Evaluating Damage to Onshore and Offshore Pipelines Using Data Acquired Using In-line Inspection Efforts

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EXECUTIVE SUMMARY

Evaluating the integrity of pipelines often involves assessing data acquired from an in-line inspection (ILI) run. ILI generates a range of data types including one being geometric data from a caliper tool run. Once the data is collected engineers are required to evaluate the relative severity of any indications that might have been found. With recent advances in storage capacity and instrumentation, the resolution of the acquired data is of sufficient magnitude to make relatively accurate assessments of the potential damage that might exist within a given pipeline system.

In this paper an example case study is provided that used data collected during an in-line inspection run of a damaged pipeline. The assessments included the development of finite element models constructed using the geometric ILI data. Integral to the assessments were integration of actual pressure history data that when used in conjunction with a cumulative damage assessment model determined the remaining life of the selected anomaly. Additionally, the assessment utilized prior full-scale experimental data to confirm the accuracy of the models. Readers are provided with a systematic approach for evaluating damaged pipelines using ILI caliper tool data.

INTRODUCTION

Dents generated in onshore pipeline are typically the result of third-party damage, although rock dents are certainly a contributor for bottom side defects. Damage to subsea pipelines typically occurs as the result of impact with an anchor. After the subsea incident occurs, ROVs (remotely operated vehicles) are then deployed to survey the damage, followed by survey efforts to determine if the pipeline has been moved or laterally displaced. If it is believed that localized damage has been inflicted, it is essential that the profile of the dented region be determined. In-line inspection is ideally-suited for collecting this data. From a geometry standpoint, the data collected includes points measuring radius, circumferential orientation, and longitudinal position (i.e. R-θ-Z coordinates)

Presented in this paper is a background section that discusses how to evaluate dents considering previous research efforts and experience. Also included is a brief discussion on how raw ILI geometry data is converted into the mesh for evaluation using the finite element (FEA) method. FEA is used to calculate the alternating stresses in the dented region. Once the stresses due to cyclic pressure are calculated, a fatigue curve is used to estimate the remaining life for the given dents. Results are also presented from previous research on fatigue testing of pipes having plain dents. A final section of this paper provides recommendations for industry in using ILI data to estimate the remaining life of damaged pipelines and integrating previous test data where appropriate for validation purposes.

BACKGROUND

In the 1990s a significant body of work on evaluating dented pipelines was performed under the direction of the Pipeline Research Council. Other work was also performed on plain dents and related defects for the American Petroleum Institute. For the most part this work focused on damage to pipelines involving plain dents and dents with gouges. Full-scale testing involving pipelines subjected to static and cyclic pressures were used to evaluate the effects of dents having varying degrees of severity on the integrity of pipelines. Interested readers are encouraged to consult the reference documents provided in this paper. The predominant conclusion from these research efforts is that to properly assess a defect's severity one must appropriately categorize the defect. Listed below are the major defect classifications that typically arise when assessing pipeline damage.

- Plain dents
- Constrained dents
- Gouges
- Mechanical damage
- Wrinkles

The sections that follow discuss in detail experimental testing that has been conducted to address the several classes of dents listed previously by different research programs around the world. Detailed in each section are the appropriate references, critical variables associated with the defect in question, and the effects of loading (static or cyclic) on failure behavior.

Plain Dents

Plain dents are defined as dents having no injurious defects such as a gouge and possessing a smooth profile (they are often classified as smooth dents). The critical variables relating to plain dents are,

- Dent depth (depth after rerounding due to pressure)
- Pipe geometry (relationship between diameter and wall thickness)
- Profile curvature of the dent profile
- Pressure at installation
- Applied cyclic pressure range.

While the effects of certain variables are not clearly understood, it is apparent that the denting process plays a critical role in determining the future behavior of the dent. Early research recognized that dent depth was one of, if not the most important, variable of interest. The dent created initially changes as a function of applied pressure (statically or cyclically).

The following equation was developed Maxey (Maxey, 1986) and correlates the relationship between initial dent depth and the residual dent depth as a function of applied pressure and yield strength.

$$D_o = \frac{D_R}{\left[-0.5066 \cdot \log\left(\frac{\sigma}{\sigma_y + 10{,}000}\right)\right]} \tag{1}$$

Where:
σ = Hoop stress at instant of damage (psi)
σ_y = Yield strength of pipe (psi)
D_o = Dent depth at instant of damage (inches)
D_R = Residual dent depth after removal of damaging tool (inches)

A review of the preceding equation by Hopkins (Hopkins et al., 1989) revealed some levels of unconservatism because the above formulation is lower-bound and ignores the elastic spring-back of the dent at zero internal pressure. Later work by Rosenfeld indicates that some degree of progressive rerounding occurs with pressure cycles (Rosenfeld, 1998a). It is these changes in dent depth, and associated changes in dent profile, that determine the eventual long-term behavior of the dent. When considering pipes with relative high diameter to wall thickness ratios, a significant level of rerounding occurs on pressurization. Work conducted for the American Petroleum Institute (API) (Alexander and Kiefner, 1997c) showed that for 12.75-in x 0.188-in, Grade X52 pipes, it was not possible to achieve dents depths greater than 3 percent of the pipes diameter when the pipe was pressurized to the maximum allowable operating pressure, even though initial dent depths as great as 18 percent were initially installed. As will be discussed later in this paper, this rerounding reduces the severity of the dent.

The behavior of plain dents in static and cyclic pressure environments differ. The sections that follow provide insights on these differences.

Response of Plain Dents to Static Pressure Loading

The response of plain dents to static pressure loads deals primarily with the effects of the damage on the burst strength of the pipe. In addition to concerns relating to dent depth and profile, the mechanical properties of the damaged pipe material are also important. Work was reported in the 1980s that correlates burst pressure with dent depth and material properties for pipes with different geometries and grades (Hopkins, 1989). The tests involved pipe ring samples that were dented prior to pressure testing. Table 1 provides a summary of the test results.

