

REPAIR OF PIPELINES HAVING MECHANICAL DAMAGE AND PLAIN DENTS USING COMPOSITE MATERIALS

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ABSTRACT

This article is the second in a four part series highlighting the history of composite repairs, state of the art, and ongoing research programs focusing on validating the use of composite materials for long-term service. This article specifically addresses the use of composite materials in repairing pipes having either mechanical damage involving dents and gouges or plain dents. Previous and on-going research programs, that are the subject of this article, have generated performance data on nine different composite repair systems. The predominant conclusion is that when properly designed and installed, composite repair systems have the ability to restore the pressure integrity to pipelines having either mechanical damage or plain dents.

BACKGROUND AND INTRODUCTION

The two main anomalies that pipeline companies have to address are corrosion and mechanical damage. For more than a decade operators of liquid and gas pipeline systems have utilized composite materials as an alternative to conventional repair techniques. Most repairs using composite materials have been made on corroded pipelines. The purpose of this article is to provide the pipeline community with current information on how composite materials can also be used to repair mechanical damage and plain dents.¹

Industry's understanding on how corrosion impacts the mechanical integrity of a pipeline is well understood. There are tools available that can be used to estimate the safe operating pressure for a given corrosion defect based on parameters such as the length and depth of the corrosion (e.g. B31G, RSTRENG, etc.). However, the same cannot be said of mechanical damage and plain dents, both of which are significantly more complicated to analyze from a mechanics and materials standpoint than corrosion. There have been more than 40 years of accumulated data on the impact of mechanical damage and plain dents on the performance of pipelines, yet there is still no unified industry consensus on how to assess dent severity. In the absence of a unifying assessment process, industry must be cautious in not only how to assess the damage itself, but also how it should be repaired.

In 1994 the pipeline industry started an effort to evaluate the ability of composite materials to repair mechanical damage. This program was initiated by the Gas Research Institute (GRI) to evaluate the performance of Clock Spring in repairing mechanical damage. Mechanical damage in the form of dents with gouges was installed in 12-inch and 24-inch nominal diameter pipes. Repairs involved removing the gouges by grinding and then installing Clock Spring. The test samples were then subjected to cyclic pressures until a failure occurred in the form of a leak. This program demonstrated that composite materials can effectively be used to repair mechanical damage and significantly increase the fatigue lives of damaged pipe material.

¹ For purposes of discussion in this particular article, mechanical damage involves the combination of a dent with a gouge (i.e. metal loss), whereas a plain dent only involves local deformation of the pipe material. This distinction is used throughout as mechanical damage is the more severe of the two anomalies due to the presence of the gouge.

Using the basic framework of the GRI test program, studies were completed on an additional five composite systems that included Armor Plate Pipe Wrap, Aquawrap, Pipe Wrap A+, Diamond Wrap HP, and I-Wrap over the next decade and a half. Additionally, another program is currently being co-funded by the Pipeline Research Council International and six (6) manufacturers to evaluate the use of composite materials in repairing three anomaly types: plain dents, dents in seam welds, and dents in girth welds. Composite systems being evaluated in this program include: Aquawrap, Armor Plate Pipe Wrap, Diamond Wrap HP, Furmanite, Pipe Wrap A+, and WrapMaster. As with the previous studies, application of cyclic pressure to failure is the loading of interest.

The sections that follow include a brief discussion on the previous test programs, a presentation of results, and a section discussing the implications of using composite materials for pipeline operators.

TESTING METHODS

A specific test program was carried out to evaluate experimentally each of the composite repair systems. The test methods associated with each program represent experience in testing and analyzing mechanically-damaged pipes spanning more than a 15-year period, with the basic elements of the program being based on the original GRI program started in 1994. Many of the photographs and data provided in this section of the paper are based on work done in evaluating the Air Logistics, Inc. system, Aquawrap (work originally presented at the 2006 International Pipeline Conference in Calgary, September 2006, Paper No. IPC2006-10482).

For most of the tested systems, the program involved the two pipe sizes shown below (Clock Spring was also evaluated using 24-inch diameter pipe and Pipe Wrap A+ was tested using a 12.75-inch x 0.422-inch wall pipe as opposed to the conventional 0.375-inch thickness). The purpose in selecting two pipes with different diameter to wall thickness ratios (D/t) is that the fatigue lives of dented and mechanically-damaged pipes have been shown to be directly related to the pipe D/t ratio (i.e. effective stiffness of the pipe). 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 with a diameter to wall thickness ratio of 68
- 12.75-in x 0.375-in, Grade X52 with a diameter to wall thickness ratio of 34

The test procedures for the cyclic pressure fatigue test are outlined below. Some minor deviations existed in testing the different repair systems, but in general the information provided is applicable.

