

# DEVELOPMENT OF STANDARDS FOR COMPOSITE REPAIR SYSTEMS

Dr. Chris Alexander  
Stress Engineering Services, Inc.

## ABSTRACT

A significant amount of work has transpired over the past several years in generating consensus-based standards that include ASME PCC-2 and ISO 24817 for developing composite repair systems. The intent in developing these standards has been to provide industry with guidelines for designing composite repair systems to ensure that damaged pipelines are safely and properly reinforced. With the numerous composite repair systems currently available to pipeline operators, the importance of evaluating the capabilities of each system cannot be overstated. The fundamental design variables available to manufacturers are stiffness, strength, and thickness of the composite. A properly-designed repair system ensures that strains in the reinforced steel and reinforcing composite material do not reach unacceptable levels. This article provides a basic overview of the design philosophy embedded into the current design codes, as well as presenting results associated with several specific studies that were conducted to evaluate composite repair performance.

## INTRODUCTION

In order for composite systems to repair damaged pipelines, it is critically important that they be designed to ensure that adequate reinforcement is present. The ASME PCC-2 and ISO 24817 composite repair codes (hereafter referred to as *Codes*) provide the required details to design a system that has sufficient stiffness, strength, and thickness.

Provided below are the Scope and Applicability sections from Part 4 (*Nonmetallic and Bonded Repairs*) of the 2006 edition of ASME PCC-2.

**1.1 Scope** This Article provides the requirements for the repair of pipework and pipelines using a qualified Repair System. The Repair System is defined as the combination of the following elements for which qualification testing has been completed.

- (a) substrate (pipe)
- (b) surface preparation
- (c) composite material (repair laminate)
- (d) filler material
- (e) adhesive
- (f) application method

The composite materials allowed for the Repair System include, but are not limited to, glass, aramid, or carbon fiber reinforcement in a thermoset resin (e.g. polyester, polyurethane, phenolic, vinyl ester, or epoxy) matrix. Fibers shall be continuous.

**1.2 Applicability** This Article addresses the repair of pipework and pipelines originally designed in accordance with ASME B31.1/B31.3/B31.4/B31.8, and ISO 15649 and 13623.

The *Applicability* section goes on to state that the Code covers situations involving damage that include internal and external corrosion, external damage such as dents, gouges, and cracks, as well as manufacturing defects. The repair of leaks is also permitted, although for high pressure transmission pipelines, this repair option is unacceptable at the present time based on the author's opinion. Because the focus of this article is repairing high pressure gas and liquid transmission pipelines, there is no discussion on the repair of leaking pipes.

The function of the Codes is design and within ASME PCC-2 there are three basic approaches for determining the minimum required thickness for a particular composite material in repairing corrosion and are listed below.

- Section 3.4.3 Pipe Allowable Stress
- Section 3.4.4 Repair Laminate Allowable Strains
- Section 3.4.5 Repair Laminate Allowable Stresses Determined by Performance Testing

The contents of this article should not be used as a substitute for actually consulting and utilizing the composite repair design codes (i.e. ASME PCC-2 and ISO 24817). These design codes provide details that deal with specific issues when using composite materials in repairing and reinforcing damaged pipelines that should not be ignored.

### **DETERMINING COMPOSITE REPAIR THICKNESS**

The sections that follow provide specific details on the above referenced ASME PCC-2 sections and their unique design approaches. An example problem is also provided to demonstrate the level of conservatism associated with each calculation method and the benefits in designing a performance-based system as detailed in Section 3.4.5, even though additional efforts and costs are associated in qualifying a given composite system to this level. Due to limited space in this article, all calculations assume structural contribution of the remaining corroded steel, although the option for not including this contribution is an alternative provided by the Codes that results in a greater required minimum composite thickness.

The following ASME PCC-2 nomenclature (i.e. variable descriptions) is used in the calculations that follow.

D	External pipe diameter (inches)
$E_c$	Tensile modulus for the composite laminate in the circumferential direction (psi)
$E_s$	Tensile modulus for the pipe steel (psi)
f	Service factor (inverse of safety factor, provided in ASME PCC-2 Table 5)
P	Internal design pressure (psi)
$P_s$	Maximum Allowable Working Pressure (MAWP) for corroded pipe using B31G, etc.
s	Specified Minimum Yield Strength (SMYS) for pipe (psi)
$s_{lt}$	95% lower confidence limit of the long-term composite strength via testing (psi)
t	Nominal wall thickness of pipe (inches)
$t_{min}$	Minimum repair thickness of composite (inches)
$t_s$	Minimum remaining wall thickness of pipe (inches)
$\epsilon_c$	Allowable circumferential strain

