Final Report

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Selection of Pipe Repair Methods

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Selection of Pipe Repair Methods

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Executive Summary

A) Objective

The objective of this research is to provide pipeline operators with testing procedures and results of the performance of composite pipe repair methods and ultimately, improve their selection and installation, and reduce the risks associated with faulty or ineffective repairs. This will be achieved by:

- Establish and modify testing protocols to evaluate long-term properties of the repair systems.
- Work with the suppliers, service providers, and ASME PCC-2 Subcommittee on Post-Construction Repair and Testing in developing and modifying standards to test and evaluate the performance of the composite repair systems available in the market.
- Provide the pipeline operators with guidelines for evaluating and selecting the appropriate repair method based on pipe characteristics, damage criteria, and performance of the repair.

B) Summary and Conclusions

Composite systems were investigated in this report for the permanent repair of liquid and gas transmission and distribution pipelines with corrosion and mechanical damage (i.e., dents and gouges). The application of the repair to these pipes involves the following steps:

- An assessment of the defect should be completed to identify the need for the repair, remaining strength of the defected pipe, and selection of the appropriate repair options. Such assessment should be performed in accordance with relevant industry standards.
- Determination of the short and long-term properties of the repair, its interaction with the carrier pipe under the expected internal and external loads, and its long-term durability in the pipe environment.
- An evaluation of the surface preparation procedures. Pipe grinding should be used on the damaged area to produce smooth surface and remove the harmful stress concentration of defects and micro cracks. If cracks in the defected are not entirely removed, an alternative repair technique should be applied.
- Qualification of the installers and the installation procedure (e.g.; number of layers, application of the adhesive, and curing of the composite systems).
- A risk assessment to assess all other potential hazards such as surface preparation of a pressurized pipeline, fire and electrical hazards, and cathodic protection of the system.

A parametric study using the Design-of-Experiment (DoE) methodology was performed to model the pipe-composite repair at various material properties and loading conditions. The results of the study provided an understanding of the influencing properties which is further investigated in the experimental program. The most significant parameters which affect the performance of the repair are the pipe size, applied pressure, and repair tensile modulus. On the other hand, the size of the damage and the Poisson's ratio of the wrap did not have a significant effect on the performance of the pipe-composite system.

There are two potential failure modes for composite repair systems. The first failure mode is a consequence of overloading the composite laminate or wrap. The second model is the loss of bonding strength and delamination of the composite laminates. The report investigated the testing requirements to determine the properties relevant to both failure modes. These tests included the following:

- Short-term tests: Including tensile strength, tensile modulus of the composite, shear strength at the pipe-composite interface, and the interlaminate shear between the composite laminates.
- 1,000-hour tests: Including the tensile strength of the composite, interlaminate shear strength, and hydrostatic pressure tests on pipe samples with composite repairs. The results of these tests are used with the appropriate safety factors in the design of the composite system.
- 10,000-hour tests: The results of these tests at elevated temperatures were extrapolated to predict the service life strength of the composites. The rate process procedure was presented and used to predict the 20-year bonding strengths of the composites. The results provided a comparative analysis and demonstrated the significant effect of temperature on the bond strength of the composites.

A testing procedure and analysis were developed to evaluate the composite repairs under internal hydrostatic loading, cyclic loading, and external bending loads. The ASME PCC-2 standard for repair of pressure equipment and piping was used for the estimation of the stresses from the bending test results.

Guidelines for evaluating the effects of cyclic pressure on the performance of composite repairs were presented. In particular, a testing procedure was established to provide a consistent protocol so that meaningful test results are generated to permit the assessment of composite technologies. Additionally, guidance is provided on interpreting the test results to quantify the long-term performance and to establish a useful service life condition for the repair system.

The ability to resist cathodic disbondment is a desirable quality for the repair. Cathodic disbondment tests on composite repairs were performed using the ASTM G95 testing procedure as it is more applicable to composite repairs. When comparing the disbondment of the composite repairs to those of the pipeline coatings, larger disbonded sizes were measured in the composites. The disbondment was highly dependent on the quality of the pipe surface preparation during composite installation.

The composite repair system should be protected from surface conditions and damaging chemicals that may exist in the environment. Tests were performed to evaluate the environmental compatibility of the repair systems with respect to the following:

- Chemical resistance to gasoline, fertilizer, sodium Hydroxide, and hydrochloric acid,
- Ultraviolet light deterioration,
- Temperature stability,
- Oxidation Resistance,
- Abrasion resistance, and
- Stress cracking.

In general, composite repair systems consisting of glass and carbon fibers with thermoset polymers demonstrated high resistance to temperature and oxidation. These systems were also compatible with a wide range of environments. However, exposure to high acidic environment significantly reduced the strength of this material.

Most of the composite repair manufacturers develop their own design procedures to determine the required number of layers based on pipe and damage characteristics. The manufacturers' designs were compared with the design requirements of the ASME PCC-2 standard. The evaluation showed that the numbers of wraps of the repair systems are generally more conservative in the ASME PCC-2 standard than the ones provided by the manufacturers.

The ASME PCC-2 design procedure was implemented in the web-based program: Composite Pipe Repair (CPR). The program provides the properties and design parameters of the composite repair methods, the number of layers, and the length of repair for a given damage on the pipe surface; providing that appropriate DOT regulatory requirements and applicable industry standards are observed.

A parametrical study was carried out using the computer program to evaluate the effect of the various design parameters on the strength of the composite, and consequently, the number of layers required for the repair. The results demonstrated the increase of the number of composite wraps with the increase of pipe pressure and wall thickness. The number of composite layers also increased with the increase of pipe yield strength (SMYS). The web program was accordingly limited to yield strength up to 70,000 psi since the use of higher yield strength pipes required larger number of wraps for most of the repair systems, which was impractical for field installation.

1. Introduction

The ability to utilize effective repair methods is critically important for gas and liquid transmission lines which are subject to the requirements of the Department of Transportation (DOT). Currently, CFR 49 Part 192 for transmission of natural gas requires damaged pipelines to be cut out and replaced, or repaired by methods in which reliable engineering tests and analyses show that they can permanently restore the serviceability of the pipe.

Several repair methods are currently being used to permanently restore serviceability of transmission pipes. These methods include full-encirclement steel reinforcing sleeves and composite wrap material. A wide variety of composite materials are used in pipeline repair systems. They mainly consist of glass and carbon fiber reinforcement in a thermoset polymer (e.g., polyester, polyurethane, and epoxy) matrix.

Chapter 2 of the report provides a review of current pipeline repair methods and identifies the tests and procedures used to determine their properties. A Design of Experiment (DoE) analysis was performed to identify the parameters that affect the performance of the repair.

