ANALYSIS OF COMPOSITE REPAIR METHODS FOR PIPELINE MECHANICAL DAMAGES SUBJECTED TO CYCLIC LOADING

Christopher R. Alexander
Stress Engineering Services, Inc.
13800 Westfair East Drive
Houston, Texas 77041-1101

Joe R. Fowler
Stress Engineering Services, Inc.
13800 Westfair East Drive
Houston, Texas 77041-1101

Keith Leewis
Gas Research Institute
8600 West Bryn Mawr
Chicago, Illinois 60631

ABSTRACT

In service mechanical damage occurring on operating transmission pipelines can induce leakage and eventual failure. Considering that there are approximately 250,000 miles of domestic gas pipelines, repair of these anomalies results in significant costs to the industry. This paper describes a research project sponsored by the Gas Research Institute to determine the capabilities of a composite based assembly designed as an alternative to steel sleeves. This system was evaluated as a repair for mechanical dents and gouges on line pipe with D/t ratios of 51, 68 and 96. The composite wraps were placed over mechanical defects consisting of dents 15% of the diameter and gouge depths of 15, 30, and 50% of the wall thickness. Internal pressures were cycled from 0 - 50% MAOP and 50 - 100% MAOP. Results indicate that sharp axial defects in the pipe can be successfully reinforced if they are first blunted by grinding to remove the stress concentrators. The repair system increases fatigue life by 2 to 5 times over those dents with gouges that were not ground.

INTRODUCTION

The mechanical damages caused to gas transmission pipelines are some of the primary factors which induce leakages and eventual failures. Stress Engineering Services, Inc. has conducted a significant level of research in studying the effects of damages such as dents and gouges on the fatigue life of pipes subjected to internal cyclic pressure loading. Previous findings indicated that dents combined with gouges of 5% to 15% of the wall thickness significantly reduced the fatigue life of pipes with D/t ratios less than 68. The failure mechanism for these pipes with dent/gouge defects was propagation of the microcracks which were created in the gouge during the denting process.

The dent/gouge defects have a serious bearing on pipeline operation. Current pipeline standards require that any dent which is greater than 2 percent of the pipe diameter must be removed. The standards also state that all gouges must be removed. One of the primary aims of the original research studying dents and gouges was to determine if these standards are too conservative. As would be expected, pipeline operators would benefit significantly if it could be shown that in fact the codes are overly conservative and that greater dent depths and gouge are permissible.

In light of this information, it is desirable to determine a repair method which will reduce the effects of the dents and gouges on fatigue life. Previous work indicates that grinding out gouges increases the fatigue life of samples significantly; however, it would still be beneficial to the pipeline industry if a method were developed to lower the stress values in the regions where mechanical damages have occurred. The Clock Spring pipeline wrapping system proposes to accomplish this objective. The principal aim of this research is to determine if Clock Spring is in fact a possible means by which to increase the fatigue life of pipes with defective regions. In this study, experimental testing was conducted on pipes which had Clock Spring installed over regions that had been gouged, dented, and the gouges ground out. Since this research is designed to help the pipeline operators in repairing their lines, when Clock Spring is employed as a repair method over the dents and gouges, the gouges were always ground. In this study the following parameters were determined to be important and served as variables in testing,

1. D/t Ratio (12 inch pipe with D/t ratios of 51, 68 and 100)
2. Installation pressure of Clock Spring (0, 50, and 90% MAOP)
3. Gouge Depth (0, 15, 30 and 50% of wall thickness)
4. Pressure ratios for cycling (50% and 100% MAOP)
5. Mean Pressure.

The primary objectives of the fatigue testing phase of this project are:

1. Experimentally determine the fatigue life of defective pipes reinforced with Clock Spring. Several of the samples had one dent/gouge combinations which were not repaired with Clock Spring. These specimens will serve as baseline test cases to which the additional fatigue data for Clock Spring will be compared. It was also important to determine which of the above parameters affect the capability of Clock Spring to maximize fatigue life.
2. Compare previous findings associated with the effects of dent/gouge combinations (unreinforced) on fatigue life of pipes to the experimental data of the Clock Spring results.

EXPERIMENTAL TESTING PROCEDURES

As stated earlier, one of the primary aims of this research was to verify if Clock Spring is indeed a means to reduce the effects of dents and gouges on the fatigue life of a pipe. With this perspective in mind, a test matrix was developed which would aid in accomplishing the research objectives and also provide useful insights for pipeline operators in repairing their systems. The experimental set-up work associated with the Clock Spring testing involved the four steps listed below,

1. Pipes purchased in order to fulfill the research objectives (geometry and grade)
2. Selection of Dent/Gouge Configuration
3. Dent/gouge installation in pipes and grinding out gouges
4. Installation of Clock Spring
5. Fatigue testing of specimens at 50% and 100% MAOP

Pipe Selection

In order to understand the performance of Clock Spring on a variety of pipe sizes, pipes with D/t ratios ranging from 51 to 100 were used. All pipes purchased fulfilled the requirements for the X52 grade. **Table 1** shows the pipes which were purchased to fulfill this requirement.

