

ANALYSIS, TESTING AND PROPOSED GUIDELINES FOR REPAIRING PIPELINES WITH COMPOSITE MATERIALS

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SUMMARY

A considerable level of work has been conducted relating to the use of composite materials in repairing corroded and mechanically-damaged pipelines. This paper presents information relating to the development and testing of the Armor Plate Pipe Wrap (APPW 360), a fiberglass pipeline repair system for repairing pipes with corrosion and mechanical damage. Due to its compliant nature, repair of fittings such as elbows and tees is also permitted.

The purpose of this paper is two-fold. First, a list of proposed requirements for the pipeline industry is submitted for assessing composite materials used to reinforce pipelines. While the authors do not claim that the provided list covers all aspects on this issue, as a minimum it can be used as a spring board for the development of an industry-accepted standards for composite repair methods. With the introduction of several repair methods over the past several years, it is important that the pipeline industry be advised of the critical; elements relating to any composite system.

The second intent of this paper is directed more toward application and testing of Armor Plate Pipe Wrap. A test program was developed to address all aspects of the recommended guidelines presented in this paper. Results of the experimental test program and details of the on-going research are provided.

INTRODUCTION

The introduction of composite pipeline repair methods has been a source of great interest over the past several years. The primary aim of these repair methods is to reinforce the damage done to pipelines by both corrosion and mechanical damage (such as dents and gouges), while alleviating the need for welding and in some cases repairing with pressure in the pipeline. Typically, these repair processes involve issues such as the following,

- Restoring the strength of a damaged pipe to the point where its burst pressure is increased to some minimum amount (idealistically 100 percent of the undamaged burst pressure)
- Reducing the strain in the damaged areas of the pipe by providing reinforcement and increased stiffness to the region in question
- Providing a restraint so that leak-before-break occurs (prevents failure by rupture), due to local cracks developed as a result of corrosion or crack propagation in a dent or gouge.
- Sealing the damaged area of the pipe from further development of corrosion.

This section of the report is designed to provide the reader with an understanding of the critical issues associated with the development of a composite pipeline repair system. The following list compiled by the authors reflects the minimum requirements that any composite repair should meet. The need for industry standardization in terms of required testing and qualifications is the motivation for providing this list.

1. The composite material used in the repair system should possess sufficient tensile strength (on the order of 30,000 psi failure strength). The combination of the remaining pipe wall and composite material should possess a failure strength that is at least equal to the specified minimum yield strength (SMYS) of the pipe material. Although a strength equal to 100 percent SMYS is sufficient, it is recommended that a safety factor be placed on the maximum operating pressure (MOP). If MOP is assumed to be 72 percent, a safety factor of two corresponds to a stress level of 144 percent SMYS. While this may be an overly-conservative safety factor, the unknowns relating to the long-term performance of composites in aggressive soil environments require that a conservative position be taken.
2. The material should demonstrate that it can perform adequately in repairing corroded pipelines. This involves strength in burst mode, but also involves ensuring that the repair does not degrade with time or cyclic pressure service. Experimental testing must be conducted to address this issue. In

addressing the effects of cyclic operating pressures, the service conditions in actual operating lines should be considered. A typical liquid pipeline may see approximately 1,800 cycles per year (at a 200 psi pressure differential), while gas transmission lines see 10 times fewer, or 60 cycles, for the same pressure level.

3. Testing should be conducted to address creep of the material under dead weight loading. Idealistically, a battery of tests should be conducted using weights as a percentage of the lower bound failure load for the given material (e.g. 10, 25, and 50 percent of tensile failure strength). Creep testing should also be conducted over several different loading time periods (e.g. 24 hours, 6 months, 2 years, etc.).
4. Lap shear testing should be conducted to ensure that an adequate bond exists between the pipe and wrap. For composite repair methods that are not monolithic (*monolithic* meaning that all layers combine to form a homogenous unit), these tests should also include composite-composite test samples as well as the composite-steel test coupons. The composite-composite sample is used to assess the bond strength between the layers, while the composite-steel samples are used to determine the lap shear strength at the interface between the pipe material and composite.
5. Testing should be conducted to address cathodic disbondment and the system should meet the requirements as set forth in ASTM G8 (*Standard Test Methods of Cathodic Disbonding for Pipeline Coatings*).
6. Repair materials should resist mild acid and alkaline environments, including a range of 4 to 11 pH. Alkaline soils may have a pH of 11 or higher, which will attack fiberglass and polyester resin. In general, epoxies can handle mild acids and strong alkalines.
7. Testing should be conducted to address water penetration into the system using test method ASTM G9 (*Standard Test Method for Water Penetration and Pipeline Coatings*).
8. The composite material should be able to withstand temperatures of the operating line on which it is to be installed. The operator should consider the effects of temperature in selecting regions of application (e.g. compressor station may see temperatures of 205°F).
9. Product must be environmentally-safe and possess low toxicity for the applicator.
10. To minimize the possibility for improper installation, the system must be user-friendly and have instructions that are easily understood. For two-part systems, the greatest problem associated with improper application involves incorrect mixing of the adhesive. Installation should only be conducted by a certified applicator.

