ASSESSING THE USE OF COMPOSITE MATERIALS IN RE-RATING LIQUID AND GAS TRANSMISSION PIPELINES

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ABSTRACT

The use of composite materials in repairing damaged pipelines has increased significantly over the past decade. Issues such as economic feasibility, safety, performance, anti-corrosion and ability to make in situ repairs have been key factors to their popularity. Recent activities by the Office of Pipeline Safety have removed many of the limitations that existed previously. In this paper a composite repair method designed to remediate corroded and mechanically-damaged pipes is discussed. This repair technique has been extensively tested and evaluated based upon the requirements associated with gas and liquid pipelines.

While composite material are characteristically used for the repair of pipes, it is recognized these materials may be installed to re-rate pipelines to higher operating pressures. To the authors knowledge, this method of pipeline design has not been employed to date; however, the proposed method has profound implications when considering the economic benefits as well as safety issues in not having to conduct hot taps or shutting down the line.

This paper discusses the specific details associated with the mechanics of composite materials used to repair pipes. Also presented are the efforts to address the effects of internal pipe pressure at installation, required thickness of the repair, and interaction of the steel pipe and composite wrap materials. In terms of evaluating the technical merits of using composites for re-rating pipelines, non-linear finite element methods were used.

BACKGROUND

Pipeline codes governing pipeline operation are specific in the methods used to determine operating pressures. For example, the maximum operating pressure permitted in gas and liquid transmission lines is eighty (80) and seventy-two (72) percent of the specified minimum yield strength of the pipe material, respectively (Paragraphs 402.3.1 of B31.4 (liquid) and 841.11 of B31.8 (gas)). Gas transmission pipelines are restricted to a greater degree than liquid lines when one considers the class location system. Pipelines in areas with denser population are required to have lower operating pressures than pipelines in rural, less densely-populated regions. Because of these limitations, pipeline companies that wish to operate at high pressures are forced to install new pipelines, often alongside the existing pipeline in the available right-of-way. Also, liquid or gas pipelines having significant corrosion may be required to reduce their operating pressures. In these situations, the only recourse for these companies is to either cut out the corroded sections or install full-encirclement sleeves. Armor Plate, Inc. observed that neither of these options are ideal for operators and that a potential for employing composites in these applications exists. The use of composite material for re-rating pipelines is an extension of the existing Armor Plate Pipe Wrap (APPW) repair method. Discussions are provided herein on the development, testing and evaluation of this repair system.

Current regulations are rather restrictive in recognizing innovative repair technologies such as composite repair sleeves. Recently proposed rulemaking by the Office of Pipeline Safety (Federal Register, Vol. 64, No. 68/April 7, 1999) is proposing the adoption of a safety performance standard for the repair of corroded or damaged steel pipe in gas or hazardous liquid service (Caldwell, 1999).

The following bullets detail the current federal pipeline repair safety standards (Furrow, 1999).

- If a pipeline operator discovers an unsafe pipe dent during the construction of a steel gas transmission line or main to be operated at 20 percent or more as specified minimum yield strength (SMYS), DOT safety standards require that the operator remove the dent by cutting out the damaged piece of pipe as a cylinder (49 CFR 192.309(b)). This repair requirement does not allow operators to use new or more innovative technologies to repair the dent.
- One of the DOT maintenance standards for steel gas transmission line operating at 40 percent or more of SMYS similarly disallow the use of new technologies (49CRF 192.713). Under this standard, if an operator discovers an imperfection or damage to pipe that impairs the serviceability of the line, the operator must either replace the pipe or repair it by installing a full encirclement split sleeve of appropriate design.

It is apparent from the above two items that current regulations are restrictive in terms of their latitude in making repair to pipelines. These regulations forbid pipeline operators from taking advantage of innovative repair methods such as composites and at the same time preclude the associated development of these technologies. For this reason, the Office of Pipeline Safety has proposed a change in the rulemaking which will have a significant impact on the development of composite repair methods as well as the pipeline industry. The following quote is taken from Federal Register, Vol. 64, No. 66, which addresses the issue of innovative repair technologies.