The application of the repair materials is mostly based on manufacturers' data and industry experience. Many of the composite repair systems providers perform their own material evaluation tests to determine the design parameters as per the requirements of ASME PCC-2 Standard: Repair of Pressure Equipment and Piping.

A testing program was performed in this project to establish the procedures for qualifying the repair methods available in the market. The project utilized previous work performed in the co-funding research projects on composite repairs. New procedures were established when needed to model the long-term performance of these repairs and their interaction with the steel pipe. Chapter 4 presents the tests used in evaluating the mechanical properties of the composites. A procedure is provided for predicting the service life of the bonding strength of the repair from long-term tests.

The long-term performance of composite repairs depends on a combination of engineering tests and qualifications of the following elements of the repair:

- Structural component and interaction of the repair system with the carrier pipe,
- Surface preparation and application of repair method (e.g.; welding of the metal sleeves, and curing of the composite systems).

The effect of the repair characteristics on the long-term performance of the repaired pipe is investigated in Chapters 6 and 6 of the report. Testing procedures and analysis were developed to evaluate the composite repairs under internal hydrostatic loading, cyclic loading, and external bending loads. A procedure is provided for the analysis of the test results to predict the service life of the repair fro cyclic loading tests.

The long-term effects of the cathodic disbondment and environmental durability of the composite repairs are presented in Chapters 7 and 8, respectively. Chapter 9 provides guidelines for the selection of the repair systems and a review of the ASME PCC-2 design procedures for composite repair systems. A web-based computer program was developed to provide the repair thickness and properties of various composite systems which are used in the repair of pipelines

The results of the project should provide operators with the tools to properly select the repair systems based on sound engineering tests. Working with the manufacturers in this testing project would help accelerating the implementation of the results regarding the products' long-term reliability. This work is expected to benefit industries with liquid and gas transmission lines as well as utility distribution lines.

2. Review of Pipe Repair Systems

A) Pipe Repair Methods

Several methods are currently being used for the external repair of corrosion and mechanical damage to permanently restore the serviceability of transmission pipes. These methods include the following techniques [1, 2]:

1. Grinding out and recoating,
2. Steel reinforcement sleeve repair (Type A Sleeve),
3. Steel pressure-containing sleeve repair (Type B Sleeve),
4. Composite wrap repair,
5. Hot tap section, and
6. Pipe replacement.

The selection and evaluation of these methods is a challenging task due to the wide range of metallic and composite repair products in the market, the variety of their characteristics, and the various parameters that affect the repair's long-term serviceability.

A repair can be considered temporary or permanent. Temporary repairs are used when the operator plans to complete a more comprehensive repair or replacement in a later time and its duration is commonly specified by the pipeline operator. A permanent repair is typically intended to restore the pipeline to service for a period greater than five years without a requirement for re-evaluation [1].

Guidance for repair selection may be found in the Pipeline Repair Manual [3] and the applicable industry standards such as ASME B31.8 [4] and ASME B31.8S [5]. During the repair operation, the Code of Federal Regulations CFR 49 Part 192.713 requires that the pipeline operating pressure is lowered to a safe level.

The option of pipe replacement is generally a conservative and safe one since the damaged pipe section is removed and replaced. However, pipe replacement is expensive and causes service interruption. Furthermore, appropriate procedures for welding and inspection of in-service pipelines should be used. Some important factors to be considered for welding on live lines are the use of low hydrogen welding process, the welding sequence, and the effect of heat input and wall thickness on the gas flow [6].

The process of hot-tapping consists of bypassing the damaged pipe section. A new pipe section is tapped and welded at locations before and after the damaged section, thus allowing the pipeline to stay in service. The process, however, involves performing welding of the new pipe section while the line is in-service and it requires testing and welding inspections similar to pipe replacement. The other pipe repair options are further discussed in the following sections.

A.1) Pipe Grinding and Recoating

Pipe grinding is used to produce smooth surface and remove the harmful stress concentration of defects and micro cracks. Repair of mechanical damage by grinding has historically been allowed by several standards [7].

The ASME B31.8 [4] permits repair by grinding to a depth of 10 percent of the pipe wall thickness during the installation of new pipes and provides certain criteria for grinding of dents with gouges for in-service pipelines. The ASME B31G [8] provides limits on the allowable extent of damage and the remaining strength of corroded pipelines. Certain restrictive conditions are also commonly applied for grinding, including [2]:

- The operating pressure should be reduced to 80 percent during the repair process.
- If the crack or the affected material near the defect is not entirely removed by grinding, an alternative repair technique must be applied.
- The removal of all cracks must be verified by non-destructive NDT testing after grinding.
- Removal by grinding of more than 40 percent of the wall thickness is not accepted.

A.2) Metallic Sleeve Repair

Mechanical sleeves mainly consist of the following two types:

- Steel Reinforcing Sleeves (Type A): This type consists of two halves of a steel cylinder which are placed around the pipe and welded to fully encircle the damaged section and restores the strength of the pipe. Type A sleeve is not welded directly onto the pipe and is not intended to contain pressure or a leak.
- The main advantage of type A is that it can be made of pre-fabricated units and do not require rigorous nondestructive inspection. It can be used for temporary and permanent repairs but it is not used to repair circumferentially oriented defects and leaking defects.
- Pressure Containing Sleeves (Type B): Type B sleeve is similar to type A sleeves, except that the ends of the sleeve are welded onto the pipe with full encirclement fillet welds as shown in Figure 1. Appropriate procedures for welding and inspection of the sleeve are required when the sleeve is installed while the pipe is in-service.

The thickness of the sleeve is designed to contain the Maximum Allowable Operating Pressure (MAOP) and the axial stresses imposed by secondary loads. Thus, type B sleeve can be used to repair leaks and to reinforce the circumferentially oriented defects.

Several research studies evaluated the characteristics of types A and B welded repairs [9-13] in addition to the deposition of weld metal directly into a defect [14]. In these projects, pipe samples were prepared with varying dents and gouges, and were pressurized to simulate conditions which a defect would develop in the field.

Figure 1 - Steel Repair Sleeve (T.D. Williamson)

Several reports and publications on the evaluation of metallic sleeve repairs [15-17] further evaluated the repairs through weld analysis and field trials. The results of these studies enhanced understanding the characteristics of the steel repairs, as well as the defects and their corresponding effect on the repair.

