RECENT TEST RESULTS AND FIELD EXPERIENCE WITH ARMOR PLATE PIPE WRAP IN REPAIRING CORRODED AND MECHANICALLY-DAMAGED PIPES

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SUMMARY

This paper provides documentation on the testing program that has evaluated the technical capabilities of Armor Plate Pipe Wrap (APPW) in repairing corroded and mechanically-damaged pipes. Armor Plate, Inc. started testing the repair method in December of 1997 that involved burst testing of 6-in nominal diameter pipes with various defects repaired with APPW. Since that period, numerous tests have been conducted to address issues ranging from repair of corroded pipes to increasing the fatigue life for pipes with dents and gouges. Also included in this test program are issues relating to material performance.

Test results confirm that Armor Plate Pipe Wrap is a viable means for repairing corroded and mechanically-damaged pipes. Failure data were obtained for the repair of dents with gouges in cyclic pressure service. The results showed that the repair method increased the fatigue life for unrepaired defects by more than three orders of magnitude.

To ensure a safe and technically-sound installation, Armor Plate, Inc. developed an installation procedure that includes a series of tables that specify the required number of wraps for a given corrosion depth and length. In addition to the pipeline repair, testing has been conducted on *Aqua Wrap*, a leak repair method, and *Armor Clamp*, a stainless steel clamp to be used in conjunction with the composite material for additional reinforcement.

BACKGROUND

From a historical perspective, implementation of composite materials in repairing pipelines is a relatively new concept. While composite materials are not new to the engineering community, especially in the aerospace industry, their acceptance into the pipeline community may be described as cautious.

Armor Plate Pipe Wrap was developed to provide industry with an economical structural repair system that is easy to use and apply for structural repair on corroded or damaged pipe. The material will also repair concrete, steel, asbestos, vinyl, and fiberglass pipe. Armor Plate Pipe Wrap venture was originated from Wil-Cor, Inc. which has the registered trade name of Armor Plate. Wil-Cor, Inc. started business in 1978 and formulates epoxy polyester resins for floor coatings, tank linings, grouts, and adhesives for industry. Wil-Cor, Inc. also has field crews that have been repairing fiberglass pipe and structures, fabricate fiberglass pipe and apply chemical resistant linings to concrete pits and tanks since 1978.

Recognizing the potential for developing a repair method using composite materials, Armor Plate initiated an extensive test program. Stress Engineering Services, Inc., Houston, Texas, was selected because of their extensive experience in pipeline repair and testing. Charter Coatings Services Ltd., Calgary, Alberta, Canada, was also selected as a testing laboratory because of their experience in cathodic disbondment, impact, corrosion and cold weather testing.

The intent of the test program was to evaluate the structural integrity of the system in terms of composite materials and interaction with various piping geometries. An imperative in the evaluation was that testing must simulate field conditions and possess representative loads that are common to pipeline systems.

This paper provides details on the test program that is evaluating Armor Plate Pipe Wrap for repairing corroded and mechanically-damaged pipes. The objective is to provide the reader with an understanding of the important facets of the repair design and why particular test methods were chosen. At the end of this paper, a section details a list that was submitted to the Office of Pipeline Safety as a recommended criteria for composite materials used to repair pipelines. While there appears to be greater latitude from regulatory bodies in permitting composite repairs, there is concern from the industry that repair methods meet a minimum set of requirements to ensure safe and long-term operation of the pipelines.

MATERIAL EVALUATION

While initial testing of the Armor Plate focused on the repair of corroded pipes, addressing the properties of the composite material was a primary concern. This involves quasi-static conditions such as found in a tensile rupture test, but also involves testing properties to address the effects of time and environment on the material.

From a mechanics standpoint, determining the Modulus of Elasticity and lower bound failure strength were of primary importance. Once these values were obtained, it was possible to predict within a relatively high degree of accuracy the actual reinforcement that was provided by APPW to a repaired pipe. Lap shear testing provided insights regarding the adhesive bond strength between the pipe and composite. A series of tests also involved elevated temperatures in an effort to quantify the decrease in strength of Armor Plate due to elevated temperatures.

A detailed discussion is outside the scope of this paper; however, the items below represent the fundamental tests associated with the material evaluation of the Armor Plate Pipe Wrap system. For additional information on the material evaluation of APPW, interested readers are referred to **Reference 1**.

- Composite tensile rupture testing
- Lap shear rupture testing
- Effects of elevated temperature on composite rupture strength
- Cathodic disbondment testing
- Impact testing
- Chemical resistance testing

REPAIR OF CORROSION

The repair of corrosion is the most basic and fundamental application of Armor Plate Pipe Wrap. It is at this level that the mechanics of the wrap are understandable and that the wrap can be evaluated in a meaningful manner. The repair of mechanical damage and other piping geometries is more complicated due to the extensive non-linear behavior of the pipe beneath the wrap. As stated previously, the current test program started with a series of test on 6-in nominal diameter pipe samples. From that initial effort, an extensive battery of tests and analyses were performed to quantify the repair capabilities of Armor Plate. This section of the paper details the findings associated with this effort.