The definitive conclusion based on all available research is that plain dents do not pose a threat to the structural integrity of a pipeline other than the potential for reduced collapse/buckling capacity associated with the induced ovality. A discussion on the subject matter will follow in a later section of this paper. However, the classification of a plain dent assumes that no cracks, gouges or material imperfections are present in the vicinity of the dent. Interaction of plain dents with weld seams, especially girth welds and submerged arc welds (SAW), can significantly reduce the burst strength of the damaged pipeline (Alexander and Kiefner, 1997c). The primary cause of the reduction is crack development at the toe of the welds during pressurizing the pipe and associated rerounding of the dent.

Response of Plain Dents to Cyclic Pressure Loading

While plain dents do not pose a threat to pipeline integrity in a static environment, cyclic pressure applications can reduce the life of a pipeline. A poll of several gas and liquid transmission companies revealed the number of applied pressure cycles that can be expected for the respective fuel types (Fowler et al., 1994). A gas transmission line can be expected to see 60 cycles per year with a pressure differential of 200 psi; however, the same pressure differential can occur over 1,800 times on a liquid pipeline in the course of a year. For this reason, liquid pipeline operators are considerably more concerned with fatigue than gas pipeline operators.

The impact that a plain dent has on the fatigue life of a pipeline is directly related to two factors. The first factor concerns the dent geometry in terms of shape and depth. Dents that are deeper and possess greater levels of local curvature reduce fatigue lives of pipes more-so than dents that are shallow with relatively smooth contours. Work conducted for the American Gas Association (Fowler et al., 1994), American Petroleum Institute (Alexander and Kiefner, 1997c) and by EPRG (Hopkins et al, 1989) all validate this position. The second factor determining the severity of plain dents is the range of applied pressures. In general, a fourth-order relationship can be assumed between the applied stress range and fatigue life. In other words, a dented pipeline subjected to a pressure differential of 200 psi will have a fatigue life that is 16 times greater than if a pressure differential of 400 psi were applied. Barring the effects of rerounding (which change the local stress in the dent), the fatigue lives of plain dents are reduced to a greater degree when increased pressure differentials are assumed.

Table 2 provides several data points extracted from the API research program showing the effects of dent depth on fatigue life. As noted in the data, the 6 percent dent never failed and had a fatigue life that exceeded the fatigue life for the 18 percent dent by one order of magnitude.

In assessing the overall impact that plain dents have on pipelines subjected to cyclic service, one must consider both the applied pressure range and geometry of the dent. A given dent may not be serious in gas service, but could pose a detriment to fatigue life when considering the service requirements of liquid transmission pipelines.

Dents with Gouges

While plain dents may be regarded as rather benign in terms of their impact on structural integrity, dents with gouges are a major concern for pipeline companies. The leading cause of pipeline failures is mechanical damage, which often occurs during excavation of pipelines. The United States Department of Transportation (U.S. D.O.T.) has specific criteria for reporting outside incidents. The rate of reportable incidents for gas pipelines from 1970 to June 1984 was 3.1 x 10^{-4}/km-yr, while the rate was approximately 6.8 x 10^{-5}/km-yr for the period from July 1984 to 1992 (Driver, 1998). A more conservative estimate assumes that the actual incident rate may be as high as 10-3/km-yr due to unreported incidences (Zimmerman et al., 1996). Regardless of the assumed incident rate, world-wide efforts have focused on the need for mechanical damage research. In the United States, most of the experimental work has been conducted by Battelle Memorial Institute and Stress Engineering Services, Inc. and has been funded by the American Gas Association and the American Petroleum Institute. In Europe testing has been conducted primarily by British Gas and Gaz de France with funding from the European Pipeline Research Group.

The severity of mechanical damage is rooted in the presence of microcracks that develop at the base of the gouge during the process of dent rerounding due to pressure (and to some extent elastic rebound). As with plain dents, dents with gouges respond differently to static and cyclic pressure loading. The discussions that follow provide greater details regarding the associated responses.

<u>Response of Dents with Gouges to Static Pressure Loading</u>

Unlike plain dents that do not severely affect the pressure-carrying capacity of pipelines, the deleterious nature of dents with gouges requires careful investigation. The failure patterns of dents with gouges that are subjected to static pressure overload involve the outward movement of the dent region, while development and propagation of microcracks at the base of the gouge occur with increasing pressure levels. Hopkins et al conducted numerous ring tests to address the failure pattern of dents combined with gouges and concluded that the failure mechanism was ductile tearing within an unstable structure (Hopkins et al., 1989).

Testing was conducted by Kiefner & Associates, Inc./Stress Engineering Services, Inc. (Alexander et al., 1997a) for determining the burst pressure of dents containing gouges. All testing was conducted using 12-inch NPS, Grade X52 pipes. Machined V-notches were installed at various depths in the pipe samples, which were pressurized to 920 psi (60 percent SMYS) and then dented with a 1-in wide bar. Table 3 lists six of the test samples and the pressures at which they failed. As noted in the table, dent and gouge combinations that exceed 10 percent of the pipe diameter and wall thicknesses (respectively) are likely to have burst pressures that are less than the pressure corresponding to SMYS. The pipes used in testing had relatively good ductility and toughness (32 percent elongation and Charpy V-notch Impact Energy of 51 ft-lbs at room temperature); however, pipes without such material qualifications will fail at lower pressures. Work conducted by the Snowy Mountains Engineering Corporation in Australia (Wade, 1983) validates the importance of having sufficient ductility and toughness in reducing the potential for low failure pressures.

Based upon review of the data and experience of the author in experimental testing, it is difficult to envision a closed-form solution for predicting the failure pressure due to static overload of dents containing gouges. Although attempts have been made to do so, a paper written by Eiber and Leis (Eiber and Leis, 1995) shows that the current models (developed for the PRC and EPRG) do not satisfactorily predict burst pressures. Several of the primary reasons for the complexities in predicting burst pressure of dents with gouges are listed below.

- Material properties (especially ductility and toughness)
- Sharpness and depth of gouge
- Pressures at indentation and during rerounding
- Dent profile and depth as well as resulting plastic deformation of pipe
- Local work-hardening and variations in through-wall properties due to denting

The key to future experimental testing is to only address one variable while holding all others constant. The above list represents a satisfactory starting point for such investigations.