### Laminate Thickness Based on Pipe Allowable Stress (ASME PCC-2 Section 3.4.3)

The first design option that is provided in ASME PCC-2 is the most conservative of the three options presented in this article. Equation 1 is used to calculate the minimum required thickness considering hoop stresses based on internal pressure. Note that by including the  $P_s$  term credit is taken for strengths associated with the remaining steel.

$$t_{\min} = \frac{D}{2s} \cdot \left( \frac{E_s}{E_c} \right) \cdot (P - P_s) \quad (\text{ASME PCC-2 Equation 1})$$

In reviewing Equation 1 it is clear that the relative stiffness values of the steel ( $E_s$ ) and the composite ( $E_c$ ) are integrated to calculate the minimum required thickness. The use of this equation assumes that the substrate (e.g. remaining reinforced pipe material) does not yield and remains elastic throughout operation.

### Laminate Thickness Based on Allowable Strains (ASME PCC-2 Section 3.4.4)

The next design option that is available in PCC-2 is calculating the minimum composite thickness based on hoop strain due to internal pressure using Equation 4. Also included in PCC-2 is Equation 3 that integrates the effects of internal pressure in the pipe at the time of the composite installation, although this equation is not presented in this article.

$$t_{\min} = \frac{1}{\epsilon_c E_c} \left( \frac{PD}{2} - st_s \right) \quad (\text{ASME PCC-2 Equation 4})$$

In solving Equation 4 the designation of an allowable long-term strain,  $\epsilon_c$ , is required. Table 4 from ASME PCC-2 specifies that for continuous (sustained) loading conditions the allowable long-term strain for the repair laminate is limited to 0.25%, while for rarely occurring loads it is 0.40%.

### Laminate Thickness Based on Allowable Stresses Determined by Performance Testing (ASME PCC-2 Section 3.4.5)

The minimum required thickness using the ASME PCC-2 Section 3.4.5 method is based on performance testing of the composite material itself. This approach requires additional testing on the composite material beyond what is required for the other calculation methods, such as the 1,000 hour survival test as presented in Section V-2.1 in Appendix V of ASME PCC-2 based on ASTM D 1598. In this particular test internal pressure is applied to a test sample having a minimum diameter of 4 inches and a minimum thickness of 0.120 inches. The sample's internal pressure and composite laminate thickness are selected to maximize the long-term composite stress,  $s_{lt}$ , using the equation below.

$$s_{lt} = \frac{P_{\text{test}} DE_c}{2(E_c t_{\min} + E_s t_s)} \quad (\text{ASME PCC-2 Equation V-1})$$

In this qualification test three identical test samples must be repaired and survive 1,000 hours of testing with no deterioration of the laminate in the form of cracking, delamination, or leaking.

Once the long-term composite design strength is established based on the 95% lower confidence limit, the minimum composite repair thickness is calculated using Equation 9 from ASME PCC-

2. In reviewing this equation, the use of a service factor,  $f$ , is required. The service factors are basically the reciprocals of safety factors and are listed in Table 5 of ASME PCC-2. If one opts to establish long-term laminate strength using the 1,000 hour data, the service factor is 0.5 (i.e. safety factor of 2.0 for the composite material's strength).

$$t_{\min} = \left( \frac{PD}{2} - t_s s \right) \cdot \left( \frac{1}{f s_{lt}} \right) \quad (\text{ASME PCC-2 Equation 9})$$

### Calculating Composite Repair Thickness Using ASME PCC-2

Table 1 provides calculations associated with the reinforcement of a 12.75-inch x 0.375-inch, Grade X42 pipeline having 50% corrosion where the MAOP is de-rated from 1,778 psi to a MAWP of 1,000 psi due to the corrosion. Presented are results for all three calculation methods discussed previously (i.e. pipe allowable stress, repair laminate allowable strains, and repair laminate allowable stresses determined by performance testing). It should be noted that the contribution of the remaining steel is considered in all provided calculations.

