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ASSESSING THE USE OF COMPOSITE MATERIALS IN REPAIRING MECHANICAL DAMAGE IN TRANSMISSION PIPELINES

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ABSTRACT

Mechanical damage involving dents with gouges is one of the leading causes of transmission pipeline failures in terms of both static and cyclic pressure loading. Because of the severity of this defect type, pipeline companies are required to respond to these anomalies by either removing damaged sections or repair using welded sleeves. For more than 10 years, composite materials have been used to repair corroded pipelines and their use has gained wide acceptance across the pipeline industry. Numerous systems have been tested with results being presented in the open literature.

Testing was recently performed to assess the use of a water-activated composite repair system, Aquawrap®, in terms of its ability to repair mechanical damage subjected to cyclic pressure service. The Aquawrap® repair system has been extensively tested on corrosion defects but testing on pipes with dents had not been done. The water activated pre-preg urethane resin system offers excellent long tern (creep-rupture) strength combined with easy low cost field installation.

Pipes having diameter to wall thickness ratios ranging from 34 to 68 were fitted with dents and gouges. Repair involved removing the gouged material of the pipe after indentation and repairing using the composite sleeve. The result of this specific test program showed that on-average the fatigue life for mechanically-damaged pipes can be increased on the order of three orders of magnitude when repaired by grinding and installing composite sleeves. This paper provides details on the methodology of the test program, results, and most importantly, information that can be used by operators in repairing their pipeline systems.

TESTING PROGRAM AND PROCEDURES

A specific test program was carried out on the composite repair system. This program represents experience in testing and analyzing mechanically-damaged pipe spanning more than a 15-year period. The test program involves the two pipe sizes shown below. The purpose in selecting two pipes with different diameter to wall thickness ratios (D/t) is that the fatigue life of dented and mechanically-damaged pipes has been shown to be directly related to the pipe D/t ratio. All test samples had a minimum length of 8 feet to ensure that end effects did not contribute to the final test results.

- 12.75-in x 0.188-in, Grade X52, diameter to wall thickness ratio of 68 (designated as *Sample AL-188*)
- 12.75-in x 0.375-in, Grade X52, diameter to wall thickness ratio of 34 (designated as *Sample AL-375*)

The test procedures for the cyclic pressure fatigue test are outlined below.

1. Purchase pipes and install end caps that have been fitted with 1-inch weld-o-let bossets.
2. Use EDM (electron discharge machining) to create 6-inch longitudinally-oriented gouges that are 15 percent of the pipes nominal wall. The cross-sectional profile of the gouge is similar to a Charpy V-notch configuration with a 90° bevel and a 0.002-inch radius at the base of the notch. Four (4) gouges were installed in each of the two (2) pipe samples, making for a total of eight (8) defects. The following gouge defects were made 90 degrees relative to the longitudinal pipe weld seam.
   a. Four (4) 6-inch long gouges, 0.028-inch deep in the 12.75-in x 0.188-in pipe
   b. Four (4) 6-inch long gouges, 0.056-inch deep in the 12.75-in x 0.375-in pipe
3. Install dents in the pipe using a 6-inch wide plate. The initial indentation depth was 15 percent of the pipes outer diameter and the indenter plate. Four dents were installed in each 20-ft long pipe samples. Each dent was offset 2 inches longitudinally from the respective gouge, resulting in a total defect length of 8 inches. Figure 1 shows the dent installation rig.
4. Allow each dent to reround elastically with removal of the indenter and measure the longitudinal profile (side view of dent and process shown in Figure 2).
5. Apply internal pressure equal to 50 percent of the maximum operating pressure (36 percent of SMYS) and hold for 5 minutes. Return the internal pressure to 0 psi and measure the profile.

It should be noted that four (4) dent-gouge defects were installed in each pipe sample. Three (3) of these defects were repaired using the composite material and removal of the gouge by grinding; however, one defect was NOT repaired by grinding. The intent of the single defect was to serve as a baseline test case for unrepaired defects.

The following sequence of events was used in performing the repair of the defects:

1. Remove the gouge by grinding with a hand-held grinder. Dye penetrant was used to ensure that the crack was completely removed. Measure the remaining wall thickness. Figure 3 shows one of the samples polished in its final state before installation of the repair material.