Response of Dents with Gouges to Cyclic Pressure Loading

Initial efforts in the pipeline research community focused on static burst testing of mechanical damage, but once a basic level of understanding of the fracture mechanisms were developed efforts focused on fatigue testing. Cyclic pressure tests have been conducted on pipe specimens with a variety of defect combinations (Hopkins et al., 1989, Fowler et al., 1994, Alexander et al., 1997a). The research efforts conducted for the EPRG, AGA and PRC indicate that if the fatigue life for plain dents is on the order of 105 cycles, then the presence of gouges (in dents) reduces this value to be on the order of 103. Table 4 summarizes data from research conducted for the EPRG on ring test specimens for relating plain dents and dents with gouges subjected to cyclic pressure service (Hopkins, 1989). As noted, the presence of a gouge significantly reduces the fatigue life of a plain dent, although a gouge by itself is non-threatening (an observation validated by Fowler et al., 1994).

Response of Dents in Welds to Cyclic Pressure Loading

In addition to considering interaction of dents with gouges, efforts to assess the interaction of welds with dents have been conducted. Testing on submerged and double submerged arc welds indicated that the dents in seam welds could significantly reduce the burst pressures and fatigue lives of the effected pipelines. The recommendation by Hopkins is that these defects should be treated with extreme caution and immediate repair considered (Hopkins, 1989).

Research efforts funded by AGA and API indicate that when dents are installed in ERW seams the fatigue resistance is on the same order as plain dents (Fowler et al., 1994 and Alexander and Kiefner, 1997c). This assumes that good quality seam welds are present in the pipe material. The presence of girth welds was shown to reduce the fatigue life of dents to a level less than ERW seams, but more than SAW seams. As an example, consider that the research program for API tested a dent in a SAW weld seam that failed after 21,603 cycles, while the same dent in a girth weld failed after 108,164 cycles (Alexander and Kiefner, 1997c).

Experimental Study of Strains in Dented Pipes

While numerous studies have addressed the failure patterns of plain dents and dents with gouges, less effort has been made to evaluate the strains in dented pipes. Obviously, the complex nature of dent mechanics is a contributing factor. Also, the use of finite element analysis (FEA) permits engineers to accurately understand the stress/strain distribution in dents as will be discussed later in this paper.

Lancaster has conducted numerous tests directed at developing an understanding of strains caused by pressurization of pipes with dents (Lancaster et al., 1994 and 1992). He employed the use of both strain gages and photoelastic coatings. His work provides several useful findings,

- During the process of rerounding the dents with internal pressure, approximately 60 percent of the dent had been recovered at a pressure equal to 70 percent of the yield pressure. There was evidence of creep at pressures above yield.
- The locations having the highest strains are on the rim of the dent. Interestingly, this location was consistent with the failure location for unconstrained dome dents in the API research program that resulted in longitudinally-oriented cracks that developed on the exterior of the pipe (Alexander and Kiefner, 1997c).
- The highest strain measured on the rim of the dent was 7000 με, and the maximum hoop stress concentration (SCF) was calculated to be 10.0. In comparing this SCF with those generated by finite element methods (FEM) for the API research program, the maximum FEM SCF was calculated to be 7.2 for an unconstrained dome dent having a residual dent depth of 10 percent (Alexander and Kiefner, 1997c).

In addition to the work conducted by Lancaster, Rosenfeld developed a theoretical model that describes the structural behavior of plain dents under pressure (Rosenfeld, 1998a). His efforts also involved dent rerounding tests for validation purposes.

Wrinkle Bends

Wrinkle bends are associated with the bending of pipe that results in creating local indentations that may be regularly or irregularly spaced, along the length of the affected area. Wrinkle bends are not considered favorably by the pipeline codes and most operators. As a point of reference, ASME B31.8 841.231(g) states that wrinkle bends are permitted only on systems that operating at hoop stress levels less than 30% of the specified minimum yield strength.

As part of the American Petroleum Institute study (Alexander and Kiefner, 1997c), experimental efforts were undertaken to assess the effects of wrinkle bends on the fatigue life of pipelines. Three 36-inch x 0.281-inch pipes were fitted with wrinkle bends having nominal depths of 2%, 4%, and 6% (wrinkle depth percentage calculated by dividing wrinkle depth by the nominal diameter of the pipe). Figure 1 shows the pipe sample with 2% wrinkles, while Figure 2 shows the corresponding profiles for the three wrinkles that were tested.

Pressure cycle testing was performed where the samples were pressure cycled to 100% of the operating pressure. The following fatigue results were obtained.

- 2 percent wrinkle - NO failure after 44,541 cycles
- 4 percent wrinkle - failure after 2,791 cycles
- 6 percent wrinkle - failure after 1,086 cycles

The above results were a significant find for the API research program. The critical observations is that although depth of damage is important (wrinkle or dent), the more important factor is the profile shape of the damage. The change in radius of curvature along the length of the line is directly related to bending strains. As noted in the fatigue data, a wrinkle having a depth of 6% poses a significant threat to the integrity of the pipeline. Although intentional wrinkle bends are unlikely to occur offshore, the authors have observed several anchor impact zones that clearly resembled the damage profile associated with wrinkle bends. For this reason, any damage in an onshore or offshore pipeline that resembles a wrinkle bend (i.e. defect having a sharp curvature as in a kink) should be removed as soon as is prudent.

Summary of Experimental Work

The information presented in this paper indicates that a significant level of research has been conducted world-wide in an effort to characterize and assess the severity of plain dents and dents with gouges. It can be concluded that a certain hierarchy exists in terms of defect severity, although unquestionable scatter is present in both the static and fatigue data. Empirical models and semiempirical models have been able to predict with some success the failure pressure for dents with gouges; however, the large number of variables has so far precluded the development of a general model that can accurately forecast the burst and fatigue behavior of all possible types of mechanical damage. Any evaluation involving numerical modeling based on ILI geometry data should be validated by referencing previous experimental work.

