REPAIR OF MECHANICALLY-DAMAGED PIPES USING ARMOR PLATE PIPE WRAP

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SUMMARY
This paper details the testing of mechanically-damaged pipes repaired using Armor Plate Pipe Wrap (APPW). In this discussion, mechanical damage means local indentation of a pipe with an external gouge. This type of defect results in reduction of structural integrity when internal pressure is applied both statically and in a cyclic manner. A significant level of research on mechanical damage has been conducted over the past twenty years based upon the observation that third-party damage is the leading cause of pipeline failures in the United States. More recently, efforts have addressed the effects of cyclic pressure service on mechanical damage and the number of cycles required for the development of leaks.

In this study, mechanical damage was created by installing dents in pipes that were previously gouged by an end mill. The gouge depths and dent depths were 15 percent of the pipe wall thicknesses and diameters, respectively. Two pipe sizes and grades were used. One being 12.75-in x 0.188-in, grade X52 and the other being 12.75-in x 0.375-in, grade X42. Four defects were created in each of the two pipe samples, giving a total of eight defects in the test program. In each sample one defect was not repaired, two were repaired by grinding and installation of APPW, and the fourth defect was repaired by grinding, installation of APPW plus installation of a stainless steel clamp. Internal pressure was cycled in each sample at a range of 100 percent of the maximum operating pressure (MOP) until failure occurred in each dent. As failures occurred, the failed sections were cut out and the remaining segments welded together so that additional cycle testing could occur.

In terms of failure data, the following trends were observed. Samples repaired by grinding had fatigue lives that were approximately 10 times those of unrepaired dents and gouges. Those defects that were repaired by grinding and APPW had fatigue lives that were approximately 1,000 times those of unrepaired dents and gouges. Slight improvements were obtained over the grinding/APPW repair with the installation of the Armor Plate stainless steel clamp. The minimum cycles to failure at 50 percent MOP for any given defect was greater than 100,000 cycles. The conclusion based upon these test results is that dents and gouges can be repaired using Armor Plate Pipe Wrap in conjunction with grinding when considering the normal cyclic pressure loads for most liquid and gas transmission pipelines.

INTRODUCTION
Because third-party mechanical damage to both liquid and gas transmission pipelines is a serious problem, a considerable amount of research has been conducted to address mechanical damage as it relates to pipeline integrity. The bulleted items below represent the major U. S. works in this area. These research programs have considered both hydrostatic as well as cyclic pressure loadings.

Battelle Memorial Institute (Battelle) has been active in works relating to pipeline research. In the 1960s and 1970s they received a significant amount of the research money available from the Pipeline Research Committee at the American Gas Association. Numerous works were produced by Battelle in this area (Maxey, 1986, 1987 and Eiber et al., 1981).

In the early 1990s a research program was funded by the Pipeline Research Committee at the American Gas Association to address the cyclic pressure effects on the fatigue life of pipelines with plain dents. This program was conducted by Stress Engineering Services, Inc. (Fowler et al., 1994). Based upon the insights gained with this program, additional research was conducted to address dents combined with gouges and dents combined with welds. Dents were installed using a flat plate indenter with no internal pressure. The predominant conclusion was that plain smooth dents with depths less than 5 percent of the pipe’s outer diameter should not be a problem. However, the experimental results showed that dents with gouges have a significant impact on fatigue life, with gouge depth being the critical issue. Finite element efforts were also used to develop stress concentration factors for estimating the fatigue life of dents given a specified dent depth and cyclic pressure range.

Another research program was funded by the Pipeline Research Committee International (PRCI) to address the repair of mechanical damage (dents with minor scratches) by grinding (Kiefner et al., 1999). This program was conducted jointly by Kiefner & Associates, Inc. and Stress Engineering Services, Inc. Dents were installed with internal pressure (60 percent SMYS) and a slender 1-in wide bar was used to indent the pipes. The objective was to determine which defects can be repaired by grinding and the best procedure for doing so. In all testing, the defects were conducted in pairs so that the repaired defects could be compared to the unrepaired defects. Results indicated that shallow...
Pipeline Repair Manual developed with funding from the Pipeline Research Committee International (Kiefuer et al., 1994) provides a list of the defects and repair configurations associated with the two pipe samples.