2. Repair three of the four pipe defects using the composite reinforcement system. This includes the following activities:
    a. Prepare surface of pipe (for present short-term study, sandblasting not required)
    b. Fill in dented region of the pipe with a filler material to ensure proper load transfer for composite material from the carrier pipe.
    c. Install the composite material using the appropriate number of wraps.
        i. 12.75-in x 0.188-in pipe (composite thickness measured to be 0.830 inches)
        ii. 12.75-in x 0.375-in pipe (composite thickness measured to be 1.125 inches)
    d. Allow to cure in accordance with the manufacturer's recommendations.
3. Start fatigue testing. Each sample was pressure cycled at 100% MAOP (72% SMYS or 100 to 1,200 psi for the 0.188-in wall pipe and 100 - 2,300 psi for the 0.375-in wall pipe) until failure occurs. As failures occur, the defects were cut out and removed to permit continued pressure cycling.

Figures 4 and 5 are photographs taken during the installation of the composite repair on the damaged sections of the test pipes.

RESULTS OF THE TEST PROGRAM

The results associated with implementation of the test program involve several important aspects. The first involves documentation of the dents themselves such as information on the force required to create the dents, dent depth, profile length, and response to internal pressure. This information is important as the ability to relate test data to actual field dents is directly related to the geometry of the dent. Additionally, it is important to document the test conditions and results associated with cyclic service. The conditions associated with the test pressure ranges are much more severe than most pipelines will experience in several lifetimes. For this reason it is important that the presentation help the reader make sense of the results as they relate to actual operating conditions of typical pipelines. The sections that follow provide details on these two areas of documentation.

Measurements Associated with Dent Geometry

There are several important parameters that were measured during the process of creating the test dents. These include:

- Dent depth as a function of indentation load step (initial dent, rebound after indentation, and depth after pressurization)
- Dent profile measured along the length of the pipeline
- Force required to create the dents
- Pipe wall thickness before and after grinding

Table 1 provides a list of dent depth measurements taken during testing. Also included in this table are the average forces required to create the dents. As noted, the average force required to generate dents in the thicker-walled pipe is approximately 3.5 times the average force required to create dents in the thinner pipe having a nominal wall thickness of 0.188 inches. Table 2 provides a list of measured wall thicknesses taken near the two defects in each sample that were repaired by grinding. Also included in this table are the percentages of remaining wall after grinding.

Figure 6 shows the longitudinal profile measurements for test samples AL-188-1 and AL-375-1. The measurements correspond to readings taken after initial indentation that capture the elastic rebound and measurements taken after pressurization to 50 percent MAOP. As with the data presented in Table 1, it is clear that a significant portion of the dent is removed by the application of internal pressure.

Fatigue Test Results

Fatigue testing applied a range of pressures equaling 100 percent of the MAOP (72% SMYS) to each pipe. The following pressure ranges were applied to the test samples:

- 12.75-in x 0.188-in, Grade X52: pressure range from 100 psi to 1,200 psi (1,100 psi MAOP)
- 12.75-in x 0.375-in, Grade X52: pressure range from 100 psi to 2,300 psi (2,200 psi MAOP)

Table 3 provides a summary of the fatigue test results including the cycles to failure for each of the 8 test samples. There are several noteworthy trends associated with the tabulated data.

- None of the wraps cracked, delaminated or failed in any way during the test.
- The cycles to failure for the unrepaired defects in the 12.75-inch x 0.188-inch pipe are unusually high. It is quite likely that the trend is due to the fact that the yield strength for this pipe was measured to be 69,700 psi. In this situation the applied stress range was insufficient to generate and grow the crack in a short period of time. The thicker wall pipe did not demonstrate this trend and showed a greater difference between the unrepaired and repaired samples.
- As expected, the pipe having the larger D/t ratio had a long fatigue life. This is consistent with the mechanics of the problem and previous research that show thinner wall pipes reround with internal pressure. As the effects of the dent are reduced, the fatigue life is increased.
- Although the composite material increased the fatigue life of the AL-188 sample, the effects of the repair were more pronounced with lower D/t pipe of the AL-375 sample.

In addition to the tabulated data, Figure 7 presents results that show cycles to failure for the composite-repaired samples, as well as data from previous research programs associated with mechanical damage. The predominant observation made in viewing this figure are the benefits derived in repair by grinding and using composite materials as compared to unrepaired mechanical damage. If one considers a pipe having a D/t ratio of 50 with a dent of 15 percent and a gouge of 15 percent, the fatigue life can be estimated from Figure 7 as follows.