ANALYSIS OF DENTS

The primary focus of this paper is to specifically address the use of ILI data in evaluating dent severity. The approach presented herein can be used for onshore and offshore pipelines. The presentation includes a discussion on converting raw ILI data into a format useful for generating a finite element mesh, actually performing the analysis using finite element methods, and interpreting the data in terms of estimating future performance.

Converting Raw ILI Data

The ILI data that is typically measured by an in-line inspection tool in presented in cylindrical coordinates (i.e. R-θ-Z). Figure 3 provides a portion of an example data set taken from an ILI tool run. As noted, radial coordinates are provided as functions of circumferential and axial positions. In this particular data set the circumferential positions are provided every 12 degrees, or approximately every 1.75 inches for the given pipe diameter. To generate accurate analysis results, this coordinating spacing is too large. Therefore, an algorithm was developed to increase the mesh density and generate a more refined mesh for the finite element model based on a fast Fourier transform (FFT) routine. As a point of reference, where the raw data had 30 points circumferentially resulting in nodal spacing of 1.75 inches, the FFT-modified produces 177 points circumferentially spaced at approximately 0.50 inches. The number of data points in the axial direction is adjusted to match the circumferential spacing so that the two are approximately equal (i.e. element aspect ration of 1:1).

Finite Element Analysis

Once the required level of mesh refinement has been made, the finite element model is generated. The R-θ-Z coordinates serve as the nodes. A FORTRAN code was developed to read the reduced data and generate an ABAQUS input file. The coordinates for each node were developed using the relationships shown below.

$$X = (r + t/2) * \sin\theta$$

$$Y = (r + t/2) * \cos\theta$$

$$Z = Z$$

In these relationships, r is the inside radius from the ILI data. Theta, θ, is the circumferential position relative to the pipe axis measured clockwise from the top of the pipe. The thickness of the pipe, *t*, is taken based on the pipe’s nominal wall thickness. The axis of the pipe was taken as the global z-axis. Figure 4 shows an overall view of a dent model, while Figure 5 shows an enlarged view of the region where the mesh density can be seen. The “S4” type shell elements were specified in ABAQUS. Symmetry boundary conditions were specified at each end of the pipe model. For each analysis, a linear elastic analysis was performed where the internal pressure was the yield pressure of the pipe using the Specified Minimum Yield Strength (SMYS) of the respective pipe grade (e.g. Grade X52 has a SMYS of 52,000 psi). A typical finite element model has on the order of 25,000 elements.

Once the model pre-processing was completed, stresses were calculated based on the internal pressure loading. Although plastic strains are induced in any dented pipeline, experience has shown that after several pressure cycles a shakedown to elastic action occurs and the alternating stresses are typically within the elastic regime. Therefore, it is appropriate to elastically model cyclic stresses in dents. From the finite element model, the principal stresses in the dented region of the model are calculated. From this stress state a stress concentration factor (SCF) is calculated by dividing the maximum principal stress by the nominal hoop stress. Figure 6 provides a contour plot showing the maximum principal stresses in a dent that resulted in a maximum SCF of 3.58. It is noted in this figure that the maximum stress occurred on the outside surface of the model. These results are consistent with previous findings from experimental studies where fractures in plain dents subjected to cyclic pressures initiated on the outside surface of the pipe.

Interpretation of Data

Once the FEA model results are calculated and a representative SCF has been determined, the next step involves estimating remaining life. It should be noted that for this particular discussion that the focus is on plain dents where failure due to static pressure overload is unlikely. If plain dents do fail, they are most likely to do so in the presence of cyclic pressures. Even if a large number of cyclic pressures are not likely, the process of calculating SCFs provides operators with a means for evaluating the relative severity among competing dents.

From the author's experience, the API X' fatigue curve from API RP2A, *Planning, Designing, and Constructing Fixed Offshore Platforms*, reasonably predicts the fatigue behavior of plain dents subjected to cyclic pressure conditions. Provided below is the equation for the API X' curve where $\Delta\sigma$ represents stress range in units of psi.

$$N = 2.978 \times 10^{21} \Delta\sigma^{-3.74} \quad (2)$$

As an example, consider the previously presented dent analysis with the SCF of 3.58 (cf. Figure 6). If one assumes a cyclic pressure range of 36% SMYS for a Grade X52 pipe, the nominal hoop stress range is 18,720 psi. Including the SCF the corresponding stress range in the dented region is 67,000 psi. Using the API X' curve, the resulting fatigue life is 2,657 cycles.

While the above presentation is certainly useful, for most operators an important unanswered question remains – how many years of useful service remain? In the absence of actual historical operating data, the 2,657 cycle number is not entirely useful. Therefore, to complete the analysis one must consider actual operating history. Listed below are the steps involved in evaluating the remaining life of a dented pipeline considering the ILI-based stress concentration factor used in conjunction with actual operating pressure cycle data.

1. Obtain pressure history plot similar to one shown in Figure 7.
2. Use rainflow counting to develop a pressure cycle histogram similar to one shown in Figure 8.
3. Use histogram to determine a single equivalent cycle count such as 100 cycles at ΔP = 36% SMYS.
4. Divide the calculated fatigue life by the annual cycle count to determine the remaining life in years.

Referring once again to the previous example, we determined that for a stress range of 36% SMYS the fatigue life was 2,657 cycles. If a given pipeline experienced annually 100 cycles at ΔP = 36% SMYS the remaining life in years would be 26.5 years.

DISCUSSION

The integrity of dents is related to not only the severity of the dent itself, but also the possibility that the dent can interact with other features such as seam and girth welds. SES was the Principal Investigator of a study conducted for the American Petroleum Institute evaluating the severity of plain and constrained rock dents. Included in this study were evaluating the effects of seam and girth welds that interacted with dents.

Listed below are the major dent groupings extracted from the data set from this API study. Related data for these test samples are included in Table 5. Within these samples are groups based on the following common characteristics. These groups are important as they serve as the basis for some of the assumptions regarding dent performance. As an example, the test results associated with girth welds in dents provides information regarding the expected performance of plain dents versus those dents containing girth welds. Unless noted, all dents are unconstrained.