1. Purchase pipes and install end caps that have been fitted with 1-inch weld-o-let bosssets.
2. Use EDM (electron discharge machining) to create 6-inch longitudinally-oriented gouges that are 15 percent of the pipe's 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 pipe's outer diameter and the indenter plate. Four dents were installed in each 20-ft long pipe sample. 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 typically installed in each pipe sample. In addition to the repaired samples, some tests were also conducted involving mechanical damage that was not repaired to serve as a baseline data set 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
 - ii. 12.75-in x 0.375-in pipe
 - d. Allow system to cure in accordance with the manufacturer's recommendations.
3. Start fatigue testing. Each sample was pressure cycled at 100% MAOP (for Grade X52 pipe: 72% SMYS equals 100 to 1,200 psi for the 0.188-in wall pipe and 100 - 2,300 psi for the 0.375-in wall pipe). Pressure cycle until a failure occurs. As failures occurred, the defects were cut out and removed to permit continued pressure cycling.

Figure 4 and **Figure 5** are photographs taken during the installation of the Aquawrap composite repair on the damaged sections of the test pipes. This system uses an E-glass material pre-impregnated with a water-activated urethane resin system.

TEST RESULTS

The results associated with the different test programs 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 correlation of 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. This statement is especially true for gas transmission pipelines that experience few annual pressure cycles. 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 of the Aquawrap system. 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 188 and 375 numbers correspond to the 0.188-inch and 0.375-inch nominal wall thicknesses, respectively). 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 Lives of Repaired Mechanical Damage

While the level of rerounding and measurements made prior to testing are of interest, the primary demonstration of performance is associated with the ability of the composite repair to extend the fatigue life of a damaged section of pipe. As mentioned previously, independent tests have been completed on six different composite repair systems. All of the systems have been shown to extend the fatigue lives of mechanically-damaged pipes to varying degrees.

Figure 7 plots all data acquired to date on mechanically-damaged pipes repaired using composite materials. Also included in this plot are curve fits (and their corresponding algebraic equations) for each of the following data sets:

- Unrepaired mechanical damage including dents with gouges
- Mechanical damage repaired by grinding ONLY
- Mechanical damage repaired by grinding and composite materials

As noted in **Figure 7**, there is some inherent scatter in the above data sets. This is typical for fatigue data. Initially, there might be some concern over the scatter in the composite repair fatigue data; however, what should be noted is that there is a significantly smaller level of scatter associated with the results for each individual composite repair system. As a point of reference consider the following data sets for two different composite repair systems.

Citadel with grinding (pipe D/t = 34)

- 274,768 cycles to failure
- 239,840 cycles to failure
- 274,048 cycles to failure

From this data set the average cycles to failure is 262,885 cycles. The standard deviation is 19,961 cycles, which is only 7.6% of the average value.

Armor Plate Pipe Wrap with grinding (pipe D/t = 68)

- 984,928 cycles to failure
- 781,088 cycles to failure

From this data set the average cycles to failure is 883,008 cycles. The standard deviation is 144,137 cycles, which is only 16.3% of the average value.

The primary purpose in running the fatigue experiments was to determine the level of improvement that is achieved when a composite material is installed. Previous research and experience had demonstrated that removing gouges by grinding significantly increases the fatigue life of mechanical damage, an observation that is clear in reviewing the data plotted in **Figure 7**. However, until the tests involving composite materials were completed, it was not possible to quantify the level of improvement. To provide a direct comparison between the three data sets presented in **Figure 7**, consider the average cycles to failure for a pipe having a D/t ratio of 50 (e.g. approximately equal to a 12.75-inch diameter with a wall thickness of 0.25 inches).

- | | |
|--|----------------|
| • Unrepaired mechanical damage including dents with gouges | 1,144 cycles |
| • Mechanical damage repaired by grinding ONLY | 6,710 cycles |
| • Mechanical damage repaired by grinding and composite materials | 221,918 cycles |

Even considering the inherent scatter associated with fatigue data, it is clear that composite materials can be used to repair dents and mechanical damage. Operators are encouraged to contact specific manufacturers to obtain data associated with their respective composite repair systems. Several of the systems are better suited for repairing pipelines subject to large numbers of pressure cycles, as one might expect with some liquid transmission pipeline systems.