Following the widespread testing and implementation of welded steel sleeves, a system was introduced in the late 1990s which incorporated the use of an epoxy underneath the traditional steel sleeve repair. The epoxy acts as a lubricant when first applied, allowing the sleeve to slide over the pipe when installed, and tightened around the pipe. Following the application, the epoxy then hardens, creating a solid material which can better distribute the load from the inner pipe to the repair when pressurized. Throughout the late 1990s, several experiments [18, 19] investigated epoxy-filled steel reinforcements through burst and cyclical loading tests and field trials.

In addition to metal sleeves, several types of mechanical clamps are available in the market. Figure 2 shows a typical bolt-on clamp. These clamps are designed to contain full pipeline pressure, so they are generally thick-walled and heavy because of the large bolts used to provide the required clamping force [7]. The clamps normally have elastomeric seals to contain the pressure if the pipeline is leaking at the defect. They can be either installed like a Type A sleeve or can be fillet welded to the pipe like a Type B sleeve to contain a leak in case the seals fail [1]. Similar to other repair methods that involve welding on a live pipeline, appropriate procedures for welding and inspection of the sleeve are required.

Mechanical clamps were often favored over many methods due mainly to the availability of seemingly dependable leak clamps. Although the clamps were simple to install and sealed leaks initially, problems arose through time with corrosion of bolts, improper application methods, and poor seal retention.

Figure 2 - Repair Clamp (T.D. Williamson)

In an effort to understand and improve the classical leak clamp design, the clamps underwent a series of evaluations and modifications to ensure that their use is accompanied by safe and proper working conditions. Several reports have provided technical insight into the use of leak clamps. One report [17] simulated various dents and leaks in non-linear finite element analysis to identify the limits of pipe damage to which leak repair clamps may be used.

In addition, another report [9] focused on safety while installing a leak clamp. The report outlined a procedure that includes: notification and confirmation of the leak, job site analysis and preparation for repairs, excavation, pipe and clamp preparation, clamp installation, line restoration to normal operation, and welding of the repair.

A.3) Composite Sleeve Repair:

Although steel sleeve repairs were widely used during the 1980s, research continued to advance with interest in new materials to aid in the repair. From the mid 1980s into the late 1990s, the Gas Research Institute (GRI) participated in a development program of a composite repair system: Clock Spring. Throughout a series of reports [20-26], GRI conducted several testing programs for establishing the composite physical properties, long-term creep of the adhesives, and field performance in multiple-year monitoring program.

In addition to the work performed by GRI, development and testing of new composite repair materials have been conducted by composite manufacturers and other research agencies [27-29]. These reports addressed several performance tasks, including cyclical fatigue tests, lap shear testing, and long-term performance. A PHMSA report [30] proposed recommended procedures for the certification of the composite repair materials. This work addressed cathodic disbondment testing, as well as an overview of the composite to metal interface characteristics.

In order to document commonly accepted techniques, a manual was created by the Pipeline Research Council International (PRCI) [3]. The repair manual provides general understanding of the repair methods; thus assisting operators in selecting proper methods, developing repair procedures, and training staff on the use of repairs.

As composite repair system became increasingly popular, new standards were developed to identify the procedures for evaluating these material. Many of these standards are used in evaluating the entire composite systems as they were carried over from other materials' standards such as those initially developed for plastics and adhesives.

Currently, a wide variety of composite materials are used in pipeline repair systems. They are mainly proprietary manufactured products consisting of glass or carbon fiber reinforcement in a thermoset polymer matrix (e.g., polyester, polyurethane, and epoxy) (Figure 3). The installation process results in a final composite which is shaped around the damaged part with the number of wraps designed according to the severity of the defect.

Composite wraps work by sharing the hoop stress in the pipe wall so that the MAOP pressure can be safely maintained. The repair, accordingly, offers the advantage of restoring the full strength of damaged pipeline, increasing its stiffness, and inhibiting the external corrosion since the composite acts like an external coating.

The ASME B31.8 [4] currently limits the use of composites to corrosion repair of non-leaking pipes unless the repair is proven through reliable testing and analysis. The ASME PCC-2 [31] and the ISO 24817 [32] standards provide the testing procedures and design requirements for using composite systems in the repair of leaking and non-leaking pipe sections.

Figure 3 - (a) Carbon fiber, (b) Glass fiber composite repairs

B) Operators Experience with Pipeline Repair Options

A survey of natural gas pipeline utilities was performed in the cost-sharing project: Composite Pipe Repair Technologies Evaluation [33]. The survey identified the repair needs of the pipe operators and their experience with the various repairs in the market. The survey was sent to 21 gas utilities and the responses from 11 of these companies are compiled in Figure 4 to Figure 8.