11. The product must have clearly stated on it the expiration date (if applicable) of any component within the system. The system must demonstrate that it possesses adequate strength over a long period of time (2 to 3 year testing period). This should involve testing of the composite itself as well as adhesive bonds under load. Samples should be exposed to harsh environments (such as saturation in water) where composite properties are known to degrade with time.
12. A field monitoring program should be conducted to assess performance of the wrap over several years. This involves inspection of the buried line at least one year after installation. The repair should be inspected for soundness and any possible signs of degradation. Strain gages should be installed beneath the wrap to determine any changes in the pipe strain that occur with time.
13. The adhesive system must demonstrate that it can be used in a variety of temperature environments and permit installation in a range of ambient temperature conditions (e.g. between 0°F and 120°F). Ultimate responsibility is on the operator to ensure that the system can adequately cure and is not damaged at elevated ambient conditions.
14. The cured material should have a minimum Barcol hardness of 40.
15. For cold weather applications, the system should have sufficient toughness to ensure that the material does not become brittle and lose its ability to properly reinforce the pipeline.
16. When a repair method is used for restoring corroded pipes, calculations relating to its strength should incorporate severity of the corrosion using methods such as those used in ANSI/ASME B31G.

As stated previously, the objectives of this paper are to provide a list of minimum requirements for composite materials used to repair pipelines and introduce specific information relating to a program developed to test the Armor Plate Pipe Wrap repair system. This paper does not address all aspects of composites used in repairing pipelines, but limits itself to discussing details of the Armor Plate Pipe Wrap test program.

EXPERIMENTAL TEST PROGRAM

To validate Armor Plate Pipe Wrap as a viable pipeline repair method, a testing program has been developed.

The major components of the current test program are,

- Repair of corrosion
- Cyclic pressure effects on burst pressure of a repaired corrosion sample
- Load transfer from pipe to wrap using strain gages
- Testing to address installing APPW 360 on pipes with different internal pressures
- Installation of APPW 360 in repairing corroded elbow and tee pipe fittings
- Tensile testing of the APPW 360 composite material
- Lap shear testing to address the interface between the composite and steel.

Presented in this section of the paper are the test methods and results associated with the investigation of these experimental variables. A later section will discuss issues relating to the long-term test program.

Repair of Corrosion

Several samples were specifically fabricated to address the reinforcement of corrosion using the APPW 360. Corrosion defects were machined in 6 inch and 12 inch nominal pipes. The corrosion lengths were selected so that without repair the corrosion would have failed at a pressure less than the *safe maximum pressure* per ASME B31G. These corroded sections of pipe, assuming they were present on an actual pipeline, would need to be removed, repaired, or have the operating pressures reduced.

Prior to installing the wrap on each sample, the pipe was sandblasted to a near-white metal finish with a 2.5 to 3-mil anchor pattern. End caps were then attached to the pipe by welding. The wrap was installed with no internal pressure in the pipe. The remaining steps in terms of installing the wraps were conducted by Armor Plate, Inc. personnel and are as follows,

- Primed surfaces where the wrap was to be installed with Armor Plate 360 A&B
- Filled in the corrosion region of the sample using AP360 epoxy putty
- Installed wraps having 8 layers over the corroded region
- The edges of the wrap were contoured with AP360 epoxy putty
- The wrap cures sufficiently when placed beneath a heating blanket for one hour at 130°F.

Figure 1 shows Armor Plate Pipe Wrap being installed on a test sample and **Figure 2** is a photograph of a completed installation on a pipeline.

Listed in **Table 1** are the sample descriptions and test results for the corrosion test samples. The minimum pressure that any repair should achieve is the 100 percent SMYS pressure; however, the APPW 360 system is designed to provide reinforcement up to two times the B31.4 *maximum operating pressure* or B31.8 *maximum allowable operating pressure* (144 percent SMYS) assuming that the appropriate number of wraps is applied.

As noted in all three tests, the burst pressure for the repaired samples exceeded not only the 100 percent SMYS pressure, but were also greater than the predicted failure pressures for the base pipe material assuming no defects were present. None of the repaired samples failed at pressures less than the expected burst pressure for pipe without corrosion or defects.

Cyclic pressure effects on burst pressure

In an effort to address the effects of cyclic pressure on the strength of APPW 360, a test sample was cycled 3,290 times prior to conducting a burst test. Data is provided in **Table 1** relating to this particular test, Sample *WC-4F*. As shown, the burst failure pressure for this sample is equal (within 24 psi) to the burst pressure for the non-cycled test, Sample *WC-3B*. Based upon an industry survey relating to typical operating pressure fluctuations for liquid pipelines (Fowler et al., 1994), pressure fluctuations of this order (1,100 psi) would occur less than 500 times per year. This being the case, the 3,290 cycles for Sample *WC-4F* correspond to approximately six years of service in a liquid pipeline. In contrast with liquid service, cyclic pressure is typically not an operating issue for gas pipelines (pressure fluctuations of 200 psi every five months, Fowler et al., 1994)

Strain Gage Testing

Strain gages were installed on one section of a 16-in x 0.375-in, grade X52 pipe to determine the level of restraint provided by the APPW 360 repair system. In addition to the gages installed under the wrap, one exterior gage was installed on the pipe away from the wrap. These locations served to indicate the level of nominal strain in the pipe due to internal pressure.