Dent/Gouge Configuration and Selection

A considerable amount of research has been conducted regarding the range of dent and gouge dimensions (Fowler et al.) and this information was used in selecting the defect sizes for this research. It has been found that the combination of dents and gouges contributes significantly to the reduction in burst test and fatigue life of pipelines. With this data in mind, initial testing involved installation of gouges that were 15% of the wall thickness (d/t) combined with residual dents which were 5% of the pipe diameter (d/D). Dent lengths of 12" and 24" were selected for this study. Work performed in the final phases of this research involved gouge depths which were as deep as 30% and 50% of the wall.

Previous research was also used in determining the configuration for the gouge shape. The installation of the gouge is an important part of this study when considering that the defining characteristic of the dent/gouge combination which makes it so dangerous is the presence of microcracks which occur at the base of the gouge upon indentation. The most reproducible microcracks were made from a machined groove with a 0.002" radius as shown in **Fig. 1**. The gouges were milled into the pipe sample prior to indentation. The minimum longitudinal distance between dent/gouge regions relative to one another was selected based on the recommendations regarding *Local Bending Stress* as outlined in the ASME Boiler Pressure Vessel Code. The minimum meridional gap between selections was greater than the value determined using **Eq. 1**. An example has been included using this equation for a 12-inch pipe with a wall diameter of 0.188 inches. Since all defects (with and without Clock Spring) were a minimum of 24 inches apart, there was no interaction between adjacent defect regions.

$$D_{meridional} = 2.5\sqrt{R\ t} = 2.5\sqrt{(6.375'')(0.188'')} = 2.74\ \textit{inches} \quad \textbf{(1)}$$

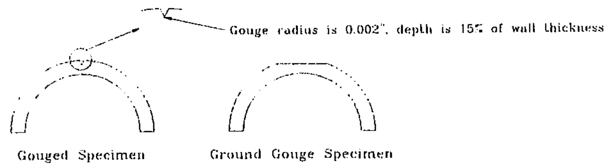


Fig. 1 Gouge Configuration in Pipe Wall

Installation of Dent/Gouge Combinations

As discussed previously, the gouges were installed in the pipe samples prior to the installation of the dents. The dents were installed in the pipe using the loading frame illustrated in **Fig. 2**. The dents were offset longitudinally from the end of the gouges 2 inches for *6 inch gouges* and 6 inches for *24 inch gouges*. This was done so that the gouge would reside in both the transition area and the middle of the dent. Results from previous research indicate that failures are more likely to occur in the transition area of the dent/gouge combination.

The schematic diagram in **Fig. 2** shows the loading frame used to dent to the pipe samples. The pipe samples were placed in the saddle region and the indenter plate was lowered into the pipe. Two indenter plates were used - one that was 6" in length longitudinally and another which was 24" long. The hydraulic cylinder was placed between the plate and the top flange. Denting of the pipe was accomplished by increasing the pressure to the hydraulic cylinder which in turn pressed the loading plate against the pipe. The dent depth was pre-determined by multiplying the respective outside pipe diameter by the desired dent percentage (in this case all dents were 15%). Because of the elasticity of the materials, the actual applied dent depths were much greater than the calculated in order to achieve the correct residual dent depth. In other words, to achieve a dent depth that was 2 inches into the pipe, compression actually required that the loading plate be depressed 4 inches. Shown in **Table 2** are the experimental values for some of the dent depths as well as the hydraulic ram forces required to achieve them. This process was continued until all of the desired dents were installed.

Previous research indicated that grinding of the gouges significantly increased the fatigue life of the specimens (Fowler et al.). In light of this information, all gouges were ground after denting prior to the installation of the Clock Spring. Grinding was accomplished using a hand-held grinder. The gouges were ground until they were no longer visible to the eye. At this point, dye penetrant was applied to the regions to determine if any of the gouge was still present. If the gouge was detected, the process continued until all of the gouge was removed. The wall thickness values were measured before and after the grinding process. **Table 3** lists these values for Specimens *B*, *A2*, and *B2*.

Installation of Clock Spring

The last step prior to cycling was installation of the Clock Spring. The installation process basically involved,

1. Ensuring a clean pipe surface on which to mount the Clock Spring
2. Filling in the damaged (dented) region of the pipe with a filler agent (a putty-type epoxy)
3. Installation of the Clock Spring wrapping with the provided adhesive.
4. *Cinching* the Clock Spring onto the pipe to ensure a tight fit. The Clock Spring was then taped circumferentially to ensure that the configuration remains tightly bound until the glues are allowed to cure.

