement. On the other hand, offshore pipes (especially risers), unlike onshore pipelines, can experience significant tension and bending loads. As a result, there is a need to evaluate the current state of the art in terms of assessing the use of composite materials in repairing offshore pipelines and risers. There is related applicability of this study for onshore pipelines in regions where bending stresses are likely such as regions experiencing earthquakes, ground movement, and mudslides.

Recognizing the need for a study to assess bending loads on composite repairs, a joint industry effort involving the Minerals Management Service, the Offshore Technology Research Center at Texas A&M University, Stress Engineering Services, Inc., and several composite repair manufacturers was undertaken to assess the state of the art using full-scale testing methods. Loads typical for offshore risers were used in the test program that integrated internal pressure, tension, and bending loads [3].

The program incorporated 8.625-inch x 0.406-inch, Grade X46 pipe (219 mm x 10 mm) test samples that were prepared with simulated corrosion by machining. The program destructively tested a total of 12 separate samples with three being repaired by each of the four manufacturers. The tests included a burst test (increasing pressure to failure), a tension-to-failure test (pressure held constant with increasing axial tension loads to failure), and a four-point bend test (pressure and tension held constant with increasing bending loads to achieve significant yielding in steel pipe) for each of the repair systems.

Figure 9 and **Figure 10** provide a schematic of the test samples with strain gage locations and a photograph of the load frame, respectively. The simulated corrosion shown in **Figure 9** is certainly an extreme case in that the geometry axisymmetric (i.e. the same all the way around the pipe). This was done for two reasons. First, damage to offshore risers often occurs randomly around the riser and is especially prevalent at the air-water interface in the splash zone. Secondly, it is necessary that the tested composite repair systems demonstrate their ability to provide reinforcement all the way around the riser.

The load frame shown in **Figure 10** has a tension capacity of 1 millions lbs and a bending capacity of 750,000 ft-lbs (1017 kN-m). The primary objective in testing was to demonstrate the capability that composite materials have in reinforcing corroded pipes, especially with regards to bending loads.

Figure 11 is a plot providing bending strain as a function of applied bending loads for one of the test samples. Also included in this plot are annotations showing the design load subject to a strain-based design criterion. As noted, the composite reinforcement provides sufficient reinforcement to ensure that unacceptable levels of strain are not induced in the reinforced steel.

The primary purpose of the state of the art assessment and associated JIP study was to identify and confirm the critical elements required for an effective composite repair. Other benefits were also derived in the execution of the program, including the development of guidelines for industry and regulators and providing the manufacturers with the opportunity to assess their given repair systems subject to loading conditions associated with offshore risers. Testing played a central role in the evaluation and demonstration of the composite repair technology.

Pressure Cycling Flat Spot in New Pipeline

The author was contacted by a gas pipeline company who had detected flat spots in a new large diameter pipeline during the commission phase efforts. The operator had questions about the acceptability of these flat spots and what long-term threat they posed to the integrity of the pipeline. **Figure 12** is a photograph showing the side view of one of the flat spots.

A study was initiated and considered three resources for evaluating the impact that the flat spots would have on the mechanical integrity of gas pipeline system. The three resources included a review of prior research efforts, especially those associated with a program sponsored by API on fatigue testing of plain and rock dents. The second resource utilized finite element analysis to assess stress levels in the flat spot region in the pipeline. The results of this effort demonstrated that the design fatigue life for the most severe defect considered in this study was approximately 1.5 million cycles with a pressure range of 10% SMYS. **Figure 13** shows contour plots from the FEA models. While **Figure 14** shows the corresponding fatigue life as a function of the applied pressure range. The third resource involved fatigue full-scale testing of a pipe sample that contained an actual flat spot removed from the field. This sample was subjected to 13,819 pressure cycles at 80% SMYS (DP = 100 to 1,168 psi (0.68 to 8.1 MPa)) before a failure resulted in the end cap girth weld attached to the sample, preventing additional testing. No fatigue cracks were developed in the flat spot during this cycle period. Even with a design margin on cycle number this cycle number represents more than 50 years of service for a typical gas pipeline, which do not typically experience a significant number of large range pressure cycles.

The predominant conclusion, based on all aspects of this work, was that the flat spots considered in this study did not pose a significant threat to the mechanical integrity of the pipeline. While the use of finite element analysis was important in providing a general understanding of the likely fatigue life of the damaged pipeline, it was the experimental work that solidified confidence in the analysis findings and convinced the operator to proceed with operation of the new gas pipeline that included the presence of flat spots.

Reinforcing Branch Connections with Composite Materials

Field fabricated branch connections are manufactured in lieu of forged tee fittings. To be used in accordance with ASME B31.8, these connections are subject to the area replacement method to ensure that sufficient material is present to reinforce the opening in the run piping. If insufficient material from the branch and run pipes as well as the weld, reinforcing pads are welded into place to serve as the reinforcing mechanism. Integrally reinforced connections are also used. One question posed to the author by a gas pipeline company was the feasibility of using composite materials to reinforce previously-fabricated branch connections that did not have sufficient steel material present to satisfy the requirements of the area replacement method [4].

Initial evaluation of the concept involved calculating the strength required to ensure that the branch connection would have sufficient long-term strength to withstand operating condition. A finite element analyses was also performed using elastic material properties to determine the minimum composite thickness that was required as shown in the contour plot in **Figure 15**.

Once all analytical efforts were completed, a full-scale test was performed on an exemplar branch connection fabricated from a 24-in x 0.375-in pipe (610 mm x 9 mm) and a branch pipe fabricated from 12.75-in x 0.375-in pipe (323 mm x 9 mm) where both pipe are Grade X42. Pressure levels exceeding 2.9 times the MAOP of the 24-inch pipe (787 psi, 5.4 MPa) were reached before the branch connection leaked at a maximum pressure level of 2,314 psi (15.9 MPa). This burst pressure is 1.76 times SMYS. A burst in the connection did not occur, but rather a leak developed in the weld joining the branch and the run pipes and most likely initiated in the crotch region where the highest levels of strain occurred during pressure testing. **Figure 16** shows the test set-up with a close-up view of the region where the crack and leak occurred.

Considering the results of the test program and the calculated results, the pipeline operator concluded that a sufficient design margin existed to warrant the use of the composite materials as a valid method for reinforcing the field branch connections.

INTEGRATING TESTING AND ANALYSIS

As discussed previously, one of the most powerful resources associated with full-scale testing is validating numerical modeling techniques such as finite element analysis. Full-scale testing is intensive in terms of both cost and time. Using tools such as finite element analysis affords engineers the opportunity to develop assessment models for a wide range of variables without having to incur the costs associated with testing every possible scenario.