An 8-in x 8-in corrosion area having a depth of 50 percent was machined into the 0.375 inch wall. This thickness was verified to be 0.188 inches using a hand-held ultrasonic meter. Two biaxial strain gage rosettes were installed in this region. One was placed in the center of the corrosion, while the other was offset 2 inches along the axis of the pipe.

After installation of the wrap was complete, the strain gages and associated cables were connected a data acquisition system. This equipment was necessary for monitoring the strain gages during the pressurization process. This step was the last procedure conducted before testing the wraps.

The level of internal pressure was related to the minimum specified yield strength for the pipe. The X52 grade pipe has a SMYS of 52,000 psi which corresponds to a pressure of 2,438 psi. According to ASME Codes for liquid and gas piping, the allowable stress is limited to 72 percent of SMYS (for B31.4 all cases and for B31.8, Division 1, Class 2 - *pipelines, mains, and service lines*), which for the given pipe corresponds to an internal pressure of 1,755 psi. Using these two pressure values (1,755 and 2,438 psi), a pressure sequence was developed for testing the pipe sample. **Figure 3** shows the pressure-time map used in loading the sample. The three pressure cycles shown were applied three different times, being designated as *Run #1* and *Run #2*, and *Run #3*. The purpose in repeating the pressure cycles was to provide information relating to the hysteresis of the system.

The properties for the 16-inch pipe according to the Mill Test Report were,

- Yield strength of 68,900 psi (API Spec 5L minimum yield strength of 52,000 psi)
- Tensile strength of 88,500 psi (API Spec 5L minimum tensile strength of 66,000 psi)
- Elongation of 35.0% (API Spec 5L minimum of 23.5%).

As can be seen from these values, the tested pipe far exceeds the minimum values for the X52 grade piping material as specified by the American Petroleum Institute's (API) Specification 5L. While strain gages were installed in the corroded region of the 16-inch pipe beneath the wrap, no measurements were taken in this region without reinforcement. For this reason a finite element analysis (FEA) model was constructed to determine the strains in an unrepaired corroded region. **Figure 4** provides the analytical results with the experimental values for the strain gages located in the corroded region beneath the APPW 360 wrap. In the

finite element model, strains were extracted from the same location as the strain gages placed on the 16-inch pipe test sample.

In studying the information in **Figure 4**, there are several noteworthy observations,

- In the initial pressurization, the wrap does not provide significant reinforcement to the corroded region of the pipe. This is validated in observing that the sub-wrap strain values differ little from the nominal pipe strain readings.
- During the later stages of the pressurization (after approximately 2,000 psi internal pressure), the strain in the pipe increases significantly. It is at this point that the wrap begins to take on the load required to provide restraint to the pipe. At the maximum pressure of 2,438 psi, it is apparent that the wrap is providing reinforcement to the corroded region. Using the previous equations and the ultimate strength of the pipe, the calculated burst pressure for the corroded region without reinforcement is 2,476 psi.
- Using the hand calculations and FEA results, it is apparent that the pipe repair is providing reinforcement once the corroded region exhibits yielding. If the APPW 360 repair was not installed, the two sets of plotted curves (red/blue and yellow/green) would be more closely related.

While strain gages were not installed in a corroded region that was not repaired, the finite element analysis provides useful information relating to the expected stress/strain levels. This comparison of results provides insights as to the mechanical behavior of the wrap and at what pressure the transformation of the load from the pipe to the wrap occurs.

Effects of Installation Pressure on Performance of APPW 360

One issue commonly raised when discussing any repair method is the pipe internal pressure at which installation of the repair can be made. When discussing composite repairs, this is perceived by many as an important issue. To address the effects of installing Armor Plate Pipe Wrap at different pressures, a series of tests were devised using three 12.75-in x 0.188-in, grade X42 pipe samples. An 8-in x 8-in region was machined in each of the 8-foot long samples having a depth of 50 percent of the nominal wall. Based on the remaining wall thickness in the corroded regions of the pipes, the pressure required to cause yielding was calculated to be 585 psi. Each of the samples were pressurized prior to installation of the wraps so that a 0.20 percent strain was induced, which corresponded experimentally to an internal pressure of 600 psi. The

purpose of this stage of testing was to insure that yielding had occurred in the pipe prior to installation of the wrap. During installation of the wraps, one sample was pressurized to 540 psi (90 percent of 600 psi), another at 270 psi, and a third sample had no pressure during installation. The wraps were installed and cured beneath a heat blanket for one hour at 130°F. Burst tests were conducted and all three test samples failed at pressures of 2,240 psi. This pressure is on the same order as the ultimate tensile strength pressure for the given pipe material. The results associated with this series of tests clearly indicate that the burst strength of the Armor Plate repair system is not significantly affected by variations in installation pressure.