Figure 3 shows how the Clock Spring was positioned on the pipe relative to the dent/gouge regions. The Clock Spring wraps are 12 inches wide and sufficiently cover any dent/gouge combination which is less than 8 inches in length longitudinally (it was recommended that a 2 inch gap exist on each side of the defect). The Clock Spring samples were installed at 0, 50, and 90%

MAOP as discussed previously. Pressurization of the samples was achieved by filling the pipes with water and pressurizing to the respective pressures. As a safety measure, all samples were pressurized to 100% MAOP and held for thirty minutes prior to the installation of the Clock Spring. The change in dent depths was measured at this time and can be found in **Table 4** through **Table 9**. Once all of the Clock Spring samples were installed, the final step in the experimental phase was pressure cycling.

Fatigue Testing of Specimens

Fatigue testing was accomplished using the schematic layout shown in **Fig. 4**. The layout includes a test-specimen and the oil pump which was used to pressurize the system. A water/oil transfer cylinder was used so that water could be used in the pipes as opposed to oil. Oil which came from the pump was injected into the transfer cylinder and would pressurize the other side which was filled with water that would in turn pressurize the pipe. This process was found to be an effective and efficient means for pressure cycling the pipes. A typical complete pressure cycle in a pipe which was 20 feet long would take approximately 12 seconds, and a shorter version (maybe 10 feet) would take about 7 seconds. A shut-down mechanism was installed so that cycling would cease in the event of a specimen failure. A counter was installed in the loop to keep count of the number of cycles.

In the event of a specimen failure, the failed sample was removed from the pipe and a girth weld was used to reconnect the remaining sections. This process was continued until all the samples had failed or a suitable stopping point was determined.

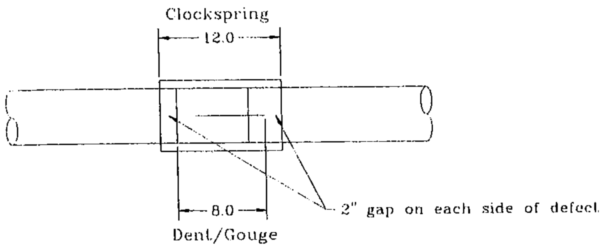


Fig. 3 Location of Clock Spring Relative to Defects

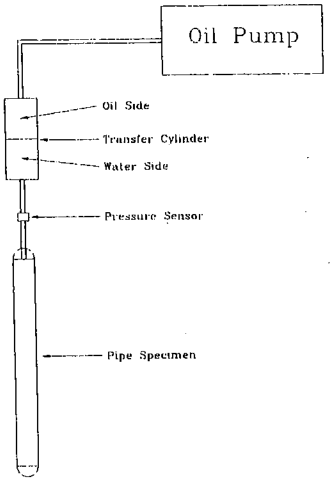


Fig. 4 Layout for Fatigue Testing

EXPERIMENTAL RESULTS

In presenting the experimental results associated with the Clock Spring fatigue testing, there are three areas of primary concern:

1. Present results which show the fatigue life for each of the tested samples as functions of pipe dimensions, dent and gouge depths, Clock Spring installation pressure, and internal pressure differentials.
2. Compare the fatigue results for reinforced samples with unreinforced samples in order to determine what effect Clock Spring has on increasing the fatigue life for the defective piping. Current data will be compared with results from previous fatigue testing of pipes with comparable geometries and defects.
3. Presentation of strain gage results which indicate the variations which occur in alternating strain over a periods of time for Samples #1 and #2.

Each of the above items will be discussed in greater detail in this section.

Effect of Clock Spring on the Fatigue Life of Specimens

Tables 4 through **9** present the fatigue results for all samples tested in this research. Included in these tables are the material properties of the pipe, information on the respective dents and gouges, installation pressure of the Clock Spring, and number of cycles experienced by each sample. As can be noted from these charts, several of the defect sections were not fitted with Clock Spring. The results for these sections indicate how the Clock Spring performed in terms of its ability to increase the fatigue life for a damaged region.

It was the initial objective of this project to cycle the samples 50,000 times at both 50% and 100% the MAOP. The proposed number of cycles at the lower pressure differential was achieved; however, the number at the higher pressure values was not achieved in some samples because of weld failures. Girth welds were required whenever one of the defect sections had to be removed as a result of failure. The intersection of the girth weld and the longitudinal weld were prone to failure. Termination of cycling at the higher pressures was required because both Samples *A-2* and *B-2* had weld failures that occurred three times. Once this point in the testing was reached, the testing became an issue of the fatigue strength of the welds and not that of the Clock Spring.

In order to determine where the failures were occurring in the samples beneath the Clock Spring, the wrap was removed from several of the failures and examinations using dye penetrant techniques were used. **Table 10** shows where the location of the failure occurred for the selected specimens and **Fig. 5** indicates graphically where the failures occurred. A ground region of a dent/gouge region for one of the samples in shown in **Fig. 6** prior to the installation of Clock Spring. **Figure 7** is a photograph taken of Specimen *A2-3* after the removal of the Clock Spring. The surface was cleaned and dye penetrant was used for crack detection.

