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EVALUATING THE EFFECTS OF WRINKLE BENDS ON PIPELINE INTEGRITY

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ABSTRACT

Concerns exist among the pipeline industry about the effects of wrinkle bends on the long-term integrity of pipelines. For this reason, a study was sponsored to assess the relative severity of wrinkle bends present in the El Paso pipeline system. The study involved a combination of full-scale cyclic pressure fatigue tests, along with finite element analysis, to determine cycles to failure. Strain gages were installed on select samples to determine alternating stresses. Also included in the study was installation of E-glass composite repair materials (Armor Plate® Pipe Wrap) on selected wrinkles to determine the potential for life extension considering the presence of reinforcement. The study helped in developing “in-the-ditch” evaluation criterion and a tool to determine the severity of a specific wrinkle bend based on geometric parameters including wrinkle height and length. The effects of metal loss due to corrosion were also considered. Additionally, the experimental results demonstrated that composite materials can extend the fatigue life of wrinkle bends

HISTORY AND APPROACH

Wrinkle bending is a process where wrinkles are introduced in a steel pipe during construction to obtain pipeline alignment. Bending practices used during pipeline construction, up until 1955, typically resulted in circumferential pipe deformation or wrinkles on the inside bend radius of the pipe. The wrinkle bends found on the El Paso Pipeline are generally of the wave shape with outward deformations. Additionally, “Mild ripples” are those developed using modern day field bending techniques where such ripples bear a length to height ratio on the order of 12. Whereas the wrinkle bends found typically on pre-1955 built pipelines are sharper than these ripples with length to height ratios on the order of 4.

Using some of the insights extracted from prior wrinkle bend study, SES and El Paso developed a program to specifically assess the performance of wrinkle bends as a result of vintage construction on a vintage pipeline. The wrinkle bends used in the program were those cut out from the pipeline which were installed in late 1940s. This program involved the following aspects.

- Each pipe sample integrated two wrinkle bends. A total of three (3) test samples were pressure cycled, resulting in a total of six (6) wrinkles. **Table 1** provides details on the pipe materials that were used in this test program, along with historical data, as well as operating pressure information.
- Strain gages were placed on all of the wrinkles to make measurements during pressure cycling. The strain gage results also provided information regarding the level of strain reduction provided by the addition of composite materials.
- One wrinkle on each of the samples was reinforced using Armor Plate® Pipe Wrap.
- After testing to failure, several of the wrinkles were fractured to determine the location of crack initiation.
- After testing was completed, finite element analyses were performed to determine the stress concentration factors (SCFs) associated with the wrinkles. The primary variables studied during testing were the wrinkle severity ratio, h/L, from 0.05 to 0.5 and the pipe diameter to wall thickness ratio, D/t, from 50 to 100.
- Selected strain gage results were used to confirm the relative accuracy of the SCFs. As will be shown, uniformly spaced wrinkles such as those tested in this program characteristically fail with a circumferential crack. This direction of fracture indicates that the maximum principal stress is oriented axially.
- Using the calculated SCFs, fatigue lives were estimated using the API X’ curve [1]. The calculations were compared to actual cycles to failure data from the testing efforts to determine the level of conservatism associated with the estimated fatigue lives.

Included in this paper are discussions on the methods used to test the wrinkle bend samples as well as results. Details are provided on the finite element model results and how the stress concentration factors were calculated. Finally, a methodology is developed and presented for estimating an acceptable design life for a given wrinkle profile.

The results of this program show the benefits associated with integrating test results along with analytical calculations based on finite element methods. The primary objective that was accomplished was to provide El Paso with a grading method for assessing the relative severity of wrinkle bends using profile measurements available via either caliper tool data or actual in-the-ditch field measurements, made by hand.

EXPERIMENTAL METHODS AND RESULTS

The initial focus of this study was to determine the fatigue lives for wrinkle bends extracted from El Paso’s pipeline system. This was accomplished by welding end caps to each of the three test samples and pressure cycling to failure. Prior to pressure cycling, an extensive level of effort was involved in sample preparation that included making wrinkle profile measurements, installing strain gages, grinding to represent corrosion, and reinforcing select wrinkles with composite material.

Previous research demonstrated that the dominant stress in wrinkles as axial based on the circumferentially-oriented fracture that typically develops [2]. This information is important for several reasons. First in designing the composite repair architecture the importance of axially-oriented fibers was noted. Secondly, the capped end condition of test samples generates axial stresses that are greater than axial stresses present in an actual pipeline where plane strain conditions exist. Consequently, experimental fatigue life results are likely conservative when compared to actual conditions.

The sections that follow provide specific details on test methods and also include results for the measured strains and recorded cycles to failure.

Measuring Wrinkle Profiles

As discussed prior studies, the wrinkle severity ratio, h/L, is the geometric characteristic that best describes the severity of a given wrinkle. Any integrity management program charged with assessing wrinkles (and dents for that matter) should consider the h/L ratio as the first-line grading tool. This ratio is simple to acquire in the field from an exposed pipeline.

From the welded test samples, wrinkle profile measurements were made. **Figures 1** and **2** are photographs showing the equipment that was used, which included:

- Steel straight edge with graduated markings (1 inch minimum spacing)
- Magnetic bases for offsetting the steel straight edge
- Dial calipers
- Steel profile comb

Table 2 provides the profile measurements that were made on the six wrinkles to be pressure cycled. Highlighted in the table are select depth measurements that were used to assess the h/L ratio for each wrinkle. Using these data, the following h/L ratios were captured: It should be noted that profile measurements for Sample EP30 (both 1A and 1B) were originally made prior to grinding the simulated 40 percent wall loss. The adjusted h/L ratios are noted in parentheses adjacent to the original values.

Sample EP22-1A h/L = 0.093
Sample EP22-1B h/L = 0.121
Sample EP22-2A h/L = 0.095
Sample EP22-2B h/L = 0.119
Sample EP30-1A h/L = 0.132 (0.108 if adjusted for 40 percent corrosion)
Sample EP30-1B h/L = 0.123 (0.103 if adjusted for 40 percent corrosion)

In addition to measuring the wrinkle profiles, a useful tool is the steel profile comb. A photograph showing the use of this comb on Sample EP22-1B is shown in **Figure 2**. Using this tool provides a quick check on the h/L ratio as the profile can be traced onto a sheet of paper thus permitting h and L to be measured. **Figure 3** shows the geometry associated with the length, *L*, and height, *h*, values. The length, *L*, is represented as the distance over which the curvature of the wrinkle decays back to the original profile of the pipe. For the pipes used in this study, the length was relatively well defined as the pipe was generally straight outside of the wrinkle. This might be possible for all wrinkle profiles.