Repair of Elbow and Tee Fittings Using APPW 360

Armor Plate Pipe Wrap was installed on several pipe fittings to determine its ability to repair complex geometries. The fittings of interest were 6-in standard size-on-size tees (Grade X65) and 6-in standard 90 degree long radius elbows (Grade X52). A total of four test assemblies were fabricated: two repaired and two unrepaired. Prior to testing, simulated corrosion was induced in each sample using a hand-held grinder. Material was removed from selected locations to a depth of 50 percent of the original wall thickness. Measurements were taken before and after grinding using a hand-held ultrasonic meter to verify that the appropriate thicknesses were obtained.

Burst tests were conducted on each of the four test assemblies. The burst pressure for the unrepaired, corroded tee was 6,546 psi while the repaired tee was 7,500 psi. The testing for the elbows generated a burst pressure of 4,532 psi for the unrepaired elbow and 6,780 psi for the repaired fitting. The repaired configurations resulted in improvements of 15 and 50 percent for the elbow and tee fittings, respectively. **Figure 5** is a photograph of the installation of APPW 360 on the elbow, while **Figure 6** shows a layer of the fiberglass being installed in a criss-cross pattern on the tee fitting.

The results of this test program indicate that Armor Plate Pipe Wrap serves as a viable method for repairing elbow and tee fittings. While the repair of the fittings using Armor Plate showed favorable results, had more wraps been applied greater failure pressures would have been obtained. These tests confirm that when composites are used to repair pipeline defects, selecting the appropriate number of wraps for proper reinforcement is critical.

Composite Tensile Testing

Armor Plate, Inc. fabricated several flat panels of the APPW 360 composite material. The approximate dimensions for each of the panels were 6 inches wide by 12 inches long, with thickness being dependent upon the number of layers. Testing was conducted on two and four-layer samples. Identical 1-in x 8-1/2-in samples were prepared from each of the panels. The fibers of the composite were oriented with the long direction of the samples. Tensile testing was conducted using a constant cross-head speed of 0.05 inches/minute in a laboratory temperature of 70°F. The output for the testing procedure was load and deflection; however, using the cross-sectional area of the samples and gage length, stress and strain were computed, respectively. Also obtained as a result of the testing was the modulus of elasticity. The modulus of elasticity, E , is calculated by dividing change in stress by change in strain for the linear portion of the load-deflection curve. During the testing, deflection was only monitored to approximately 75 percent of failure due to the potential for damaging the deflection-measuring extensometer at the point of rupture. Based on the test results, the average failure stress for the AP 360 epoxy formulation was 26,441 psi, while the average modulus of elasticity was 1.75×10^6 psi.

Lap Shear Testing

While testing has been reported herein relating to the performance of the pipeline wrap in reinforcing pipe defects as well as determining the composite tensile strength, information has not been presented relating to the adhesive bond between the pipe and composite. The most effective method for evaluating this interface is by using lap shear samples. In this application, the lap shear testing method uses either steel or composite adherends to test the adhesive bond. As shown in **Figure 7**, the adherends are assembled to create a tensile coupon with a test zone having an area of one square inch. The sample is loaded to the point where failure occurs. This failure shear stress is known as the lap shear rupture strength. In addition to the rupture method of loading, the lap shear samples can be used to determine creep in the adhesive bond considering a specified load, temperature and time period.

Armor Plate, Inc. fabricated two panels involving a steel-on-steel assembly and a composite-on-steel assembly. The approximate dimensions for each of the assembled panels were 7 inches wide by 9 inches long. The nominal adhesive thickness for the samples was 0.010 inches. From these panels, 1-inch wide samples were cut.

Of the two lap shear adherend combinations, the composite-on-steel lap shear sample is more representative of the actual application. In addition to the general strength of the composite material, the bond between the pipe and steel pipe (adhesive interface) determines the structural integrity of the repair method.

The lap shear testing was conducted using a constant cross-head speed of 0.05 inches/minute in a laboratory temperature of 70°F. The output for the testing procedure was load and deflection; however, using the cross-sectional area of the adhesive, the failed shear stress was computed. The steel-on-composite failures all resulted in fiber pull out from the composite. The average failure shear stress for the steel-on-steel and steel-on-composite samples were 1,504 psi and 1,495 psi, respectively. Had fiber pull out not occurred with the composite material, the debonding of the steel-on-composite samples would have occurred at higher shear stresses.

PROPOSED TEST PROGRAM TO ADDRESS ADDITIONAL ISSUES

The initial test program employed by Armor Plate, Inc. to evaluate the pipeline repair system addressed issues relating to the pressure-capacity restoration of damaged pipes. Results for this test program are provided herein. While favorable hydrostatic burst and short-term cyclic have been obtained using a limited number of samples, it is recognized that long-term issues such as creep and environmental effects have not been addressed thoroughly. For this reason, Armor Plate, Inc. has included this section of the paper to provide information regarding the long-term test program. This list below provides an outline of the testing needed to address performance of the adhesive and composite system for long-term service.

- Strength rupture and creep testing on the composite material (including elevated temperature testing)
- Strength rupture and creep testing on lap shear samples addressing bond strength between pipe and wrap (including elevated temperature testing)
- Cathodic disbondment and water penetrations testing (per ASTM G8 and G9 test procedures)
- Long-term composite and lap shear testing (dead weight loading in saturated environment)
- Field validation program involving installation of wraps on pipelines that will be monitored over several years. A standard method for installation and inspection should be employed for all wraps installed.
- Installation of Armor Plate on pipes having mechanical damage (dents with gouges) subjected to cyclic pressure service. The results for the repaired test samples will be compared to the results of fatigue test failures for unrepaired test samples.