It was noted on several samples that the glue debonded from the pipe leaving a localized gap between the Clock Spring and pipe of as much as 0.005" - .010" before the pipe failed.

The fatigue strength of the pipe itself also became an issue in the process of testing. A longitudinal weld failure which occurred in Sample B-2 between specimens B2-5 and B2-6 is shown in **Fig. 8**. Although these samples did not fail, their removal was required because there was no way to repair this section or weld these specimens to adjacent pipe regions. Most of the failures in the Clock Spring samples were not catastrophic and typically appeared like the leak shown in **Fig. 9**. The failure of the Clock Spring seemed to be caused by the detachment of the wrapping from the surface of the pipe which prevented the Clock Spring from combating the opening and closing of the gouge region (thus inducing crack propagation). This bending is what causes the fatigue failures in the damaged sections.

The initial tests focused on pipes with D/t ratios of 51 and 68 having mechanical defects consisting of 15% dents and 15% gouges. All defects were installed without internal pressure. After the tests for Samples *B*, *A2* and *B2* were completed, it was determined that additional tests were needed. Replication of these initial tests was accomplished with Samples #1, #2, #3, and #4, although the effects of increased mean stress were studied in these tests. Samples #5 and #6 were used to determine the effects of more severe defects. These severe defects consisted of gouge depths as deep as 50% of the wall combined with 15% dents. Sample #6 provided results for a pipe having a D/t ratio of 96. It was found that in general the severe defects failed during the initial pressurization to 90% MAOP in the lower D/t sample. The two tests which were conducted on Sample #5 were obtained by bypassing the initial hold pressurization to 90% MAOP and installing the Clock Spring wraps at 50% MAOP. Cycling was started on these samples without ever pressurizing to the initial hold pressure.

The high fatigue life results for Sample #6 were obtained because of the high D/t possessed by this pipe. It is quite likely that if the initial 15% gouges and dents had been installed, no failures ever would have occurred.

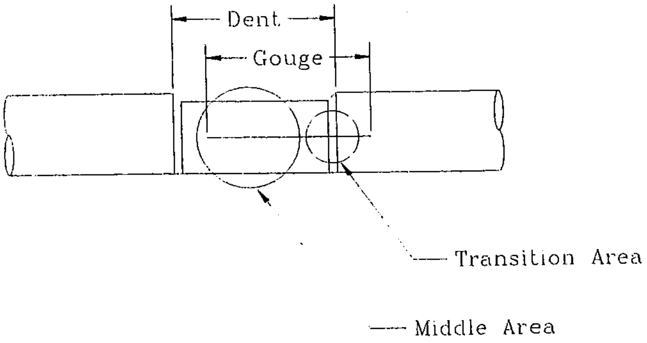


Fig. 5 Failure Location Guide

Comparison of Fatigue Results for Clock Spring with Unreinforced Defects

In order to determine the effectiveness of Clock Spring as a repair method, comparisons are required which correlate the results for reinforced sections with results for unreinforced regions. This information can serve as the basis for making determinations regarding the life extension provided with the addition of Clock Spring to a damaged pipe section.

The results plotted in **Fig. 10** compare the Clock Spring data to previous fatigue data obtained for pipes with various dent and gouge defects. Before discussing the data found in this figure, the method by which the *equivalent* number of cycles was obtained must be presented. Because most of the samples were tested with different pressure ratios, direct comparison of the fatigue data requires modification in order to present meaningful results. This was accomplished using an equation based on a combination of Miner's Rule and the DOE-B curve. This method calculates an equivalent number of cycles at a specified pressure for a pipe which was pressure cycled at other pressure ratios. This equation is presented in addition to an example problem where:

$$N_{B_{eq}} = N_{B_1}\left(\frac{\Delta P}{\Delta P_{B_1}}\right)^{-4} + N_{B_2}\left(\frac{\Delta P}{\Delta P_{B_2}}\right)^{-4} \qquad (2)$$

N_{Beq} = equivalent number of cycles for Sample B at the specified pressure differential, ΔP
ΔP = Base pressure differential
N_{B1} = Number of cycles obtained for Sample B at ΔP_{B1}
ΔP_1 = First pressure differential for Sample B
N_{B2} = Number of cycles obtained for Sample B at ΔP_{B2}
ΔP_2 = First pressure differential for Sample B.

Example
Assume that Sample B had the following fatigue data,
25,000 cycles at ΔP = 500 psi
13,000 cycles at ΔP = 1200 psi
Using **Eq. 2** determine the equivalent number of cycles for ΔP = 1000 psi

$$N_{1000} = 25000\left(\frac{1000}{500}\right)^{-4} + 13000\left(\frac{1000}{1200}\right)^{-4} = 28{,}519 \ \textit{cycles} \qquad (3)$$

This procedure was done for all data found in **Fig. 10**.

