REVIEW OF EXPERIMENTAL AND ANALYTICAL INVESTIGATIONS OF DENTED PIPELINES

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ABSTRACT

It is well known that mechanical damage is the leading cause of failure in both gas and liquid transmission pipelines. These damages often involve pipes inflected with injurious dents containing gouges. Over the past several years, significant levels of research have been conducted around the world in an effort to address the critical issues associated with mechanical damage. These efforts have involved both experimental and analytical efforts. The principal aim has been to assess defect severity in terms of future behavior involving both static burst and cyclic pressure conditions.

The intent of this paper is to present an overview of the current research observations including first-hand knowledge of the author as well as insights available from the current literature. In addition to issues relating to mechanical damage, information is provided relating to constrained dent configurations such as those created by rocks. Also discussed are several remedial options for repairing damaged pipes. The anticipation is that pipeline operators and others in the industry can benefit from this information in assessing defects discovered using tools such as in-line inspection.

INTRODUCTION

Because of the extensive research that has been conducted world-wide relating to dented pipelines, it is important to appropriately classify the critical issues related to the defects in question. The driving motivation in all of the research programs is to develop a better understanding of damaged pipelines in an effort to characterize their behavior. As with many areas of engineering, the ability to accurately predict the response behavior of structures is important to ensure adequate safety and consistent performance. The complexities associated with damaged pipelines make this a challenging task. Material issues, cyclic pressure conditions, soil-pipe interactions and complicated stress fields are but a few examples.

From an application standpoint, the current codes are viewed by many as over-conservative. Like many codes that were developed prior to extensive research programs such as those detailed herein, the pipeline code writers chose to take such positions based on limited information. For purposes of review, consider the acceptance criteria for damaged pipelines as outlined by the ASME B31.4 and B31.8 pressure piping codes.

Code for Liquid Pipelines - ASME B31.4 (1992 edition):

- Dents which affect the curvature of the pipe at a seam or girth weld must be removed by cutting out the damaged portion of the pipe as a cylinder.
- Dents that exceed 6 percent of the nominal pipe diameter (greater than 4-in NPS) are not permitted in pipelines that operate at hoop stress levels greater than 20 percent of the specified minimum yield strength of the pipe.
- Dents containing a stress concentrator, such as a scratch, gouge, groove or arc burn must be removed.
- Gouges or grooves having depths greater than 12.5 percent of the nominal wall thickness must be removed or repaired.

Code for Gas Pipelines - ASME B31.8 (1992 edition)

- Dents which affect the curvature of the pipe at a seam or girth weld must be removed.
- Dents that exceed 2 percent of the nominal pipe diameter (greater than 12-in NPS) are not permitted in pipelines that operate at a hoop stress greater than 40 percent of the specified minimum yield strength of the pipe.
- Dents containing a stress concentrator, such as a scratch, gouge, groove or arc burn must be removed by cutting out the damaged portion of the pipe as a cylinder.
- Gouges and grooves having depths greater than 10 percent of the nominal wall thickness must be removed or repaired.

As noted, both codes are extremely conservative in their assessment of dents with gouges, although B31.4 does permit the installation of full-encirclement welded or mechanically applied split sleeves on liquid pipelines. B31.4 permits the removal of gouges using approved repair methods, but B31.8 does not. It is well recognized throughout the pipeline industry that research on pipeline damage over the past 30 years has shown these (and other) regulations to be over-conservative. One impetus for funding research related to pipeline damage is to ensure that the current codes reflect safe practices, but are based upon up-to-date advances and understanding of damaged pipe behavior.

In the context of this paper, damage is limited to plain dents and dents containing gouges. The origin of these defects are most often earth-moving equipment, while environmental factors such as rocks are also contributors. Four basic areas are addressed herein. The first two consider efforts that have assessed damage based upon experimental and analytical efforts, respectively. The third area of interest concerns appropriate methods for repairing damaged pipelines, while the final topic proposes future research efforts to assist the industry in more accurately assessing the severity of certain types of pipeline damage.

EXPERIMENTAL RESEARCH EFFORTS

Because the conditions that create damage to pipelines are different, it is important to establish a system for categorizing defects. For purposes of this discussion, pipeline damage will be divided into the following classes,

- Plain dents (dents having no gouges)
- Dents with gouges

- Constrained dents (typically created by rock with three classes: plain, puncture-inducing and fretting)

Each of the above class of dents responds differently to pipeline loads. For example, it is well-known that plain dents do not pose a severe threat to pipelines when considering burst strength, but in the presence of cyclic pressure they have the potential to severely reduce the structural integrity of a pipeline (Hopkins et al., 1989, Jones et al., 1983, and Alexander and Kiefner, 1997c).