- Plain dents — Samples 1, 3, and 28
- Constrained dents — Samples 15, 26, and 27
- Dents with welds — Samples 16 and 20
- Dents with welds subjected to hydrotest — Samples 30 and 31
- Double dents — Sample 32

As noted in Equation (2) for the API X' RP2A S-N Curve, there is a numerical relationship of 3.74 between design cycles and applied stress range. This exponent will be used in developing empirical stress concentration factors for specific pipeline imperfections.

One of the objectives of this study was to evaluate how the fatigue life of plain dents is reduced when considering features such as girth welds, seam welds, and double dents. The data presented in Table 5 is used to provide numerical correlation among these dents as presented below.

<u>Stress concentration factor for dents interacting with ERW seam welds</u>

Sample 16 (unconstrained dents with ERW)	22,375 cycles
Sample 3 (unconstrained dent)	684,903 cycles

A stress concentration factor is calculated using the above cycles to failure using a 3.74 order relationship between stress and cycle life.

$$\mathrm{SCF} = \left(\frac{22{,}375 \text{ cycles}}{684{,}903 \text{ cycles}} \right)^{\frac{-1}{3.74}} = 2.49 \tag{3}$$

<u>Stress concentration factor for dents interacting with girth welds</u>

Sample 16 (unconstrained dents with ERW)	20,220 cycles
Sample 3 (unconstrained dent)	684,903 cycles

A stress concentration factor is calculated using the above cycles to failure using a 3.74 order relationship between stress and cycle life.

$$\mathrm{SCF} = \left(\frac{20{,}220 \text{ cycles}}{684{,}903 \text{ cycles}} \right)^{\frac{-1}{3.74}} = 2.56 \tag{4}$$

<u>Stress concentration factor for double dents</u>

Sample 16 (unconstrained dents with ERW)	217,976 cycles
Sample 3 (unconstrained dent)	684,903 cycles

A stress concentration factor is calculated using the above cycles to failure using a 3.74 order relationship between stress and cycle life.

$$\mathrm{SCF} = \left(\frac{217{,}976 \text{ cycles}}{684{,}903 \text{ cycles}} \right)^{\frac{-1}{3.74}} = 1.36 \tag{5}$$

Using the calculated stress concentration factors, it is possible to develop a fatigue reduction factor, *FRF*, for each respective imperfection type. This value can then be used to estimate the effect that a particular anomaly has on the fatigue life of a plain dent. Several example calculations are provided. The FRF is calculated using the following equation, with results for the three anomalies tabulated in Table 6.

$$FRF = (SCF)^{-3.74} \tag{6}$$

A final comment concerns two factors that were not considered in the analysis efforts discussed herein. The first concerns the presence of corrosion. If corrosion is expected, one can assume that the remaining life of the dent will be reduced relative to the non-corroded case. Secondly, no consideration of tool tolerance was included in the geometry of the finite element models. On this second issue readers are encouraged to interface with tool vendors regarding tolerances and what, if any, effect they would have on the resulting dent geometry.

CONCLUSIONS

This paper has discussed methods for using in-line inspection data to evaluate the severity of dents in pipeline systems. At the end of the day, the most powerful feature of this technique is the ability of an operator to compare the relative severity of multiple dent-like defects in an effort to make decisions regarding which ones require immediate attention. In a world of unlimited resources, operators could evaluate and repair all defects; however, in the real world such options do not exist and operators must prioritize their responses based on the best available sources of information.

From the author’s perspective there is no standardized method for evaluating the severity of dents. It is hoped that the methods presented herein can serve as a means for opening lines of communication between in-line inspection companies, pipeline companies, and industry experts in formalizing a more systematic approach for evaluating dents. There is certainly ample evidence to suggest that a reasonable understanding of dent behavior exists among subject matter experts. When this knowledge is coupled with a standardized analysis approach, the pipeline community at large will be well-served.

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Figure 1 – Photo of 36-inch diameter pipe with 2% wrinkles

PROFILE MEASUREMENTS OF WRINKLES AFTER COMPLETION OF APPLIED CYCLES

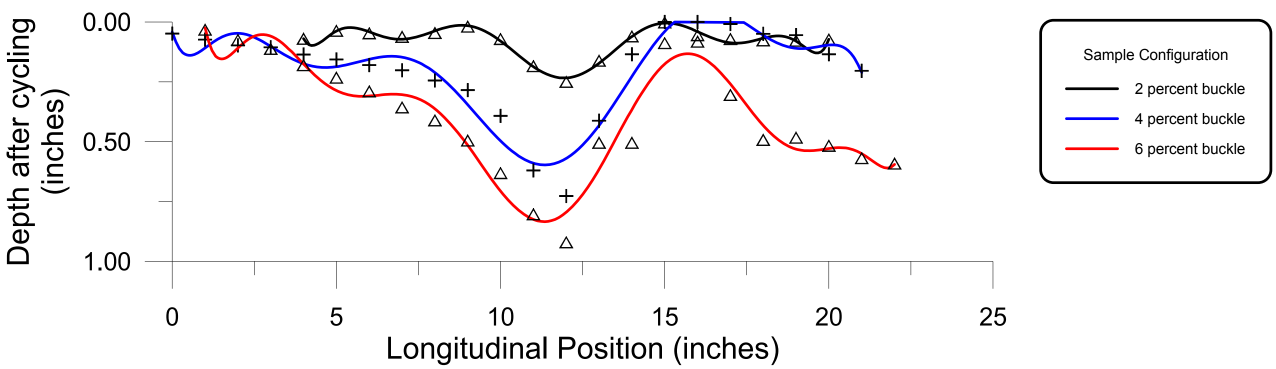

Figure 2 – Wrinkle profile for the three test samples

Circumferential position (every 12 degrees)

Axial position

Data shown (other than first column) are radial coordinates.