Table 1 – ASME PCC-2 Calculated Thickness Values

ASME PCC-2 Equation Number	ASME PCC-2 Equation	Calculated Values (see Note below for variable values)
(1)	$t_{\min} = \frac{D}{2s} \cdot \left( \frac{E_s}{E_c} \right) \cdot (P - P_s)$	0.787 inches
(4)	$t_{\min} = \frac{1}{\epsilon_c E_c} \left( \frac{PD}{2} - st_s \right)$	0.306 inches
(9)	$t_{\min} = \left( \frac{PD}{2} - t_s s \right) \cdot \left( \frac{1}{f s_{lt}} \right)$	0.138 inches

Notes (input variables used in above equations)

- $E_s$  30 x 10<sup>6</sup> psi (steel pipe modulus)
- $E_c$  4.5 x 10<sup>6</sup> psi (composite laminate modulus)
- $s$  42,000 psi (pipe Minimum Specified Yield Strength, or SMYS)
- $P$  1,778 psi (MAOP)
- $P_s$  1,000 psi (de-rated operating pressure due to presence of corrosion)
- $t$  0.375 inches (pipe nominal wall thickness)
- $\epsilon_c$  0.25% (allowable long-term composite strain from ASME PCC-2 Table 4)
- $f$  0.5 (Service Factor from ASME PCC-2 Table 5)
- $s_{lt}$  50,000 psi (long-term composite strength based on ASME PCC-2 Appendix V directives)
- $t_s$  0.188 inches (remaining pipe wall thickness due to corrosion)

An extremely important observation in reviewing the calculated results provided in Table 1 is the reduction in the minimum required laminate repair thickness associated with the three calculation options. It is clear from this presentation that with the inclusion of the long-term data as required for using Equation (9), a less conservative composite thickness results due to the greater effort undertaken in determining the actual long-term strength.

## CASE STUDIES

One of the consistent elements associated with the development and qualification of composite repair systems has been experimental evaluation. This evaluation has involved assessments at both the coupon and full-scale levels. Evaluating material performance at the coupon level is an effective means for determining the strength of the composite, while at the same time being less expensive than full-scale testing. The primary emphasis in the Codes up to this point in time has been in designing composite repair systems to reinforce corrosion; however, there is also an abundance of data demonstrating that composite materials can be used to reinforce wrinkle bends, elbows, field branch connections, dents, and others anomalies. Results from several prior studies have been presented in the previous articles associated with this series.

Two case studies are presented that deal specifically with the reinforcement of corrosion using composite materials. The first case study involves the repair of an 8-inch nominal diameter pipeline with 50% corrosion that was reinforced using a carbon-epoxy system. During testing strain gages monitored strain in the reinforced steel region and were used to demonstrate the level of reinforcement provided by the composite material. The second case study discusses results associated with a testing program used to evaluate the capacity for a carbon-epoxy system to reinforce 75% corrosion in a 12-inch nominal diameter pipeline subjected to cyclic pressures.

### Case Study #1 – Burst Testing a Composite-reinforced Corroded Pipe

In 2006 a program was conducted for the U.S. Minerals Management Service to evaluate the use of composite material in repairing offshore risers. Part of this study involved repairing a burst test sample having 50% corrosion using a 0.60-inch thick carbon-epoxy system that included two pre-cured half-shells. Strain gages were installed in the corroded region of the 8.625-inch x 0.406-inch, Grade X46 pipe sample and monitored during pressurization to failure. Results from this test are provided in Figure 1. Included in this plot are a few annotations that designate the lower bound collapse load (5,975 psi) from which the design pressure (2,988 psi) is calculated. This design pressure exceeds the maximum allowable operating pressure of 2,887 psi of a non-corroded pipe. The results of this program demonstrated that the carbon repair was effective in reinforcing the corroded pipe and ensured that strains in the reinforced steel did not reach an unacceptable level. This study is classified as one based on strain-based design limits.

### Case Study #2 – Pressure Cycle Testing a Composite-reinforced Corroded Pipe

Most of the experimental research associated with the composite repair of corroded pipelines has focused on burst tests. The general philosophy has been that in the absence of cyclic pressures during actual operation, there are few reasons to be concerned with qualifying composite repairs for cyclic conditions. One could argue that only liquid transmission pipelines need to be concerned about cyclic pressures. However, recent studies have indicated that for severe corrosion levels (on the order of 75%) there is a need to take a closer look at the ability of the composite to provide reinforcement. The case study presented herein was actually preceded by a series of tests using E-glass materials that evaluated the number of pressure cycles to failure in reinforcing 75% corrosion in a 12.75-inch x 0.375-inch, Grade X42 pipeline. Figure 2 is a schematic show the geometry of the test sample used in this study, while Figure 3 shows the positioning of strain gages beneath each repair in the corroded region. The test samples were pressure cycled at a pressure range of 36% SMYS (i.e. 894 psi for this pipe).