Fig. 6 Ground Region of Dent/gouge Prior to Clock Spring Installation

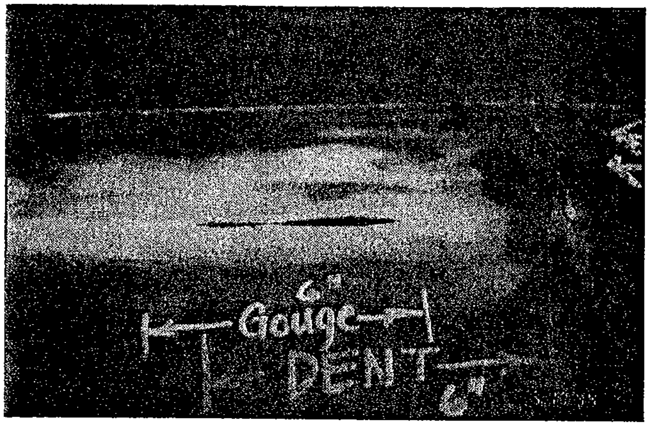


Fig. 7 Inspection of Specimen A2-3 After Removal of Clock Spring

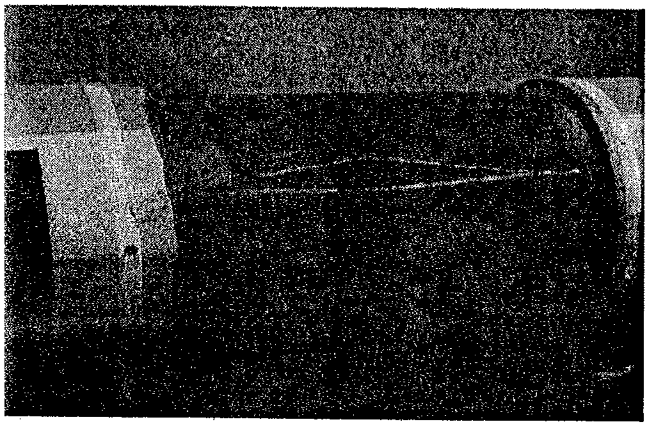


Fig. 8 Longitudinal Weld Seam Failure in Sample B2

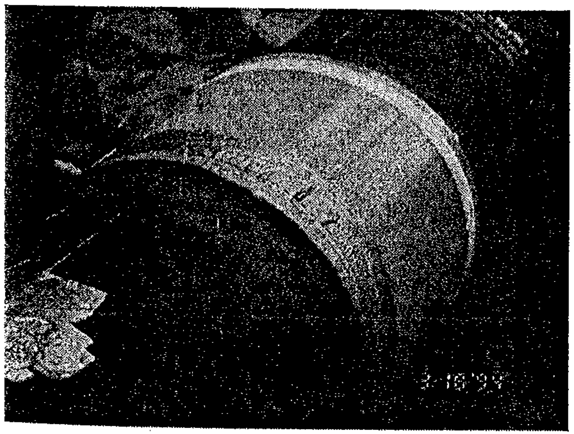


Fig. 9 Typical Failure in a Clock Spring Sample

CONCLUSIONS

The research associated with the Clock Spring has provided several significant findings when considering its impact on the fatigue life of pipelines. As discussed previously, the most dangerous defective combinations are dents with a deep gouge. Although the data indicates that Clock Spring should increase the fatigue life of most damaged regions, its application seems most aptly suited for this extreme defective case with pipe D/t ratios less than 68. The conclusions which follow are based on the experimental findings from the fatigue tests and will also provide pipeline operators with some important recommendations to maximize the effectiveness of the Clock Spring.

Considering that 5 cycles per two months (with a pressure differential of 200 psi) is typical for a gas pipeline (Fowler et al.), the 54,000 cycles experienced by the failed longitudinal weld in Specimens B-2 (see **Fig. 8**) corresponds to an infinite life. Even the life for this weld in a liquid line would be over 70 years (600 psi at 730 cycles per year).

When samples covered with Clock Spring are compared with uncovered defective regions, the covered samples exhibit fatigue lives approximately 2 to 5 times as long as their uncovered counterparts for pipes with D/t ratios less than 68. Based on this information, Clock Spring serves to increase the fatigue life of pipes with dent/gouge defects for these pipes. However, the results for the 24" sample (D/t=96) indicate that Clock Spring does not have as significant a contribution as with the lower D/t pipes. The likely basis for this observation is the unusually high cycle numbers that existed even with the unrepaired defects.

Although discussed in previous reports, the importance of grinding gouges can not be overstated. Grinding serves to increase fatigue life by as much as three times. This information is presented because all of the gouge samples tested in this project were ground.

When considering the testing parameters discussed previously (D/t, installation pressure, gouge depth, and applied pressure differentials), there are several important observations. The gouge depth has a significant impact on reducing fatigue life, which is supported by earlier findings. In spite of insufficient data, the installation pressure appears to have an effect on fatigue life. **Table 7** indicates that for short defects (6", contained in one Clock Spring unit), wraps installed at 0 psi have longer fatigue lives than their counterparts installed at 90% MAOP. This position is logical when considering that the Clock Spring is acting to compress the pipe when installed at the lower pressure.