Provided in this paper is a discussion on how a grading tool was developed for evaluating the severity of wrinkle bends in a pipeline. The basis of the tool was a series of finite element (FEA) models that evaluated the stress concentration factors (SCFs) considering a range of variables that included wrinkle height (h), wrinkle length (L), pipe diameter to wall thickness ratio (D/t), and cyclic pressure range. The basis of this program was pressure cycle testing to failure wrinkle bends removed from the pipeline. Strain gages were installed and monitored during pressure cycle testing, and strain data were also compared to results from the FEA models.

Figure 17 shows the elastic SCFs that were developed from the FEA models. Although not all of the SCFs calculated using finite elements are verified using the experimental results, the data set provided below for one of the samples verifies the methodology.

Sample EP30-1A
30-inch x 0.312-inch, Grade X52 (D/t = 96.2)
Alternating applied pressure of 680 psi (100 – 780 psi)
40 percent corrosion
h/L = 0.12

(762 mm x 8 mm with DP = 4.7 MPa)

From the strain gage results, the alternating strain was measured to be 1,960 me, which corresponds to an alternating axial stress of 58,800 psi (405.4 MPa). It should be noted that this calculated stress level is elastic and in reality some level of plasticity will occur at a stress of this magnitude for a Grade X52 pipe. The corresponding axial SCF measured by the strain gages on the outside surface of the pipe, SCF_{SG_OD}, is calculated as follows (note that the 0.60 value in the denominator accounts for the remaining wall thickness assuming a corrosion wall loss of 40 percent):

$$SCF_{SG\_OD} = \frac{58{,}800\, psi}{\left(\dfrac{680\ psi \cdot 15\ inches}{2 \cdot 0.6 \cdot 0.312\ inches}\right)} = 2.15 \qquad (5)$$

Because the strain gages are placed on the outside surface of the pipe, it is necessary to use an ID/OD correction factor to determine the maximum tensile strains that occur on the inside surface. From the finite element results, the ratio of axial SCFs from the inside to the outside surfaces in a pipe having a D/t of 100 and an h/L of 0.1 is 1.20; therefore, the adjusted SCF_{SG} is:

$$SCF_{SG} = 1.20 \cdot 2.15 = 2.58 \qquad (6)$$

From the finite element work and calculated SCFs presented in **Figure 17**, interpolation of data yields an axial SCF of 2.96 for a pipe having a D/t of 96.2 and an h/L of 0.12. Comparing the analytical SCF of 2.96 with the experimental strain gage SCF of 2.58, the difference between the two is 12.8 percent. Although the comparison of results is not exact, a reasonably accurate solution is presented.

Using the methodology developed previously that generated the single closed-form solution relating design cycle life as a function of pressure state, wrinkle geometry, and pipe D/t ratio, a nomograph was developed as shown in **Figure 18**. This figure relates the h/L ratio to design life and years of service. An example data set is shown considering an h/L ratio of 0.25 (a relatively severe wrinkle) in a pipe having a D/t ratio of 100. As noted in the chart, the corresponding number of design cycles is 563, which then corresponds to 56 years of service assuming 10 cycles per year.

ENGINEERING-BASED INTEGRITY MANAGEMENT PROGRAM

The prior discussion provides a good example of how analysis and testing can be integrated to provide improved confidence in analysis results. The greatest contribution when considering numerical modeling techniques is the development of grading tools for quantitatively assessing pipeline damage. At the present time there are several areas of interest for pipeline operators where the development of these types of tools will be of significant benefit. **Figure 19** is a flow chart that shows the basic central elements involved in developing an Engineering-Based Integrity Management Program (EB-IMP). As noted, analysis and testing methods work hand in hand to produce tools that can be used by operators to evaluate the level of criticality associated with a particular defect or anomaly.

Based on recent observations and discussion with several pipeline operators, there are several areas of concern that pose a threat to the integrity of pipeline systems. A grading tool could be developed for each of the following defect types in association with an EB-IMP.

- Plain dents
- Dent in girth and seam welds
- Rock dents
- Vintage girth welds
- Seam welds (with detected crack-like flaws)
- Wrinkle bends
- Effects of composite materials in increasing the burst capacity and fatigue strength of any of the above

To ensure the validity of any tool that is developed, both analysis and testing are required. At the outset of any project whose intent is to develop a grading tool, it is essential that planning be conducted to maximize information gained from collected results. Of particular note is the fact that significant savings can be realized in conducting select tests to validate specific numerical models as opposed to conducting an extensive array of full-scale tests. Proper planning increases the likelihood that a useful grading tool will be developed.

CONCLUSIONS

This paper has provided details on how full-scale testing methods can be used by pipeline operators to gain understanding about how pipelines respond to loading conditions that can lead to failure. By understanding how pipelines fail, operators are better positioned to identify/understand which defects are of most concern and what margins of safety actually exist in operating a pipeline. While numerical modeling is useful for understanding the general response of pipe materials, it is unwise to rely on guidance based solely on analytical findings. As has been demonstrated herein, when tests are properly coordinated and planned, they can be used to validate numerical models and improve the overall confidence in grading tools.

In addition to validating numerical models, testing provides a powerful resource in helping operators predict the future performance of pipelines. The most appropriate example based on information presented in this paper includes conducting full-scale burst tests on pipe samples that have been previously pressure cycled to simulate future service conditions.

It is hoped that the information in this paper will encourage and foster additional discussions among those in the pipeline industry. Because of the critical role that pipelines have in terms of the world-wide infrastructure, significant benefits are derived in conducting tests as part of an engineering-based integrity management program.

REFERENCES

1. Alexander, C. R. and Worth, C., *Assessing the Use of Composite Materials in Repairing Mechanical Damage In Transmission Pipelines*, Proceedings of the 6th International Pipeline Conference, Paper No. IPC2006-10482, Calgary, Alberta, Canada, September 2006.

2. Alexander, C. R. and Francini, *State of the Art Assessment of Composite Systems Used to Repair Transmission Pipelines*,
Proceedings of the 6th International Pipeline Conference, Paper No. IPC2006-10484, Calgary, Alberta, Canada, September 2006.

3. Alexander, C. R., *Evaluating the Use of Composite Materials in Reinforcing Offshore Risers Using Full-scale Testing Methods*, Proceedings of the ASME International Offshore Pipeline Forum, Paper No. IOPF2007-104, Houston, Texas, USA, October 2007.