The sections that follow discuss in detail experimental testing that has been conducted to address the three 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 developed by Battelle (Maxey, 1986) correlates the relationship between initial dent depth and the residual dent depth as a function of applied pressure and yield strength.

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

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 Battelle 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 burst strength on the damaged pipe. In addition to concerns relating to dent depth and profile, the material of the damaged pipe are also important. Work was reported in the 1980s by British Gas correlating 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. 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 pole 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 British Gas (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 discussion that follow discuss in greater detail the associated responses.

Response of Dents with Gouges to Static Pressure Loading

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. British Gas 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 on 12-in nominal, 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); 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 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 10^5 cycles, then the presence of gouges (in dents) reduces this value to be on the order of 10^3. **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).

Constrained Dents

Most experimental testing over the past 30 years has been directed toward unconstrained plain dents and dents with gouges; however, the presence of constrained dents have caused failures (constrained dents are held in place during the process of pressure cycling). For this reason, the American Petroleum Institute funded a research program that resulted in the publication of API Publication 1156, *Effects of Smooth and Rock Dents on Liquid Petroleum Pipelines* (Alexander and Kiefner, 1997c). While efforts are continuing on this research program, this publication provides numerous insights about the mechanics and failure behavior of rock dents. In this study, a dome cap was used to indent 12-in x 0.188-in pipe that was subjected to cyclic pressure service. The dents were tested in both the unconstrained (smooth dents) and constrained (rock dents) configurations.

Results of the fatigue testing indicated that the fatigue life for constrained dents is significantly longer than the fatigue life for unconstrained dents. One obvious reason for this is that an unconstrained dent has a significant level of rerounding and can never have the sustained dent depth of a constrained dent. For example, a 12 percent constrained dent had a fatigue life that was 426,585 cycles, while an unconstrained dent having a residual depth after pressurization of 2.5 percent (initially 12 percent) failed after 684,903 cycles. Research efforts conducted for the Office of Pipeline Safety (of the U.S. D.O.T) by Texas A&M University yielded similar findings (Keating, 1997).

Although the fatigue resistance to failure of constrained dents is much greater than for unconstrained dents, one area of concern is the capacity for puncture. It has been well-established that a direct correlation exists between the puncture resistance of pipes and wall thickness. Research conducted for the EPRG (Corder and Corbin, 1991) and PRC (Maxey, 1986) support this relationship.

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 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 consistently 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 $\mu\epsilon$, 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.

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. In 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 semi-empirical models have been able to predict with some success the failure pressure for dents with gouges; however, the extreme number of variables precludes the development of a general model that can accurately forecast the fatigue behavior of mechanical damage.

ANALYTICAL RESEARCH EFFORTS

The international attempts directed at analysis of plain dents and dents with gouges pales in comparison to the vast efforts that have been conducted experimentally. Much of the experimental investigations were initiated in the 1960s and 1970s when the use of finite elements and computer-aided software was limited; however, the 1990s have seen greater levels of analytical research because of the advances in high-speed computers. The advantage of computationally studying dents is that it is relatively simple to make variable modifications in the course of a given investigation, while full-scale testing is expensive, prevents assessment of a single variable, and can require significant levels of time in order to generate one data point.

The most comprehensive body of analytical efforts have been funded by the American Gas Association (Fowler et al., 1995), Pipeline Research Committee International (Leis, 1998), Office of Pipeline Safety (Keating, 1996) and the American Petroleum Institute (Alexander and Kiefner, 1997c). The analytical efforts have addressed areas such as the following.

- Rerounding behavior of dent due to elastic rebound applied pressure
- Effects of pipe and indenter geometry
- Constrained versus unconstrained dent configuration
- Effects of soil response
- Alternating stress/strain response to internal pressure differentials

All of these programs incorporated insights learned experimentally in developing analytical efforts.

The finite element modeling by Keating resulted in the development of strain concentration factors, although stress concentration factors were used in the report for estimating fatigue life. Keating rightly recognized the need for the development of damage factors for characterizing defects of varied configurations and proposed that the strain-based model could be used in future studies for such developments.

The analytical efforts by Fowler and Alexander focused on the development and application of stress concentration factors (SCFs) in order to predict the number of cycles to failure for different dent and pipe geometries. Finite element methods were used in these analytical efforts. Because of the familiarity of the author with these research programs, discussions herein will relate to the SCFs and their use in predicting the fatigue behavior of dented pipelines developed for the American Petroleum Institute.

Finite Element Methods

A detailed description of the principles associated with finite element analyses is outside the scope of this paper; however, the basic components and variables involved in the API research program will be discussed. **Figure 1** shows a mesh for the 12-in nominal diameter pipe models used in the analysis. As illustrated in this figure, a dense mesh is applied locally to the dented region of the pipe. Also shown are the associated boundary conditions for each of the exposed edges of the model. The model was constructed using the PATRAN modeling package (version 3.1) and analyzed using the ABAQUS (version 5.4) general-purpose finite element program.