Introduction to the Mechanics of Composite Wraps

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 paper provides the reader with an understanding of the critical issues associated with the development of a composite pipeline repair system. While not exhaustive, this discussion focuses on restoring burst strength and reducing the strain in the damaged area of the pipeline. For a complete discussion on this subject, readers are encouraged to review **Reference 1**.

The burst pressure of a pipe is directly related to the ultimate strength of the pipe material for a material possessing an adequate level of ductility. While yielding of the material is certainly important, it is not directly involved in the calculation of burst strength.

When a composite sleeve is placed over a region of the pipe the following are achieved.

- Increases the thickness of the cross-sectional area resisting the internal pressure force
- Introduces another material with different material properties (in most circumstances) than the pipe. The thickness of the composite material in conjunction with its ultimate strength determines the level of reinforcement provided when a repaired section is taken to burst-level pressure.

Figure 1 shows a cross-sectional view of a pipe and a composite wrap installed on the outside of the pipe. This schematic illustrates how the pipe and wrap mechanically resist the force created by the internal pressure.

The other issue to be addressed in assessing the performance of a pipeline repair system is the level of restraint provided to reduce strain in the reinforced pipe section. Calculations associated with this topic are more complicated than those presented because of the issues related to plasticity of the pipe material. From a loading standpoint, the following sequence of events occurs when a repaired corroded region is pressurized so that plastic flow is induced in the material,

- The pipe and composite are both stressed as the internal pressure is increased. The stiffer of the two will be stressed to a higher level (with composite repairs this is typically the pipe material).
- Once the corroded section of the pipe begins to yield, its relative stiffness is reduced. At this point the wrap begins to be the critical source of strength for the assembly. Basically this phase of loading can be modeled assuming that the pipe material has a modified (reduced) modulus of elasticity related to the slope of the yield to ultimate strengths.
- The final burst pressure is governed by the ultimate capacities of the pipe and wrap material.

Several samples were fabricated to address the reinforcement of corrosion using APPW. 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 in an actual pipeline, would need to be removed, repaired, or have the operating pressures reduced.

Table 1 provides a listing of three burst tests that were conducted on Armor Plate Pipe Wrap. In all tests, the burst pressures 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.

In addition to basic burst tests, additional investigations were carried out to address issues such as the following,

- Cyclic pressure effects on burst strength
- Pipe to composite load transfer
- Effects of internal pressure at installation
- Repair of pipe fittings (elbows and tees)

Reference 1 provides details on the test results for these specific testing efforts.

REPAIR OF MECHANICAL DAMAGE

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

Based upon current industry practices in repairing damaged pipe. The *Pipeline Repair Manual* developed with funding from the Pipeline Research Committee International **(Reference 17)** provides the following list of options,

1. Removal and replacement of a defective segment
2. Grinding
3. Deposited weld metal
4. Full-encirclement sleeves (Type A and Type B)
5. Defect repair using composite reinforcement sleeves
6. Mechanical bolt-on clamps
7. Hot tapping
8. Patches and half soles.

Based upon these previous developments and the effectiveness in using Armor Plate Pipe Wrap to repair corrosion, it seemed appropriate to evaluate APPW for repairing mechanical damage. This paper provides the test methodology and results associated with this effort.

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

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

Table 2 provides a list of the defects and repair configurations associated with the two pipe samples.

After the dents were installed and the gouges repaired by grinding, the Armor Plate Pipe Wrap sleeves were installed. The information in **Table 2** provides the specific number of wraps installed on each sample. The general rule of thumb for repairing mechanical damage (after gouge removal) is for the thickness of the wrap to be 1.5 times the thickness of the pipe wall thickness. Each layer of the wrap is approximately 1/16-in thick. Four layers of APPW were used in conjunction with the clamps.

While the focus of this testing was on the use of Armor Plate in repairing mechanical damage, the recent development of a stainless steel clamp by Armor Plate, Inc. (used in conjunction with the composite wrap materials) was implemented into the fatigue test program. One clamp was installed on each of the pipe samples. **Figure 2** is a photograph of one of the clamps. As seen, the clamp is comprised of two halves that are bolted together. Both Sample A1 and Sample B1 involved four layers of APPW in addition to the clamps. The clamps are fabricated from 1/8-in 316 stainless steel material and are bolted together using six 3/4-in bolts. Prior to their installation, the APPW sleeves were applied and permitted to cure. The surfaces of the wrap were ground smooth and grease was applied to reduce friction during the bolt-tightening process. The bolts were tightened to 125 ft-lbs which corresponded to an approximate bolt stress of 52,000 psi.