DISCUSSION AND IMPLICATIONS OF FINDINGS

This article has presented technical data to support the use of composite materials in repairing dented pipelines. The basis for this observation is rooted in performance testing. Through testing, confidence is achieved in observing the capacity that composite materials have to restore mechanical integrity to a damaged pipeline. Several schools of thought exist with regards to the best methods for establishing design criteria for composite repair systems. One is to establish the design basis using primarily material coupon data and the other is to establish the design using performance testing where simulated defects are taken to failure. It is the author's opinion that technical merit exists for both evaluation methods; however, when discussing the repair of defects that are not completely understood (i.e. mechanical damage and plain dents), performance-based testing is required. Test results, such as those reported in this article, provide

industry with a clear understanding on the level of performance that can be expected from the composite repair. Industry should expect composite materials to restore the integrity of damaged sections to be at least equal to the original integrity of the pipe. Research to date has shown that this is possible.

A final comment is made on the cycles to failure presented for the composite repair systems. It is not appropriate to directly use the experimental data to estimate the number of design cycles that can be expected in repairing an actual pipeline. To include the effects of standard deviations and the inherent scatter associated with fatigue data, the author conservatively recommends that experimental fatigue data be divided by a factor ranging from 10 to 20 (this is also consistent with the methodology employed by the ASME Boiler & Pressure Vessel Code that places a design margin of 2 on stress and 20 on cycle number). If one considers the example provided previously (i.e. pipe with $D/t = 50$, dent depth of 15%, original gouge depth removed by grinding of 15%, and pressure cycled at 50% MAOP), the average experimental cycles to failure of 221,918 cycles corresponds to a design life of 11,096 cycles (i.e. 221,918 cycles / 20). For an equivalent pipeline that cycles 100 times annually at 50% MAOP, the remaining life using the calculated design life is approximately 110 years (i.e. 11,096 cycles / 100 cycles per year). Operators should utilize this approach when making any decision regarding the use of composite materials in repairing mechanically-damaged pipelines.

The research programs discussed in this article are good examples on how industry (operators, manufacturers, regulators, and research organizations) can work together to specifically evaluate the repair of anomalies such as mechanical damage and dents using composite materials. It is expected that in the near future additional studies will be undertaken to evaluate the use of composite materials in repairing elbows and field bends, tees and branch connections, vintage girth welds, and offshore risers.

CLOSING COMMENTS

For the past 15 years the pipeline industry has evaluated the use of composite materials in repairing mechanically-damaged pipelines. Some of this work has involved the repair of actual damaged pipelines, although the focus of this article was on experimental evaluation. Operators are encouraged to consider the contents of this article when determining if a composite material can be used to repair a particular dent defect. When designed appropriately and installed properly, composites provide an alternative to conventional repair techniques that involve welding. It should be noted that not all composite repair systems are equal in their ability to repair dented pipelines subject to cyclic pressures. Therefore, as with all engineering-based decisions, operators are encouraged to consider performance requirements before selecting a composite repair system to ensure that a long-term repair solution is utilized.