The dimensions for the pipe models were 12.75-in outer diameters, wall thicknesses of 0.188-in and 0.375-in, and the lengths of the pipes were 30 inches total (approximately 2.5 diameters from the center of the dent). The geometry for the indenters was equivalent to those used in the API experimental work (Alexander and Kiefner, 1997c). As illustrated in **Figure 1**, the saddle supports the bottom portion of the pipe and is similar to the saddle arrangement that exists with the experimental dent set-up. The radius of curvature for the saddle was larger than the pipe radius to prevent any over-constraining the bottom of the pipe.

The four basic load steps for the unconstrained smooth dents were as follows:

- Indent to a depth specified as a percentage of pipe diameter
- Remove indenter and allow elastic rebound of the pipe
- Apply pressure inside the pipe
- Remove internal pressure (determination of final residual dent depth).

Seventy-two dent combinations were analyzed, although they will not all be reported in this paper.
One of the primary objectives of the API research program was to provide pipeline operators with a method for predicting the number of cycles to failure for a given dent depth or defect type. The experimental results may be applied to certain defect combinations, assuming they have similar geometries and load histories as those tested. However, the benefit of having analytical results resides in the capacity to calculate fatigue lives for a variety of dent depths and pressure levels. Validation with experimental findings adds greater confidence in applying these analytical results.

Provided in **Tables 5** are the some of the SCF tables calculated using the FEA results. The table considers the following variables,

- Residual dent depth
- Stress concentration factor
- Alternating pressure level.

The tabulated values for each of the dent depths (e.g., 1%, 2%, . . .) were computed using a polynomial curve fit of the FEA data. For example, at the <u>lower pressure level</u>, the <u>unconstrained dome dent</u> with a pipe <u>D/t ratio of 68</u> had SCF * values of 120.7, 188.9, and 231.0 for residual dent depths of 2.8, 6.4, and 9.0, respectively. These values were used in developing the following second-order polynomial,

$$\frac{\Delta\sigma}{\Delta P} = -0.5346\left(\frac{d}{D}\right)^2 + 24.006\left(\frac{d}{D}\right) + 57.675$$

where $\Delta\sigma/\Delta P$ represents the stress concentration factor. This procedure was done for all 72 dent cases and produced a total of 24 curves (each curve has 3 dent depths). Using these curves, the SCF values were determined for integer dent depths. As noted, some curve fits produced non-linearities which prohibited their use over the entire range of the tabulated dent depth levels. Based upon experimental data, the residual dent depths for the 12-inch pipe (D/t of 68) never exceeded 6% of the pipe's diameter when an internal pressure of 72% SMYS was applied, even with an initial indentation of 18%. For this reason, those SCF values not listed due to excessive non-linearities for the respective curve fits that were outside the range of practical application.

Once the stress concentration factors and tables were developed, calculation of fatigue lives for the respective defect combinations were possible. This process was also used for validating the analytical efforts. While numerous fatigue curves could be used, the one selected was from the ASME Boiler & Pressure Vessel Code, Section VIII, Division 2, Appendix 5 (Figure 5-110.1). This curve is for carbon steels with yield strengths less than 80 ksi. While this curve is design-oriented, it is conservative by a factor of two with respect to stress and twenty with respect to cycle number. The curve is described by the following equation,

$$N = \exp\left(43.944 - 2.971\cdot\ln\left(\frac{\Delta\sigma}{2}\right)\right)$$

where $\Delta\sigma$ is computed by multiplying the SCF by the applied pressure range, ΔP.

Consider a dented pipe with the following characteristics:

Residual Dent Depth:	3 percent of pipe diameter
Pipe D/t:	68
Pressure Level	550 - 1100 psig (50% MOP)
Dent Type:	Unconstrained Dome Dent.

For calculating the expected fatigue life for such a defect, consult **Table 5** and extract the appropriate SCF which is ***101.4*** for this problem. Using this SCF and ΔP equal to 550 psig, the fatigue life is computed to be,

* By this definition the SCF for a pipe with D/t = 68 with no dent is 34. This is because $\Delta S = \Delta PD/2t$ by the Barlow formula. Thus, the relative effect of any given value of SCF calculated for a pipe with D/t = 68 by the finite element analysis can be visualized by dividing the SCF by 34. For the highest value shown in **Table 5**, (244.3 for a 10 percent residual dent) the relative effect is 244.3/34 or more than a factor of 7. Even for small residual dents, however, one can see that the relative SCF can be expected to result in cyclic stress ranges 2 to 3 times as large the Barlow stress range.

$$N = \exp\left(43.944 - 2.971 \cdot \ln\left(\frac{101.4 \cdot 550}{2}\right)\right) = 754{,}120 \; cycles$$

For the same problem, consider the pressure range to be 1,100 psig (100% MOP). The SCF is found to be ***107.1*** and ΔP is equal to 1,100 psig. The fatigue life is computed to be,

$$N = \exp\left(43.944 - 2.971 \cdot \ln\left(\frac{107.1 \cdot 1100}{2}\right)\right) = 81{,}755 \; cycles$$

This set of calculations shows the significant impact that the applied pressure range has on the fatigue life, even though there is only a 5.6 percent difference in the respective stress concentration factors.