Figure 1 shows the indenter test rig used to install the dents, while Figure 2 provides a close-up view of the indenter profile for Sample A. The denting procedure was repeated to create four dents in each pipe sample. In the process of creating the dents, measurements were made to acquire the dent profile and dent depth. Table 2 provides the dent depth measurements for all of the test samples, while Figure 3 plots the axial profile for Sample A4 and Sample B4. Note the significant level of rerounding that occurs in the dented region as a result of internal pressurization.

Table 3 provides the changes in wall thickness that resulted from the grinding process. The significance in the remaining wall is that one can determine the extent of the cracked material in comparison to the original depth of the gouge.
After the dents were installed and the gouges repaired by grinding, the Armor Plate Pipe Wrap sleeves were installed. The information in Table 1 provides the specific number of wraps installed on each sample. The general rule of thumb for repairing mechanical damage (after gouge removal) is for the thickness of the wrap to be 1.5 times the thickness of the pipe wall thickness. Each layer of the wrap is approximately 1/16-in thick. Four layers of APPW were used in conjunction with the clamps. Figure 4, Figure 5 and Figure 6 show different stages of the wrap installation process.

While the focus of this testing was on the use of Armor Plate in repairing mechanical damage, the recent development of a stainless steel clamp by Armor Plate, Inc. (used in conjunction with the composite wrap materials) was implemented into the fatigue test program. One clamp was installed on each of the pipe samples. Figure 7 is a photograph of one of the clamps. As seen, the clamp is comprised of two halves that are bolted together. Both Sample A1 and Sample B1 involved four layers of APPW in addition to the clamps. The clamps are fabricated from 1/8-in 316 stainless steel material and are bolted together using six 3/4-in bolts. Prior to their installation, the APPW sleeves were applied and permitted to cure. The surfaces of the wrap were ground smooth and grease was applied to reduce friction during the bolt-tightening process. The bolts were tightened to 125 ft-lbs which corresponded to an approximate bolt stress of 52,000 psi.

Following the repair of the dents and gouges, the two pipe samples were subjected to cyclic pressures. The selected pressure ranges were based upon percentages of the Maximum Operating Pressure (MOP) which was assumed to be 72 percent of the SMYS for each pipe. The applied pressure ranges were both 100 percent of the MOP which corresponded to the following ranges (100 psi minimum permitted by pumping unit).

- Sample A, 100 - 1,200 psi
- Sample B, 100 - 1,880 psi

The samples were cycled until a failure developed in one of the damaged areas. The failure was then cut out and the remaining pipe segments were welded together. This process was continued until all eight samples had been tested.

**TEST RESULTS**

In terms of test results and their presentation, the essential element is cycles to failure for each test sample. The evaluation of the Armor Plate system is directly related to the improvement in fatigue life for those samples repaired using APPW. As will be shown, significant improvement is derived in application of Armor Plate. Additional benefits are derived with installation of the stainless steel clamp.

Two modes of presentation are used. First, data is presented in tabular form. Table 4 presents the raw fatigue data for the applied pressure range as well as a modified fatigue value that corresponds to a lower applied cyclic stress range. The second method of presentation is Figure 8, a plot showing cycles to failure for the test samples. Also included in this plot are test data from other research programs concerning with dents containing gouges (Alexander et al., 1998 and Fowler et al., 1994).

**Table 4 provides the cycles to failure for the eight samples tested in this program. As noted in the table, installation of APPW significantly increased the fatigue life when compared to the unrepaired test samples.**

**Plotted Test Results**

The benefit derived in plotting the fatigue results from this project are that direct comparisons can be made with existing fatigue data on mechanical damage. As stated previously, work conducted for the American Gas Association (Fowler et al., 1994) and the Gas Research Institute (Alexander et al., 1998) provide the key data for making this type of comparison.

Figure 8 plots the cycles to failure for the samples repaired using APPW as well as the data for the two stainless steel clamps. Four sets of data are plotted.