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

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

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

Tabulated Test Results

Table 3 provides the cycles to failure for the eight samples tested in this program. As noted in the table, installation of APPW significantly increased the fatigue life when compared to the unrepaired test samples.

Plotted Test Results

The benefit derived in plotting the fatigue results from this project are that direct comparisons can be made with existing fatigue data on mechanical damage. As stated previously, work conducted for the American Gas Association (**Reference 14**) and the Gas Research Institute (**Reference 2**) provide the key data for making this type of comparison.

Figure 3 plots the cycles to failure for the samples repaired using APPW as well as the data for the two stainless steel clamps. Four sets of data are plotted.

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

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

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

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

INDUSTRY STANDARDS AND REGULATIONS

Effective January 13, 2000, Final Ruling **RSPA-98-4733** issued by the Office of Pipeline Safety went into effect. The ruling essentially states that any composite repair system used to repair pipelines should be *a method that reliable engineering tests and analyses show can permanently restore the serviceability of the pipe*. While there was varied reaction to this ruling, from industry there is no doubt that this decision will have a profound impact on the application of composite materials in repairing pipelines.

One issue cited by several who commented during the response period to the Office of Pipeline Safety addressed concerns over the apparent absence of industry standards in evaluating composite repair methods. This section of the paper provides the reader with an understanding of the critical issues in the development of a composite pipeline repair system. The following list compiled was by the authors and was sent to the Office of Pipeline Safety and is referenced in **RSPA-98-4733**. 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 600 cycles per year (at a 600 psi pressure differential), while gas transmission lines see 10 times fewer, or 60 cycles, at 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.

FIELD EXPERIENCE

Over the past two years, Armor Plate, Inc. has installed numerous repairs on pipeline systems. Several of these include,

- Repair of risers for Equistar Chemicals (**Figure 4**)
- Repair of risers for ENRON
- Repair of risers for Copano
- Repair of pipeline in tidal wave area in Venezuela (Petravesa)
- Repair of corrosion on offshore pipeline for Equilon (**Figure 5**)
- Repair of corroded pipeline for Pemex
- Repair of corroded pipelines for KOCH
- Repair of corroded pipe for CONOCO
- Repair of corroded pipe for ARCO Alaska

CONCLUSIONS

Even a cursory review of this document shows that a significant level of testing and evaluation has been conducted on the Armor Plate Pipe Wrap system. As a result of the experimental efforts, insights have been gained in understanding the mechanical behavior of the wrap and its ability to repair corroded and mechanically-damaged pipes.

As a minimum, the following conclusions are derived in evaluating Armor Plate as a repair method for pipelines.

- The strength contribution from Armor Plate to a corroded pipe is governed by the thickness of the wrap and the failure tensile stress for each layer of the wrap. A handbook was developed for Armor Plate that shows the required number of wraps for a given corrosion depth and length. A safety factor of two on the Maximum Operating Pressure for the given pipe is considered in the calculated number of wraps. Experimental testing validated that the specified handbook thicknesses were sufficient to cause the pipe to fail at its ultimate strength and not in the corroded area.
- While Armor Plate provides some reinforcement to a damaged pipe at low pressures, the greatest contribution initiates once plastic flow in the steel occurs beneath the pipe. Although there has been little published research in this area, the mechanics of the problem are consistent with results obtained for the Gas Research Institute (**Reference 2**). The stiffness contribution from the wrap is directly related by the following ratio,

$$Stiffness\ ratio = \frac{E_{wrap} \cdot t_{wrap}}{E_{steel} \cdot t_{steel}}$$

where E is the modulus of elasticity (psi) and t is thickness (inches). Increasing either the thickness or modulus of elasticity of the wrap will increase the stiffness of the repair system.

- From a materials standpoint, testing determined the lower bound failure strengths for both the composite material as well as the lap shear strength for the adhesive. Testing also showed that composite rupture stresses are on the order of 18,000 psi when the material is heated to 300°F. Favorable results were obtained in evaluating the adhesive as a coating in terms of cathodic disbondment.
- One concern that existed early in the evaluation process was the effect that pressure in the pipe at the time of installation would have on the burst pressure repaired corrosion. Armor Plate was installed on pipes with corrosion with 0, 270 and 540 psi (0, 45 and 90% of the pressure required to cause yielding in the corrosion, respectively). Burst tests were conducted on these three pipe samples and they all failed at 2,240 psi. These tests confirm that pressure at installation is not the central issue, but rather the pressure at which yielding in the pipe occurs. It is at this point that load is transferred from the pipe to the wrap.
- The fatigue testing of APPW used to repair mechanical damage provided several useful insights. First, the benefits derived in grinding out gouges that reside in dents increased the fatigue life for unrepaired defects by approximately one (1) order of magnitude. This confirms previous findings by PRCI (**Reference 16**) and the Gas Research Institute (**Reference 2**). The second observation showed that the addition of APPW (in conjunction with grinding) increased the fatigue life for unrepaired dents with gouges by three (3) orders of magnitude.