Table 6 provides a comparison of results for the experimental and analytical fatigue lives of samples *UD6A-2* and *UD12A-3* (Alexander and Kiefner, 1997c). As noted in the table, an *Experimental Equivalent Number of Cycles* is provided for two of the experimental dented fatigue samples. The tabulated results indicate that a reasonably accurate method of estimating fatigue life has been developed. The results are adequately close given the inherent variability in all fatigue testing and the uncertainties in predicting fatigue life, in addition to issues relating to modeling difficulties and assumptions.

Response of Dents to Soil Loading

Although it is certain that numerous independent studies have been conducted to address the interaction of dented pipes and soil, an extensive research program has not been conducted to date. It is interesting to note that many researchers recognize the need for such a study, but no one has undertaken the effort. Briefly discussed in this section of the paper is a small-scale effort directed at assessing the effects of soil stiffness on the behavior of a dented pipeline (Alexander et al., 1998).

A series of finite element models were used to address the effects of,

- Dent shape and depth
- Pressure at instant of indentation
- Variations in soil stiffness
- Effects of hydrotesting of the dent rerounding behavior.

The general observation was that the presence of soil acts to increase the effective stiffness of the pipe during the denting process, much like internal pressure. The models showed that greater dent depths could be achieved with increasing soil stiffness, representative of compacted soil around a pipeline. During the process of rerounding due to internal pressure, the residual dent depth of the dented pipe in soil was deeper than if no soil had been present. Also, the analysis showed the benefits of hydrotesting in rerounding the dent. Similar findings were found on the experimental program conducted for API by Alexander and Kiefner in that the fatigue lives of dents subjected to hydrotesting (90 percent SMYS) exceeded the fatigue lives for those dents that were not subjected to such one-time elevated stress levels.

Implications of Analytical Results

In this section of the paper, results from the finite element work were related to the overall API research program. First, it must be recognized that the analytical efforts were a cursory evaluation to show how one might generate and use stress concentration factors based on finite element analyses to compare the effects of dents of different sizes involving different pipe geometries. It does appear that the approach is valid and useful. However, much more work is necessary to permit the analyses to be applied extensively with a high degree of confidence. Additional comparisons with experimental results is desirable. It is likely that further comparisons would show the need to *calibrate* the model because neither the mechanics nor the material factors could be defined adequately by the size of effort undertaken in this project.

Second, as in-line inspection technology to detect mechanical damage evolves, there will be a need to rank dent-like indications based on size and shape. An expanded and well-validated version of the SCF approach (or strain-based approach) developed herein could serve as the basis for dent-ranking guidelines just as the B31G criterion now does for corrosion-caused metal loss anomalies.

METHODS FOR REPAIRING DAMAGED PIPELINES

Having an understanding of the failure patterns of plain dents and dents with gouges is important, but the greater concern is how to conduct appropriate repairs if they are available. All codes recognize the damage that exists when a gouge is combined with a dent. What is not specifically addressed is the appropriate course of action once such an anomaly is detected. As stated previously, many codes do not completely reflect the technology advances associated with on-going research efforts. While not exhaustive, this section of the paper attempts to provide the reader with an understand of the basic understanding of potential repair methods for repairing dents with gouges.

One item worth noting is the method in which damage to pipelines is discovered. Current advances involving in-line inspection bear directly on the ability of the pipeline industry to operate safe pipelines. In terms of dents to pipeline, the inspection tools must be able to locate and characterize the defect in question. Tools are currently available that can locate dents, gouges and corrosion-related wall losses (Porter, 1998 and Kiefner et al, 1989). a research program involving the Gas Research Institute, Battelle, Iowa State University and Southwest Research Institute is addressing the use of Magnetic Flux Leakage for mechanical damage detection in pipelines (Haines et al., 1998). Once in-line tools determine the presence of damage, it is important to properly interpret the data and assess the severity of the defect. A good example of this effort was conducted jointly by Tuboscope Vetco Pipeline Services and Kiefner & Associates, Inc. (Rosenfeld, 1998b). As discussed later in the paper, additional efforts are needed to develop a useable damage assessment package that can be used by industry to appropriately manage safe pipelines. As a minimum, this involves the following,

- Detection of the defect
- Assess severity of the defect
- Classify defect severity
- Determine appropriate response
- Conduct repair of damage if needed.