- An unrepaired defect has an approximate fatigue life of 100 cycles
- A defect that has been repaired by grinding has an approximate fatigue life of 1,000 cycles
- A defect that has been repaired by grinding and fitted with a composite sleeve has an approximate fatigue life of 100,000 cycles

This trend is consistent in what has been observed with other composite repair systems. The primary reason for the increase in fatigue life is that the composite material restrains the dent and prevents significant rerounding during the process of pressure cycling. It is the flexure of the dent that is the basis for the initiation and propagation of fatigue cracks in both mechanically-damages pipes as well as pipes having plain dents (i.e. dents without gouges). Even though plain dents have fatigue lives that are significantly longer than pipes with mechanical damage (i.e. dents with gouges), the long-term failure of plain dents results from fatigue cracks that initiate in the dented region of the pipe.

DISCUSSION OF RESULTS

In order for composites to be used on gas and transmission pipelines, pipeline operators will eventually require compliance with a recognized code or standard. Although the use of composites in repairing steel pipelines is widely-accepted among both gas and liquid operators, only recently have the ASME transmission pipeline codes recognized their use (B31.4 for liquid transmission pipelines and B31.8 for gas transmission pipelines). Additionally, in general the emphasis in using composite material has been on the repair of corrosion and not dents, gouges, or mechanical damage. This is expected as the greater potential for catastrophic failure in pipelines resides in the repair of mechanical damage as opposed to repairing corroded sections of pipe.

This section of the paper has been prepared to address statements in the ASME B31.4 and B31.4 pipeline codes that relate to using composite materials to repair pipelines as well as comments related to repairing mechanical damage.

ASME B31.4 - Pipeline Transportation Systems for Liquid Hydrocarbons and Other Liquids

In terms of composite usage the following statement is made in ASME B31.4.

> ***451.6.2 Disposition of Defects***
> ***(c) Repair Methods***
>
> > *(14) Mechanically applied composite material wrap may be used to reinforce the pipeline provided that design and installation methods are proven for the intended service prior to application. The user is cautioned that a qualified written procedure performed by trained personnel is a requirement and records shall be retained…*

ASME B31.8 - Gas Transmission and Distribution Piping Systems

In terms of composite usage the following statement is made in ASME B31.8.

> ***851.42 Permanent Field Repairs of Injurious Dents and Mechanical Damage***
> *(e) Nonmetallic composite wrap repairs are not acceptable for the repair of injurious dents or mechanical damage, unless proven through reliable engineering tests and analysis.*

FUTURE STANDARDS FOR COMPOSITES

In addition to the existing pipeline design codes and standards, several years ago ASME recognized the need for a standard for the use of composites in the repair of pipework and pipelines. A project team was established within the Post Construction / Subcommittee-Repair and Testing codes and standards activity of the ASME to review the problem and develop an appropriate repair standard. The project team has recently completed and approved its first document, *PCC-2 Article 4.1, Non-Metallic Composite Repair Systems for Pipelines and Pipework: High Risk Applications*. This Article covers two aspects of composite repair systems: material qualification and repair design methodology. The Article applies to two repair situations, corrosion defects and defects with leaks.

The case of pipe defects with dents, gouges, or dents with gouges are not covered in the current version. The ASME PCC project team is continuing work on the Article and is considering the dent-gouge defect case for inclusion in future revisions.

The project team has also developed and approved an Article for low risk applications, *PCC-2 Article 4.2, Non-Metallic Composite Repair Systems for Pipelines and Pipework: Low Risk Applications*. These two Articles will be published shortly as part of the initial issue of PCC-2, Repair of Pressure Equipment and Piping Standard (includes repair articles on welded repairs, mechanical repairs, nonmetallic / bonded repairs, and examination / testing).

One of the advantages in the development of these standards is that a uniform criterion can be established for all existing and future composite repair systems. By bringing all of the general requirements and guidelines within one single document, the pipeline industry can recommend to manufacturers what minimum expectations are required in terms of repairing pipelines. By going through this process, pipeline companies and composite repair manufacturers can work together to ensure the continued safe operation of pipelines.