This research provides new insights regarding the effects of mean cyclic pressure on the fatigue life of dented and gouged pipes. Typically, one would be led to believe that higher mean cyclic pressures would serve to reduce the fatigue life for a damaged pipe section; however, the results of this program show otherwise. From a mechanics standpoint, the high mean pressure acts to drive the dent out of the pipe, thus lowering the locally high stresses in the damaged region.

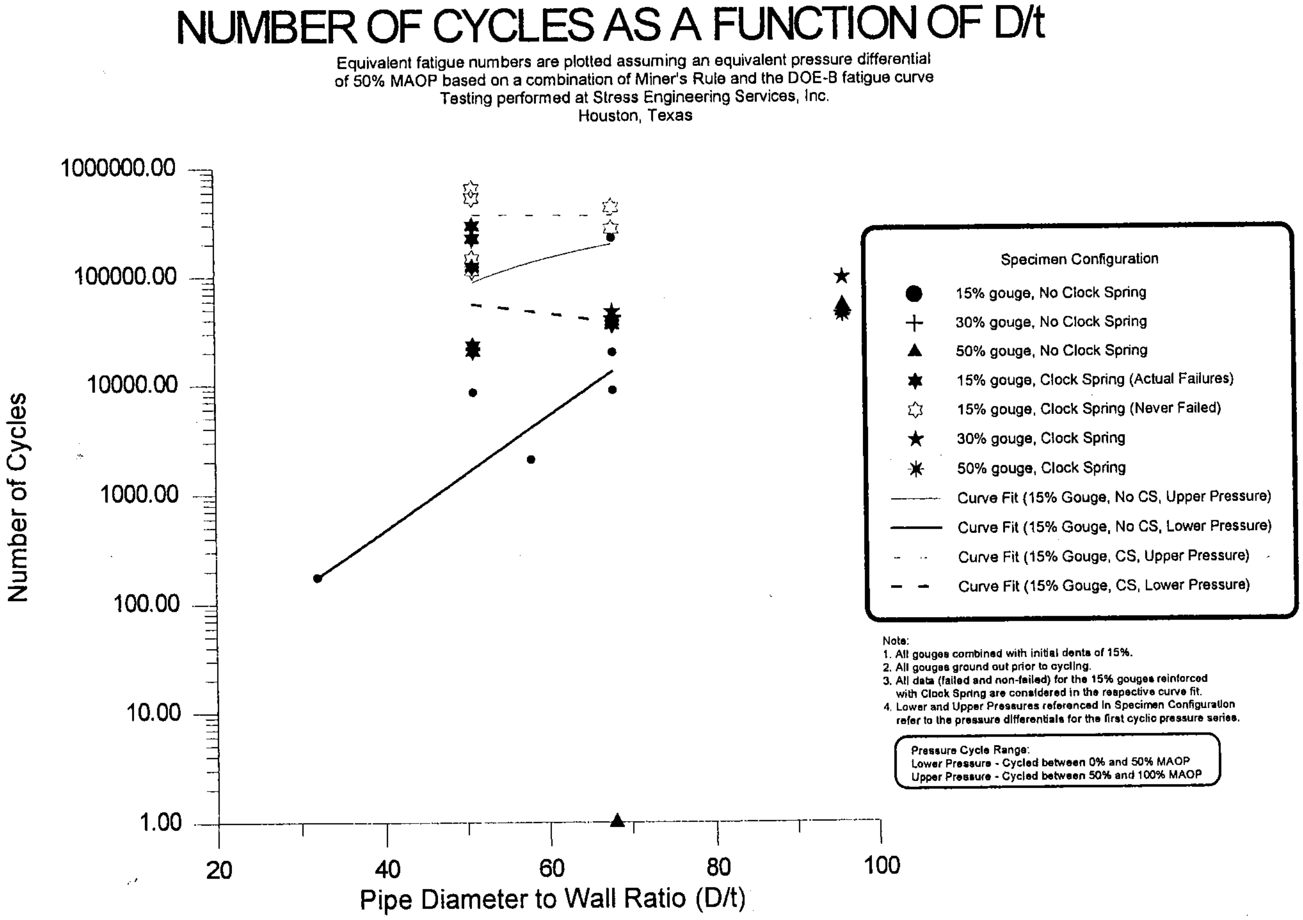
Based on the experimental findings, there are several useful recommendations for pipeline operators. First, it is recommended that all gouges be ground out since this is such an effective method for directly increasing fatigue life. Secondly, it is recommended that the Clock Spring be installed in accordance with the manufacturer's instructions (in terms of coverage area and diametric sizing). The lower the installation pressure the better the fatigue results will be considering the higher compressive stresses induced when the line is pressurized. The research suggests that the failure of the pipe occurred as a result of Clock Spring becoming detached locally from the surface of the pipe. Any means which can be developed that might minimize this effect could possibly increase fatigue life.