391300.1426	196.1399	199.0881	199.5950	201.6023	204.6078	207.6003	209.8907	211.0764
391300.1459	196.1445	199.0792	199.5974	201.6105	204.6081	207.5990	209.8935	211.0715
391300.1491	196.1445	199.0838	199.6020	201.6066	204.6069	207.6073	209.8920	211.0837
391300.1524	196.1445	199.0884	199.6066	201.6026	204.6057	207.6155	209.8904	211.0959
391300.1557	196.1469	199.0876	199.6119	201.6034	204.6089	207.6123	209.8949	211.0951
391300.1590	196.1494	199.0868	199.6172	201.6042	204.6122	207.6090	209.8994	211.0943
391300.1623	196.1518	199.0859	199.6225	201.6050	204.6154	207.6057	209.9039	211.0935
391300.1655	196.1494	199.0920	199.6131	201.6026	204.6171	207.6025	209.9008	211.0968
391300.1688	196.1469	199.0981	199.6037	201.6001	204.6187	207.5992	209.8978	211.1000
391300.1721	196.1445	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	209.8947	211.1033
[illegible]	196.1506	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	209.8981	211.1057
391300.1787	196.1567	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	209.9014	211.1082
391300.1819	196.1606	199.1311	199.5983	201.6018	204.6338	207.5974	209.8984	211.1114
391300.1852	196.1644	199.1299	199.6089	201.5985	204.6283	207.6013	209.8953	211.1147
391300.1885	196.1683	199.1287	199.6194	201.5953	204.6228	207.6051	209.8923	211.1179
391300.1918	196.1753	199.1271	199.6203	201.6001	204.6252	207.6039	209.8959	211.1130
391300.1951	196.1823	199.1256	199.6213	201.6050	204.6277	207.6027	209.8996	211.1082
391300.1984	196.1772	199.1266	199.6162	201.6050	204.6283	207.5994	209.8927	211.1171
391300.2016	196.1721	199.1277	199.6111	201.6050	204.6289	207.5962	209.8858	211.1261
391300.2049	196.1671	199.1287	199.6060	201.6050	204.6295	207.5929	209.8788	211.1350
391300.2082	196.1720	199.1381	199.6142	201.6148	204.6307	207.5978	209.8779	211.1262
391300.2115	196.1768	199.1476	199.6225	201.6246	204.6319	207.6027	209.8770	211.1173
391300.2148	196.1768	199.1541	199.6225	201.6205	204.6328	207.5954	209.8823	211.1167