COMMENTS AND CLOSURE

This paper has provided documentation on a test program performed to assess the use of a composite repair system for high pressure pipelines. Aquawrap® is a water-activated pre-impregnated (i.e. prepreg) composite system that is installed directly over areas of pipeline damage. The focus of the test program was to address the ability of the repair system to repair mechanically-damaged pipes involving dents with gouges. The test program involved full-scale testing involving two Grade X52 pipe sizes: 12.75-inch x 0.188-inch and 12.75-inch x 0.375-inch. Four 6-inch long gouges (depths of 15 percent of wall thickness) were installed in each of the 20-ft pipe samples using EDM. Dents were installed in each of these gouges with an initial depth of 15 percent of the pipe diameter (an elastic rebound occurs after the indenter is removed). After the dents were installed, the pipes were pressurized to 50% MAOP to achieve a final residual dent depth. Finally, select gouges were removed by grinding and repaired by the composite material. Once all of the repairs were made, the materials were allowed to cure and pressure cycling was initiated. Testing involved cycling the samples to a pressure range equaling 100 percent of the maximum operating pressure. The test pipes were cycled until a failure occurred. When a failure did occur it was removed (cut-out) and the remaining sections of the pipe re-welded so that pressure cycling could continue.

It is clear from the results of the test program that the reinforcement method provides an increase in the fatigue life of unrepaired mechanical damage. For the 12.75-inch x 0.188-inch pipe (D/t = 68) the fatigue life was increased from 103,712 cycles for the unrepaired sample, up to 928,736 cycles for the repaired sample (increase by a factor of 8.95). In a similar but more significant manner, the fatigue for the 12.75-inch x 0.375-inch pipe (D/t = 34) was increased from 2,272 cycles for the unrepaired sample to 49,008 cycles for the repaired sample (increase by a factor of 21.6).

When composite materials are properly used to repair damaged pipeline, including the removal of shallow gouge defects by grinding, it is possible that a significant increase in fatigue life can be achieved over unrepaired defects. The results of this test program, along with supporting data from similar repair systems, confirm the validity of this repair system. It should be noted, however, that significant care should be taken in repairing actual mechanically-damaged pipelines. Consideration of period service history, material quality, and extent of overall pipeline damage must be considered before making a pipeline repair using composite materials.

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Figure 1 - Dent installation rig to install dents

Figure 2 - Measuring dent depth and profile

Figure 3 – Gouge removal by grinding

Figure 4 – Installing composite material on pipe

Figure 5 - Perforating plastic wrap to permit off-gassing during cure

Table 1 - Sample dent depths

Sample Number	Target Dent Depth (a) (inches and percent O.D.)	Interim Dent Depth (b) (inches and percent O.D.)	Residual Dent Depth (c) (inches and percent O.D.)
12.75-inch x 0.188-inch, Grade X52 (D/t = 68) ***Average force of 26,010 lbs. required to generate dents***			
AL-188-1	1.9 (15%)	0.637 (5.0%)	0.293 (2.3%)
AL-188-2	1.9 (15%)	0.626 (4.9%)	0.290 (2.3%)
AL-188-3	1.9 (15%)	0.514 (4.0%)	0.240 (1.9%)
AL-188-4	1.9 (15%)	0.607 (4.8%)	0.272 (2.1%)
12.75-inch x 0.375-inch, Grade X52 (D/t = 34) ***Average force of 94,056 lbs. required to generate dents***			
AL-375-1	1.9 (15%)	1.001 (7.9%)	0.658 (5.2%)
AL-375-2	1.9 (15%)	1.020 (8.0%)	0.606 (4.8%)
AL-375-3	1.9 (15%)	1.001 (7.9%)	0.592 (4.6%)
AL-375-4	1.9 (15%)	1.028 (8.1%)	0.628 (4.9%)

Notes:

(a) *Target dent depth* is depth indenter initially pushed into pipe with no internal pressure

(b) *Interim dent depth* is the depth corresponding to elastic rebound as the indenter is removed from the pipe with no internal pressure.