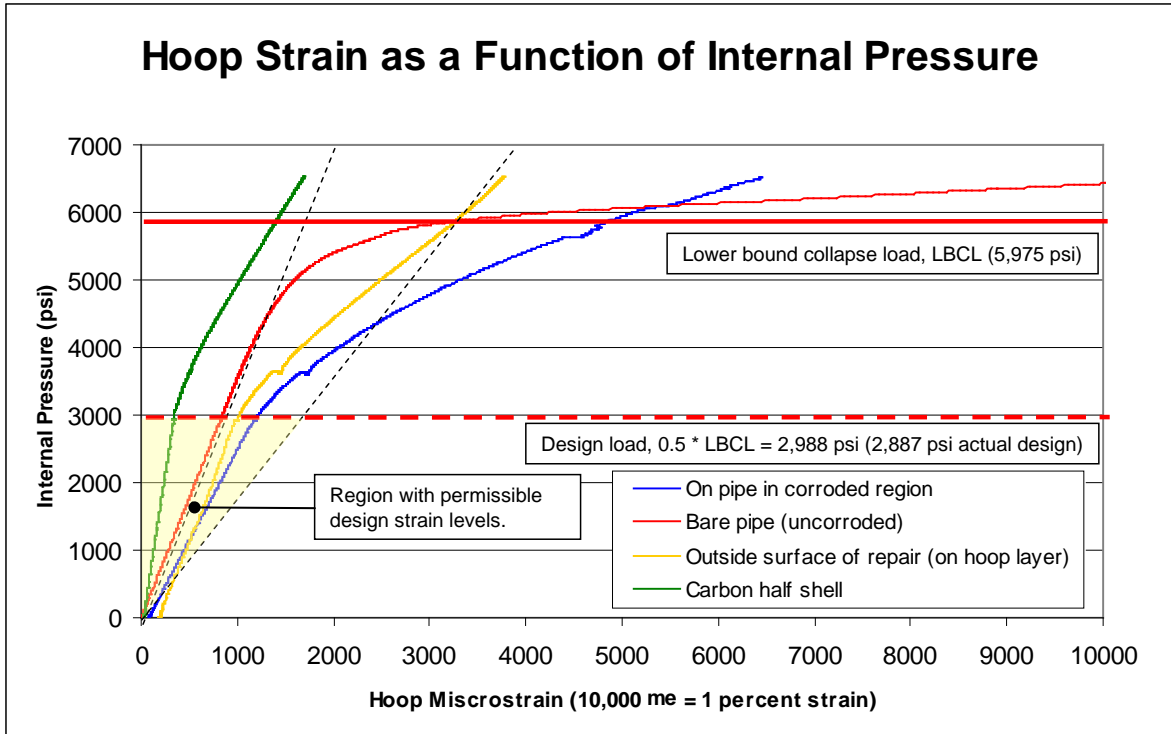
Tests were performed on five different composite systems that included the following cycles to failure.

- E-glass system: 19,411 cycles to failure
- E-glass system: 32,848 cycles to failure
- E-glass system: 140,164 cycles to failure
- E-glass system: 165,127 cycles to failure
- Carbon system (Pipe #1): 212,888 cycles to failure
- Carbon system (Pipe #2): 256,344 cycles to failure
- Carbon system (Pipe #3): 202,903 cycles to failure
- Carbon system (Pipe #4): 532,776 cycles to failure

Minimal information is provided with the above data (e.g. no information provided on thickness, composite modulus, filler materials, fiber orientation, etc.). However, one can definitely conclude that all composite repair systems are not equal. The study on the carbon composite system having four different pipe samples was specifically conducted by a manufacturer to determine the optimum design conditions for reinforcing the severely corroded pipe. Figure 4 shows the strains recorded in the four carbon-reinforced test samples. What is noted in this plot is that the lowest recorded mean strains occur in Pipe #4, which also corresponds to the test sample that had the largest number of cycles to failure.