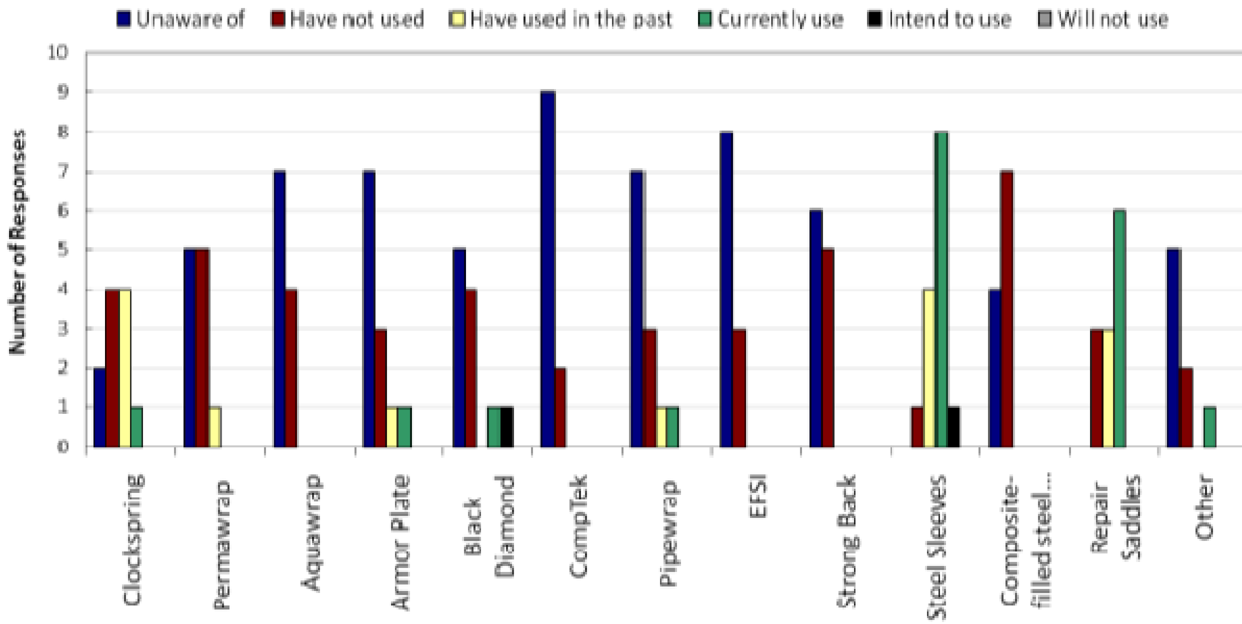

Figure 4 - Operators' familiarity with the repair systems

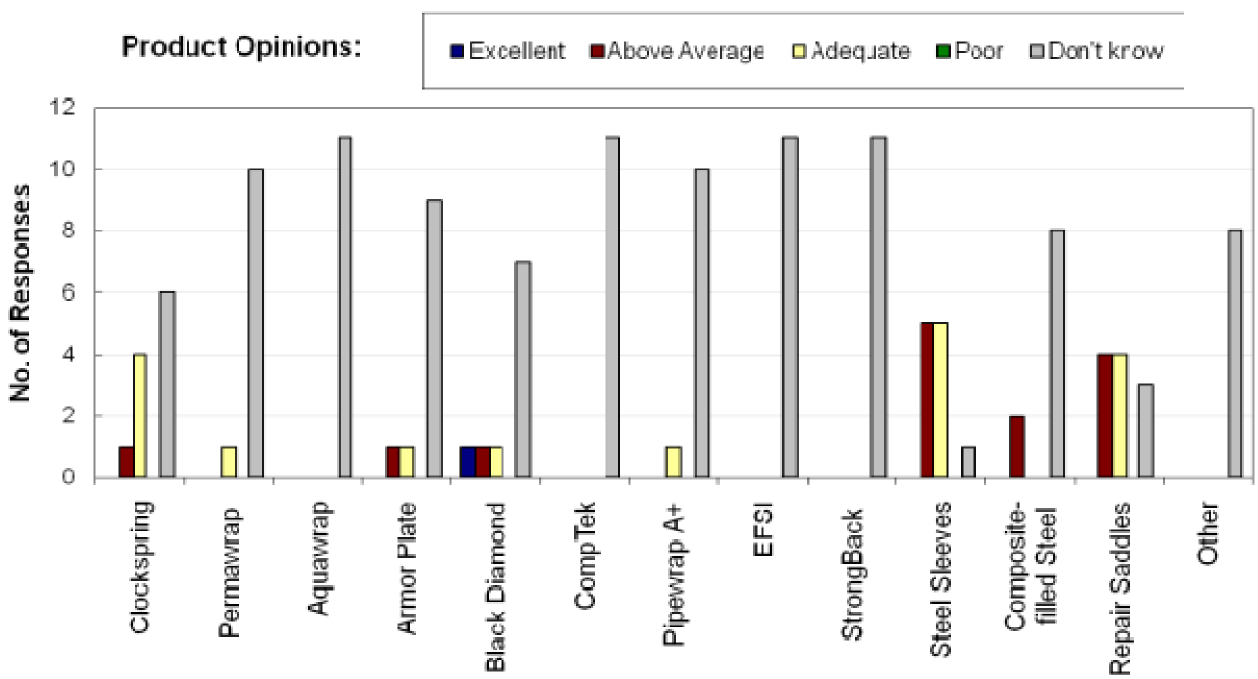

Figure 5 - operators' experience with the repair systems

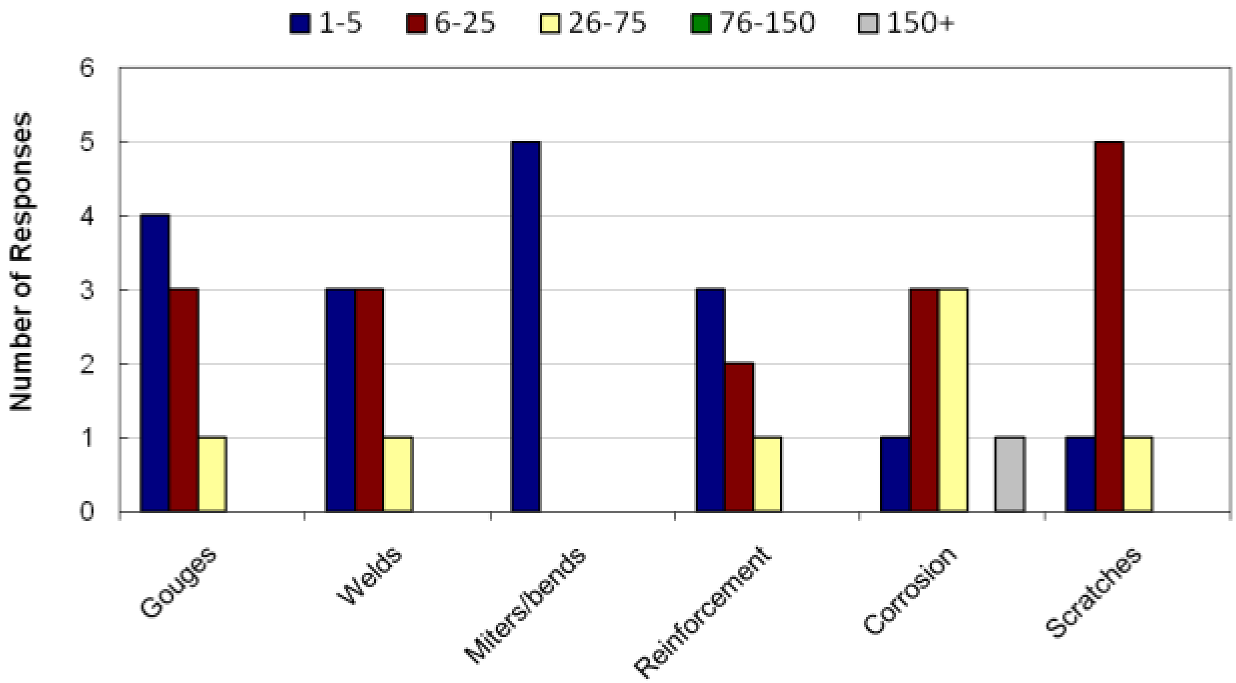

Figure 6 - Annual number of repairs per given pipe condition

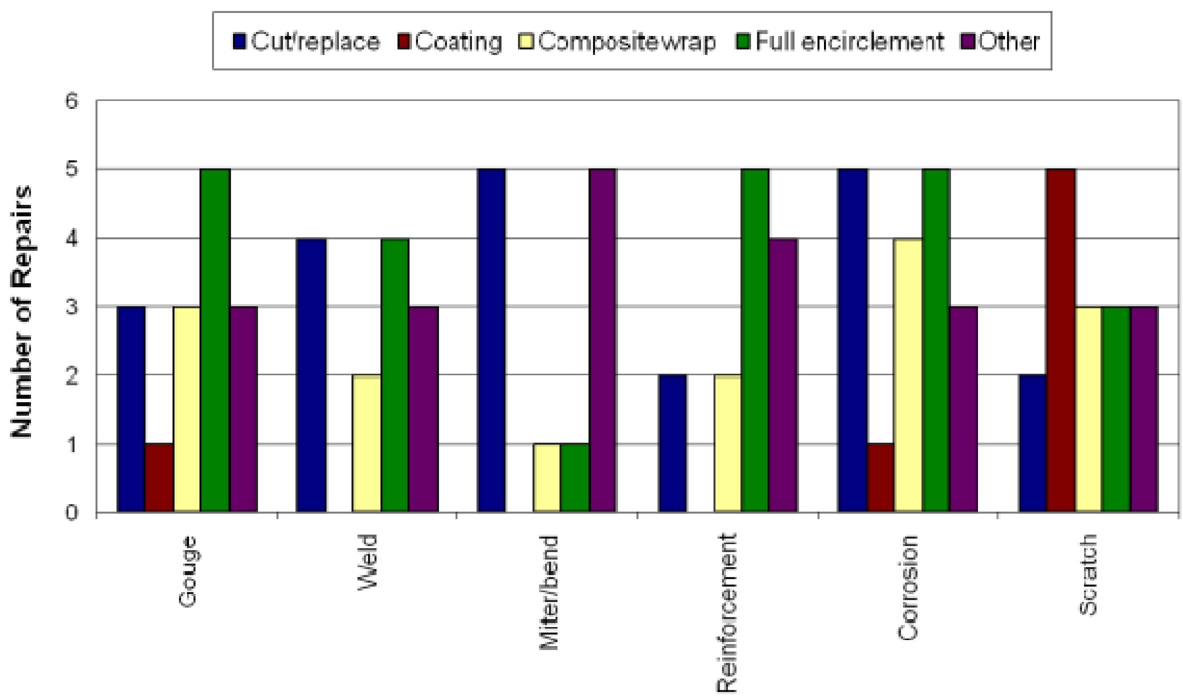

Figure 7 - Repair methods per given pipe condition

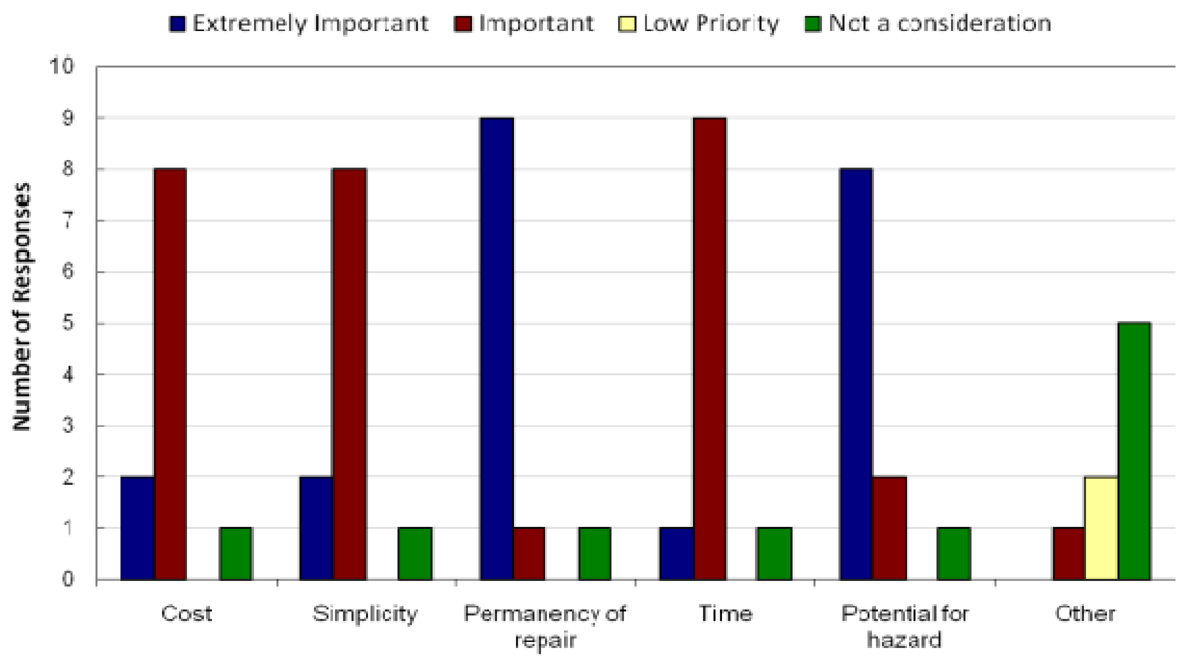

Figure 8 - Factors affecting the selection of composite repair method

The responses to the survey questions show the following:

- Corrosion repair is the most common repair need for the pipelines.
- Most of the natural gas pipeline utilities are familiar, and currently use metal sleeve repair systems. Full encirclement with steel sleeves is the most common repair technique.
- Many of the operators are familiar with, but do not utilize composite repair systems. The use of composites repairs was limited to a small number of repair systems.
- The main factor which affects the selection of the repair methods is its permanency, followed by the time of repair.
- The experience of composite repair systems was satisfactory with "above-average' to 'excellent' feedback.

3. Factors Controlling Performance of Composite Repair Systems

A) Simulation of Pipe and Repair Responses

A Finite Element analysis of composite repairs of damaged pipe sections was carried out to investigate the effect of pipe and repair characteristics on the strength of the repaired pipe. The results were incorporated in a parametric study using the 'Design-of-Experiment (DoE)' methodology to model the pipe-composite repair behavior at various geometries, material properties, and loading conditions. The results of the study provided an understanding of the influencing properties which is further investigated in the experimental program.

The pipe-repair system was modeled as a half-circle section due to the pipe symmetry, with the finite element mesh shown in Figure 9. A dent similar to an actual field condition as in Figure 10 and a gouge (a metal loss of the pipe wall thickness) were modeled in the pipe section.