> *We are also proposing that a qualified repair methods must have undergone reliable engineering tests and analyses to confirm that the methods meets the performance standard. We do not believe it necessary to propose guidelines for these tests and analyses because of the widespread use of alternative repair methods without reports failures. So the tests and analyses need only be what a reasonable and prudent professional engineer would consider adequate to demonstrate compliance wit the performance standard.*
>
> *The proposed change to 192.309(b) merely adds the performance standard to the end of the introductory clause. Operators would then have the option of either removing or repairing the described dents....*
>
> *Consequently, any corroded area, large or small, could be repaired as long as the repair method meets the performance standard.*

According to the same document, the proposed standard is that the (repair) method must be able to *permanently restore the serviceability of the pipe*.

In reading the above documentation, it is apparent that the Office of Pipeline Safety has proposed a new rulemaking that will have profound impact on the pipeline industry. From a technical standpoint, there is concern that the proposed standard is rather ambiguous and that a particular test program (or proposed standard developed by a particular company) may not specifically address the critical elements related to composite materials. For this reason, the test program implemented by Armor Plate Pipe Wrap has addressed specific issues relating to a variety of operational issues.

The sections that follow discuss in detail the analytical efforts that were undertaken to study the mechanics associated with installing a composite material over a steel pipe. Prior to this effort, a significant level of experimental and analytical work was conducted in order to understand the mechanical interaction between the pipe and composite materials. In terms of discussing the re-rating process, special emphasis is placed upon strain-based limit state design as well as comparing the existing stress-based safety factors with those obtained assuming reinforcing composite layers are installed on a pipeline.

ANALYSIS OF COMPOSITE MATERIALS

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 restoring strength to damaged pipelines, reducing strain in damaged regions, and sealing pipes from environmental exposure.

Mechanics of Composite Wraps

This section of the paper provides the reader with information on the critical issues in 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.

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. Installation of a compsoite wrap does the following when considering the burst strength for a pipe,

- Increases the thickness of the cross-sectional area resisting the internal pressure force
- Introduces another material with different yield and ultimate strengths (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 mechanical resistance provided by the pipe and wrap are governed by the equal and opposite relation, used to calculate the burst pressure for a given pipe/wrap combination,

$$P_{burst} = \frac{\sigma_{ult_{pipe}} \cdot t_{pipe} + \sigma_{ult_{wrap}} \cdot t_{wrap}}{r_{inside}}$$

For purposes of experimentally validating the previous equation, consider the results from a previous burst test (Alexander, 1999). The following data are evaluated,

Pipe size: 6.625-in x 0.280-in pipe, 47.5 ksi yield strength and 70.6 ksi ultimate strength
Wrap: 4 wraps - 0.25 inches total thickness, strength of 26.4 ksi (based on tensile testing)

The test sample had a 4-in x 4-in corroded region that was 50 percent of the wall; however, because of local reinforcement from the adjacent pipe material, the thickness used in the burst equation is 60.8 percent (0.170 inches) of the actual pipe wall.

$$P_{burst} = \frac{(70{,}400\,psi \cdot 0.170\,inches) + (26{,}400\,psi \cdot 0.25\,inches)}{3.0325\,inches} = 6{,}123\,psi$$

This calculated value corresponds well to the actual burst pressure of 6,170 psi. This pressure is also close to the calculated burst pressure for the same pipe geometry with no corrosion (5,968 psi).

The other issue to be addressed in assessing the performance of a pipeline repair system is the level of restraint provided to decrease 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). Stiffness for the piping configuration at hand is computed using the following equation,

$$k = E \cdot t$$

where: E Modulus of elasticity of material (psi)
t Thickness of material (inches)

- 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.

Validating Repair using Burst Tests

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.

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.

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 ΔP = 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.

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)

Evaluation of Pipe-to-Composite Load Transfer Using Strain Gages

Strain gages were installed on a simulated corrosion region of a 16-in x 0.375-in, grade X52 pipe to determine the load transfer and level of restraint provided by various layers of the APPW 360 repair system.

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.