Strain Gage Installation

Strain gages were installed on each of the tested wrinkle bends. The objective was to capture strains present in the wrinkle during pressure cycling. With end caps on a test sample, the axial stress in the pipe is one-half the hoop stress. However, in a buried pipeline which acts in plane strain, the axial stress is approximately one-third the hoop stress due to Poisson's effect. This is an important point, as the axial loads during testing are approximately 70 percent greater than those observed in actual service. Hence, the measured strains and measured cycles to failure represent conservative, lower bound results. In other words, in actual service the fatigue lives for the given wrinkles will likely be greater than those recorded in the lab and reported in the test program.

One of the benefits in using strain gages is the ability to experimentally determine stress concentration factors (SCFs) associated with wrinkle profiles. These SCFs will be used in further discussions to validate calculations made using finite element analysis.

Figure 4 provides a schematic showing where strain gages were installed on each wrinkle. As noted, there are two wrinkles on each test sample and a middle gage at location #5 was installed on the bare pipe between the wrinkles to capture nominal hoop and axial strain values. As noted in this figure, a total of nine strain gages were installed on each test sample. For the pressure cycle testing, data were recorded at 1 scan per second. After testing the results were output to an EXCEL spreadsheet for post-processing. Results are presented in a later section of this paper.

Installation of Composite Material

One of the primary objectives of this program was to assess the ability of composite materials to reinforce the wrinkles and reduce strain during pressure cycling. Armor Plate, Inc. provided materials and staff to install their Armor Plate® Pipe Wrap (APPW) system on three of the six tested wrinkles. Prior to testing, all pipe samples were sandblasted to near white metal.

Based on a previous research study addressing bending on corroded pipes, SES and Armor Plate, Inc. determined that because of the large axial stresses present in a wrinkle, the repair should integrate orientation of fibers in the axial direction. Typically, when APPW is used to repair corrosion, it is advantageous to maximize the number of fibers in the hoop direction. Even during normal installations, APPW has fibers that run in both the hoop and axial directions; however, coupon testing has shown that this system is approximately 50 percent stronger in the hoop direction than the axial direction. For this reason, one-third of the reinforcement material was oriented in the axial direction.

The following composite reinforcement configuration was used, resulting in a total thickness of 0.563 inches. The length of each repair was approximately two feet, with one foot being on each side of the center of the wrinkle.

- Three layers hoop-oriented cloth totaling 0.188 inches (one-third composite thickness)
- Three layers axially-oriented cloth totaling 0.188 inches (one-third composite thickness)
- Three layers hoop-oriented cloth totaling 0.188 inches (one-third composite thickness)

The total thickness of the composite material equaled a value equal to approximately 1.5 times the nominal pipe wall thickness. As noted, the inner and outer layer sets each equal 0.5 times the wall thickness and are oriented in the hoop direction, while the middle set of layers are oriented axially and have a thickness equal to 0.5 times the pipe wall thickness.

Strain gages were installed prior to installation of the APPW material. Epoxy putty was used to create a smooth profile around the strain gage lead wires. Additionally, a layer of epoxy was painted to seal the exposed pipe prior to installation of the reinforcing material. **Figure 5** shows a completed repair on the pipe sample using the composite reinforcement.

It is appropriate to discuss how composite materials are likely to reinforce wrinkle bends in situ. The composite materials used in this study utilized an E-glass material with a two-part epoxy resin. Fibers were oriented in both the circumferential and axial directions. Had the repair only included circumferential reinforcement, the level of reinforcement would have been reduced. Additionally, the elastic modulus of the material used in this program is on the order of 2 million psi. It is possible that further reduction in wrinkle bend stresses beneath the repair could be achieved using a material with a larger elastic modulus. However, based on previous research the E-glass material of the system used in this study out-performed other repair systems in extending the fatigue life of mechanical damage [3], even those composite material having greater elastic modulii and failure strengths.

Pressure Cycle Testing

Once preparation of the samples was completed, pressure cycling was started. As part of the test lab, SES has a pressure cycle fatigue pump that permits pipe samples to be cyclically loaded using internal pressure. The pump uses water as the testing medium. To start testing, the maximum and minimum pressures are programmed into the pumping unit's control box. **Table 3** provides details on the pressure cycle conditions applied to each sample.

Strain Gage Results A significant body of strain data was collected; however, the focus in this presentation is the maximum strain range that occurred in each of the samples. **Figure 6** provides hoop and axial strain gage results for sample EP22-1. Also included in this plot are the nominal hoop and axial strains calculated using the following relations. Note that these units of strain (and all strain gage data presented herein) are in microstrain, $\mu\varepsilon$, where 10,000 $\mu\varepsilon$ equals 1 percent strain. To convert strain to stress, simply multiply strain (measured in units of microstrain) by 30 (units are in psi).

$$\varepsilon_{hoop} = \frac{1}{E}\left(\sigma_{hoop} - \sigma_{axial}\right) \qquad (1)$$

$$\varepsilon_{axial} = \frac{1}{E}\left(\sigma_{axial} - \sigma_{hoop}\right) \qquad (2)$$

where:

ΔP	Range of cyclic internal pressure (psi)
R	Outside pipe radius (inches)
t	Nominal pipe wall thickness (inches)
E	Modulus of elasticity for steel (30 million psi)
σ_{hoop}	Hoop stress calculated as PR/t (psi)
σ_{axial}	Axial stress calculated as PR/2t (psi)

From the collected strain gage data, the strain ranges were extracted. The results from this effort are provided in **Table 4**. Note that the presented results are for the axial strain gage results. From previous research efforts and those demonstrated in this study, the maximum principal strains in the wrinkles are axially-oriented. This differs from conventional pipe mechanics where the circumferential stresses and strains dominate.

The following observations are made in reviewing the data provided in **Table 4**.

- As expected, the maximum strains are measured in Sample EP30-1 where 40 percent of the wall thickness was removed to simulate corrosion. This increased strain results in fatigue life reduction.
- The contribution of the composite materials reduces strain in the reinforced wrinkles. On average, the strain reduction is 42 percent. Considering a fourth order relationship between cycle life and strain range, a 30 percent reduction in stress effectively increases fatigue life by a factor of approximately 4.
- Elastic stresses are computed by multiplying the measured strain ranges by 30.