All tests reported in this document demonstrate that Armor Plate is a valid method for repairing corroded and mechanically-damaged pipes, even in a cyclic pressure environment.

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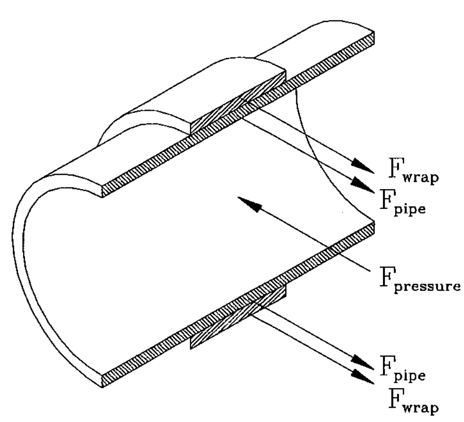

Figure 1 Cross-sectional view of pipeline repair

Figure 2 Stainless steel clamp used in conjunction with APPW

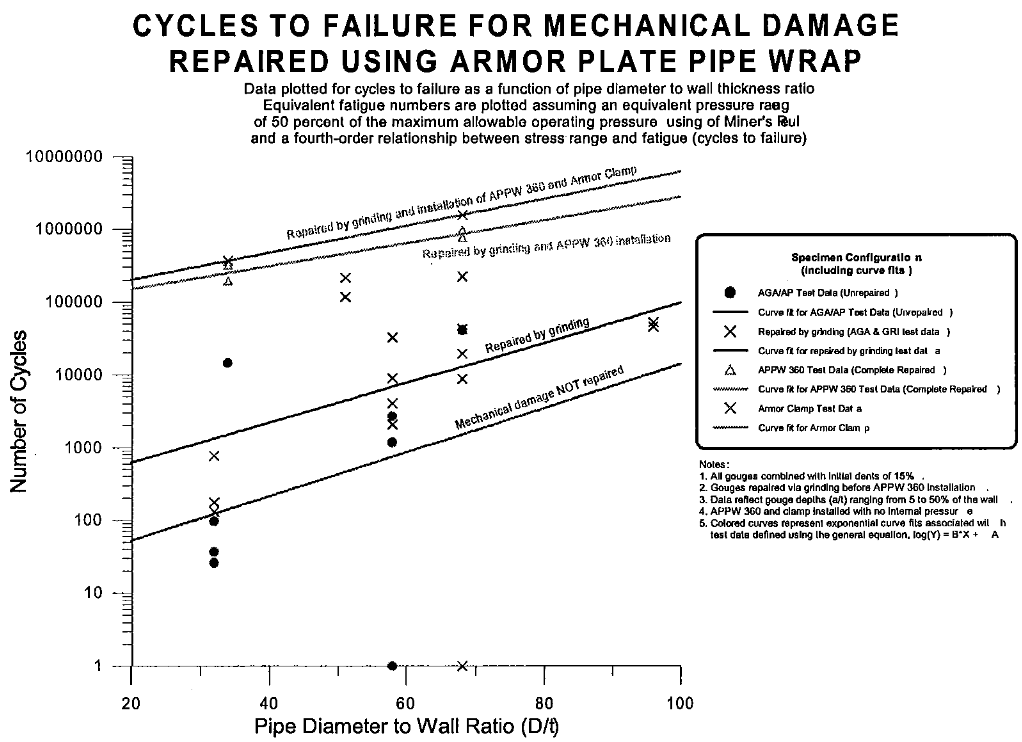

Figure 3 Fatigue data for dents and gouges in varying states of repair

Figure 4 Repair of riser pipe using APPW

Figure 5 Repair of offshore pipeline using APPW

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 ÄP = 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.

Table 2 Dent and gouge sample configuration

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

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

Table 3 Cycles to failure for test samples

Sample Number	Cycles to Failure ÄP = 100% MOP	Cycles to Failure ÄP = 50% MOP(1)	Notes
A1	100,123	1,601,968	4 layers of APPW, stainless clamp
A2	61,558	984,928	5 layers of APPW
A3	48,818	781,088	5 layers of APPW
A4	2,613	41,808	Unrepaired sample
B1	23,344	373,504	4 layers of APPW, stainless clamp
B2	12,276	196,416	9 layers of APPW
B3	20,444	327,104	9 layers of APPW
B4	914	14,624	Unrepaired sample

Note
(1) Calculated fatigue lives are based upon experimental results and Miner's Rule with a fourth-order relationship between stress and cycles to failure. Refer to *Interpretation of Fatigue Data* in **Reference 1** for additional information on calculation of these values.