Undoubtedly, the most comprehensive document available to pipeline operators discussing pipeline repairs is the *Pipeline Repair Manual* developed for the Pipeline Research Committee (Kiefner et al., 1994).

This document covers topics including repair by grinding, steel sleeves and composite sleeves. According to this document, the techniques used historically in repairing pipelines are,

- Removal of the damaged pipe section
- Grinding out the damaged material
- Filling a defect region by depositing weld metal filler
- Installation of a reinforcing sleeve (Type A sleeve)
- Installation of a sealed pressure containing device (Type B sleeve)
- Installation of a partial encirclement section (patch or half sole)
- Hot tapping.

Interested readers are encouraged to consult this document. Because of recent research advances since the publication of this document, this paper only focuses on two primary types of repair,

- Repair by grinding
- Use of composite sleeves in repairing mechanical damage

Repair by Grinding

The ASME B31.4 Code permits the use of repair by grinding as long as 90 percent of the pipe wall remains after grinding. The equivalent Canadian Code, CAN/CSA-Z184-M92 permits permanent repair of gouges by grinding as long as the grinding process does not remove more than 40 percent of the nominal pipe wall. In an effort to quantify the benefits of repairing dents with gouges with grinding, the AGA and PRCI funded research programs (Fowler et al., 1994 and Alexander et al., 1997a). Both static and cyclic pressure tests were conducted on dents with gouges with samples in the unrepaired and repaired (by grinding) configurations.

The work by Fowler et al. considered only fatigue loading and did not address the effects of grinding in static burst mode. **Table 7** list data showing the improvements associated with repairing dents with gouges by grinding (12.75 x 0.220-in, Grade X56 pipe). As a minimum, repair by grinding improved the fatigue life of the mechanically-damaged samples by one order of magnitude, and in the case of the 5 percent residual dent (approximate) and 15 percent gouge, the improvement was a factor of 5,000.

Efforts by Alexander and Kiefner (Alexander et al., 1997a) addressed repair by grinding of dents with gouges considering both static and cyclic pressure conditions. **Table 8** provides the burst pressures for several repaired/unrepaired defect combinations (12.75-in x 0.188-in, Grade X52 pipe). As noted in the table, the unrepaired test samples all had burst pressures less than SMYS, but the process of repair by grinding restored the burst pressure capacity to exceed 100 percent SMYS in all cases.

The definitive conclusions associated with the research on repair by grinding are summarized below,

- Gouges in dents that are repaired by grinding can be expected to have burst strengths that exceed 100 percent SMYS as long as 80 percent of the pipe wall remains after grinding.
- The results of the fatigue testing, indicate that grinding is an effective means for restoring the fatigue life of dents with gouges. Based upon a comparison of fatigue data, repair by grinding increases the fatigue life of a dent with a gouge to be approximately that of a plain dent that has the same dent depth.

Repair Using Composite Sleeves

The Gas Research Institute (GRI) funded a research program to develop a composite repair system known as Clock Spring. Clock Spring employs glass fibers that are continuously would in the circumferential direction providing resistance to hoop stress. It is designed to be an alternative to the conventional Type A sleeve. Initial efforts were directed at the development of Clock Spring as a local repair system for metal-less defects, with most of the research being conducted by Battelle Memorial Institute (Stephens et al., 1998) and Southwest Research Institute. (Kuhlman et al., 1995). Once Clock Spring was validated as being a sound repair for corrosion, GRI determined the potential for use of Clock Spring in repairing mechanically-damaged pipes. Because of their experience in conducting fatigue tests on damaged pipes, Stress Engineering Services, Inc. conducted this research effort. Mechanical damage (dents with gouges) was inflected to 12-in and 24-in pipes in a fashion similar to the work conducted by Fowler et al. for the AGA (Fowler et al., 1994). Three classes of dents with gouges were tested for GRI (Alexander et al., 1997b),

- Unrepaired
- Repaired by grinding (partial repair)
- Repaired by grinding and installation of Clock Spring (full repair).

Fatigue testing was initiated on the different test samples. **Figure 2** provides a fatigue curve plotting fatigue life as a function of gouge depth. The colored lines represent general trends in the fatigue data. As noted in the figure, the partially repaired samples had fatigue lives that were approximately 100 times the unrepaired configurations, while the installation of Clock Spring increased the fatigue life for the partially repaired samples by a factor of 10. The conclusion drawn from the GRI research program was that Clock Spring is a valid means of repairing mechanically-damaged pipes when used in conjunction with grinding.