The FEA model constraints are based on the following:

- A static, plain-strain condition with symmetry along the center of the pipe and wrap,
- The pipe material is non-linear. The filler and composite repair materials are linear, isotropic, and homogeneous. While the composite wrap is not actually isotropic, it is modeled as a repair of a long pipe section; thus incorporating only the circumferential loading condition.
- The displacement is constrained in the X-direction along the line of symmetry,
- The effect of gravity (weight of the pipe material) is ignored,
- The pipe, filler, and composite repair are fully bonded to each other with no gaps.
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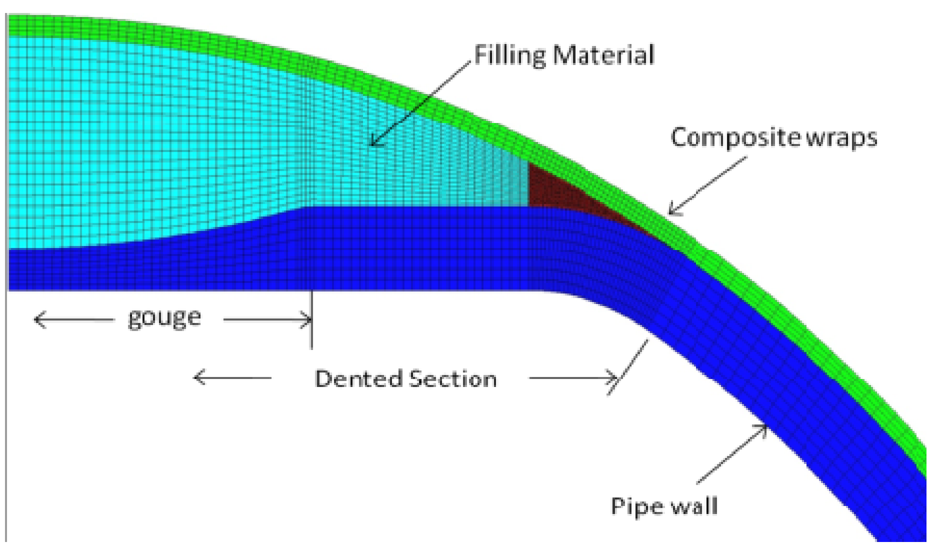


Figure 9 - Finite Element model geometry parameters

Figure 10 - A typical dent of a large diameter pipe

An example of a typical F.E. data input of a pipe-composite repair system is shown in Table 1 and the results of the analysis is shown in Figure 11. The results in the figure show the von-Misses stress plot of the repaired section.

Table 1 - Example F.E. Analysis Parameters

Parameter	Units	Value
Pipe Diameter (OD)	inch	8.625
Wall Thickness(t)	inch	0.25
Notch Depth, % t	%	50
Dent Depth, % OD	%	5.797
Outer Bend Radius	inch	1.0
Gouge Width	inch	2.0
Wrap Layer Thickness	inch	0.0155
Wrap Layers	-	4
Internal Pressure	psig	1,000
Wrap Tensile Modulus	Ksi	2,780
Wrap Poisson Ratio	-	0.2
Pipe Modulus	Ksi	30,000
Pipe Poisson Ratio	-	0.28
Filler Modulus	Ksi	3,000
Filler Poisson Ratio	-	0.3

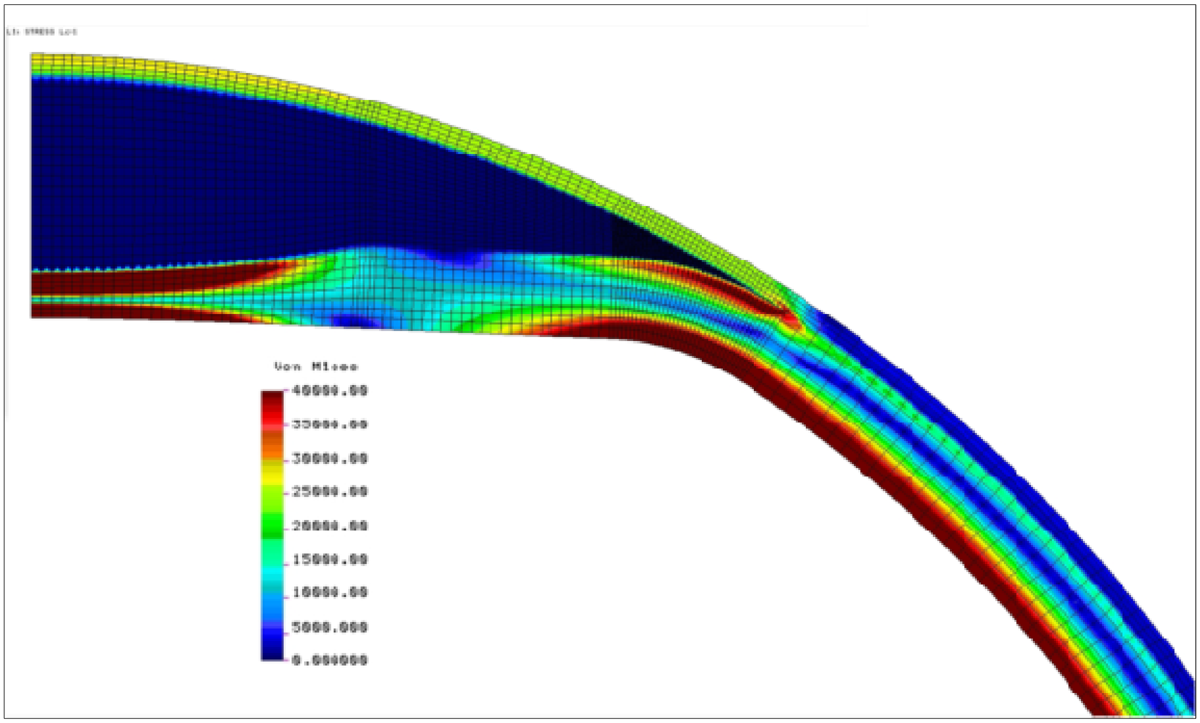


Figure 11 - von-Misses stress plot at damaged area

In order to get a predictive model that is useful for simulating the numerous conditions in the field, all variables that affect a result of interest needed to be considered. The effect of the influencing parameters forms a response surface where the results can be viewed as a function of more than one variable. Accounting for the influence of each variable required a Design-of-Experiment (DoE) approach that determines the combination of parameters which should be tested, based on a mathematical interpolation model.

The end result of the DoE is a response surface representing a closed-form formula which relates all variable parameters to all responses of interest. Having a closed-form mathematical model enables quick prediction of responses under a given condition, which is not possible with just a limited amount of empirical testing. The experimental tests are then used in the validation of the model with a relatively small number of test samples.

A number of stress analyses were conducted using the F.E. analysis, with each analysis having a different combination of geometry, pressure, and wrap material properties. A list of these parameters is shown in Table 2, including their value ranges. It is important to note that while unrealistic parameter combinations do occur, they are only used to mathematically develop the response surface. The predictions made for cases that are unrealistic are then dismissed as invalid.