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

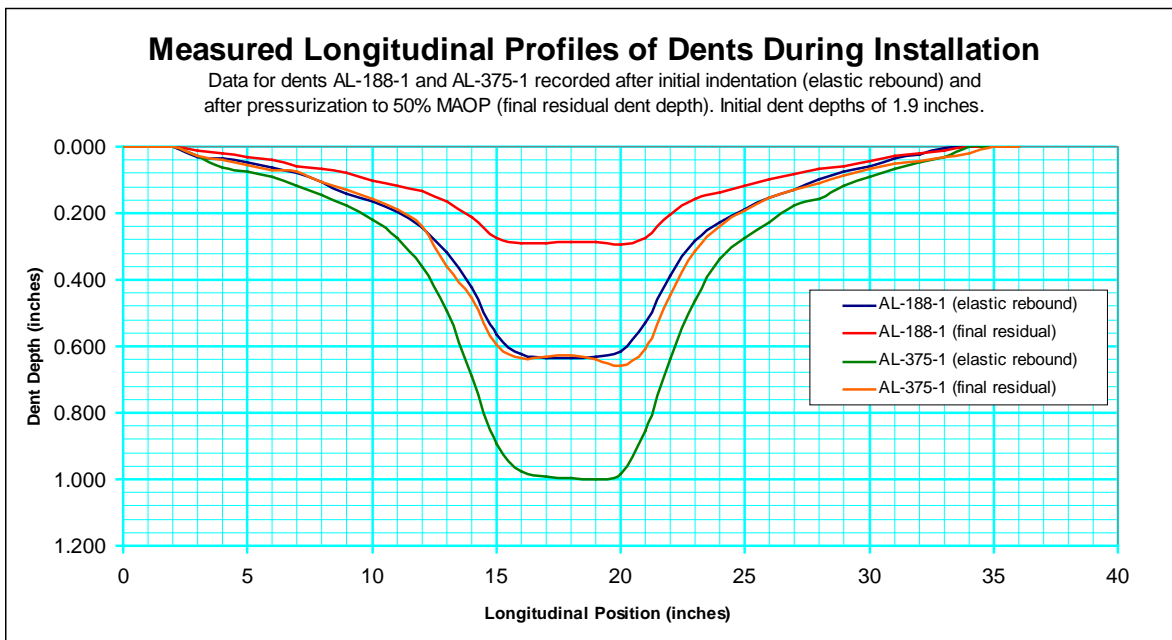


Figure 6 - Longitudinal profile measurements of exemplar dents

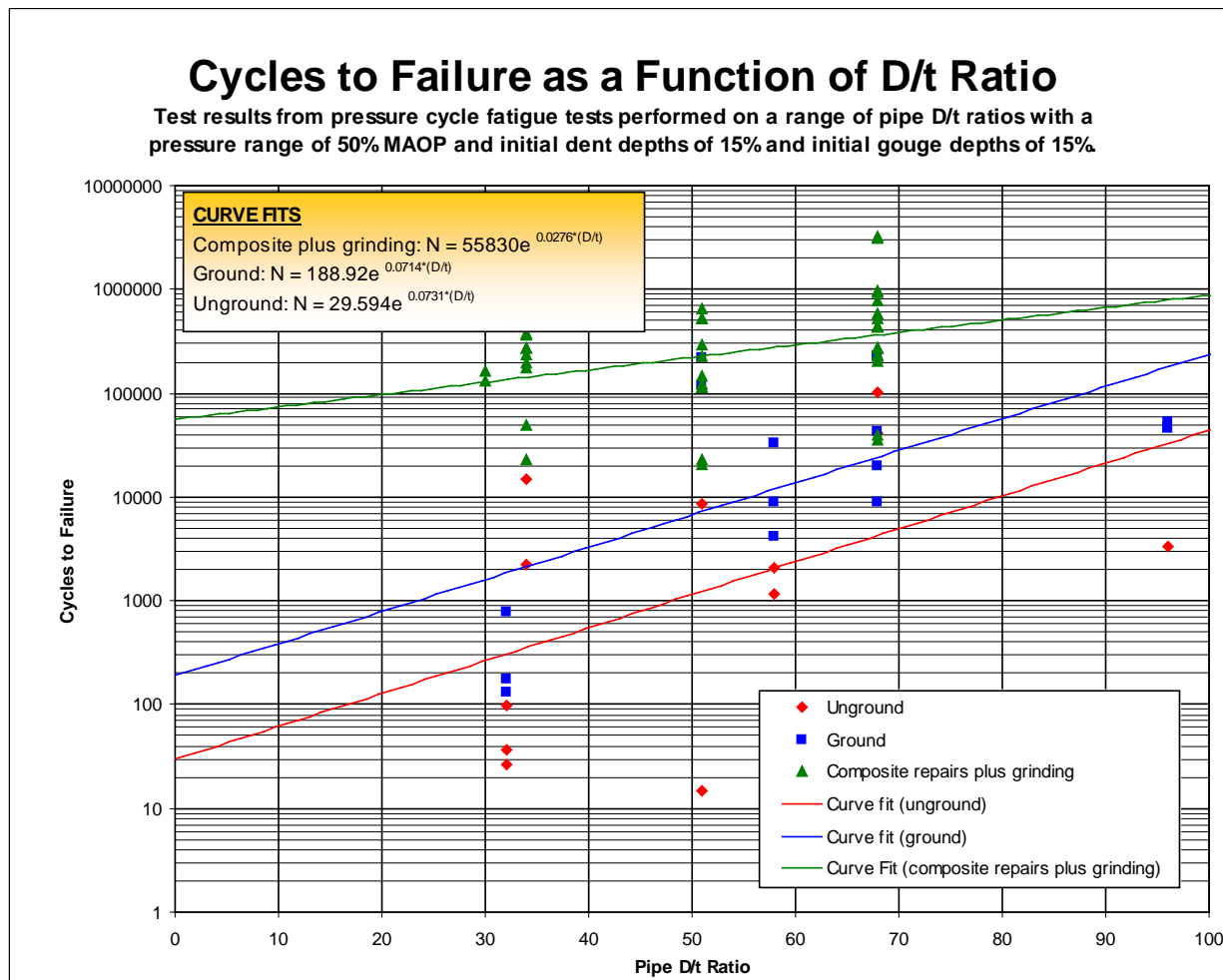


Figure 7 – Fatigue data for repaired and unrepaired mechanically-damaged pipes

Table 1 - Sample dent depths for Aquawrap

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)			
<i>Average force of 26,010 lbs. required to generate dents</i>			
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)			
<i>Average force of 94,056 lbs. required to generate dents</i>			
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	Reported Nominal Wall Thickness (inches)	Measured Wall 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%)