(c) *Residual dent depth* is the depth remaining after the pipe sample was pressurized to 50 percent SMYS (760 psi for the 12.75-in x 0.188-in sample and 1,520 psi for the 12.75-in x 0.375-in sample)

Table 2- Wall thickness change of samples repaired by grinding

Sample Number	Nominal Wall Thickness (inches)	Measured Wall Base Pipe Thickness (inches)	Wall Thickness after Grinding (inches and percent nominal wall)
AL-188-3	0.188	0.198	0.168 (89.4%)
AL-188-4			0.158 (84.0%)
AL-375-3	0.375	0.385	0.314 (83.7%)
AL-375-4			0.306 (81.6%)

Table 3 - Fatigue Test Results

Sample Number	Residual Dent Depth (a) (inches and percent O.D.)	Cycles to Failure at 50% MAOP (b) (100% MAOP)	Notes on sample
12.75-inch x 0.188-inch, Grade X52 (D/t = 68)			
AL-188-1	0.293 (2.3%)	103,712 (6,482)	Unrepaired
AL-188-2	0.290 (2.3%)	104,424 (6,544)	Aquawrap®, NO grinding
AL-188-3	0.240 (1.9%)	928,736 (58,046)	Aquawrap®, grinding (c)
AL-188-4	0.272 (2.1%)	103,536 (6,471)	Aquawrap®, grinding (pinhole leak developed under wrap, not found via inspection after testing) (d)
12.75-inch x 0.375-inch, Grade X52 (D/t = 34)			
AL-375-1	0.658 (5.2%)	2,272 (142)	Unrepaired
AL-375-2	0.606 (4.8%)	10,448 (653)	Aquawrap®, NO grinding
AL-375-3	0.592 (4.6%)	23,296 (1,456)	Aquawrap®, grinding
AL-375-4	0.628 (4.9%)	49,008 (3,063)	Aquawrap®, grinding

Notes:

(a) *Residual dent depth* is the depth remaining after the pipe sample was pressurized to 50 percent SMYS (760 psi for the 12.75-in x 0.188-in sample and 1,520 psi for the 12.75-in x 0.375-in sample).

(b) Even though the samples were pressure cycled at 100% MAOP, it is possible to estimate the fatigue life at 50% MAOP using Miner's Rule and a fourth order relationship between stress range and cycles to failure.

(c) Grinding used to remove gouge before composite material installed on pipe.

(d) The leak failure did not occur in the dented region of the pipe. This data point can be legitimately discarded and not considered as part of the repaired test program.