REFERENCES

Fowler, J. R., Alexander, C. R., Kovach, P. J., Connelly, L. M., *Cyclic Pressure Fatigue Life of Pipelines with Plain Dents*, The American Gas Association, Offshore and On shore Design Applications Supervisory Committee, Pipeline Research Committee, AGA PR-201-9324, 1994.

ASME Boiler & Pressure Vessel Code, Section VIII, Division 2, 1992 edition.

Clock Spring Installation Manual, Published by the Clock Spring Company, L. P., Houston, Texas, 1994.



Note:
1. All gouges combined with initial dents of 15%.
2. All gouges ground out prior to cycling.
3. All data (failed and non-failed) for the 15% gouges reinforced with Clock Spring are considered in the respective curve fit.
4. Lower and Upper Pressures referenced in Specimen Configuration refer to the pressure differentials for the first cyclic pressure series.

Pressure Cycle Range:
Lower Pressure - Cycled between 0% and 50% MAOP
Upper Pressure - Cycled between 50% and 100% MAOP

Fig. 10 **Fatigue Life Results**

Table 1 Mechanical Properties of Line Pipe Test Sections

Pipe Section	Dimensions (inches)	Yield Strength (ksi)	Tensile Strength (ksi)	Elongation (Percent)	Impact Strength (ft-lbs)
12" nominal pipe					
A2	12 X 0.188	52.5	71.1	39	28
B	12 X 0.188	58.8	76.4	33	39
B2	12 X 0.250	52.5	71.1	39	30
1	12 X 0.188	51.0	69.4	38	30
2	12 X 0.188	51.0	69.4	38	30
3	12 X 0.250	56.6	78.2	27	---
4	12 X 0.250	52.2	75.4	32	---
5	12 X 0.188	51.0	69.4	38	30
24" nominal pipe					
6	24 X 0.250	59.6	72.2	37	35

Table 2 Applied Hydraulic Ram Forces and Dent Depths

Pipe D/t	Force (lbs.)	Desired Dent Depth (inches)	Dent Depth After Elastic Rebound (inches)
51	53,040	3.125	1.9
68	35,360	4.0	1.9

Table 3 Wall Thickness Values Before and After Grinding

Specimen Number	Initial Wall Thickness (inches)	Final Wall Thickness (inches)	Percent Change
B-1	0.197	0.173	12.2
B-2	0.203	0.175	13.8
B-3	0.202	0.161	20.3
A2-2	0.195	0.179	8.21
A2-3	0.194	0.169	12.9
B2-1	0.257	0.224	12.8
B2-2	0.254	0.220	13.4
B2-3	0.255	0.215	15.7

Note:
All gouges initially 15% of wall.

Table 4 Fatigue Life of Reinforced 6 inch Plain Dents in 12 inch Pipe

Specimen Number	Residual Dent Depth (d/D)	Clock Spring Installation Pressure (psi)	Cumulative Cycles	Cumulative Cycles	Failure (Yes/No)
			100-570 psi	100-1050 psi	
A2-4(1)	5.7	Ambient	51,999	24,000	No
A2-5(1)	5.4	470	51,999	24,000	No
A2-6(1)	5.1	850	51,999	24,000	No
			100-740 psi	100-1350 psi	
B2-4(2)	5.4	Ambient	48,820	4,060(4)	No
B2-5(2)	5.3	640	48,820	4,060(4)	No
B2-6(2)	5.2	1150	48,820	6,160	No
			100-400 psi	100-900 psi	
I-6-3(3)	4.6	---	52,350	44,650	Yes
I-7-6(3)	6.3	---	52,350	16,120	Yes

Notes:

(1) Pipe Dimensions (12.75" X 0.198, D/t=65)

(2) Pipe Dimensions (12.75" X 0.254, D/t=50)

(3) Prior work with reinforced 24 inch plain dents, D/t=64 (See *References*, Fowler et al.)

(4) Cycling terminated due to longitudinal weld seam failure.

Table 5 Results of Low Pressure Cycling of Ground 15% Gouges in Dented 12 inch Pipe

Specimen Number	Residual Dent Depth (d/D) (1)	Gouge Depth (d/t) (2)	Clock Spring Installation Pressure (psi)	Cumulative Cycles (100 - 570 psi)	Cumulative Cycles (100 - 1050 psi)	Failure (Yes/No)
Dented Gouges 6 inches in Length						
A2-2(3)	4.8	13	470	36,120	---	Yes
A2-3(3)	5.4	13	850	51,990	24,000	No
Dented Gouges 24 inches in Length						
B-1(4)	5.5	15	Ambient	38,980	---	Yes
B-2(4)	5.9	13	---	8,920	---	Yes
B-3(4)	5.9	14	---	20,000	---	Yes

Notes:

(1) Residual dent remaining after pressurizing to MAOP

(2) Percentage of wall removed after grinding to remove dented gouge

(3) Pipe D/t = 65

(4) Pipe D/t = 50.