APPLICATION OF THE PIPELINE REPAIR SYSTEM

Recognizing the needs that pipeline companies have in repairing corrosion and implementation of the APPW 360 pipeline repair system, Armor Plate, Inc. developed a handbook to assist in installation of the wrap. While the handbook provides information relating to the installation of APPW 360, its primary intent was to designate the number of wraps required to repair a corroded section considering the pipe and corrosion geometries in the form of tables. The handbook provides a theoretical discussion on the methodology used to determine the required number of wraps.

The tabulated values provide a minimum reinforcement level to increase the burst pressure for a corroded section of pipe to twice the allowable operating pressure as discussed previously. This is conservative when compared to the B31G criterion, which requires that corroded regions withstand a pressure capacity equal to 100 percent SMYS.

An example problem is provided below using **Table AP-1A**, which is located in **Appendix B** of the *Handbook for Armor Plate Pipe Wrap*. Assuming the following conditions, how many wraps are required to repair this defect?

Pipe diameter: 6.625 inches
Pipe wall thickness: 0.219 inches
Pipe grade: X42
Corrosion properties: 6 inches long and 0.110 inches deep (depth equals nominal wall minus corroded wall)

Referring to **Table AP-1A** (see **Figure 8**), go down the first column to find the corrosion depth (if depth is between two values, choose the larger). Once the depth is selected, go across to the right and find the appropriate length. Because 6 inches falls between 3.313 and 6.625 inches, select the longer of the two. Based upon this corrosion geometry, **5 wraps** are required to adequately repair this defect.

CONCLUDING REMARKS

Based upon results of the test program, the Armor Plate Pipe Wrap has proven itself to be an effective method for repairing corroded and mechanically-damaged pipe by increasing the hydrostatic burst capacity. Repairs of elbow and tee pipe fittings have also been conducted with favorable results. In addition to the pipe testing, investigations have been conducted relating to the adhesive and composite system. These tests have also proved that the proposed repair system possesses adequate strength characteristics.

To address longevity of the repair method, the Armor Plate, Inc. long-term test program is designed to deal with concerns relating to environmental issues and performance of the composite/adhesive system over an extended period of time under load. This document has attempted to present information relating to the current test program as well as the proposed long-term research efforts. The objective of the overall test program is to fit within a standardized method that will be required for establishing the fitness of composite repair methods.

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Table 1 Repaired Burst Test Samples

Sample Number	Sample Description	SMYS pressure	Predicted burst pressure for uncorroded pipe ⁽¹⁾	Predicted burst pressure for corroded pipe ⁽²⁾	Actual burst pressure ⁽³⁾
WC-3B	12.75" X 0.188" w.t. pipe, grade X52 50% corrosion (24" long by 8" wide) $t_{actual} = 0.191$ inches (base pipe material) $t_{min} = 0.078$ inches (in corrosion) Pipe yield strength = 49,000 psi Pipe tensile strength = 76,250 psi (7 wraps used, 7 reqd. by handbook tables)	1,533 psi	2,284 psi	974 psi	2,289 psi
WC-4F	12.75" X 0.188" w.t. pipe, grade X52 50% corrosion (24" long by 8" wide) $t_{actual} = 0.191$ inches (base pipe material) $t_{min} = 0.078$ inches (in corrosion) Pipe yield strength = 49,000 psi Pipe tensile strength = 76,250 psi (sample pressure cycled 3,290 times prior to burst with $\Delta P = 100$ to 1200 psi) (7 wraps used, 7 reqd. by handbook tables)	1,533 psi	2,284 psi	974 psi	2,313 psi
Pipe #2	6.625" X 0.280" w.t. pipe, grade X46 50% corrosion (4" long by 4" wide) $t_{actual} = 0.280$ inches (base pipe material) $t_{min} = 0.140$ inches (in corrosion) Pipe yield strength = 47,500 psi Pipe tensile strength = 70,600 psi (4 wraps used, 6 reqd. by handbook tables)	3,888 psi	5,968 psi	3,629 psi.	6,170 psi

Notes:

(1) Predicted burst pressure based on actual wall thickness and ultimate tensile strength of pipe

(2) Predicted burst pressures for corroded pipes based on ultimate strength of pipe and reduction factor to account for corroded wall thickness

(3) Burst pressures for the repaired samples exceeded not only 100 percent SMYS, but were also greater than the predicted failure pressures for the base pipe material assuming no defects were present.