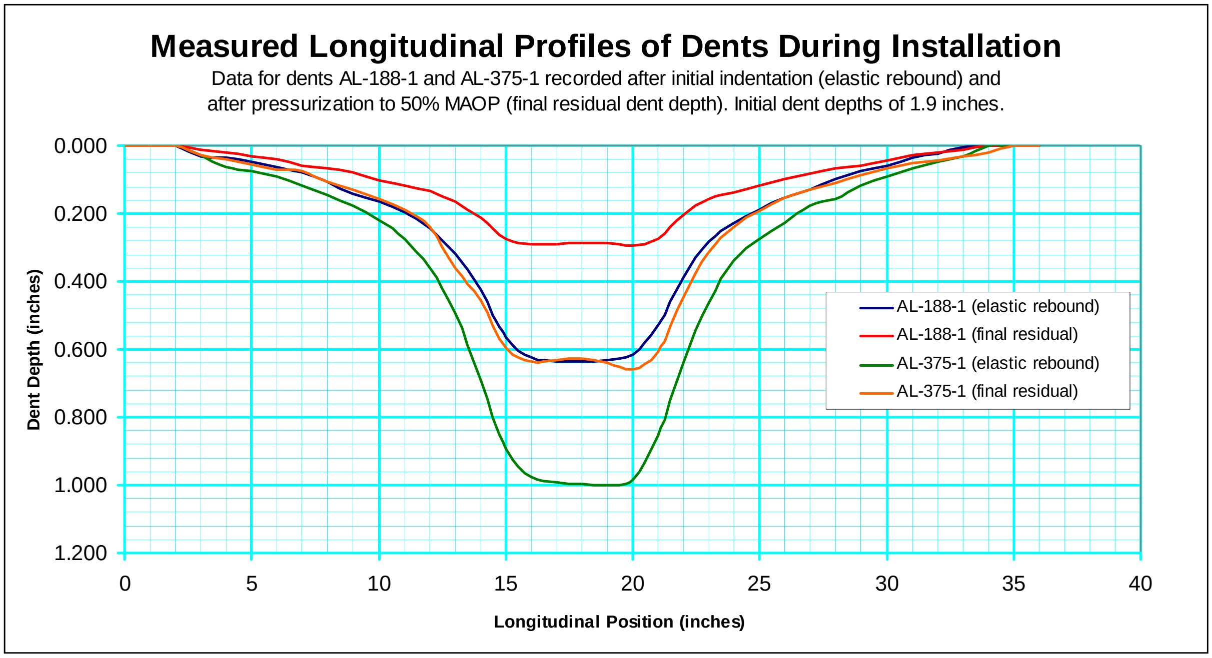

Figure 6 - Longitudinal profile measurements of exemplar dents

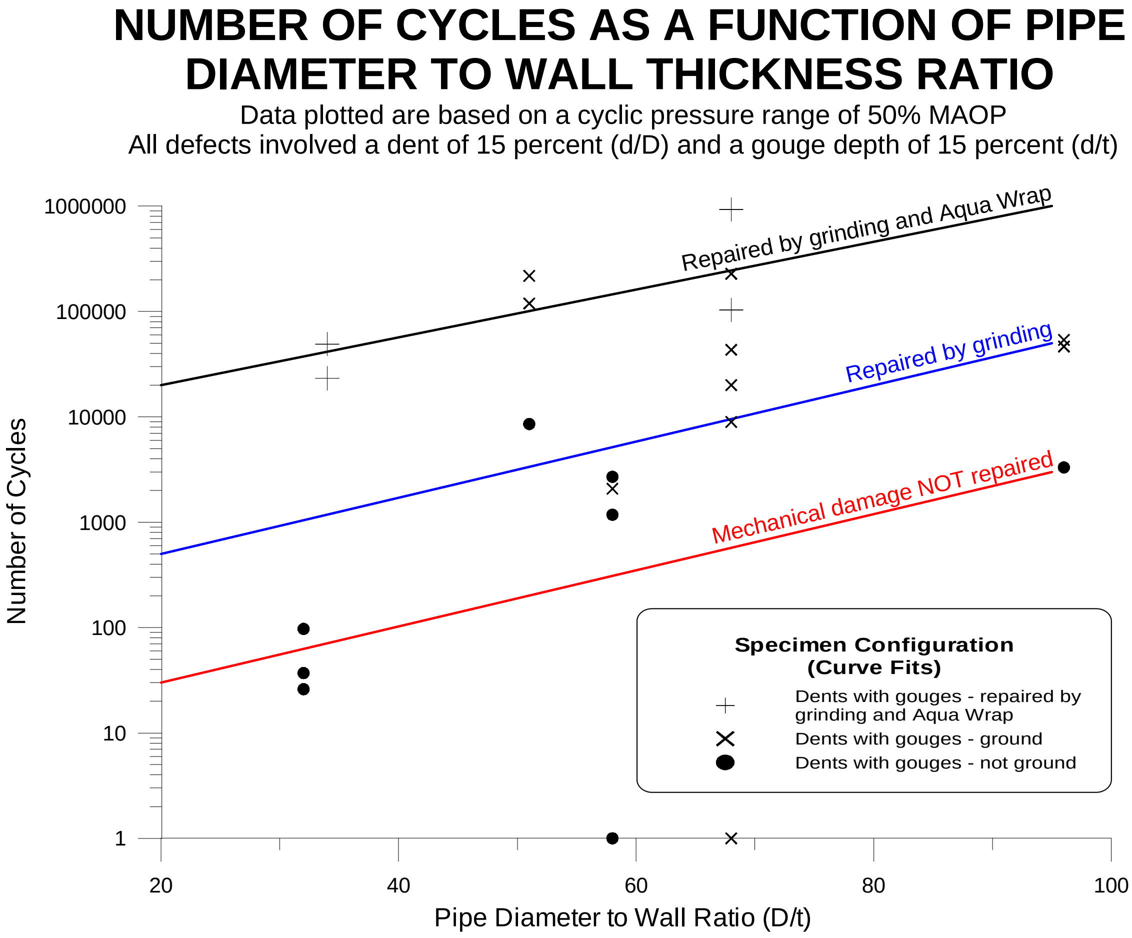

Figure 7 - Fatigue test results for mechanically-damaged samples