One important observation concerns the range of strains. Even though wrinkles (and dents) involve plastic deformation in their formation process, once several pressure cycles are applied to the sample a "shakedown" to elastic condition exists. This means that even though the defects are plastically deformed with additional pressure cycles an elastic response from the deformed region is likely. This trend was clearly evident in the recorded strain gage data. This simplifies efforts associated with estimating fatigue life from alternating stresses.

Fatigue Test Results

Each of the samples was pressure cycled until failure occurred. Each sample had two wrinkles. After the first wrinkle failed it was removed and continued testing would occur by moving the remaining end cap down and re-welding. A metallurgical evaluation was performed on several of the fatigue cracks that developed in the wrinkles. The following section of this paper provides details on this work.

Table 5 provides information on the number of pressure fatigue cycles applied to each sample. One sample (EP22-1) was cycled 93,125 cycles before failure occurred in the weld attaching the 1-inch NPT weld-o-let bosset to the sample's end caps. Pressure cycling was terminated as an extensive number of pressure cycles had already been applied. Several important observations are made in viewing the data provided in **Table 5**.

- Results from Sample EP30-1 clearly show the benefits derived in using composite materials to reinforce wrinkles. The fatigue life for the reinforced wrinkle was approximately two times the number of cycles to failure recorded for the unreinforced sample.
- The shortest fatigue lives were those associated with Sample EP30-1. The presence of the 40 percent corrosion contributed to the reduced fatigue life.
- The wrinkles in Sample EP22-1 included the presence of a flash weld seam weld. It is likely that this additional stress concentration contributed to the fracture initiation. Furthermore, additional testing involving only the reinforced sample generated a failure outside of the repair. Therefore, it is not possible to precisely ascribe the level of benefit associated with the repaired condition.

ANALYSIS METHODS AND RESULTS

Finite element analysis was used to calculate stress concentration factors for wrinkles. The intent was to determine the SCFs as functions of two primary variables: the pipe diameter to wall thickness ratio, D/t, and the wrinkle severity ratio, h/L. Most of the FEA-calculated results are presented including a brief description of the analysis methods with summary results is provided.

The ABAQUS general-purpose finite element software package was used to calculate hoop and axial stresses in the wrinkles. Because of the general symmetry conditions associated with the geometry of the wrinkles, axisymmetric conditions were assumed. Although wrinkles do not go all the way around the pipe, the circumferential decay of the wrinkle occurs over a span of 150 to 180 degrees, so for the intrados of the wrinkle bend an axisymmetric condition can be assumed. Based on comparison with the strain gage results, the axial SCFs show good agreement, thus confirming the validity of this approach.

A total of eight models were constructed integrating D/t ratios ranging from 50 to 100 and h/L ratios of 0.05, 0.1, 0.2, and 0.5. In the models the height of the\ wrinkles was varied, while maintaining a length of 6.0 inches. From the analysis results, the maximum hoop and axial stresses on the inside and outside surfaces of the models were extracted. From the results, SCFs were calculated by dividing the maximum stresses by the nominal stresses. Internal pressure was considered, along with pressure end loading associated with a capped end condition. As discussed previously, this boundary condition generates greater axial stresses than the plane strain conditions associated with a buried pipeline; however, the intent was to correlate the calculations with the experimental findings.

There are several noteworthy observations made in reviewing the finite element results.

- The maximum axial stresses occur in the center of the wrinkle and decay relatively rapidly in moving into the nominal straight section of pipe. These results are consistent with fatigue cracks initiated experimentally.
- The maximum axial tensile stress occurred on the inside surface of the pipe. This is also consistent with experimental findings showing that fatigue cracks initiate from the inside surface of the wrinkle.
- Recognizing that in a capped end sample, axial stresses are one-half hoop stress, it is clear that the axial SCFs are larger than the hoop SCFs (even with a relatively shallow wrinkle severity ratio of 0.05). In reviewing the legends associated with each of the plots, the maximum axial stress on the inside surface of the wrinkle is 43.4 ksi, while the maximum hoop stress is 50.4 ksi.

Figure 7 plots the axial SCFs on the inside surface of the pipe for the range of pipe D/t and h/L ratios considered in this study. As expected, the maximum SCF is associated with the larger D/t pipe and the wrinkle severity ratio, h/L, significantly impacts the magnitude of the SCF. These SCFs serve as the foundation for further discussions on how the wrinkle bend severity impacts integrity management.

GUIDELINES AND APPLICATION OF RESULTS

One of the clear objectives of this program was to develop a methodology for assessing the effects of wrinkle bends. While testing and finite element analyses are both of value, the greater contribution is to use insights from both of these assessment methods to develop a single tool. The ideal assessment tool is one that can take known parameters such as the wrinkle profile, pipe geometry, and operating pressure of the pipeline and estimate remaining life. The purpose of this section of the paper is to provide details on the methods used by SES to develop an assessment tool that integrates key variables. It should be noted that the quality of the tool is directly proportional to the pipes that have been tested and analyzed as part of this program. Changes to conditions such as material grade and seam weld quality can impact the assumed outcome. Additionally, guidelines are provided based on findings from this study as well as previous research efforts.

Figure 8 is a flow chart that shows the process developed to formulate an expression for estimating a design fatigue life. The discussions that follow provide specific details on how this process was completed.

An important observation relates to the statistical significance of the presented results. While the trends associated with this study are certainly consistent, it should be noted that a total of only six data points have been studied, and of these only two resulted in verifiable cracks at the center of the wrinkle. Additionally, the presented results are likely to be conservative for several reasons. First, buried pipelines are constrained which reduces that amount of deformation and resulting alternating stresses that occur during pressure cycling. Secondly, the pressure end loading (i.e. axial force) from a capped end test sample is 67 percent greater than the axial force generated in a buried pipe. Because the primary contributor to cracks in wrinkle bends is axial stress, the reduced axial loads will increase the actual cycles to failure.

Development of Stress Concentration Factors

Stress concentration factors (SCFs) are commonly used in engineering design to help engineers assess the stress increase associated with a particular component or region of a component. Examples of SCFs in pipeline systems include those associated with pipe fittings such as tees, elbows, and trunions. By knowing the nominal state of stress, SCFs are used to estimate the amplification of stress associated with specific pipe geometries. The finite element results previously presented are used in developing the SCFs for the different analysis variables considered (i.e. pipe D/t, wrinkle profile geometry, h/L).