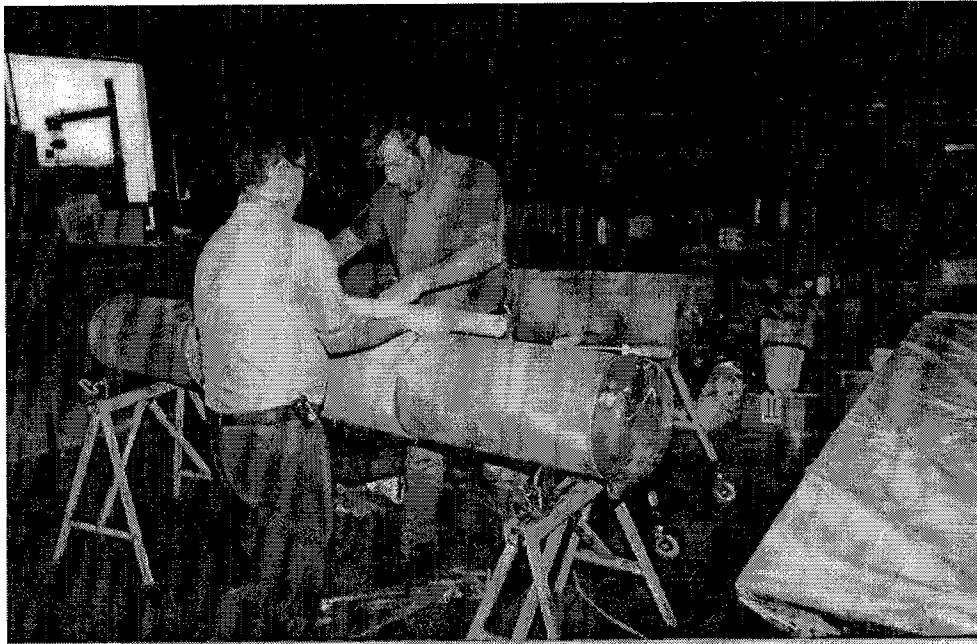


Figure 1 Installation of Armor Plate Pipe Wrap

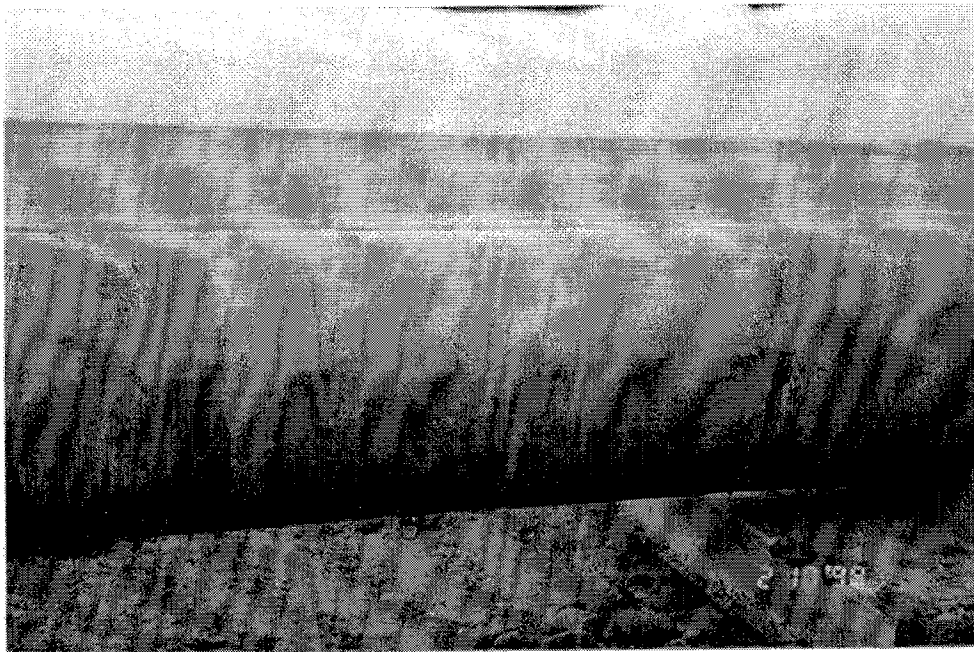


Figure 2 Completed installation of Armor Plate Pipe Wrap

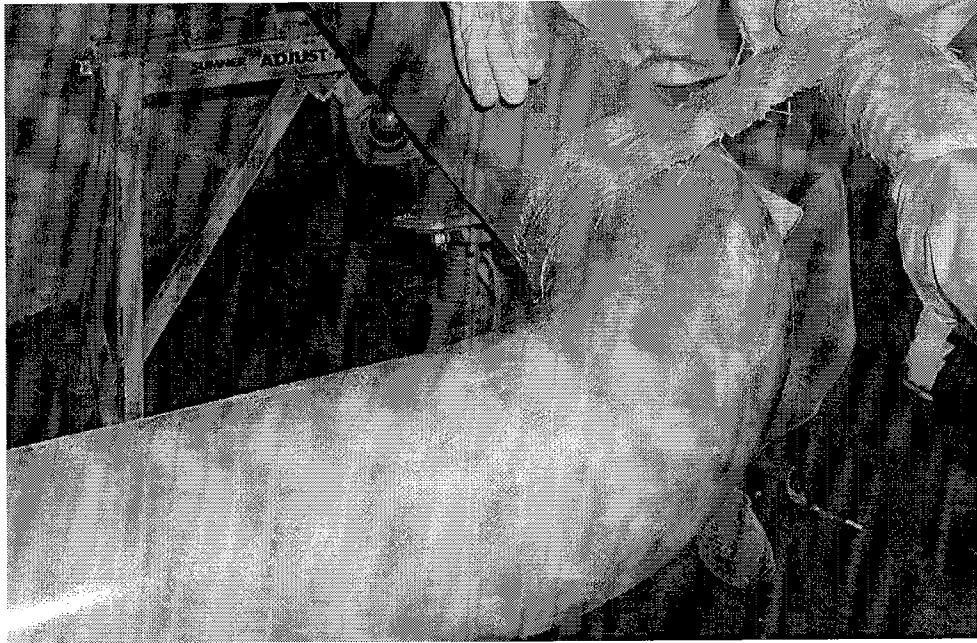


Figure 5 Installation of APPW 360 on elbow with corrosion

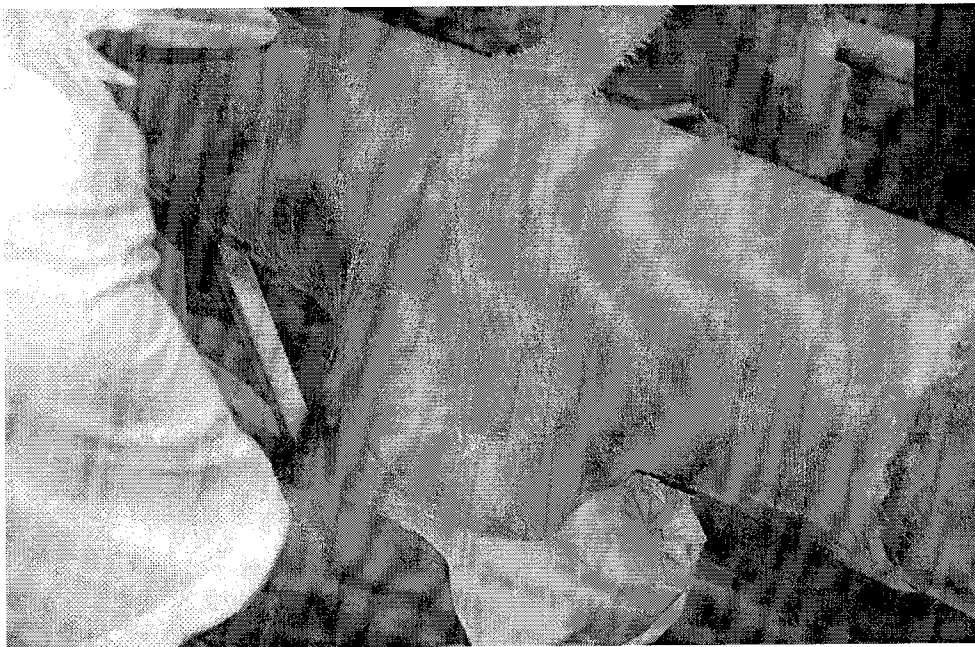


Figure 6 Installation of APPW 360 in a criss-cross pattern on tee

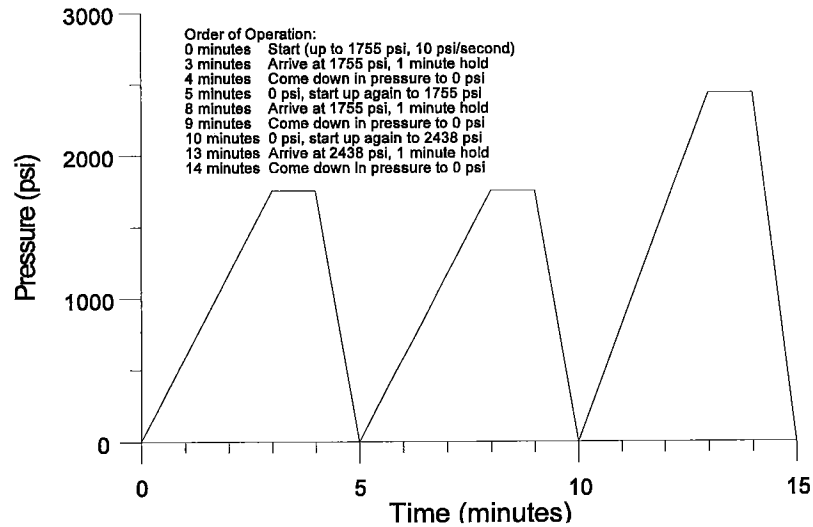


Figure 3 Pressure-time map used in experimental testing

HOOP STRAIN AS A FUNCTION OF PRESSURE IN CORRODED REGION OF PIPE CONSIDERING EXPERIMENTAL AND FINITE ELEMENT VALUES

Calculated FEA and experimental results assume a 16" X 0.375" pipe with a 8" X 8" corrosion patch, 50% of the wall (X52 grade pipe). Experimental corroded region wrapped with 8 layers of APPW 360. Testing and analysis conducted by Stress Engineering Services, Inc.