- Unrepaired dents with gouges
- Dents and gouges repaired via grinding
- Dents and gouges repaired by grinding and installation of APPW
- Dents and gouges repaired by grinding, installation of APPW, and stainless steel clamp

In terms of failure data, the following trends were observed.

- Samples repaired by grinding had fatigue lives that were approximately 10 times those of unrepaired dents and gouges
- Those defects that were repaired by grinding and APPW had fatigue lives that were approximately 1,000 times those of unrepaired dents and gouges
- Slight improvements were obtained over the grinding/APPW repair with the installation of the stainless steel clamp.

The minimum cycles to failure at 50 percent MOP for any of the repaired defects (Sample B2) was approximately 200,000 cycles, while the maximum cycles to failure at 50 percent MOP was more than 1.6 million cycles.

**DISCUSSION OF RESULTS**

This section of the paper briefly discusses some aspects of the test results and how they apply to the operation of actual pipelines. The following concepts are discussed,

- Repair by grinding
- Interpretation of fatigue data
- Location of failures

**Repair by Grinding**

To date, the most significant body of work relating to repair of mechanical damage by grinding was conducted for the Pipe Research Committee International by Kiefner and Alexander (Kiefner et al., 1999). This program focused on repair by grinding in terms of both hydrostatic and cyclic pressure loading. This previous research effort relates to the use of APPW in repairing mechanical damage because removing the material near the gouge is a key component of the repair process. The presence of the gouge in the dent results in cracks at the base of the gouge that develop during the rerounding process with increasing internal pressure. When the cracks are not removed, they continue to grow in response to increasing internal pressure (as in a quasi-static burst test) or with the application of repeated pressure cycles (as in a fatigue test). Recent research has validated this phenomenon as well as the use of grinding as a repair method (Kiefner et al., 1999). In this project, the gouges were removed using a hand-held grinder. Liquid dye penetrant was used to verify the removal of the cracked material at the base of the gouge.

The PRCI final report provided a section entitled Guidelines for Repair by Grinding. The major concepts presented from this section of the report are outlined below and discuss topics such as pressure reduction, cleaning, characterizing the visual extent of the damage, measuring the...
Mechanical damage is the most serious type of defect present in most pipelines. It is unlikely that the effect of a given gouge and dent defect on the remaining strength of the pipe can accurately be determined. For this reason, it is prudent to lower the operating pressure of the pipeline during both the inspection and repair phases.

In order to properly inspect and characterize the pipe and the defect it is necessary to remove all coating, soil, corrosion products, and other debris from the vicinity of the defect. This is necessary so that no part of the gouge or the dent will be overlooked; all of it must be addressed to assure an adequate repair. A straight-edge should be used to measure the axial profile of the dent and if possible, calipers should be used to measure the overall pipe diameters relative to the dent. The wall thickness should be measured by means of an ultrasonic method.

Metal removal by grinding should be done gradually. The ideally safe approach to grinding an axially oriented gouge with a disk grinder is to orient the wheel so it removes metal in the circumferential direction (across the gouge). The grinding should not be continued if more than 40 percent of the wall thickness required for design purposes will be removed. If the 40 percent threshold is reached before the gouge or any associated cracking disappears, repair by grinding should cease and another repair method should be applied. If the grinding required to remove all damage including cracks passes the 20 percent (of required wall thickness) threshold at any point and the depth of the groove at all points is less than or equal to 40 percent, the length of the groove between the extreme points where metal removal begins and ends should be measured and should not exceed $L$ (equation based upon Canadian Standard Z662-96, Oil and Gas Pipeline Systems, Paragraph 10.8.2.2.4)

$$L = 1.12 \sqrt{\Delta P} \left( \frac{a/t}{1.1a/t - 0.11} \right)^{1/2}$$

$D$ = outside diameter of pipe
$a$ = thickness required for design
$t$ = wall thickness required for design

The width of the ground area (i.e., the circumferential extent) need not be limited unless there is an unusual source of axial stress on the pipeline.

**Interpretation of Fatigue Data**

The intent of this section of the paper is to discuss the cycles to failure for the test samples and how these numbers can be applied to actual operating pipelines. As discussed previously, the applied pressure cycles corresponded to 100 percent of the maximum operating pressure. While most pipelines will experience pressure levels at this level, it is unlikely that they are applied frequently. Liquid pipelines tend to experience more pressure cycles (and at larger ranges) than do gas transmission pipelines.