Table 6 Results of High Pressure Cycling of Ground 15% Gouges in Dented 12 inch Pipe

Specimen Number	Residual Dent Depth (d/D) (1)	Gouge Depth (d/t) (2)	Clock Spring Installation Pressure (psi)	Cumulative Cycles (540 - 1080 psi)	Cumulative Cycles (100 - 1180 psi)	Failure (Yes/No)
Dented Gouges 6 inches in Length						
1-A (3)	4.1	13	---	50,000	11,120	No
1-B (3)	4.0	15	Ambient	97,705	11,120	No
1-C (3)	3.4	15	540	97,705	11,120	No
1-D (3)	3.7	15	970	97,705	11,120	No
Dented Gouges 24 inches in Length						
2-C (4)	4.0	7	---	50,000	11,120	No
2-B (4)	4.7	12	540	50,000	11,120	No
2-A (4)	4.0	12	970	50,000	11,120	No

Notes:
(1) Residual dent remaining after pressurizing to MAOP
(2) Percentage of wall removed after grinding to remove dented gouge
(3) Pipe D/t = 65
(4) Pipe D/t = 50.

Table 7 Fatigue Life of Reinforced 6 inch Gouged Dents in 12 inch X 0.250 inch Pipe

Specimen Number	Residual Dent Depth (d/D) (1)	Gouge Depth (d/t)	Clock Spring Installation Pressure (psi)	Cumulative Cycles	Cumulative Cycles (100 - 1180 psi)	Failure (Yes/No)
				100 - 740 psi	100 - 1350 psi	
B2-1	5.5	15	Ambient	48,820	4,650	Yes
B2-2	5.4	15	640	23,120	---	Yes
B2-3	5.8	15	1150	20,380	---	Yes
				625 - 1250 psi	100 - 1350 psi	
3-A	4.4	15	Ambient	50,850	37,080	No
3-B	4.6	15	625	50,850	15,320	Yes
3-C	4.6	15	1125	50,850	10,870	Yes
3-D	3.2	15 (not ground)	(3)	8,550	---	Yes
4-A	5.5	15	(3)	49,900	4,390	Yes
4-B	5.4	15	625	49,900	6,220	Yes
4-C	5.4	15	1125	49,900	10,530	Yes

Notes:
(1) Residual dent remaining after pressurizing to MAOP
(2) Gouge depth before grinding
(3) No Clock Spring.

Table 8 Fatigue Life of Reinforced 6 inch Gouged Dents in 12 inch X 0.188 inch Pipe

Specimen Number	Residual Dent Depth (d/D) (1)	Gouge Depth (d/t)	Clock Spring Installation Pressure (psi)	Cumulative Cycles (540 - 1080 psi)	Cumulative Cycles (100 - 1180 psi)	Failure (Yes/No)
5-A	4.1	30 (not ground)	---	(3)	---	Yes
5-B	3.9	34	---	47,400	---	Yes
5-C	3.5	37	540	47,700	---	Yes
5-D	3.8	51	---	(3)	---	Yes
5-E	4.2	52	(4)	---	---	Yes

Notes:
(1) Residual dent remaining after pressurizing to MAOP
(2) Gouge depth before grinding
(3) Sample failed in first pressure cycle to 1080 psi
(4) Sample failed during pressurization to install Clock Spring at 90% of MAOP.

Table 9 Fatigue Life of Reinforced 6 inch Gouged Dents in 12 inch X 0.250 inch Pipe

Specimen Number	Residual Dent Depth (d/D) (1)	Gouge Depth (d/t) (2)	Clock Spring Installation Pressure (psi)	Cumulative Cycles (540 - 1080 psi)	Cumulative Cycles (100 - 1180 psi)	Failure (Yes/No)
6-A	2.9	30 (not ground)	---	3,310	---	Yes
6-B	3.0	23	---	46,530	---	Yes
6-C	2.9	27	390	44,370	---	Yes
6-D	3.2	51	---	46,530	---	Yes
6-E	2.9	50	---		3,860	Yes
6-F	3.2	55	390	46,580	3,120	Yes

Notes:
(1) Residual dent remaining after pressurizing to MAOP
(2) Percentage of wall removed after grinding.

Table 10 Location of Failures

Specimen Number	Residual Dent Depth (d/D) (2)	Gouge Depth (d/t, percent)	Failure Location (refer to **Fig. 5**)
B-1	5.5	15	Middle
B-2	5.9	15	Middle
B-3	5.9	15	Middle
A2-3	5.4	15	Middle/Transition
B2-1	5.5	15	Transition
B2-2	5.4	15	Transition
B2-3	5.8	15	Middle/Transition

Notes:
(1) Specimens B-2 and B-3 were not equipped with Clock Spring
(2) Residual dent remaining after pressurizing to MAOP.