Prior to pressurizing the sample, all strain gages were zeroed. This means that any residual strains developed in the gages during installation are removed and all gage readings start out at zero microstrain. As shown in the following equation, the ability of the wrap to provide constraint to the pipe is directly related to the product of the modulus and the thickness of the wrap (E_c times t_c).

$$\sigma_{pipe} = \frac{P \cdot R}{t_p \cdot \left(1 + \frac{t_c \cdot E_c}{t_p \cdot E_p}\right)}$$

where:	σ_{pipe}	Hoop stress in pipe (psi)	t_c	Thickness of wrap (inches)
	P	Internal pressure in pipe (psi)	E_p	Pipe modulus of elasticity (psi)
	R	Outside radius of pipe (inches)	E_c	Wrap Modulus of elasticity (psi)
	t_p	Wall thickness of pipe (inches)		

Without going through an extensive analysis using this equation, it is shown with four layers of the APPW 360 wrap that the product of *E* (1.5 X 10^6 psi) and *t* (0.21 inches) is calculated to be 0.9 X 10^6 lbs/in, while for the pipe steel this product (30 X 10^6 psi and 0.375 inches) is 11.25 X 10^6 lbs/in. Comparing these two stiffnesses, the pipe steel is <u>12.5 times</u> as stiff as the composite material. This explains why the wrap does not take a higher percentage of initial loading.

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 <u>unrepaired corroded region</u>. **Figure 2** 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 2**, 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 and Surface Preparation

One issue raised during the evaluation of Armor Plate Pipe Wrap involved the effects of installation pressure on the burst performance of the repair. Prior to testing, concerns existed that if the wrap was installed at elevated pressures (in excess of 50 percent maximum allowable operating pressure), its effectiveness as a repair method would be reduced.

Three 8-ft, 12.75-in x 0.188-in, grade X42 pipes were fabricated by installing end caps. In each test sample, a corrosion region was machined having an area measuring 8-in x 8-in and a corrosion depth equal to 50 percent of the nominal pipe wall (in this case 0.094 inches).

While previous tests employed sandblasted surfaces, the surface for the three samples were sanded with a flapper wheel with 100 grit sandpaper. Due to the minimal anchor pattern, this type of preparation has reduced bond strength between the pipe and composite material when compared to the anchor patterns associated with sandblasted surfaces.

The measured wall thicknesses in the machined corrosion regions were used in calculating the pressure required to induce yielding in the corroded region. Prior to installation of the wraps, all three samples were pressurized to provide local bulging in the corroded region. Based on material testing of the pipe material, the yield and ultimate strengths were 44.9 ksi and 74.2 ksi, respectively. The yield strength of the material is used to calculate the yield pressure as shown below.

$$P_{yield} = \frac{2 \cdot \sigma_{yield} \cdot t_{corrosion}}{D}$$

where: σ_{yield} Yield strength of material (44.9 ksi)
$t_{corrosion}$ Remaining wall in corroded region (0.083 inches)
D Outside diameter of pipe (12.75 inches)

Using these values, the yield pressure is computed to be,

$$P_{yield} = \frac{2 \cdot 44.9\, ksi \cdot 0.083\, inches}{12.751\, inches} = 585 \;\; psi$$

To ensure sufficient yielding, all of the pipe samples were pressurized to 600 psi. The samples were then pressurized during wrap installation at the following levels.

- Sample #1 - 0 psi
- Sample #2 - 270 psi (45 percent of 600 psi)
- Sample #3 - 540 psi (90 percent of 600 psi)

After installation of the wraps was completed, each of the samples were taken to burst. All three samples failed at a pressure of 2,240 psi. This pressure exceeds the derated pressure of 675 psi (based upon the corrosion length and depth, per Paragraph 451.7 of B31.4, *ASME Code for Pressure Piping*) by more than 300 percent. This safety contribution, in conjunction with the minimal impact of installation pressure and surface preparation on burst strength confirmed Armor Plate Pipe Wrap as a valid repair for restoring the structural integrity corroded pipelines.

RE-RATING OF PIPELINES

Having presented technical issues relating to the mechanics and design of composite repair methods, it is appropriate to present details on how the composite material is used to re-rate pipelines. This method involves the installation of composite materials over the exterior of the pipe. The thickness of the wrap is governed by the desired (re-rated) internal pressure, strength of the pipe material, and design strength of the composite.