4. Alexander, C. R. and Wilson, T., R*einforcing Field Fabricated Branch Connections Using Composite Materials*, Proceedings of the 6th International Pipeline Conference, Paper No. IPC2006-10483, Calgary, Alberta, Canada, September 2006.

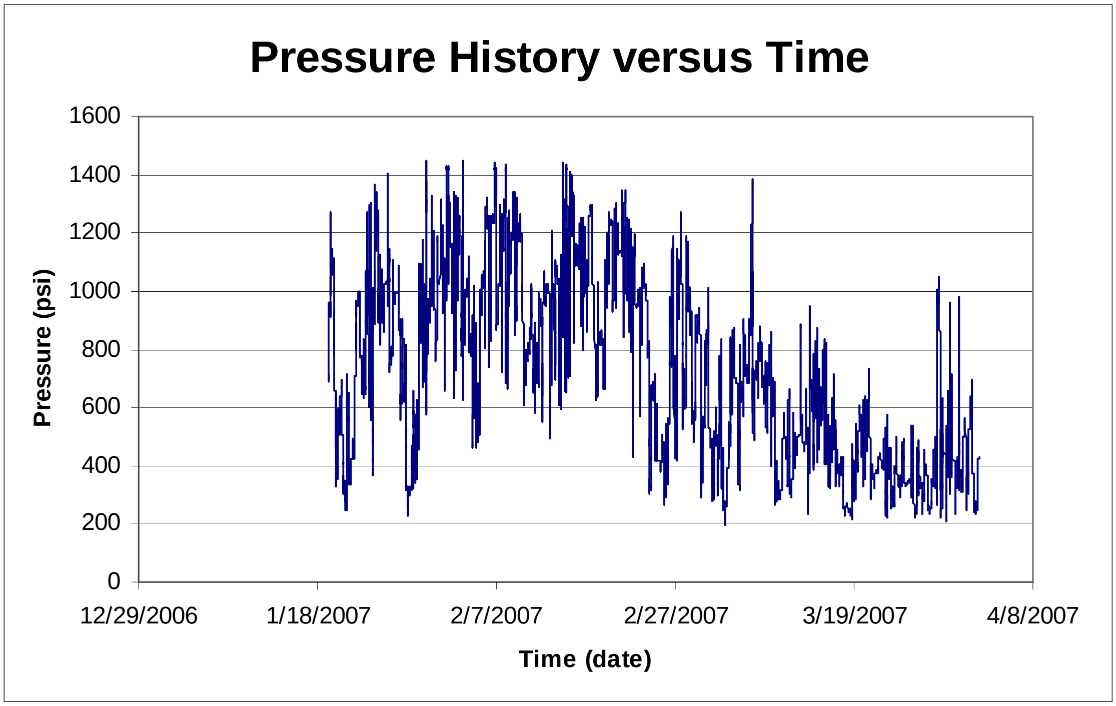
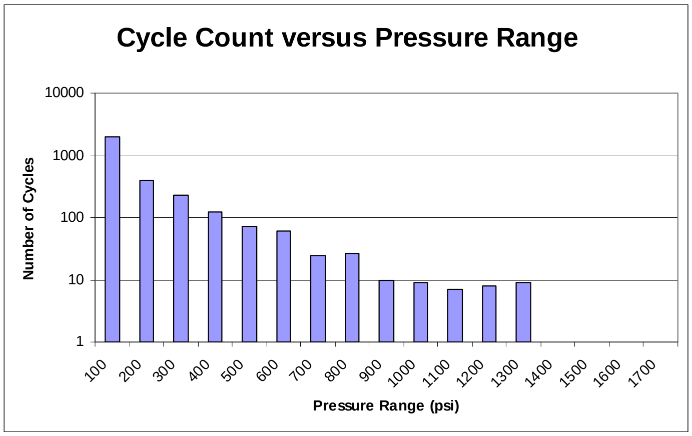


Figure 1 – Pressure history from actual liquid pipeline



Pressure Range Bin (psi)	Frequency	1140 psi Pressure Equivalent	Equivalent Cycle Number
100	2010	0.000	0
200	398	0.001	0
300	230	0.005	1
400	125	0.015	2
500	73	0.037	3
600	60	0.077	5
700	24	0.142	3
800	27	0.243	7
900	10	0.388	4
1000	9	0.592	5
1100	7	0.867	6
1200	8	1.228	10
1300	9	1.691	15
1400	1	2.275	2
1500	1	2.997	3
1600	0	3.880	0
1700	0	4.945	0
More	0	**TOTAL**	**66**
		Annual TOTAL	**69**

Figure 2 – Development of the histogram and single equivalent pressure range

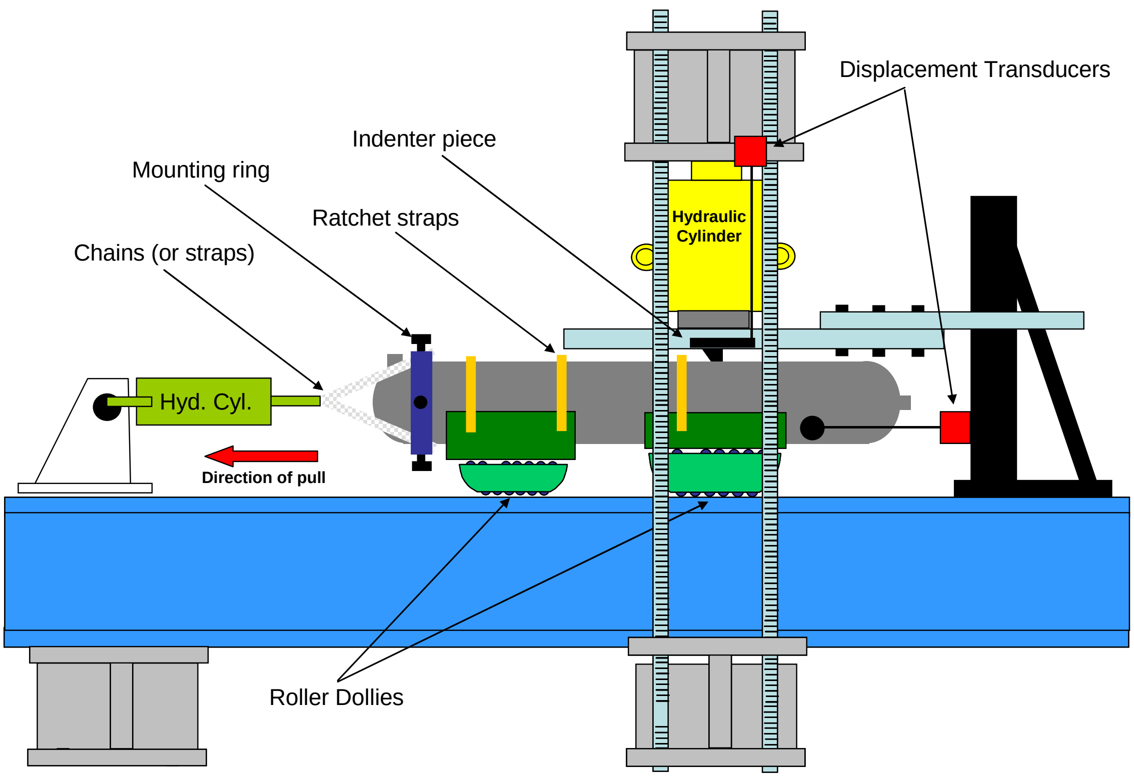


Figure 3 – Schematic of set-up used to generate mechanical damage in pipe samples