Table 2 - F.E. Analysis DoE Variable Parameters

Parameter	Units	Minimum	Maximum
Outside Diameter (OD)	inch	8.625	16
Wall Thickness (t)	inch	0.25	0.5
Notch Depth, % t	%	40	60
Dent Depth, % OD	%	6.25	12.5
Outer Bend Radius	inch	0.5	2
Gouge Width	inch	4	6
Wrap Layers	-	4	8
Wrap Layers Thickness	mils	15	85
Composite Repair Tensile Modulus	Ksi	2,000	8,500
Composite Poisson's Ratio		0.1	0.3
SMYS of Pipe Material	psi	35,000	60,000
Operating pressure, % SMYS	%	40	100

The parameter combinations were used in the DoE software Design-Expert and a total number of 4306 combinations were analyzed. Additionally, in order to try and account for the natural variation in the input parameters, each input was randomized according to established tolerances. The goal of input randomization is more realistic and statistically sound predictions of results.

The response surfaces are shown in Figure 12 by means of perturbation graphs for the maximum von-Mises stress in pipe and Figure 13 for the maximum von-Mises stress in wrap. The perturbation graphs show how the value of the particular input parameter (normalized on the graph) affects the response being studied. From these graphs the significance and proportionality of each variable is readily apparent.

As can be seen in both figures, the grinding width (E) and Poisson ratio of the wrap (K) have no significant effect on the stress in the pipe or wrap; dent and notch dimensions (C, D) have small effect; while pressure (F), pipe diameter (A), and wrap thickness (G, J) are the most significant. A decrease in wrap thickness (G, J) and pipe wall thickness (B) results in an increase in the maximum stresses of the pipe. As a point of interest, Figure 12 shows the wrap modulus (H) has a particularly nonlinear effect on pipe stress – as the wrap modulus increases, its effect on the pipe's stress decreases.

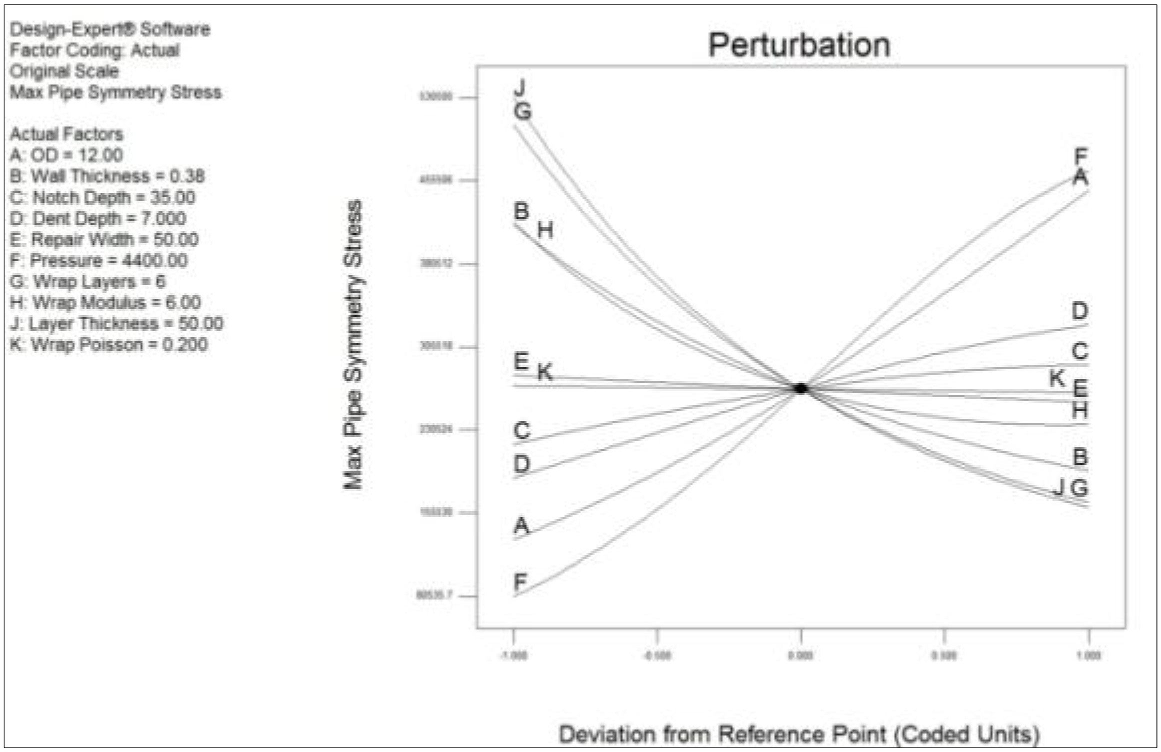


Figure 12 - Perturbation graph for maximum von-Mises stress in pipe (at notch location)