Presented in this section of the paper are the following concepts,

- Finite element modeling
- Analysis of results
- Design basis for wrap installation
- Example problem

Finite Element Modeling

A series of finite element models was constructed to study the behavior of the pipe beneath different number of composite layers. While the performance of the composite is of interest, the greater concern is the behavior of the steel beneath the wrap and how stresses and strains are reduced due to the presence of the reinforcing composite material.

Figure 3 shows one of the finite element models used in the analyses. A three-dimensional shell model was constructed that accounted for the steel pipe wall in addition to the various layers of the composite material. ABAQUS, a general-purpose finite element code, was used in this investigation. The pipe geometry evaluated was 30-in x 0.515-in, Grade X70. **Figure 4** shows the non-linear input data material model that accounted for plasticity. The material model for the composite material was assumed to be elastic with a Young's Modulus of 1.5×10^6. Symmetry planes were assumed on all four exposed edges of the model.

The primary variable of interest was the impact that different wrap thicknesses have on the strain in the pipe material. From a strain-based design standpoint, one can assume a maximum permitted strain in the pipe and determine the required thickness of the reinforcing wrap for a given internal pressure level. In a similar way, one can select a stress-based safety factor and determine the thickness of the wrap to ensure that the safety factor was maintained by accounting for the contribution of both the steel and composite materials.

Analytical Results

The stress and strain in the pipe were calculated based upon various composite thicknesses installed on the exterior of the pipe surface. **Figure 5** and **Figure 6** show the pipe strains and stresses for 0.125, 0.25 and 0.375 inch wrap thicknesses, respectively. Also shown are the stresses and strains assuming that no wrap was present. These values were extracted as functions of internal pressure.

There are several noteworthy observation. First, a linear relationship exists between internal pressure and pipe stress, because the pipe hoop stress is a result of an equal and opposite reaction to the internal pressure load. Even with a non-linear material model this relationship will exist. **Figure 6** shows that a non-linear relationship exists between pipe hoop strain and internal pressure. The curves in this figure are governed primarily by the plasticity in the pipe material. When the pipe strains are elastic, a linear relationship exists between pressure and strain.

A second important observation exists when considering the effect that the number of wrap has on the stress and strain in the pipe material. Both **Figure 5** and **Figure 6** show that the stresses and strains in the pipe material are reduced with increasing composite thickness. In terms of the strain data, the effect of the composite material occurs only after plastic flow occurs in the pipe. As noted in **Figure 6**, only after 1,200 psi does load transfer take place from the pipe to the composite material. At pressures below this threshold, there is no distinction in the effect that composite thickness has on pipe strain.

Discussion of Analytical Results

The data presented in **Figure 5** and **Figure 6** are important in determining the required number of wraps for a given design methodology and operating pressure. As stated previously, either stress or strain can be used in establishing a design criteria. Consider the following codes and the methods by which they impose design limits.

- Liquid and Gas Piping Codes (ASME B31.4 and B31.8) - Yield Strength
- Boiler & Pressure Vessel Codes - Ultimate Tensile Strength
- Welding Research Council (WRC Bulletin 254) - Strain Limit

Other modern codes, such as Division 3 of the ASME Boiler & Pressure Vessel Code, are incorporating fracture mechanics (e.g. critical crack size) as a design tool. Considering current advances associated with in-line inspection tools, at some point the piping codes will employ fracture mechanics as a method for design and evaluation on a more extensive basis.

Stress-based Design

In terms of the given problem, a stress-based design seems logical and consistent with current practices in the pipeline industry. Consider the following safety factors relative to failure at the ultimate tensile strength. The internal pressure is 1,350 psi for these calculations.

- No wrap - safety factor of 2.09
- 4 layers of wrap (0.25 inches) - safety factor of 2.40
- 6 layers of wrap (0.375 inches) - safety factor of 2.59

Although not specifically addressed, it is possible that the installation of a composite wrap could increase the safety factor for a higher operating pressure over the safety factor for bare pipe operating at a lower pressure.

Strain-based Design

The incorporation of strain-based design is more complicated than a stress based design due the non-linear material behavior that must be considered in making the necessary calculations. While 20 years ago this may have been an issue, advances in computer technology and finite element methods have made strain-based design a reality and have increased the confidence level of the design process.