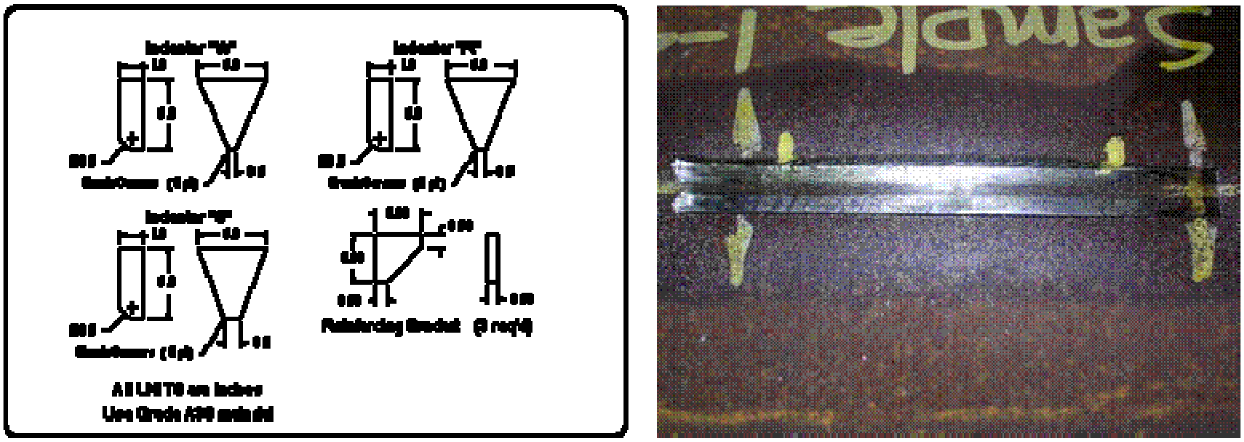


Figure 4 – Geometry of indenter teeth and resulting damage
(drawings at left show indenter geometry and photo at right shows the resulting damage inflicted to the pipe)