For discussions on mechanical integrity, SCFs can also be assigned to pipe anomalies such as dents and wrinkles. The stress risers associated with these anomalies can lead to premature failures, typically in the form of either burst or leak. As pipelines age, the remaining life is reduced as the SCFs generate elevated stresses which in turn reduces the fatigue life. Consider the expression below where S is stress range and N is fatigue life (cycles to failure). The constants *C* and *m* are material-dependant empirically-derived values (i.e. for the API X' curve from API RP2A $C=2.978\text{x}10^{21}$, m=3.74, and ΔS is in units of *psi*).

$$N = C \bullet \Delta S^{-m} \tag{3}$$

Using the above expression, if we assume a fourth order relationship between stress and cycle life (i.e. m = 4) and the stress range is doubled, it is shown that the increased stress range reduces the fatigue life by a factor of 16. This is an important observation considering that SCFs for dents and wrinkles are typically greater than two.

Based on insights observed during this and previous test programs for uncorroded wrinkles not in conjunction with seam welds, cracks develop normal to the maximum principal stress which is axial. Axial stresses dominate the failure pattern of wrinkle bends and consequently SCFs are presented using axial stresses calculated by FEA and confirmed by experimental strain gage work. The axial SCFs are calculated by dividing the calculated maximum axial stress in the wrinkle (on the inside surface of the wrinkle) by the nominal axial stress in the pipe. This is shown in the following relation where $\Delta\sigma_{\text{axial}}$ is the FEA-calculated maximum axial stress in the wrinkle, ΔP is alternating internal pressure, *R* is outside pipe radius, and *t* is the pipe wall thickness.

$$SCF_{axial} = \frac{\Delta\sigma_{axial}}{\left[\dfrac{\Delta P \cdot R}{2t}\right]} \qquad (4)$$

From the outset the focus in using finite element analysis was to determine the effects of the wrinkle profile ratio *h/L*, and pipe diameter to wall thickness ratio, *D/t*. Shown in **Figure 9** are axial SCFs calculated as functions of D/t and h/L.

Using the Proposed Methods to Estimate Remaining Life

The primary objective in assessing pipeline anomalies is to estimate the remaining life. One of the challenges associated with this task is accounting for the potential pressure variations that occur during normal operation. A methodology based on the well-known Miner's Rule has been adopted for this discussion. The following equation, based on a fourth-order relationship between stress and fatigue life as denoted by the exponent of 4, is used to develop a single equivalent cycle count for a combination of different pressure ranges and counts. In the equation below K represents the number of pressure groups.

$$N_{eq} = \sum_{i=1}^{K} Ni \cdot \left(\frac{\Delta P}{P_{MAOP}} \right)^{4} \qquad (5)$$

For purposes of application, consider **Table 6** which shows four pressure groups (K=4) along with the corresponding pressure range and frequency. Using the data provided in this table, the following equivalent pressure is calculated (cpy is cycles per year).

$$N_{eq} = 20 \cdot (0.25)^4 + 5 \cdot (0.50)^4 + 3 \cdot (0.75)^4 + 2 \cdot (1.00)^4 = 3.34\,cpy$$

For Sample EP30-1A where the estimated design life is 1,320 cycles, the corresponding estimated years of service for the assumed pressure history is 395 years. This methodology can be applied for any range of pressure histories.

Another example problem is provided. The purpose of this example is to assess the remaining life for a pipeline with a D/t ratio of 100 and an h/L ratio 0.2 having wrinkles that was installed in 1940 (1,133 design cycles on Grade X52 pipe using the above equation). By 2007 this particular pipeline will have 67 years of service. **Table 7** below provides the remaining life assuming different numbers of blowdowns per year. As noted in this table, even with four (4) blowdowns per year a remaining life of 216 still exists.

Cycle Life Nomograph

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 10**. 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.

Also included in this plot are data assuming the installation of composite reinforcing materials. These data were calculated by reducing the stress range by 30 percent based on the strain gage results from testing (refer to data presented in **Table 4** showing reduction in strain due to composite reinforcement). Using the same reference point considered above (h/L ratio of 0.25 in a pipe having a D/t ratio of 100), the fatigue life is increased from 563 cycles for the unreinforced sample to 2,139 cycles for the reinforced sample.

A limited number of variable sets are provided in **Figure 10**; however, it is possible that a family of curves could be generated considering different operating pressure ranges (i.e. functions of pipe material grade) and pipe D/t ratios.

CONCLUSIONS

This paper has provided findings on the study performed by Stress Engineering Services, Inc. for El Paso Pipeline Group to assess the effects of wrinkle bends on the mechanical integrity of their pipeline system. The study involved a combination of full-scale cyclic fatigue testing, along with finite element analysis, to determine cycles to failure and alternating stresses in the wrinkles. Also included in the study was the installation of a composite repair system on selected wrinkles to determine the potential for life extension considering reinforced conditions.

Also included as part of the study was assessing the effects of localized corrosion in the wrinkle and the effects of having a seam weld in the middle of the wrinkle. Before testing was started, the wrinkle profile was measured in order to capture the corresponding h/L ratio. Additionally, strain gages were installed on each of the wrinkles to monitor strain during pressure cycle testing and also assess the level of reinforcement provided by the composite material.

Finite element models were used to develop stress concentration factors relative to the effects of wrinkle profile and pipe geometry on the stress level in the wrinkles. Using the calculated stress values and corresponding SCFs, an estimate of remaining life was calculated using the API X' design fatigue curve.

The minimum fatigue life recorded during testing was 19,252 cycles which was in Sample EP30-1A that was fitted with 40 percent corrosion. It should also be noted that the applied pressure range was 100 percent of the maximum operating pressure. Hence, one can conclude that for wrinkles having geometries comparable to those evaluated as part of this study do not pose an imminent threat to the integrity of the pipeline. This statement is predicated on several observations. First, wrinkles in seam and girth welds are subject to inferior performance, even though the unrepaired wrinkle EP22-1A was located in a flash seam weld and cycled 42,818 cycles. Secondly, the typical wrinkle severity ratio (h/L) in this study was on the order of

0.12. As this ratio increases, the cycles to failure will decrease. Lastly, although the 40 percent corrosion had a relatively long fatigue life, the presence of severe and pitted corrosion not considered specifically in this study will significantly reduce the remaining life of the pipeline system.

It is recognized that additional research will build on the findings of this program and research conducted by others. Other areas of interest include evaluating the effects of thermal expansion due to operating temperatures, pipe-soil interaction and associated tension and bending effects on the pipeline, and expanding the pipe geometries to include a wider range of pipe diameter to wall thickness ratios (D/t). The effect of corrosion on the fatigue behavior on wrinkle bends also requires further analysis. Additional studies should be conducted to compare the findings of this program to research conducted by other investigators.