Several additional manufacturers have developed composite repair methods focused on corroded and mechanically-damaged pipes. Although none have an as extensive research program as Clock Spring, Armor Plate Pipe Wrap has conducted limited tests on the repair of mechanical damage using static burst tests (Alexander, 1999a). Further research to address the benefits in cyclic pressure service are in progress.

FUTURE RESEARCH EFFORTS

A significant level of information has been presented in this paper relating to experimental and analytical investigations of pipes containing dents and dents with gouges. While qualitative assertions have been developed by numerous organizations, the complexities associated with dents, especially when combined with gouges, have inhibited the development of quantitative correlation that can accurately predict the behavior of the related defects. Based upon a review of the literature, it appears that much of the work is rather academic in nature and is not directly concerned with assisting the pipeline operator in developing useable guidelines. It is hoped that at some point, a transformation will occur.

Based upon the need for useable guidelines, the following list has been developed. The intent in this section of the paper is to suggest areas for further research, some of which are merely extensions of existing research. Many authors who are cited in the *Reference* section of this paper have listed their opinions regarding the need for further research.

As stated previously, advances in computer modeling have greatly aided the advancement of dent mechanics and this trend is expected to continue.

- Additional efforts relating to the rerounding behavior of dents, especially in regards to cyclic pressure.
- Development of strain-based concentration factors considering variables such as dent profile (depth and curvature), pressure at indentation and during cycling, and effects of pipe material and geometry. Their development should be extensive enough to be useable in a variety of dent configurations with different operating conditions.
- Investigations relating to the development of cracks in gouges and highly-strained area of plain dents. The use of finite element methods in conjunction with fracture mechanics is required for such an effort.
- Studies to address how the localized material properties of a pipeline are affected by the presence of dents.
- Continued experimental testing of plain dents and dents with gouges in an effort to develop useable fatigue data. The inherent fatigue scatter precludes a significant level of confidence in using the available data.
- Assessment of residual stress states in dented pipes and how they interact with residual stresses created during the process of manufacturing pipe.
- Development of a manual for operators providing definite guidelines on defects that can be left in pipelines and those they must be repaired along with the most appropriate course of action. The implementation of a pipeline damage acceptance procedure is critical.
- Studies to address the effects of soil behavior on the response of dented pipes to pressure loading. Although the current trend in assessing failure of unconstrained dents is more than likely conservative, the potential for soil-stiffening during the process of creating mechanical damage may lead to greater strain levels than addressed in the current body of research.
- Implementation of insights gained in understanding dent mechanics into data acquired using in-line tool data (such as done by Rosenfeld with Tuboscope-Vetco tool data, Rosenfeld et al, 1998b). It is certainly desirous that at some point in the future in-line tool data can be used to determine how an operator should respond to a measured dent. This will involve developments for researchers in both the in-line inspection business as well as those studying dent mechanicals experimentally and analytically.

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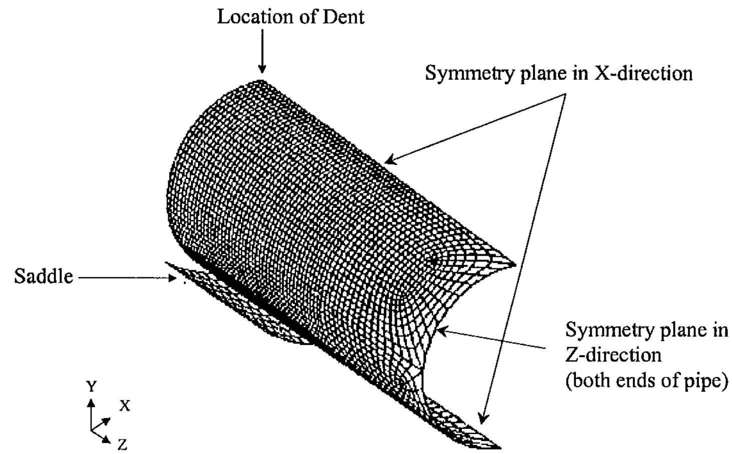