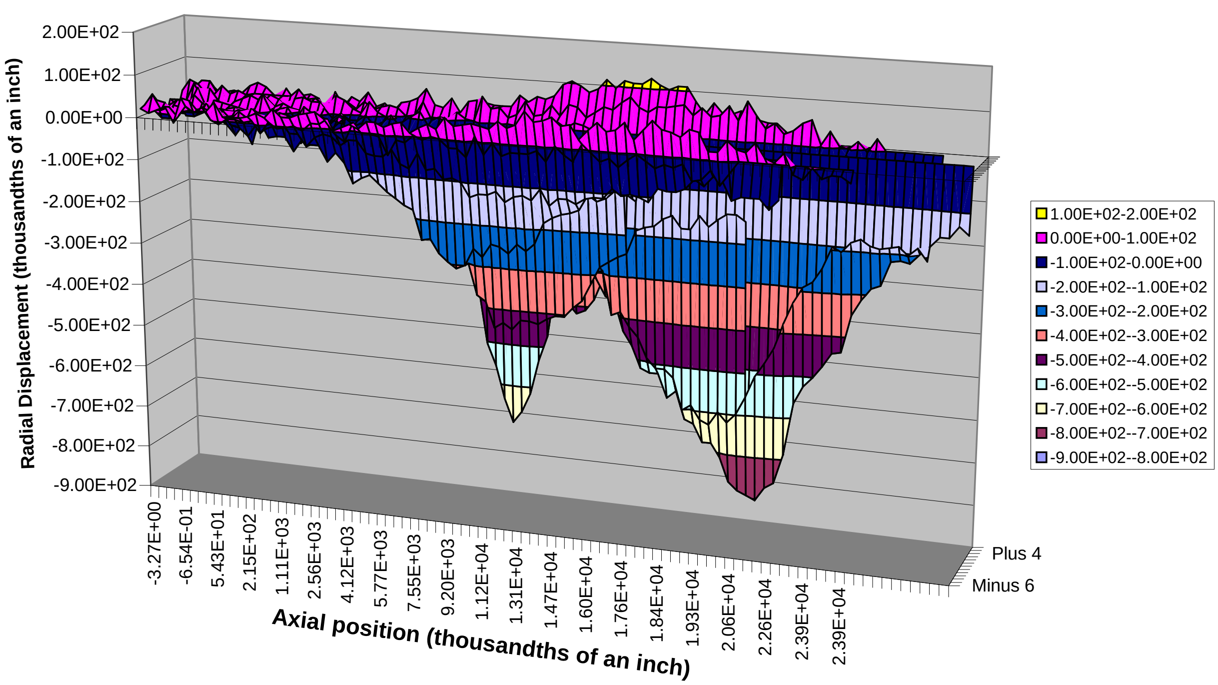


Figure 5 - Radial Profile Measurements for Dent Sample

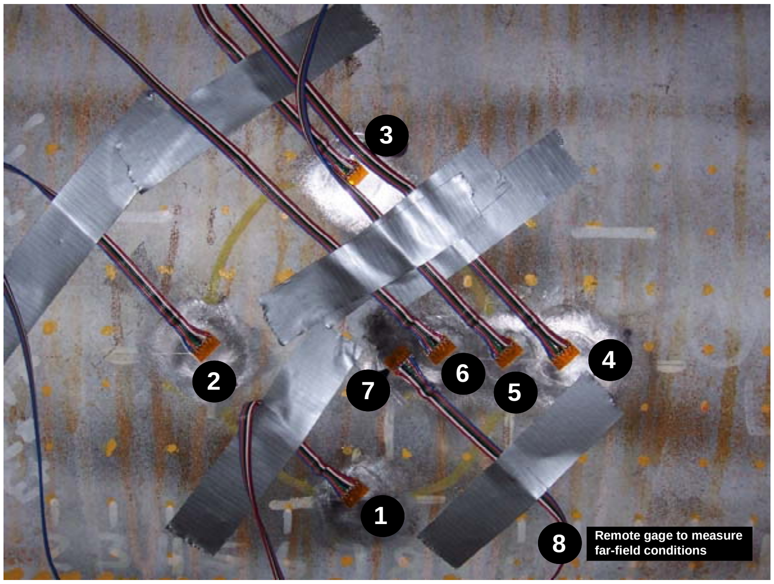


Figure 6 – Strain gages installed in dented region of one of the burst samples

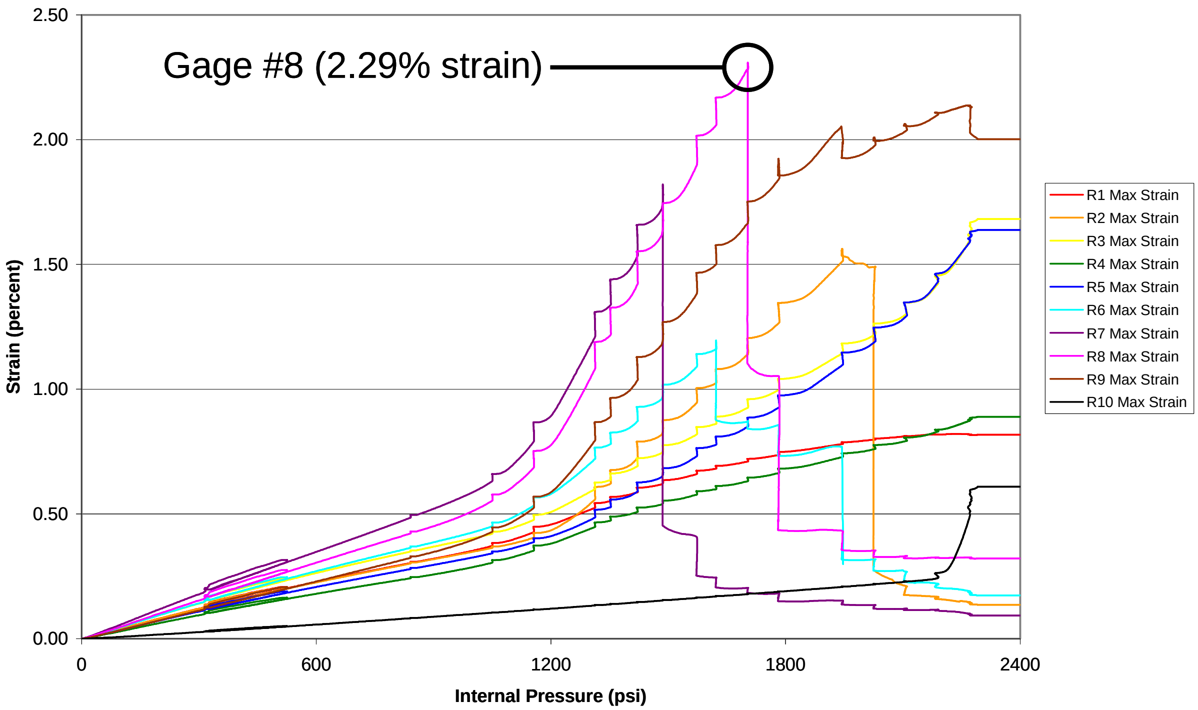


Figure 7 – Strain gages results for burst test (sample failed at 2,291 psi)

Figure 8 – Photographs from two burst tests that included repaired and unrepaired dents
(the two left photos show a dent repaired using the Clock Spring composite repair system)