For the given piping analysis, one can employ a strain-based design criteria by assuming a threshold, or maximum permissible, strain level. For example, consider a strain limit of 0.20 percent. The following pressure limits are calculated from the finite element results.

- No wrap - 1,930 psi
- 2 layers of wrap (0.125 inches) - 1,962 psi
- 4 layers of wrap (0.25 inches) - 1,991 psi
- 6 layers of wrap (0.375 inches) - 2,025 psi

As noted from the above data, the installation of 6 wraps increased the pressure of the non-reinforced pipe by approximately five (5) percent. While this may seem to be a rather benign contribution, an increase of this magnitude is often all that is required for the re-rating of a line that is operating at a marginal level. Additional reinforcement can be derived with increasing the number of wraps.

Although not specifically addressed in this analysis, the elastic modulus of the composite material plays an important role in the load transfer that takes place between the pipe and composite material. A stiffer composite material will provide greater levels of reinforcement and will minimize the required thickness of the composite material installed onto the pipeline.

CLOSING COMMENTS

The concept of using composite materials to re-rate transmission pipelines is one that certainly deserves consideration. Benefits relating to this use of composite materials are as follows,

- Barrier to further development of corrosion
- Eliminating downtime during repair process
- Continuous service and operation during repair
- Once installed, protection from rocks and trench debris during backfill
- One-day delay between installation and backfill

As shown in this technical evaluation, the proposed method has technical merit and can be used to increase the safety factor of an operating pipeline even when the operating pressure is increased. Only materials that have been qualified using full-scale burst tests should be employed in an applications of this nature. Also, any environmental and time-dependent degradation effects in the composite material should be addressed prior to installation.

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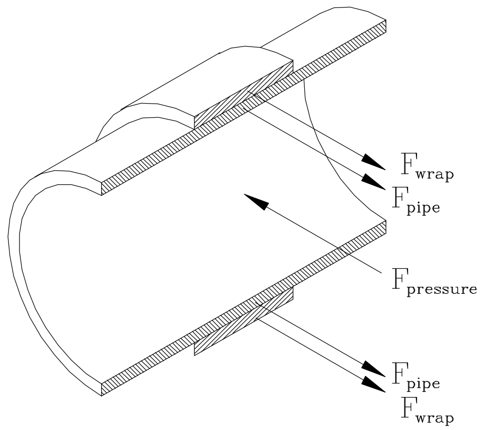