Conversion of cycles based upon stress range involves use of Miner’s Rule and an $n$-th ordered relationship between stress and cycles to failure (characteristically $n$ is between 3 and 4). Consider in our test program where the pressure range is 100 percent MOP. What is the calculated cycles to failure if the pressure level is changed to 50 percent MOP? The following equation permits this calculation and is based on Miner’s Rule and a 4th-ordered relationship between stress and cycles to failure.

$$N_2 = N_1 \left( \frac{\Delta P_2}{\Delta P_1} \right)^4$$

where:

- $N_1$ = cycles to failure assuming a pressure range of $\Delta P_1$
- $N_2$ = cycles to failure assuming a pressure range of $\Delta P_2$
- $\Delta P_1$ = pressure range #1
- $\Delta P_2$ = pressure range #2

The cycles to failure assuming a pressure range of 50 percent MOP using known cycles to failure and pressure range ($N$ and $\Delta P$, respectively) is calculated as follows.

$$N_2 = N_1 \left( \frac{50}{100} \right)^4 = 16N_1$$

Hence, reducing the applied pressure by 50 percent means that the fatigue life is increased by a factor of 16 times. An entire series of calculation can be performed by modifying the assumed pressure range. The previous data presented in Table 4 uses this methodology.

To develop a relationship between the cycles to failure and years of service in an actual pipeline, consider Sample B2. This sample had the lowest number of cycles to failure, corresponding to 196,416 cycles with $\Delta P$ equal to 50 percent MOP. For an imposed safety factor, divide this number by 20, which gives 9,820 cycles. If a pipeline is assumed to have an applied pressure range of 50 percent MOP applied every other day, the fatigue life for repair (using the modified Sample B2 data) is approximately 54 years. While there are no fixed number of cycles per year that exist on any given pipeline, as a minimum this methodology can be employed to estimate the years of service a repair can withstand for a given set of operating conditions.

**Location of Failures**

Figure 9 and Figure 10 show the failure locations for two of the repaired samples. Table 5 lists the location of the cracks the developed as a result of the fatigue testing. It is interesting to note that most of the cracks developed away from the location of the original gouge. This observation is important for two reasons. First, it indicates that the grinding procedure was effective in removing the cracked material. Secondly, it indicates that the composite sleeve provided enough reinforcement so that fatigue cracks did not develop in the area of the pipe with the thinnest remaining wall.

**COMMENTS AND CLOSURE**

The primary aim of the fatigue testing of mechanical damage repair using Armor Plate Pipe Wrap was to determine the increase in fatigue life when compared to unrepaired and ground-only repairs. While a significant level of fatigue testing has been done on plain dents and dents with gouges, little effort has been made to address the effects of sleeves on the repair of mechanical damage. The primary reason for this missing body of information is that many companies choose to
completely remove the damaged sections of pipe or install welded full encirclement sleeves. Their reasons for making such decisions are prudent based upon the available information to date; however, the use of composite sleeves and grinding in repairing mechanical damage has technical merit. The body of work reported herein contributes to the missing information in this area.

Specifically in terms of the benefits derived in application of Armor Plate Pipe Wrap, samples repaired by grinding had fatigue lives that were approximately 10 times those of unrepaired dents and gouges. Those defects that were repaired by grinding and APPW had fatigue lives that were approximately 1,000 times those of unrepaired dents and gouges. Slight improvements were obtained over the grinding/APPW repair with the installation of the stainless steel clamp. Considering that the minimum cycles to failure at 50 percent MOP was greater than 100,000 cycles, even with an applied factor of safety, this value far exceeds the number of cycles a typical gas or liquid transmission pipeline will see in its lifetime.