Figure 3 – Raw in-line inspection data in cylindrical coordinates

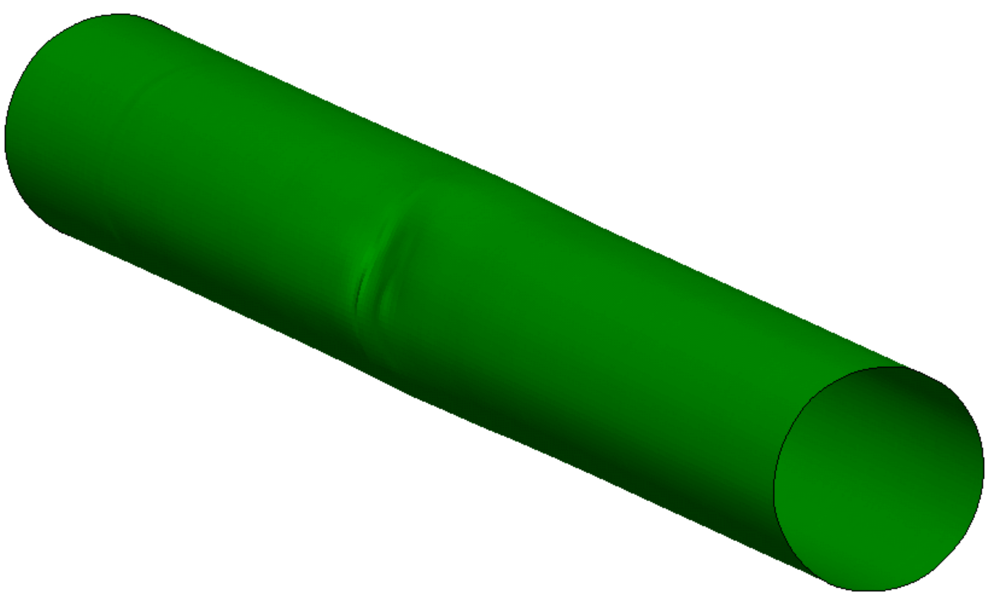

Figure 4 – Global view of dent in finite element model

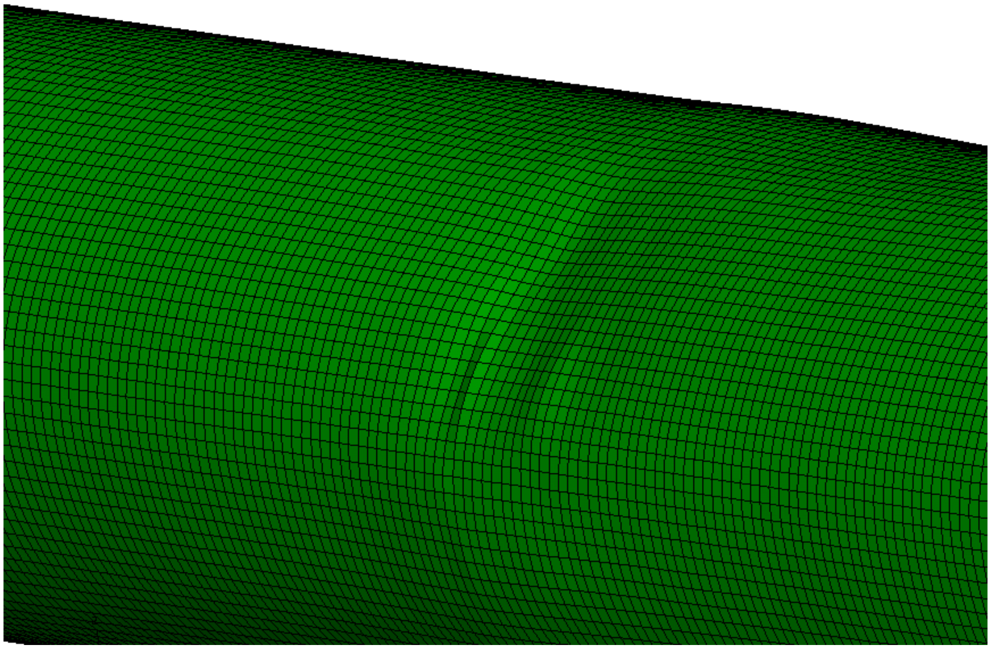

Figure 5 – Close-up view of dent in finite element model

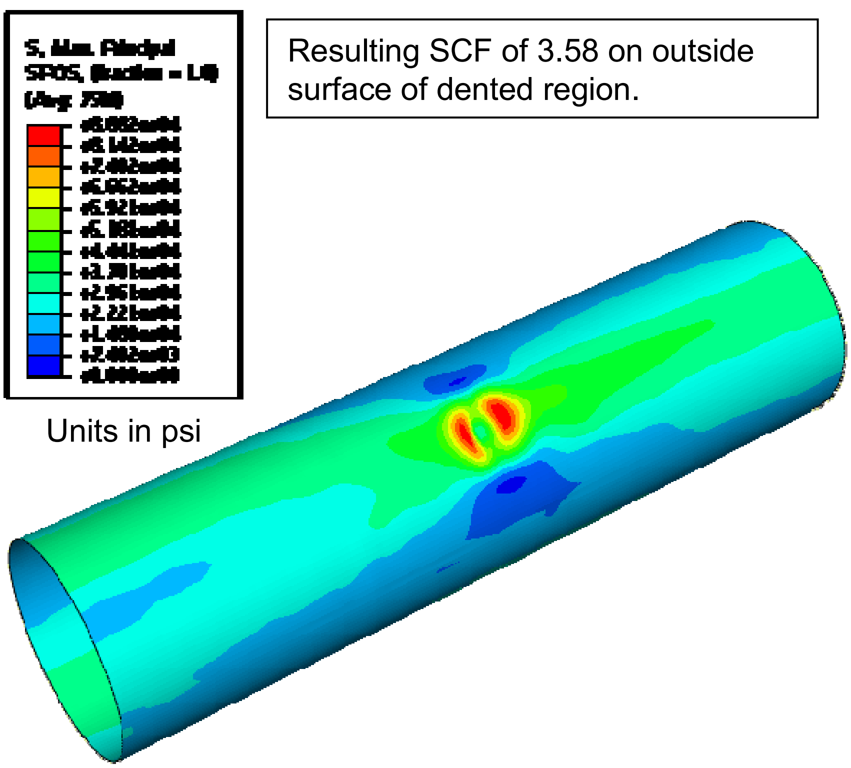

Figure 6 – Maximum principal stresses on outside surface of FEA model

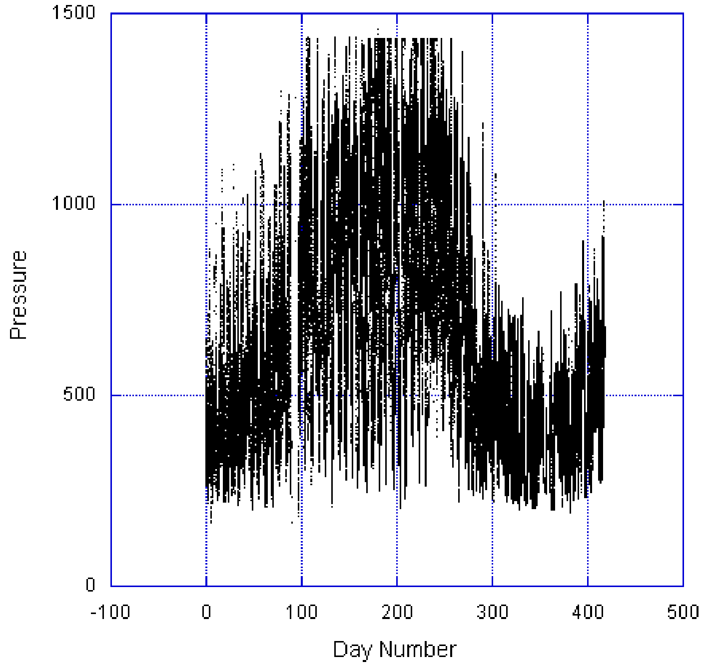

Figure 7 – Historical pressure cycle data from an operating pipeline
(pressure in units of psi)