Based on the study that was conducted, El Paso developed "in-the-ditch" wrinkle bend evaluation criteria. Some of the highlights are provided below:

1. The wrinkle bend, when exposed, should be inspected for surface conditions. Any stress risers or stress concentrators should be ground within acceptable limits and recoated.
2. Composite wrap of wet applied or wet lay-up systems (e.g. Armor Plate® Pipe Wrap or equivalent) may be used to repair metal loss of less than 40% in wrinkle bends.
3. Precautionary measures must be taken to ensure that the wrinkle bend will not be subjected to flexure (pipe movement) during application of composite wrap.
4. The composite wrap, when used for reinforcement of wrinkle bends, should be installed so that 1/3 of the thickness of the wrap is installed circumferentially (inner layers), 1/3 axially (middle layers), and 1/3 circumferentially for an effective repair (outer layers).
5. Any wrinkle bend that may be subject to flexure should be cut-out.

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Table 1 – Details on El Paso Pipe Test Materials

Sample Number	Pipe Geometry and Grade	Grade	Condition	72% SMYS
EP30-1A	30-inch x 0.312-inch	X52	Unrepaired	779 psi
EP30-1B	30-inch x 0.312-inch	X52	Repaired	779 psi
EP30-2A	30-inch x 0.312-inch	X52	Repaired	779 psi
EP30-2B	30-inch x 0.312-inch	X52	Repaired	779 psi
EP22-1A (weld)	22-inch x 0.312-inch	X42	Unrepaired	858 psi
EP22-1B (weld)	22-inch x 0.312-inch	X42	Repaired	858 psi
EP22-2A	22-inch x 0.312-inch	X42	Unrepaired	858 psi
EP22-2B	22-inch x 0.312-inch	X42	Repaired	858 psi

Sample Number	MAOP	Test Pressure	In-Service Date	Seam type
EP30-1A	750	1082 psig	1948	DSAW
EP30-1B	750	1082 psig	1948	DSAW
EP30-2A	750	1082 psig	1948	DSAW
EP30-2B	750	1082 psig	1948	DSAW
EP22-1A (weld)	714	1081 psig	1947	Flash Weld
EP22-1B (weld)	714	1081 psig	1947	Flash Weld
EP22-2A	714	1081 psig	1947	Flash weld
EP22-2B	714	1081 psig	1947	Flash Weld

Note: Data are split into two tables for readability; note that the sample numbers are the same.

Table 2 – Wrinkle Profile Depth Measurements

(Units are in inches where *L* is the axial position of the measurement)

L	EP22-1A	EP22-1B	L	EP22-2A	EP22-2B	L	EP30-1A	EP30-1B
1	0.084	0.262	1	0.246	0.326	1	0.053	0.092
2	0.080	0.272	2	0.232	0.317	2	0.060	0.111
3	0.068	0.250	3	0.228	0.298	3	0.065	0.116
4	0.057	0.232	4	0.216	0.274	4	0.077	0.130
5	0.052	0.202	5	0.211	0.257	5	0.081	0.137
6	0.055	0.186	6	0.180	0.236	6	0.100	0.130
7	0.164	0.151	7	0.183	0.231	7	0.071	0.113
8	0.471	0.238	8	0.173	0.220	8	0.061	0.092
9	0.558	0.519	9	0.132	0.205	9	0.036	0.002
10	0.177	0.728	10	0.113	0.174	10	0.000	0.000
11	0.000	0.391	11	0.184	0.181	11	0.049	0.078
12	0.015	0.030	12	0.417	0.485	12	0.399	0.545
13	0.060	0.000	13	0.570	0.712	13	0.662	0.736
14	0.087	0.060	14	0.350	0.438	14	0.467	0.467
15	0.127	0.115	15	0.039	0.032	15	0.070	0.201
16	0.157	0.160	16	0.000	0.000	16	0.103	0.174
17	0.187	0.188	17	0.023	0.052	17	0.109	0.178
18	0.197	0.210	18	0.060	0.117	18	0.120	0.174
19	0.187	0.230	19	0.095	0.173	19	0.126	0.174
20			20	0.134	0.208	20	0.127	0.184
			21	0.124	0.225	21	0.127	0.183
			22	0.161	0.230	22	0.126	0.183
			23	0.186	0.254	23	0.127	0.187
			24	0.178	0.288	24	0.127	0.185
			25	0.202	0.327	25	0.127	0.186

Notes:

1. Data presented were acquired using a straight edge that was offset from the pipe in order to locate the maximum and minimum height locations on each wrinkle
2. The cells highlighted in ORANGE were used to calculate the wrinkle severity ratio, h/L.

Table 3 – Test Sample Pressure Cycle Conditions

Sample Number	Pipe Geometry	Grade	Condition	ΔP (psi) (min to max)
EP30-1A	30-inch x 0.312-inch	X52	Unrepaired (40% corrosion)	100-779
EP30-1B	30-inch x 0.312-inch	X52	Repaired (40% corrosion)	100-779
EP30-2A	30-inch x 0.312-inch	X52	Unrepaired	100-779
EP30-2B	30-inch x 0.312-inch	X52	Repaired	100-779
EP22-1A (weld)	22-inch x 0.312-inch	X42	Unrepaired	100-858
EP22-1B (weld)	22-inch x 0.312-inch	X42	Repaired	100-858
EP22-2A	22-inch x 0.312-inch	X42	Unrepaired	100-858
EP22-2B	22-inch x 0.312-inch	X42	Repaired	100-858

Table 4 – Strain range results for wrinkle samples

Sample	Condition	Peak of Wrinkle (Axial)		3 inches from Wrinkle (Axial)	
		$\Delta\varepsilon$ ($\mu\varepsilon$)	$\Delta\sigma$ (ksi)	$\Delta\varepsilon$ ($\mu\varepsilon$)	$\Delta\sigma$ (ksi)
EP22-1A (unrepaired)	Wrinkle in seam weld	1190	36	979	29
EP22-1B (repaired)	Wrinkle in seam weld	820	25	703	21
Percent reduction due to composite		31.1 percent		28.2 percent	
EP22-2A (unrepaired)		954	29	1096	33
EP22-2B (repaired)		757	23	868	26
Percent reduction due to composite		20.6 percent		20.8 percent	
EP30-1A (unrepaired)	40 percent corrosion	1960	59	1321	40
EP30-1B (repaired)	40 percent corrosion	1259	38	1213	36
Percent reduction due to composite		35.8 percent		8.2 percent	