REFERENCES


Table 1 Dent and gouge sample configuration

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Pipe Geometry</th>
<th>Gouge Depth</th>
<th>Dent Depth</th>
<th>Repair Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>12.75 x 0.188</td>
<td>15% (0.028-in)</td>
<td>15% (1.9-in)</td>
<td>Gouge ground, 4 wraps of APPW, install clamp</td>
</tr>
<tr>
<td>A2</td>
<td>12.75 x 0.188</td>
<td>15% (0.028-in)</td>
<td>15% (1.9-in)</td>
<td>Gouge ground, 5 wraps of APPW</td>
</tr>
<tr>
<td>A3</td>
<td>12.75 x 0.188</td>
<td>15% (0.028-in)</td>
<td>15% (1.9-in)</td>
<td>Gouge ground, 5 wraps of APPW</td>
</tr>
<tr>
<td>A4</td>
<td>12.75 x 0.188</td>
<td>15% (0.028-in)</td>
<td>15% (1.9-in)</td>
<td>No repair</td>
</tr>
<tr>
<td>B1</td>
<td>12.75 x 0.375</td>
<td>15% (0.056-in)</td>
<td>15% (1.9-in)</td>
<td>Gouge ground, 4 wraps of APPW, install clamp</td>
</tr>
<tr>
<td>B2</td>
<td>12.75 x 0.375</td>
<td>15% (0.056-in)</td>
<td>15% (1.9-in)</td>
<td>Gouge ground, 9 wraps of APPW</td>
</tr>
<tr>
<td>B3</td>
<td>12.75 x 0.375</td>
<td>15% (0.056-in)</td>
<td>15% (1.9-in)</td>
<td>Gouge ground, 9 wraps of APPW</td>
</tr>
<tr>
<td>B4</td>
<td>12.75 x 0.375</td>
<td>15% (0.056-in)</td>
<td>15% (1.9-in)</td>
<td>No repair</td>
</tr>
</tbody>
</table>

Notes:
1. Gouge depth based upon percentage of nominal pipe wall thickness
2. Dent depth based upon percentage of nominal pipe diameter

Table 2 Dent depth measurements made during denting process

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Target Dent Depth (inches)</th>
<th>Interim Dent Depth (inches)</th>
<th>Residual Dent Depth (inches)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>1.9</td>
<td>0.778</td>
<td>0.276</td>
</tr>
<tr>
<td>A2</td>
<td>1.9</td>
<td>0.690</td>
<td>0.234</td>
</tr>
<tr>
<td>A3</td>
<td>1.9</td>
<td>0.561</td>
<td>0.218</td>
</tr>
<tr>
<td>A4</td>
<td>1.9</td>
<td>0.897</td>
<td>0.295</td>
</tr>
<tr>
<td>B1</td>
<td>1.9</td>
<td>1.027</td>
<td>0.490</td>
</tr>
<tr>
<td>B2</td>
<td>1.9</td>
<td>1.052</td>
<td>0.473</td>
</tr>
<tr>
<td>B3</td>
<td>1.9</td>
<td>0.991</td>
<td>0.449</td>
</tr>
<tr>
<td>B4</td>
<td>1.9</td>
<td>1.017</td>
<td>0.476</td>
</tr>
</tbody>
</table>

Notes:
1. Target dent depth corresponds to depth the indenter was pushed into pipe during denting (no internal pressure)
2. Interim dent depth is the depth resulting from elastic rebound after the indenter was removed
3. Residual dent depth is the dent depth remaining after the samples were pressurized to 60 percent SMYS (920 psi for Sample A and 1,482 for Sample B)
<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Gouge Depth</th>
<th>Wall thickness before grinding</th>
<th>Wall thickness before grinding</th>
<th>Material removed due to grinding</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>15% (0.028-in)</td>
<td>0.187</td>
<td>0.146</td>
<td>0.041</td>
</tr>
<tr>
<td>A2</td>
<td>15% (0.028-in)</td>
<td>0.186</td>
<td>0.155</td>
<td>0.031</td>
</tr>
<tr>
<td>A3</td>
<td>15% (0.028-in)</td>
<td>0.188</td>
<td>0.151</td>
<td>0.037</td>
</tr>
<tr>
<td>A4</td>
<td>15% (0.028-in)</td>
<td>0.188</td>
<td></td>
<td>Sample not ground</td>
</tr>
<tr>
<td>B1</td>
<td>15% (0.056-in)</td>
<td>0.381</td>
<td>0.322</td>
<td>0.059</td>
</tr>
<tr>
<td>B2</td>
<td>15% (0.056-in)</td>
<td>0.380</td>
<td>0.318</td>
<td>0.062</td>
</tr>
<tr>
<td>B3</td>
<td>15% (0.056-in)</td>
<td>0.371</td>
<td>0.309</td>
<td>0.062</td>
</tr>
<tr>
<td>B4</td>
<td>15% (0.056-in)</td>
<td>0.383</td>
<td></td>
<td>Sample not ground</td>
</tr>
</tbody>
</table>