Figure 1 Quarter-symmetry Finite Element Model Mesh

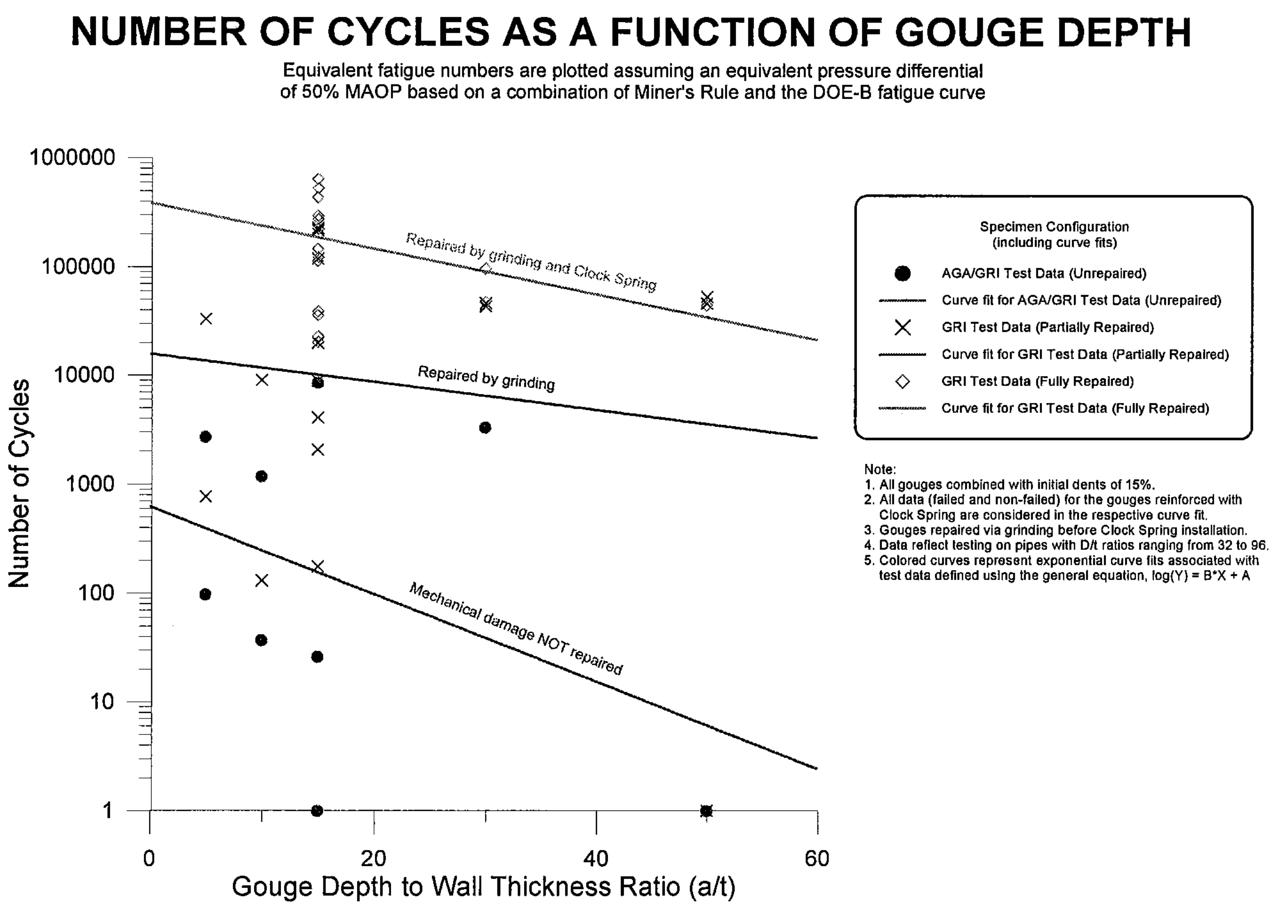

Figure 2 Repair of Mechanical Damage Considering Grinding and Clock Spring

Table 1 Burst Pressures for Plain Dents

Sample Number	Pipe Diameter/Wall thickness (inches)	Yield Strength & Grade	Charpy Impact (ft-lbs)	Percent Dent Depth (d/D)	Failure Stress (ksi)	Notes
BPU 2	36-in / 0.54-in	67.5 ksi / X60	44.2	3.4	67.2 ksi	112 percent SMYS (2)
BNO 1	36-in / 0.50-in	60.8 ksi / X60	19.9	4.5	67.7 ksi	113 percent SMYS (2)
BIE 1	24-in / 0.38-in	53.1 ksi / X52	14.0	5.4	24.9 ksi	Failed at 48 percent SMYS
BLV 1 (1)	30-in / 0.31-in	52.7 ksi	19.2	3.5	71.1 ksi	(2)
EUY 1	36-in / 0.66-in	68.9 ksi / X65	31.7	4.75	26.5 ksi	Failed at 40.8 percent SMYS
FJB 1 (1)	30-in / 0.48-in	58.8 ksi / X52	22.8	3.2	18.9 ksi	Failed at 36 percent SMYS
FJB 2 (1)	30-in / 0.48-in	58.8 ksi / X52	22.8	4.9	12.6 ksi	Failed at 24 percent SMYS

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

Table 2 Cyclic Pressure Tests on Plain Dents

Sample Number	Pipe Geometry/ Grade	Initial Dent Depth (d/D, percent)	Residual Dent Depth (d/D, percent)	Cycles to Failure ($\Delta\sigma_{nom}$ = 50% SMYS)
US6A-2	12.75-in x 0.188-in, X52	6	1.25	1,307,223
UD12A-3	12.75-in x 0.188-in, X52	12	2.5	684,903
UD18A'-28	12.75-in x 0.188-in, X52	18	0.7	101,056

Notes:
1. No pressure 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 number listed based upon use of Miner's Rule in combined results from two applied pressure ranges ($\Delta\sigma_{nom}$ = 50% and 100% SMYS, see *Alexander and Kiefner, 1997c* for details)
4. Test sample did not fail. Testing terminated due to extreme number of cycles.