Figure 1 Cross-sectional view of pipeline repair

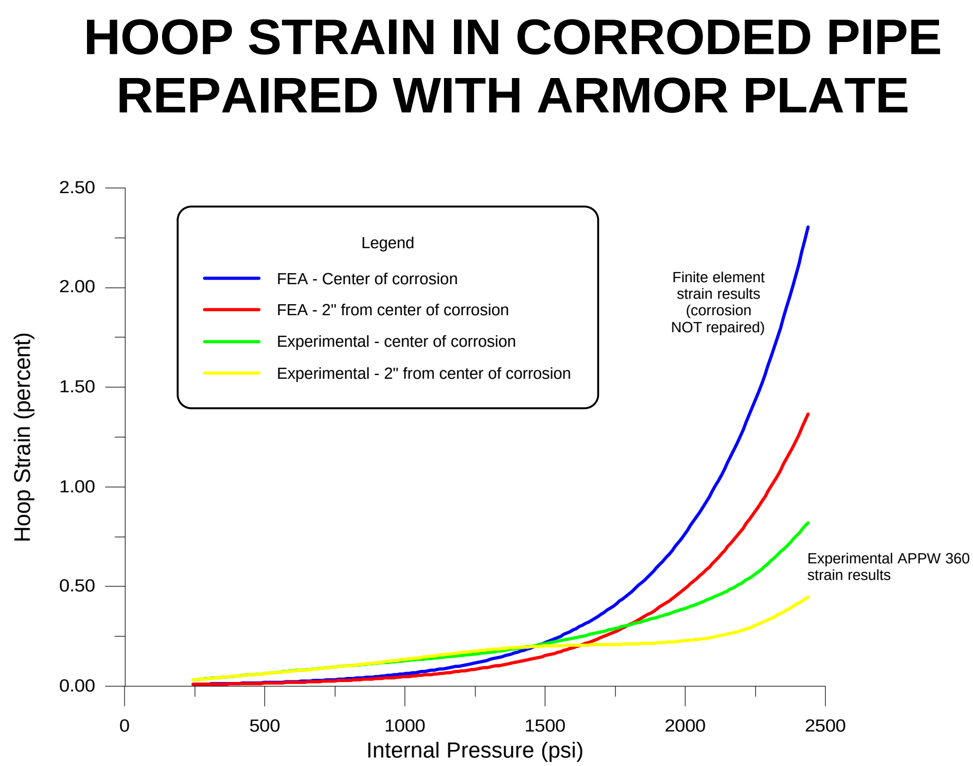

Figure 2 Hoop stress as a function of pressure

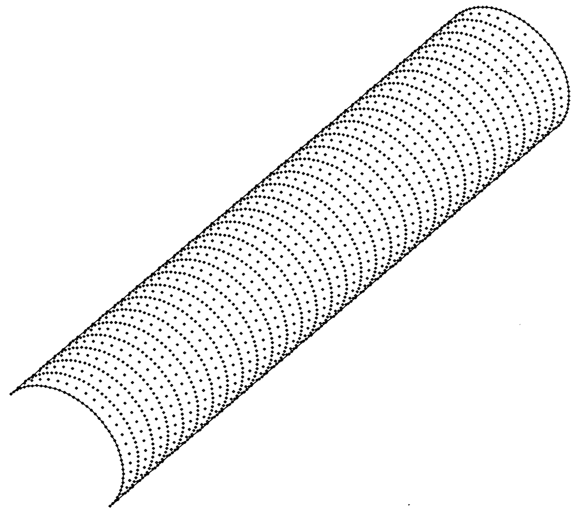

Figure 3 Finite element model

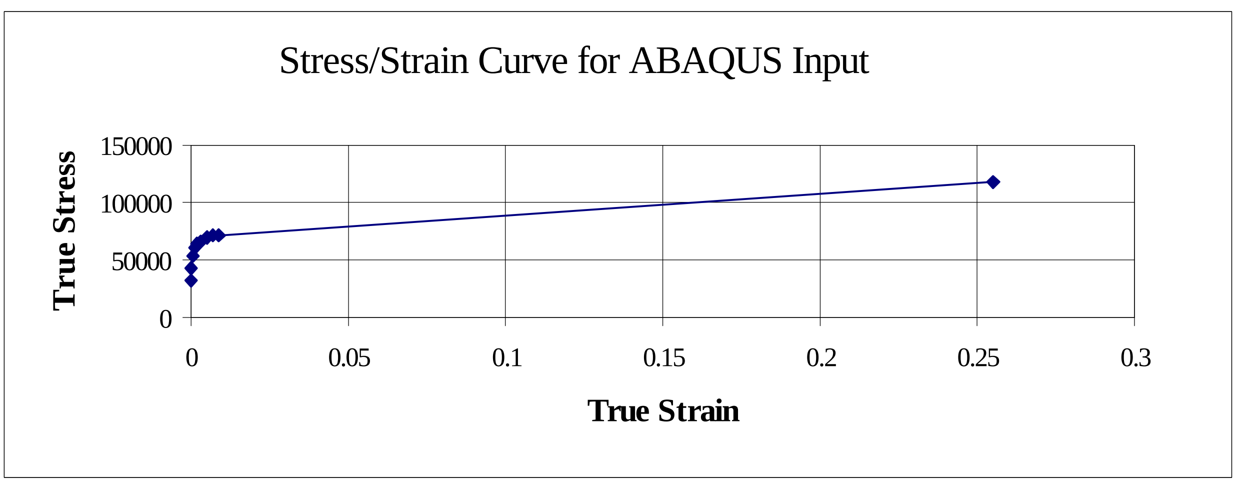