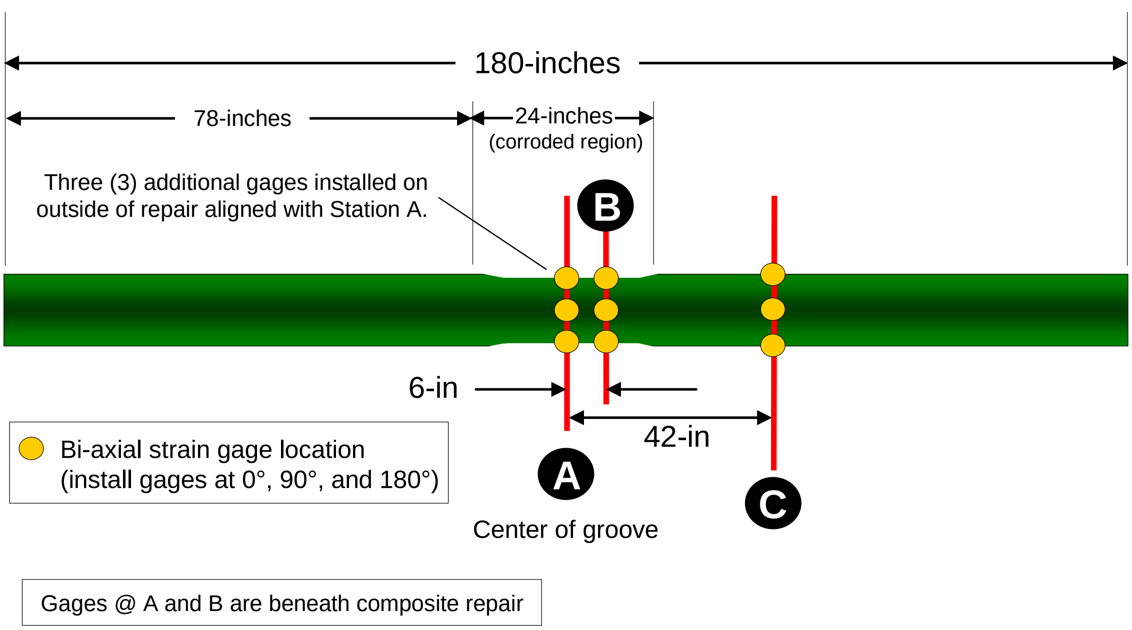


Figure 9 - Location of strain gages on the pressure-tension-bend samples

Figure 10 – Load frame used for pressure-tension-bend testing

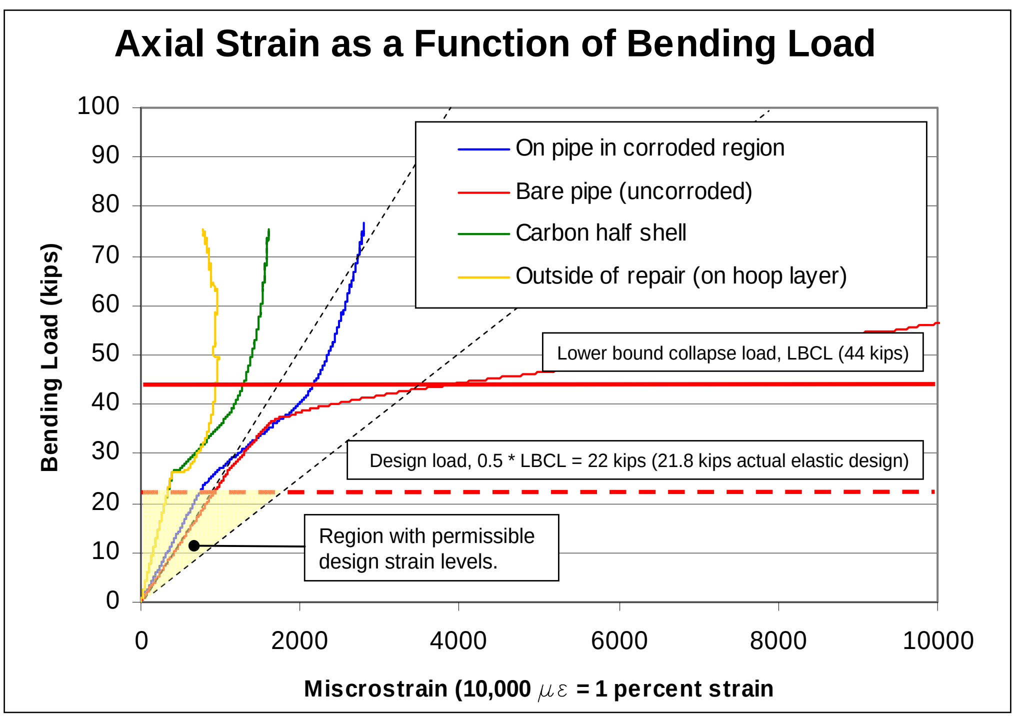


Figure 11 – Strain in one test sample subject to pressure, tension, and bending loads

Figure 12 – Photograph of flat spot in pipe prior to cyclic pressure fatigue testing

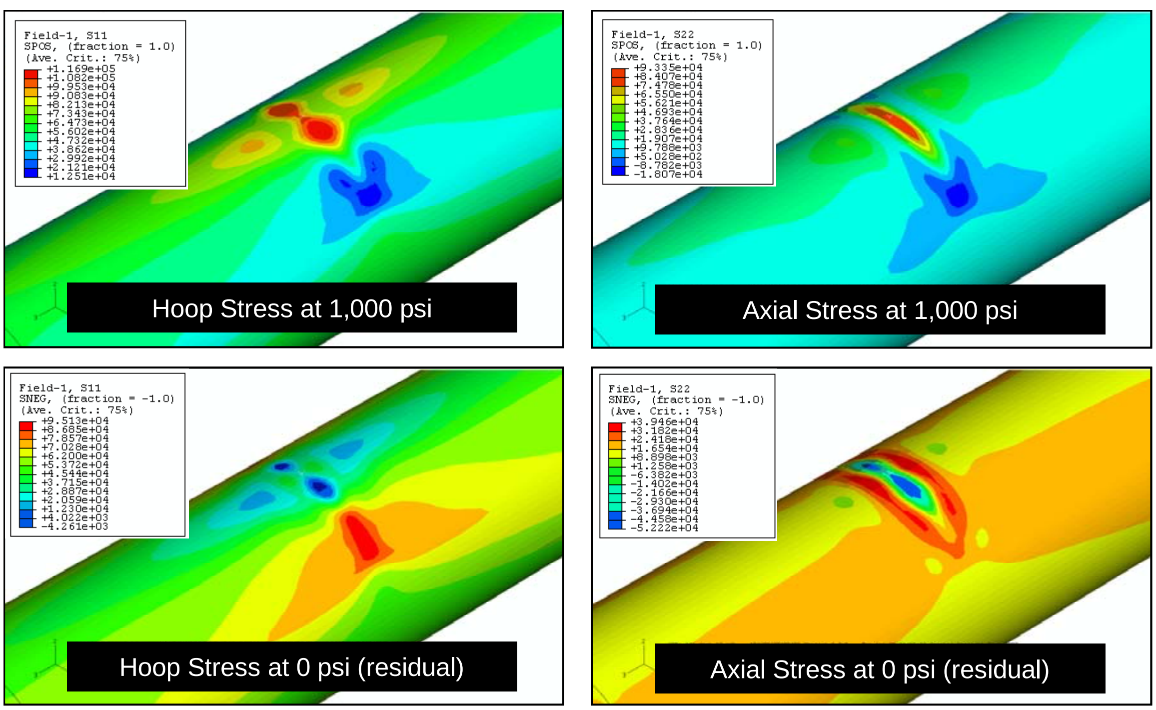


Figure 13 – Stress contour plots from FEA model showing extremes of pressure cycle