Notes:

1. Sample EP22-1 fabricated from 22-in x 0.312-in, Grade X42 pipe
2. Sample EP22-2 fabricated from 22-in x 0.312-in, Grade X42 pipe
3. Sample EP30-1 fabricated from 30-in x 0.312-in, Grade X52 pipe

Table 5 – Fatigue Test Results

Sample Number	Pipe Geometry	Grade	Condition	ΔP (psi) (min to max)	Cycles	Notes
EP30-1A	30-inch x 0.312-inch	X52	Unrepaired (40% corrosion)	100-779	19,252	Crack developed in center of wrinkle
EP30-1B	30-inch x 0.312-inch	X52	Repaired (40% corrosion)	100-779	41,171	Crack developed beneath APPW repair
EP22-1A (weld)	22-inch x 0.312-inch	X42	Unrepaired	100-858	42,818	Crack developed in center of wrinkle
EP22-1B (weld)	22-inch x 0.312-inch	X42	Repaired	100-858	55,371	Longitudinal crack developed outside of repair
EP22-2A	22-inch x 0.312-inch	X42	Unrepaired	100-858	93,135	Crack developed in bosset weld (test aborted)
EP22-2B	22-inch x 0.312-inch	X42	Repaired	100-858	93,135	Crack developed in bosset weld (test aborted)

Table 6 – Exemplar Pressure Groups for a Typical Gas Pipeline

Pressure Group	ΔP / MAOP (percentage of operating pressure)	N_i (cycles per year)
1	0.25	20
2	0.50	5
3	0.75	3
4	1.00	2

Table 7 – Estimated remaining Life for 1940 pipe as a function of annual blowdowns

Annual Blowdowns (72% SMYS for Grade X52)	Blowdowns in a 67 year period	Cycles Remaining (after 67 years)	Years Remaining
1	67	1,066	1,066
2	134	999	499
4	268	865	216

Figure 1 – Tools used to measure wrinkle profile

Figure 2 – Measurement made using steel profile comb

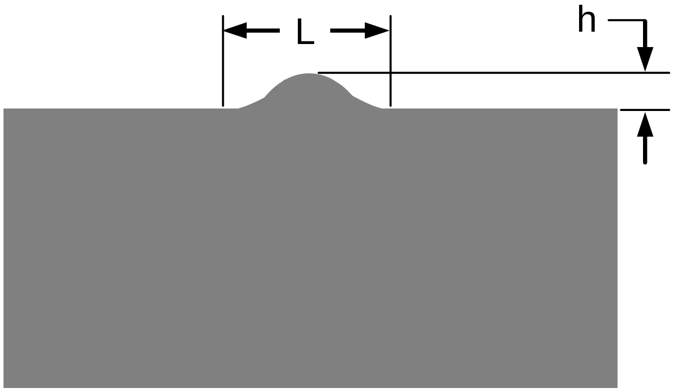

Figure 3 – Geometry measurement parameters for the wrinkle profile

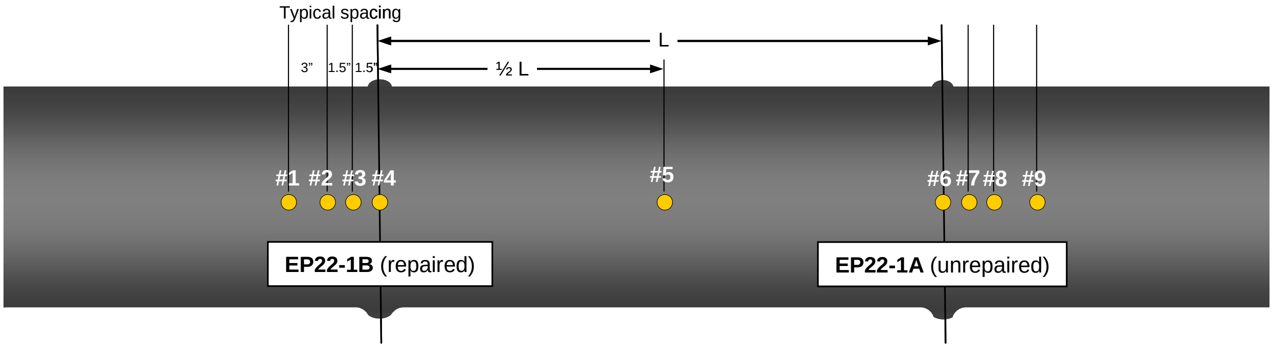

Figure 4 – Schematic showing strain gage locations
(markings specifically for Sample EP22-1)