Figure 4 Stress-strain curve for steel pipe in finite element model

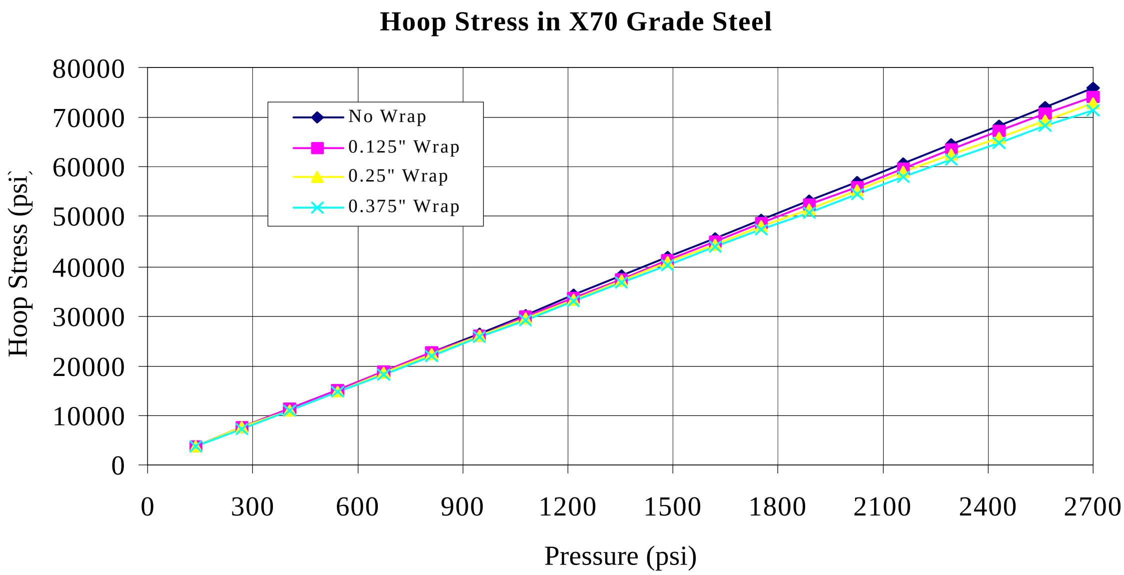

Figure 5 Stress in steel pipe as a function of composite thickness

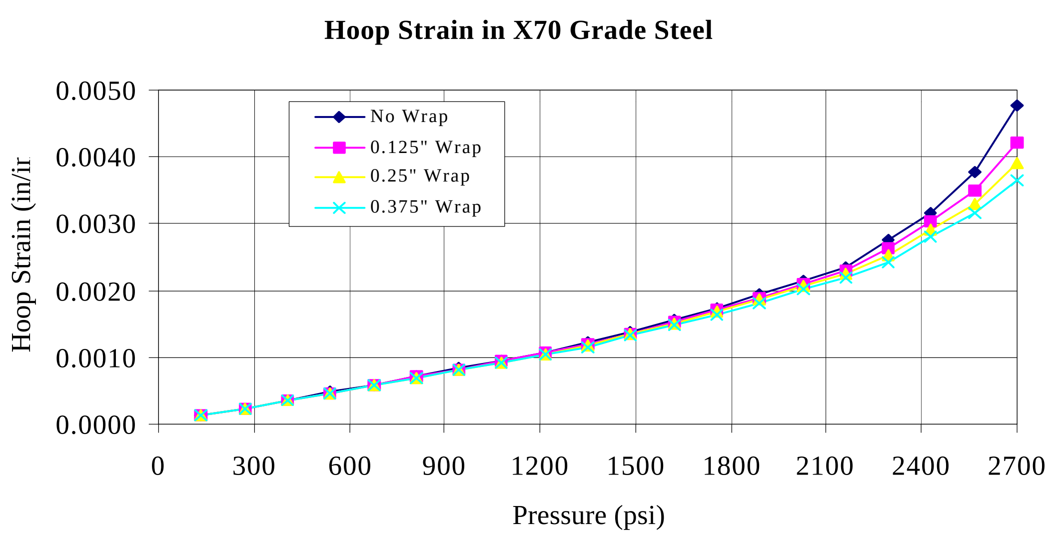

Figure 6 Strain in steel pipe as a function of composite thickness