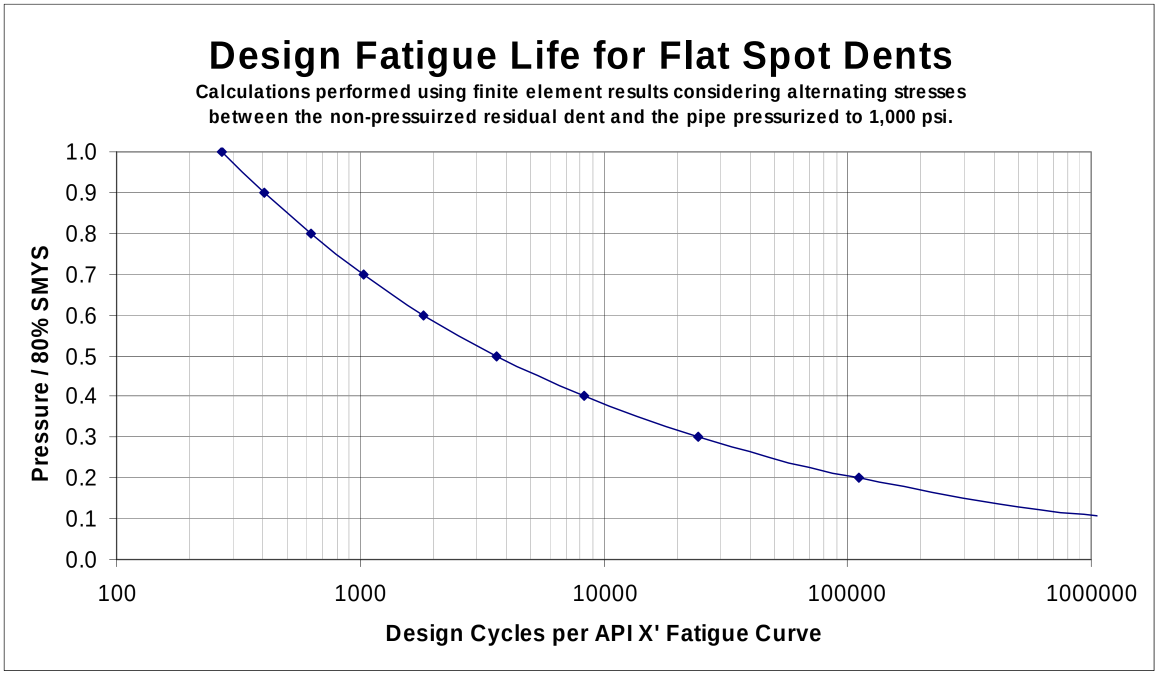


Figure 14 – Estimated design fatigue life based on FEA results
(Sample subjected to 13,819 pressure cycles at 80% SMYS, DP = 100 to 1,168 psi, with NO failure in flat spot)

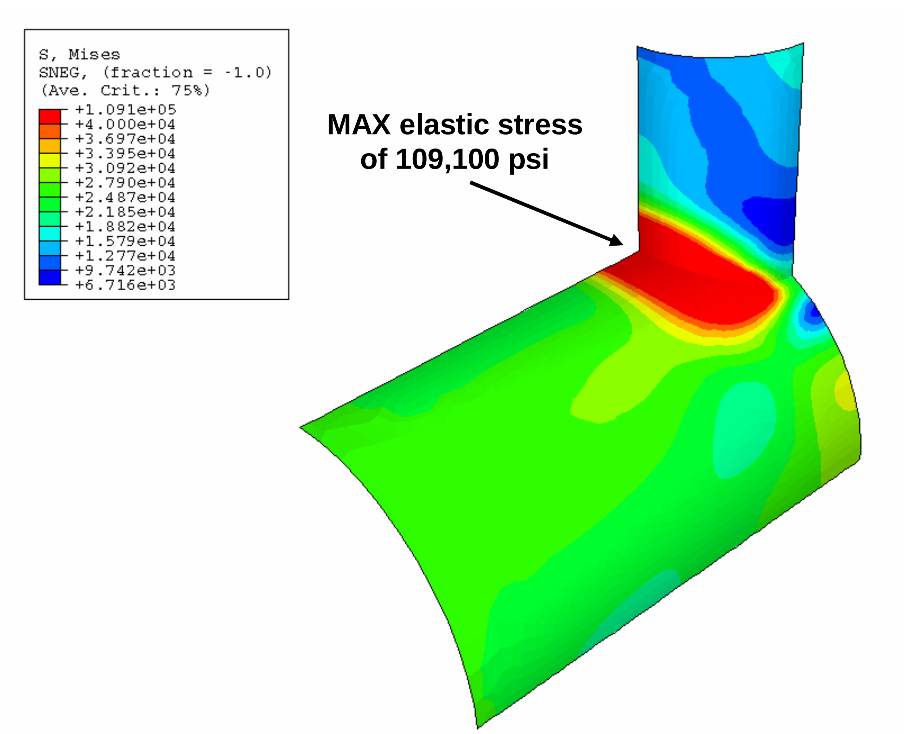


Figure 15 - Stress contour plot with 1,000 psi internal pressure (elastic stress shown)