Figure 5 – Photo showing completed installation of Armor Plate® Pipe Wrap

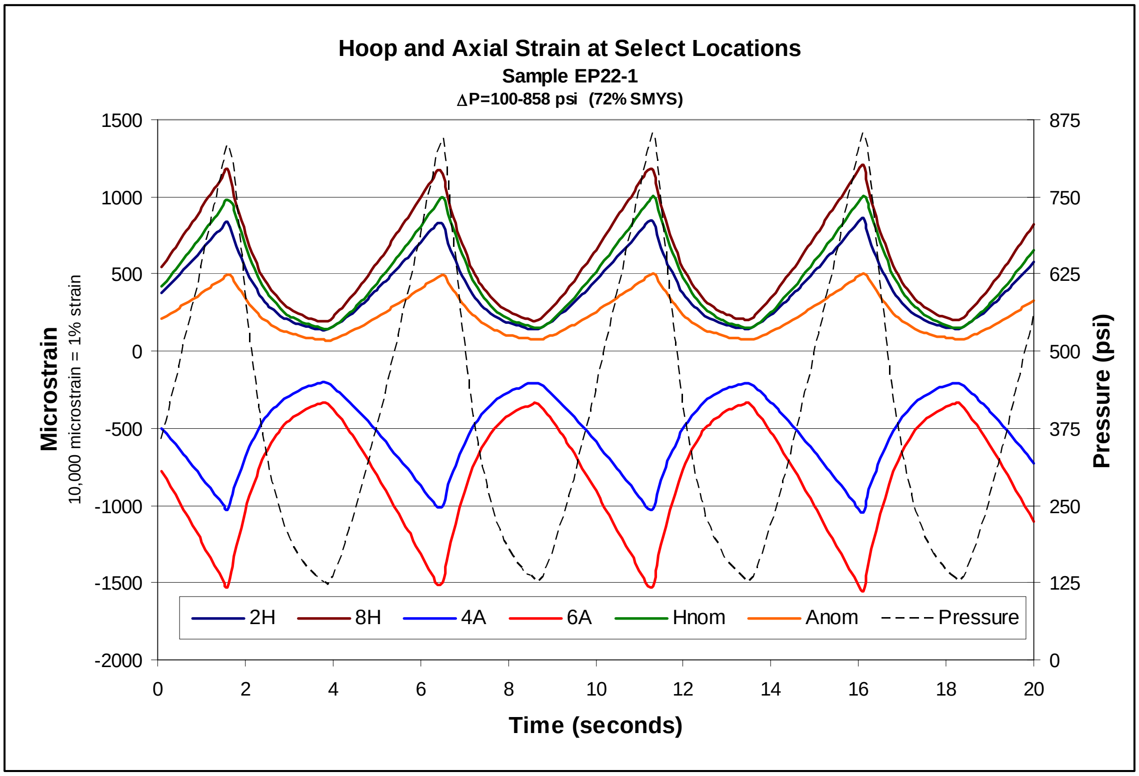

Figure 6 – Alternating hoop and axial strain gage results for Sample EP22-1
(Gages 1 - 4 REPAIRED and Gages 5 - 9 UNREPAIRED)

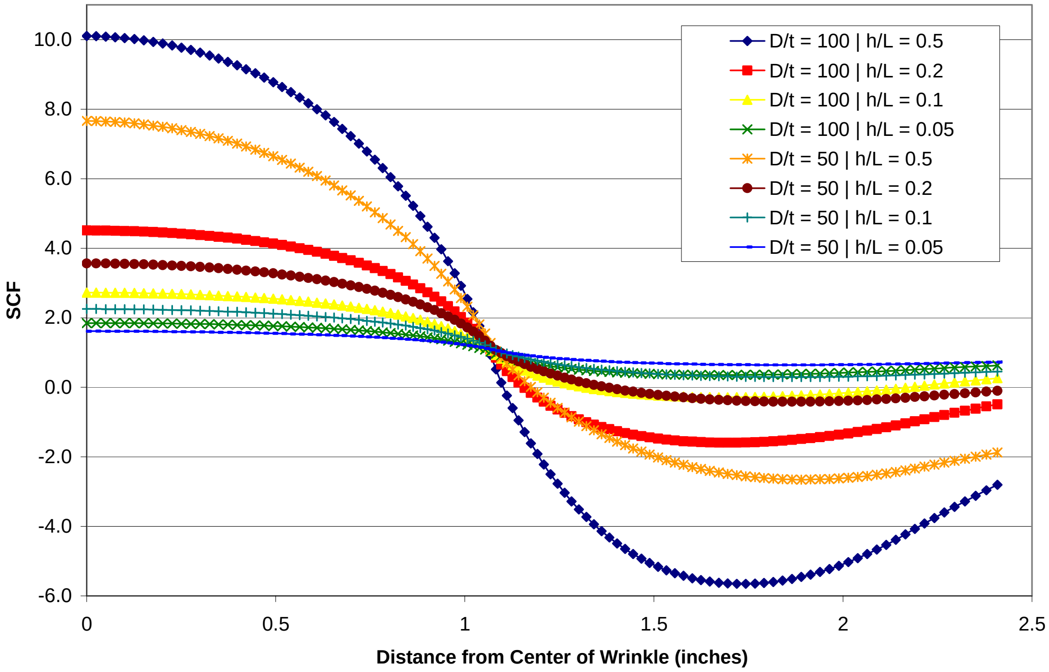

Figure 7 – Axial SCFs on inside pipe surface as a function of axial position
(the length, *L*, of the wrinkles maintained at 6.0 inches while the height, *h*, was varied which means that for the above plots the wrinkle half-length is 3.0 inches)