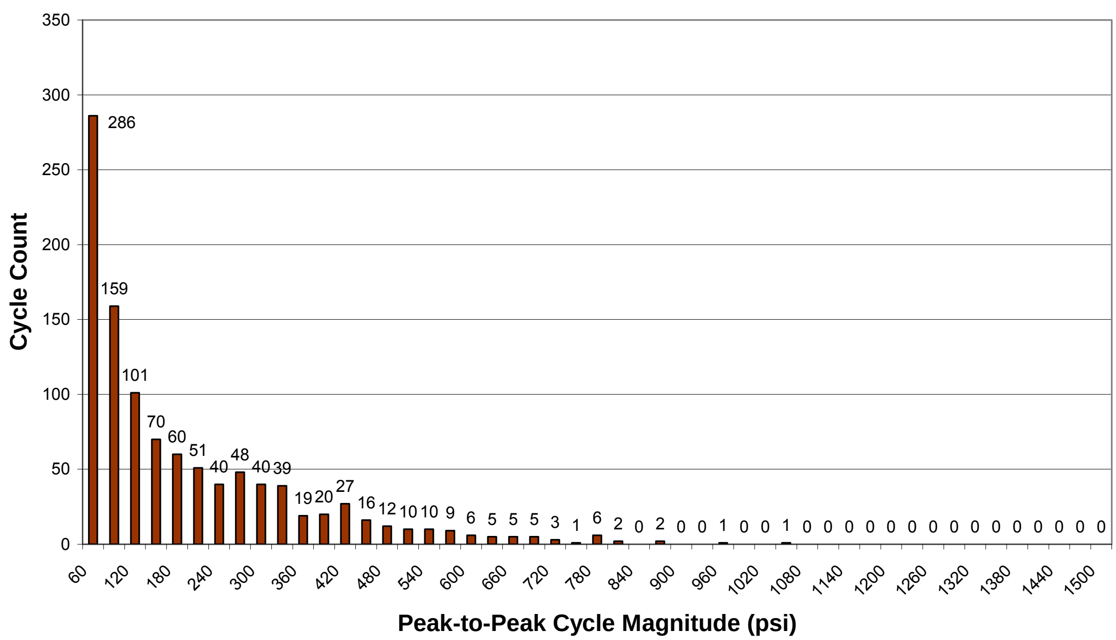

Figure 8 – Pressure cycle histogram showing stress range cycle count

Table 1 – Burst pressures for plain dents

Sample Number	Pipe Geometry	Grade and Yield Strength	Charpy Impact (ft-lbs)	Final Dent Depth (d/D, %)	Failure Stress (ksi)	Notes
BPU 2	36-in x 0.54-in	X60 (67.5 ksi)	44.2	3.4	67.2	Failed at 112% SMYS
BNO 2	36-in x 0.50-in	X60 (60.8 ksi)	19.1	4.5	67.7	Failed at 113% SMYS
BIE 1	24-in x 0.38-in	X52 (53.1 ksi)	14.0	5.4	24.9	Failed at 48% SMYS
BLV 1 (1)	30-in x 0.31-in	X52 (52.7 ksi)	19.2	3.5	71.1	(see note 2)
EUY 1	36-in x 0.66-in	X65 (68.9 ksi)	31.7	4.8	26.5	Failed at 41% SMYS
FJB 1 (1)	30-in x 0.48-in	X52 (58.8 ksi)	22.8	3.2	18.9	Failed at 36% SMYS
FJB 1 (1)	30-in x 0.48-in	X52 (58.8 ksi)	22.8	4.9	12.6	Failed at 24% SMYS

Notes
1. Cracks detected on inside seam weld of sample
2. Sample yielded but did not break

Table 2 – Cyclic pressure tests on plain dents

Sample Number	Pipe Geometry and Grade	Initial Dent Depth (d/D, %)	Final Dent Depth (d/D, %)	Cycles to Failure ($\Delta\sigma$ = 36% SMYS)
US6A-2	12.75-in x 0.188-in, Grade X52	6	1.3	1,307,223
UD12A-3	12.75-in x 0.188-in, Grade X52	12	2.5	684,903
UD18A'-28	12.75-in x 0.188-in, Grade X52	18	0.7	101,056

Notes
1. No pressure in pipe sample during indentation.
2. Residual dent measured with no pressure in pipe after sample was pressurized to a 65% SMYS stress level.
3. Cycles to failure listed based upon Miner's Rule in combining results from two applied pressure ranges (36% and 72% SMYS).
4. Sample did not fail. Testing terminated due to excessive number of applied pressure cycles.

Table 3 – Burst tests for dents with gouges

Sample Number	Gouge Depth (a/t, %)	Initial Dent Depth (d/D, %)	Burst Pressure (psi)	Percent SMYS (P_{burst} / SMYS)
B1-1N	5	5	2,165	141
B1-3N	10	5	1,985	120
B1-6N	10	10	1,479	96
B1-7N	15	15	820	53
B1-8N	10	12	1,517	99
B1-11N	5	15	775	51

Notes
1. Dents installed with an internal pressure of 920 psi. Dents permitted to reround after pressurization.
2. Material properties: 53.6 ksi yield strength | 72.1 ksi UTS | 51 ft-lbs CVN

Table 4 – Fatigue life for gouges, plain dents, and dents with gouges

Residual Dent Depth (percent pipe diameter)	Gouge Depth (percent pipe wall thickness)	Fatigue Life
None	20 percent	Greater than 145,500 cycles
4 percent	None	Less than 6,930 cycles
4 percent (in pipe weld)	None	Less than 789 cycles
4 percent	20 percent	Less than 199 cycles

Table 5 - Test results for dents subjected to cyclic pressure fatigue testing

Sample	Description	Initial Dent (% pipe OD)	Rebound Dent (% pipe OD)	Final Dent (% pipe OD)	N (△P=50% MAOP)
1	Plain dent, unconstrained	6	4.9	2.7	1,307,223
3	Plain dent, unconstrained	12	6.8	2.5	684,903
15	Constrained dent	12	N/A	N/A	426,585
16	ERW, Plain dent, unconstrained	12	7.7	1.4	22,375
20	GW, dent, unconstrained	12	7.6	1.4	2,020
21	GW 2" offset from dent, unconstrained	12	6.8	1.5	38,972
26	Constrained dent	24	N/A	N/A	98,483
27	Constrained dent	18	N/A	N/A	235,008
28	Plain dent, unconstrained	18	11.3	0.7	101,056
30	ERW, Plain dent, unconstrained, hydrotest	12	5.9	0.7	277,396
31	GW, dent, unconstrained, hydrotest	12	6.0	1.0	213,876
22	Double dent unconstrained (dents 3.5 inches apart)	12	5.2 5.6	0.8 1.2	217,976
69	Plain dent, unconstrained (4-inch dome indenter)	6	3.3	0.7	359,350
70	Plain dent, unconstrained (4-inch dome indenter)	12	7.1	2.3	263,910
71	Plain dent, unconstrained (4-inch dome indenter)	18	15.8	4.9	204,246
72	Plain dent, unconstrained (4-inch dome indenter)	24	15.9	5.0	234,934

Notes

1. Sample 1 (unconstrained 6% plain dent) and Sample 15 (constrained 12% plain dent) did not fail even after extensive pressure cycling.
2. The *Final Dent Depth* was measured after all phases of testing were completed.
3. Observed failure pattern for unconstrained dents was an OD-initiated longitudinal flaw.
4. Observed failure pattern for constrained dents was an ID-initiated circumferential flaw.
5. The tested cycles to failure, N, presented above assumed an applied pressure range of 50% MAOP (36% SMYS). For the 12.75-inch x 0.188-inch, Grade X52 pipe used in the testing the 50% MAOP value corresponds to 550 psi.

Table 6 - Fatigue Life Reduction Factors

Damage Type	SCF	FRF
Dent with ERW weld seam	2.49	0.033
Dent with girth weld	2.56	0.030
Double dent	1.36	0.318