Notes:
1. Wall thickness measurements made using a hand-held ultrasonic meter

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Cycles to Failure (\Delta P = 100% \text{ MOP})</th>
<th>Cycles to Failure (\Delta P = 50% \text{ MOP})</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>100,123</td>
<td>1,601,968</td>
<td>4 layers of APPW, stainless clamp</td>
</tr>
<tr>
<td>A2</td>
<td>61,558</td>
<td>984,928</td>
<td>5 layers of APPW</td>
</tr>
<tr>
<td>A3</td>
<td>48,818</td>
<td>781,088</td>
<td>5 layers of APPW</td>
</tr>
<tr>
<td>A4</td>
<td>2,613</td>
<td>41,808</td>
<td>Unrepaired sample</td>
</tr>
<tr>
<td>B1</td>
<td>23,344</td>
<td>373,504</td>
<td>4 layers of APPW, stainless clamp</td>
</tr>
<tr>
<td>B2</td>
<td>12,276</td>
<td>196,416</td>
<td>9 layers of APPW</td>
</tr>
<tr>
<td>B3</td>
<td>20,444</td>
<td>327,104</td>
<td>9 layers of APPW</td>
</tr>
<tr>
<td>B4</td>
<td>914</td>
<td>14,624</td>
<td>Unrepaired sample</td>
</tr>
</tbody>
</table>

Note
(1) Refer to Interpretation of Fatigue Data in this report for additional information on calculation of these values.

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Orientation of cracks</th>
<th>Position of crack</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>Longitudinal</td>
<td>1.5-in off gouge centerline</td>
</tr>
<tr>
<td>A2</td>
<td>Longitudinal</td>
<td>2.0-in off gouge centerline</td>
</tr>
<tr>
<td>A3</td>
<td>Longitudinal</td>
<td>3.0-in off gouge centerline</td>
</tr>
<tr>
<td>A4</td>
<td>Longitudinal</td>
<td>gouge centerline</td>
</tr>
<tr>
<td>B1</td>
<td>Longitudinal</td>
<td>3.5-in off gouge centerline</td>
</tr>
<tr>
<td>B2</td>
<td>Longitudinal</td>
<td>gouge centerline</td>
</tr>
<tr>
<td>B3</td>
<td>Longitudinal</td>
<td>gouge centerline</td>
</tr>
<tr>
<td>B4</td>
<td>Longitudinal</td>
<td>gouge centerline</td>
</tr>
</tbody>
</table>
Figure 1 Dent installation rig used to install dents

Figure 2 Close-up view of indenter plate creating dent in pipe
DENT DEPTH AS A FUNCTION OF LONGITUDINAL POSITION

Data Configuration
- Dent depth after indentation (elastic rebound)
- Dent depth after pressurization (residual dent depth)

Figure 3 Profile of dent depth along longitudinal axis of pipe

Figure 4 Filler material applied in dented region
Figure 5 Application of epoxy primer

Figure 6 Completed installation of Armor Plate Pipe Wrap
CYCLES TO FAILURE FOR MECHANICAL DAMAGE REPAIRED USING ARMOR PLATE PIPE WRAP

Data plotted for cycles to failure as a function of pipe diameter to wall thickness ratio. Equivalent fatigue numbers are plotted assuming an equivalent pressure range of 50 percent of the maximum allowable operating pressure using of Miner's Rule and a fourth-order relationship between stress range and fatigue (cycles to failure).

Figure 8 Fatigue data for dents and gouges in varying states of repair.