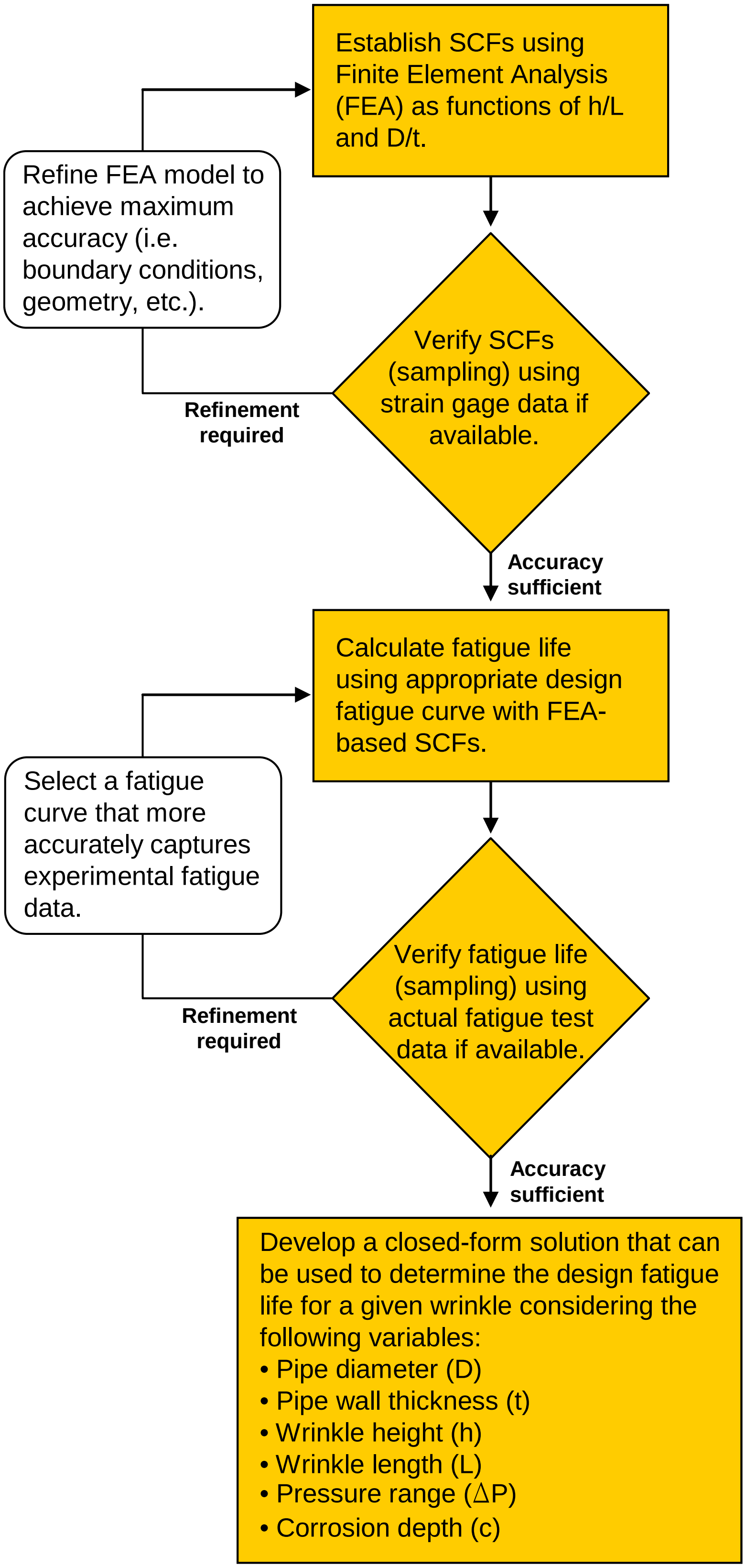

Figure 8 – Wrinkle assessment flow chart

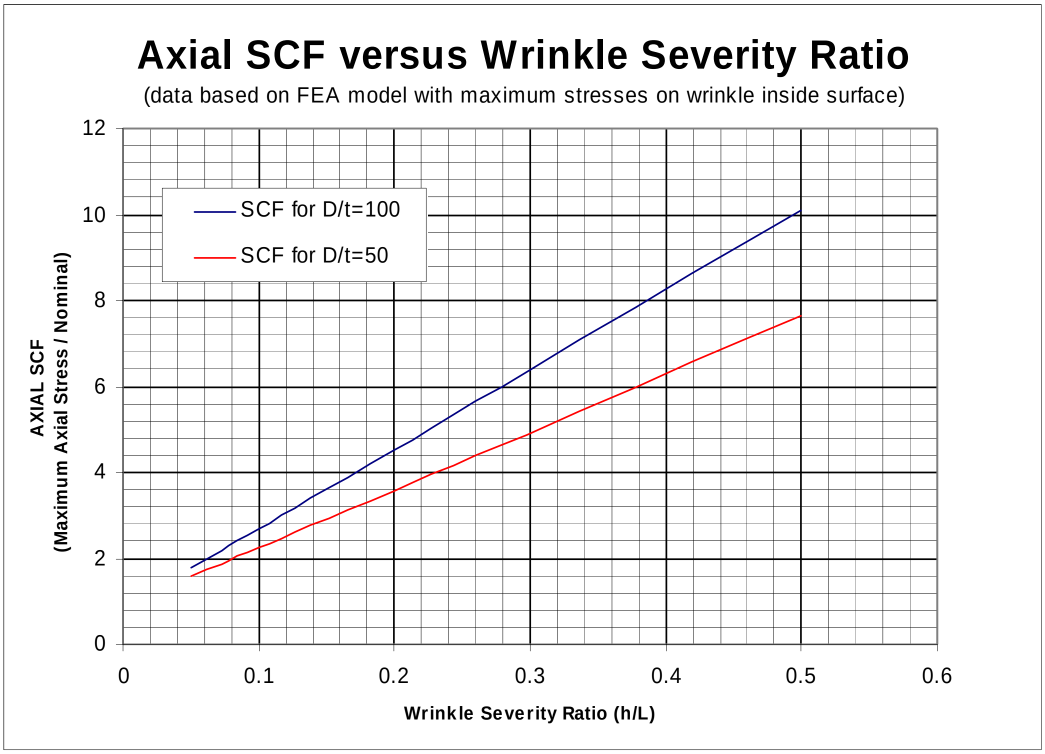

Figure 9 – Axial SCFs as functions of D/t and h/L

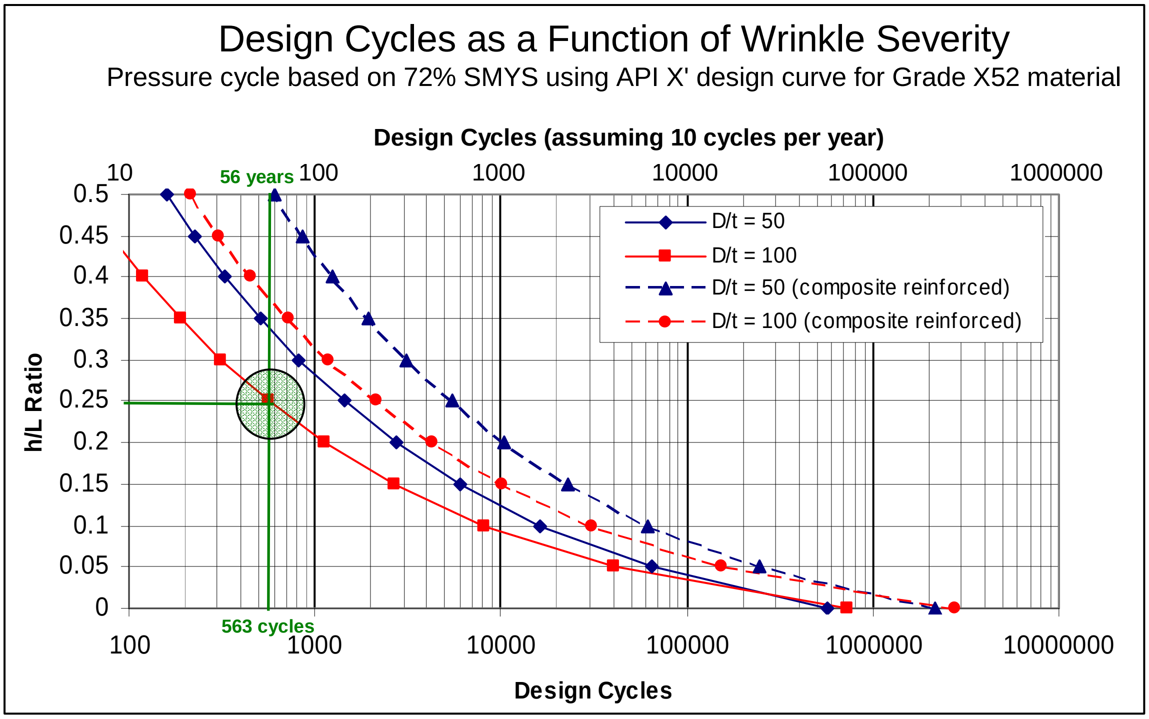

Figure 10 – Nomograph relating h/L ratio to design life and years of service
(analysis data plotted includes results with and without composite reinforcement)