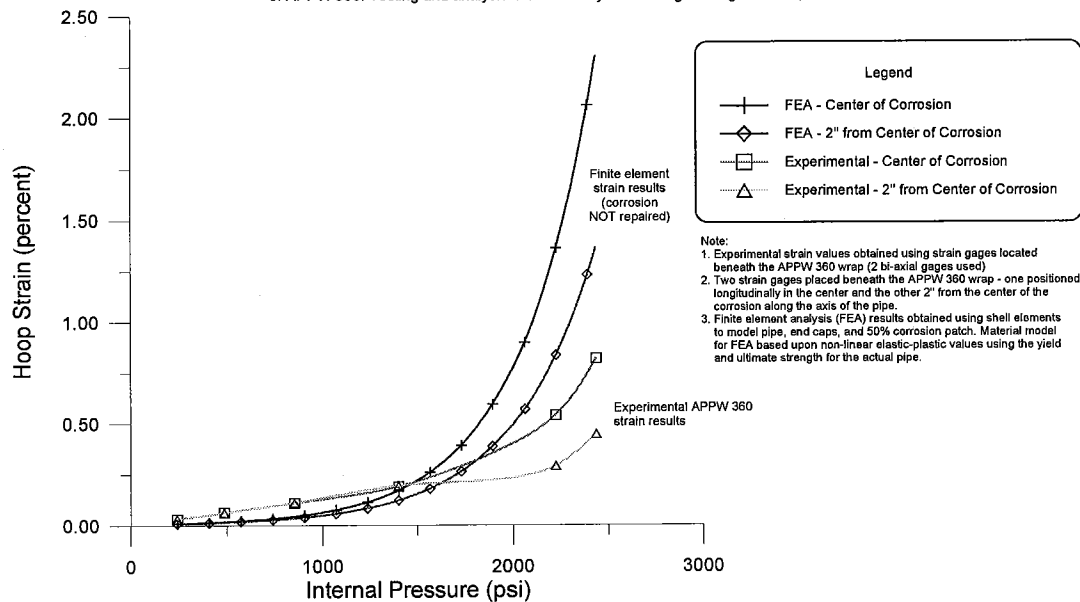


Figure 4 Hoop strain as a function of pressure for experimental and analytical work

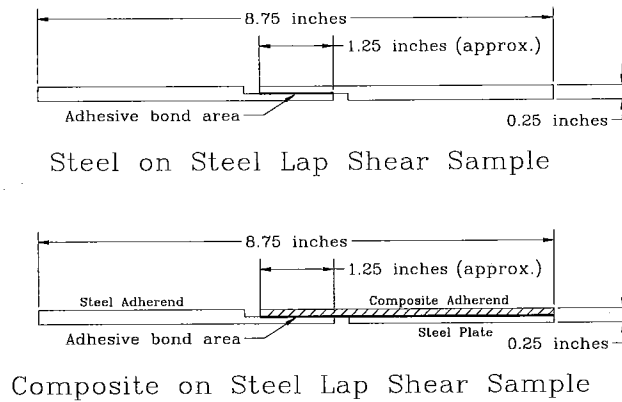


Figure 7 Configuration of lap shear test samples used in testing

Pipe Diameter (in)	6.625	Notes: 1. Repair is not required if corrosion length in table is less than the calculated limiting corrosion length, L, per B31G (see last column in table). 2. If operating pressure is greater than the calculated MAOP, then a specific calculation for the given pipe, grade and operating pressure is required. 3. If the pipe grade (e.g. X52) has a yield strength that is greater than X42 material, then a specific calculation for the given pipe, grade and operating pressure is required if a greater level of reinforcement is desired from the wrap (if wrap thickness value from table are used, result is conservative if operating pressure less than calculated MAOP at left) 4. NR in cell means that repair is not necessary per B31G for this particular corrosion length.							
Pipe wall thickness (in)	0.219								
Pipe Grade (Spec API 5L)	X42								
SMYS (psi)	42000								
UTS (psi)	60000								
Wrap UTS (psi)	30000								
MAOP (psi)	1999								
Maximum permitted corrosion depth (inches)	0.175								
Required Number of Wraps									
Corrosion Depth (inches)	Corrosion Length (percentage of pipe diameter and length in inches)								L per B31G inches
	5% D 0.331	10% D 0.663	25% D 1.656	50% D 3.313	100% D 6.625	150% D 9.938	200% D 13.250	Infinite 10000	
0.022	NR	NR	NR	NR	1	1	1	1	5.396
0.033	NR	NR	NR	NR	2	2	2	2	5.396
0.044	NR	NR	NR	NR	2	2	2	2	3.611
0.055	NR	NR	NR	2	2	3	3	3	2.337
0.066	NR	NR	NR	2	3	3	3	3	1.799
0.077	NR	NR	2	3	3	3	3	4	1.489
0.088	NR	NR	2	3	4	4	4	4	1.282
0.099	NR	NR	3	4	4	4	4	5	1.130
0.110	NR	NR	3	4	5	5	5	5	1.012
0.120	NR	NR	3	4	5	5	5	6	0.916
0.131	NR	NR	4	5	6	6	6	6	0.836
0.142	NR	NR	4	5	6	6	6	7	0.767
0.153	NR	NR	5	6	7	7	7	7	0.707
0.164	NR	3	5	7	7	7	7	7	0.653
0.175	NR	3	6	7	8	8	8	8	0.605

Figure 8 Table AP-1A from the *Armor Plate Pipe Wrap Handbook*