Figure 16 – Leak that developed in composite-reinforced branch connection

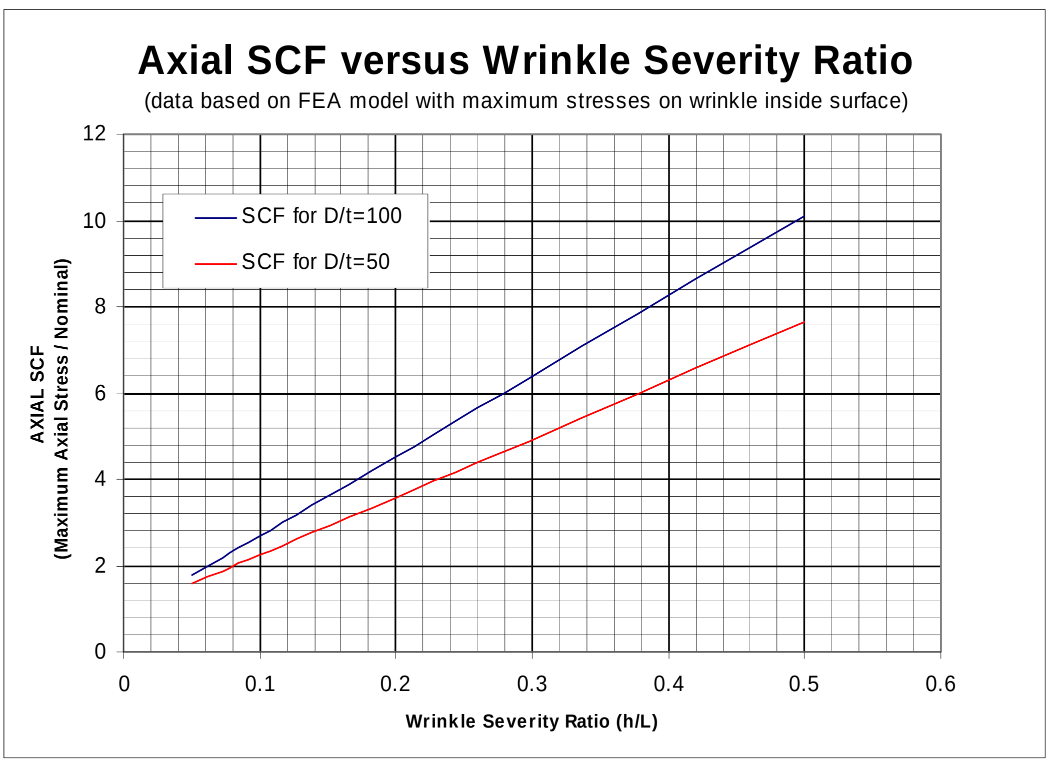


Figure 17 – Axial SCFs as functions of D/t and h/L based on elastic stresses

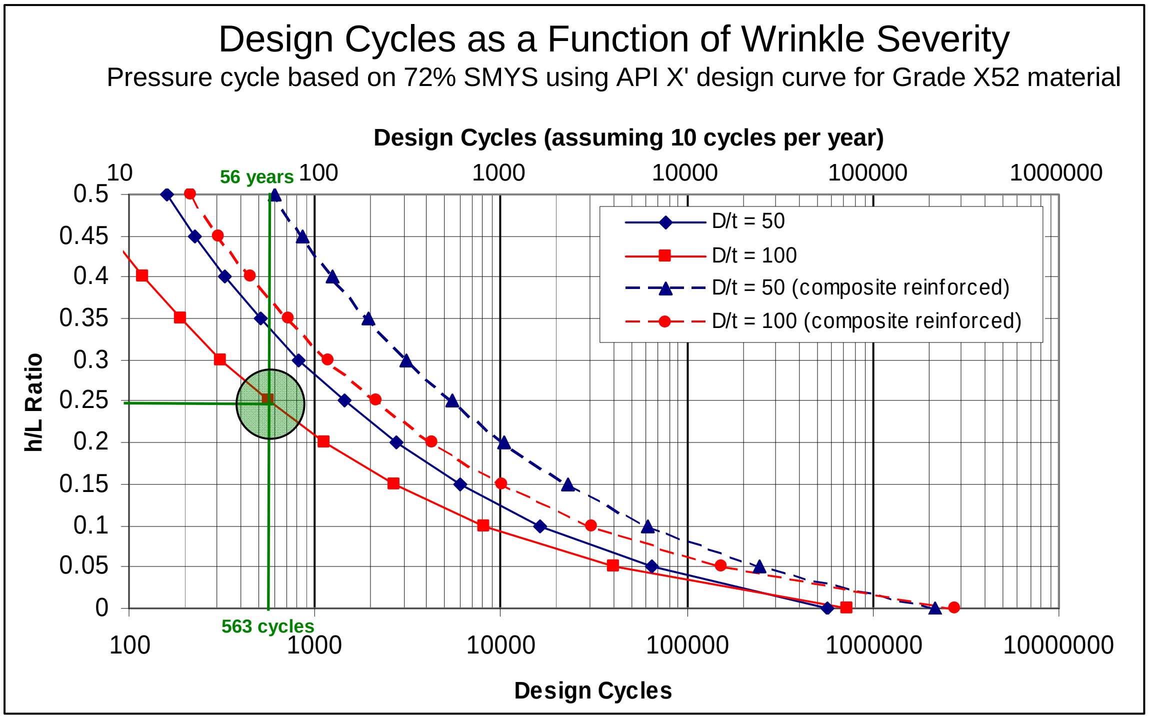


Figure 18 – Nomograph relating h/L ratio to design life and years of service
(analysis data plotted includes results with and without composite reinforcement)

Five Step Engineering-Based Integrity Management Program

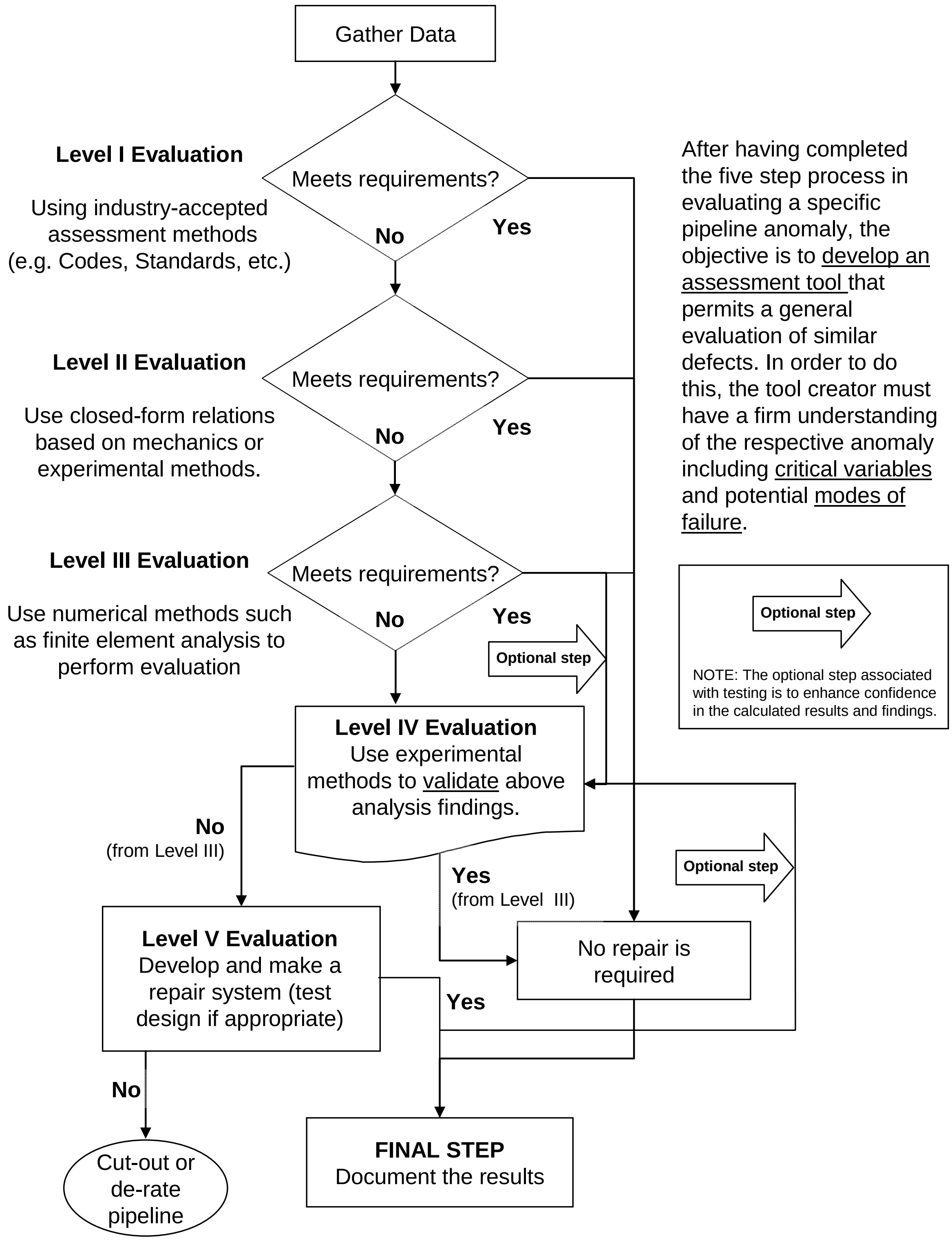


Figure 19 – Flow chart for the Five Step Engineering-Based Integrity Management Program