Table 3 Burst Tests for Dents with Gouges

Sample Number	Gouge Depth (a/t, percent)	Dent Depth (d/D, percent)	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, 72.1 ksi UTS, 51 ft-lbs CVN.

Table 4 Fatigue Life for Gouges, Plain Dents and Dents with Gouges

Dent Depth (percent pipe diameter)	Gouge Depth (percent wall thickness)	Fatigue Life
None	20 percent	greater than 145,500
4 percent	None	less than 6,930
4 percent (in pipe weld)	None	less than 789
4 percent	20 percent	less than 119

Table 5 Stress Concentration Factors (Δσ/ΔP) for Unconstrained Dome Dents

Pipe D/t	Residual Dent Depth (percent d/D)									
	1	2	3	4	5	6	7	8	9	10
Low Range Pressure Cycle (0 - 50% MOP)										
34	***38.5***	***42.7***	47.1	51.5	56.0	60.7	65.6	70.4	75.4	80.5
68	***81.1***	103.5	128.9	145.1	164.3	182.5	199.5	215.5	230.4	244.3
High Range Pressure Cycle (50 - 100% MOP)										
34	***34.8***	38.7	42.5	46.2	49.8	53.2	56.6	59.8	62.9	65.9
68	***70.7***	87.1	101.4	113.6	123.7	131.7	***137.7***	***141.5***	***143.3***	[redacted]
Full Range Pressure Cycle (0 - 100% MOP)										
34	***32.9***	38.0	42.8	47.4	51.7	55.8	59.7	63.4	66.8	70.0
68	***71.0***	90.8	107.1	119.8	128.9	134.4	***136.3***	[redacted]		

Notes:

1. Residual dent depths (d/D) based upon maximum analytical dent depths remaining after prescribed pressure range applied to sample for one cycle
2. Pressure ranges based upon percentage of MOP, Maximum Operating Pressure (100% MOP corresponds to 72% SMYS)
3. Tabulated SCF values based upon curve fit of FEA data using a second-order polynomial
4. Number in ***bold italics*** are extrapolated from the range of minimum and maximum residual FEA dent depths
5. Polynomial curve fitting process produced some invalid values (out of range with other values) and are indicated by cells that have been blacked out (■).

Table 6 Comparison of Experimental and Analytical Fatigue Results

Sample	Residual Dent Depth (d/D)	Experimental Number of Cycles with ΔP = 50% MOP	Experimental Number of Cycles with ΔP = 100% MOP	Experimental [(1)] Equivalent Number of Cycles	Analytical [(2)] Number of Cycles with ΔP = 50% MOP
UD6A-2	1.6%	28,183	79,940	1,307,223	1,494,923
UD12A-3	3.8%	28,183	41,045	684,903	573,940

Notes:

1. The values obtained by determining the equivalent number of cycles assuming an alternating pressure of 50% MOP.
2. These values obtained by calculating fatigue lives assuming upper pressure range of 50% MOP applied.
3. The above dents were installed in 12.75-in x 0.188-in, grade X52 pipe. The dents were installed with no internal pressure in the pipe and were not constrained during cycling.

Table 7 Effects of Repair by Grinding on Dents with Gouges Subjected to Cyclic Pressure

Sample #	Percent Dent Depth After Rerounding	Percent Gouge Depth (before grinding)	Unrepaired/ Repaired	Cycles to Failure (ΔP = 500 psi)
1	4.88	15	Unrepaired	3
2	4.77	10	Unrepaired	4,408
3	4.69	5	Unrepaired	10,111
10	5.49	15	Repaired	15,300
9	4.78	10	Repaired	34,000
8	4.69	5	Repaired	123,790

Table 8 Effects of Repair by Grinding on the Burst Pressure of Dents with Gouges

Sample #	Percent Dent Depth (before rerounding)	Percent Gouge Depth (before grinding)	Unrepaired/ Repaired	Burst Pressure (% SMYS))
B1-10G	5	15	Repaired	1,820 psi (119%)
B1-11N	5	15	Unrepaired	775 psi (51%)
B2-12G	5	10	Repaired	1,887 (123%)
B2-13N	5	10	Unrepaired	1,354 (88%)
B2-14G	5	15	Repaired	2,153 psi (140%)
B2-15N	5	15	Unrepaired	920 psi (60%)