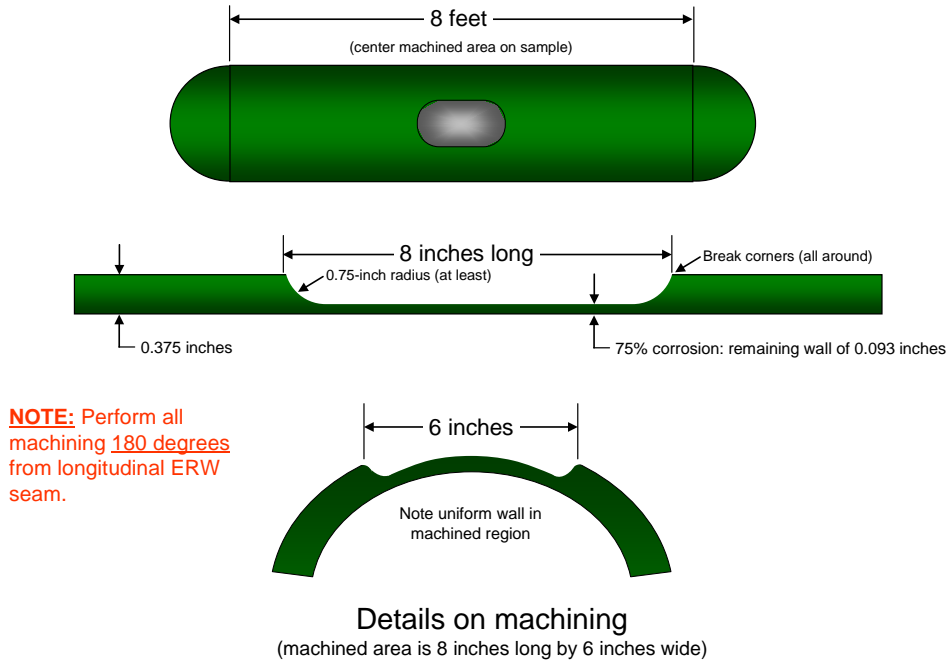
### **CLOSING COMMENTS**

Composite materials continue to play an important role in repairing damaged pipelines. When properly designed and installed, they are able to restore the integrity of damaged pipelines back to their original integrity. The relatively recent development and application of composite repair standards such as ASME PCC-2 and ISO 24817 are contributing significantly to the proper design of the composite repair technologies. These standards will continue to develop as the pipeline industry requires that composite materials provide repair solutions for pipeline anomalies as part of their integrity management programs.



**Figure 1 – Strains measured in composite reinforced corroded pipe sample (8.625-in x 0.406-in, Grade X46 pipe with 50% corrosion)**

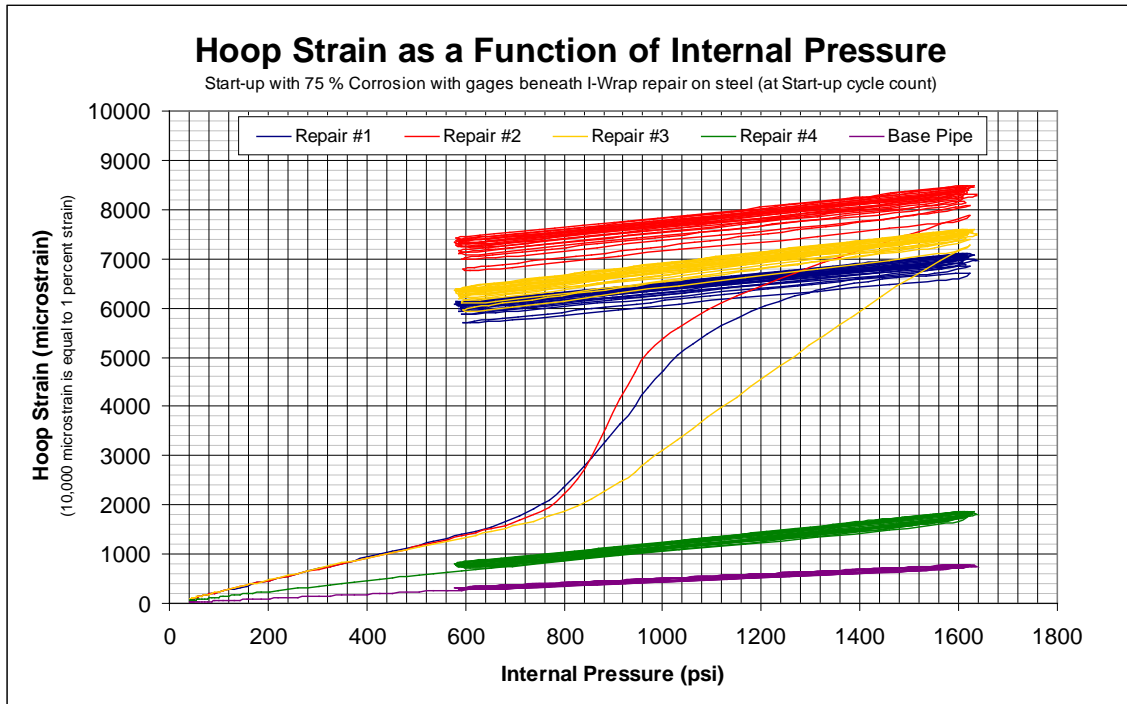
### 12.75-inch x 0.375-inch, Grade X42 pipe (8-feet long)



**Figure 2 – Schematic diagram of composite repair pipe test sample**



**Figure 3 – Schematic showing location of strain gages of photo of machined region**



**Figure 4 – Measured strain range in 75% corroded test sample (test sample cycled at DP = 36% SMYS, data plotted at start-up)**