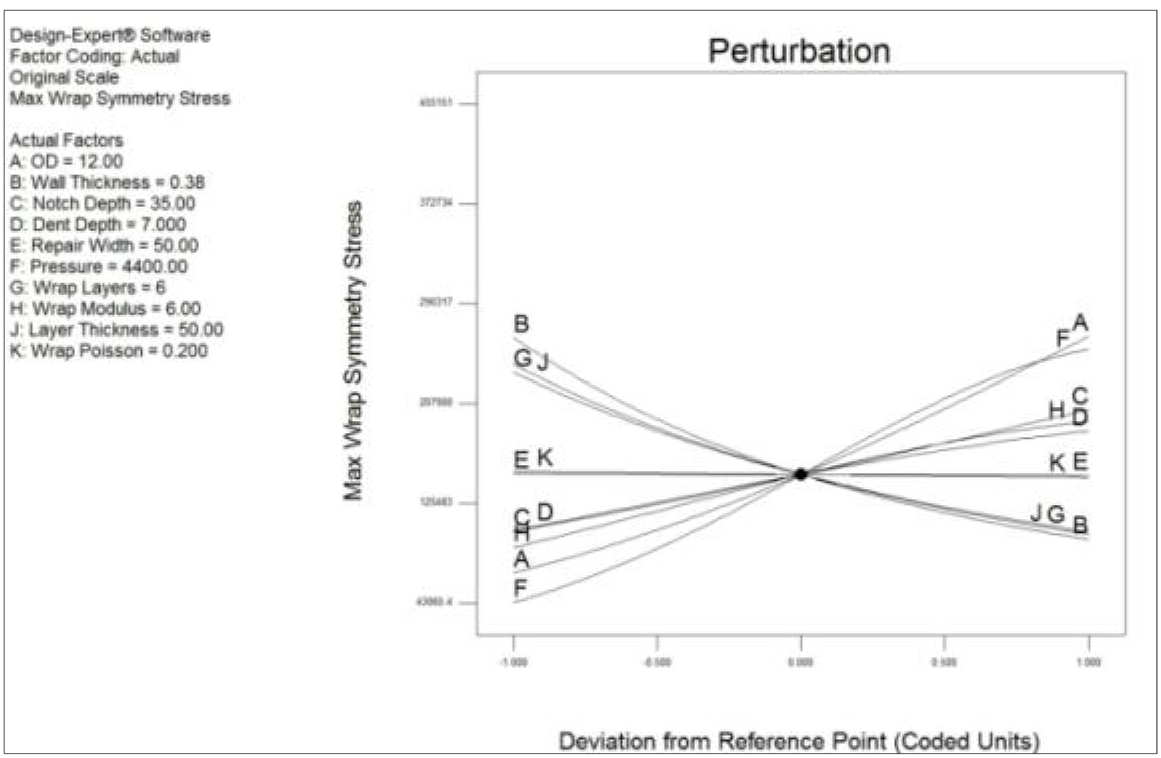


Figure 13 - Perturbation graph for maximum von-Mises stress in wrap (at notch location)

B) Material and Performance Requirements for the Composite Repair Systems

The material qualification data that the repair system supplier should provide for the composite repair material are listed in the ASME PCC-2 [31] and the ISO 24817 [32] standards. These requirements are compiles in Table 3 and Table 4. Table 3 covers the mechanical and adhesion properties of the composite material and Table 4 lists performance test requirements for the pipe-composite systems. Some of these tests are optional and based on the application and the environmental conditions of the system.

Table 3 - Repair System Mandatory tests for Mechanical Properties [31]

Property	Detail Properties	ASTM Test Method
Tensile Strength & Modulus	Tensile strength, modulus, strain to failure, and Poisson's ratio in hoop and axial directions.	ASTM D3039
Hardness	Barcol or Shore hardness data	ASTM D2583, ASTM D2240
Coefficient of thermal expansion,	In hoop and axial directions.	ASTM E831
Glass Transition Temperature (T_g), or, Heat distortion temperature (HDT)	(of polymer)	ASTM E1640, ASTM E6604 ASTM D648
Compressive Modulus	(of filler material)	ASTM D695, ASTM D6641

Table 4 - Repair System Performance Requirements (Type A repair)

Property	Test Type	ASTM Test Method
Lap shear adhesion strength	Mandatory	ASTM D3165, ASTM D5868
Long-term lap shear performance	Optional	ASTM D3165
In-plane shear modulus	Optional	ASTM D5379
Short-term spool test	Mandatory	Spool Test, PCC2 Appendix III
Long-term strength	Optional	PCC2 Appendix V
Cyclic Loading	Optional	ISO 14692
External Loading	Optional	
Cathodic Disbondment	Mandatory for cathodically protected pipes	ASTM G8, ASTM G95
Electrical Conductivity	Optional	ISO 14692, ASTM D149
Chemical Compatibility	Optional	ASTM D543, ASTM C581, ASTM D3681, ISO 10952

The following sections provide a summary of the testing requirements as listed in the above tables. Further discussions on the testing procedures and results are presented in the following chapters of the report.

B.1) Tensile Strength and Modulus:

The ASTM D3039 [34] is used to determine the short-term design tensile strength, strain and modulus of the repair laminate. The test is performed on a thin flat strip of material with a constant rectangular cross section. The test is performed on the laminates in the axial and the circumferential directions. Other parameters are obtained from the test results such as the material Poisson's Ratio.

The production of the test coupons still remains to a large extent as an art than a science. This is mainly because the laminate specimens are prepared in the lab and not obtained from the field. Accordingly, the specimen preparation, lay-up, and conditioning should be performed to represent the field installation as close as possible. The procedures regarding the gripping of the samples should also be identified to mitigate boundary effects and possible slippage from the clamps.

The results of the test should accordingly include the method of material preparation, the number of layers tested, conditioning, specimen alignment and gripping, speed of testing, temperature, and other environment of testing.

B.2) Barcol and Shore Hardness Tests:

These tests measure the surface hardness of the composite system using a surface impressor. The tests are used in the field to demonstrate that adequate cure of the field-applied repair laminate is achieved, especially for applications at service temperatures below 40°C (104°F). The ASME PCC-2 standard requires that the measured hardness values in the field to be more than 90% of the one obtained from qualification tests in the lab.

The hardness tests are performed according to ASTM D2583 [35] using the Barcol impressor to indent the surface and provide a comparative measure of the material's hardness. The ASTM D2240 [36] is also used to provide hardness measurement of thermoplastic and elastomeric materials.

B.3) Coefficient of Thermal Expansion:

The thermal coefficient of the laminate repair (α_r) is used in the design calculations since consideration should be given to the difference between the thermal expansion of the laminate and the steel pipe. The coefficient of linear thermal expansion for the composite is determined in both the circumferential and axial directions from several ASTM tests, including ASTM E831 [37]. The ASTM E831 testing procedure covers material subjected to high temperature ranges and it uses a thermo-mechanical analyzer on a small specimen material between 2 and 10 mm.

B.4) Glass Transition Temperature:

The glass transition temperature (T_g) is useful in characterizing many important physical attributes of the polymer resins in the composites; including their thermal history, physical stability, progress of chemical reactions, degree of cure, and their mechanical behavior. It is used in the design calculations to determine the maximum and minimum temperatures that the repair can be used for. The T_g may be determined by a variety of techniques including ASTM E1640 [38] and ASTM D6604 [39], and the results may vary in accordance with the technique.

In the absence of T_g data, the design limits of the maximum and minimum temperatures for the repair are determined using the Heat Distortion Temperature (HDT). The HDT is the temperature at which the polymer sample deforms under a specified load. It is determined using the ASTM D648 [40]. The ISO standard 24817 also references the ASTM E2092 test [41]. This test method is similar to the one in the ASTM D648 but is performed using a thermo-mechanical analyzer and a smaller test specimen.

B.5) Compressive Strength of Filler Material:

The load transfer between the substrate and the laminate depends on the compressive strength of the filler material. If the compressive modulus of the filler material is relatively low, large deformations of the pipe substrate may occur before the load is transferred to the laminate.

The compressive strength modulus of the filler material can be determined in the ASTM D695 test [42]. This test method covers the determination of the mechanical properties of rigid plastics, including high-modulus composites, when loaded in compression at relatively low uniform rates of loading.

B.6) Interface Shear between the Laminate and the Substrate:

The ASME PCC-2 standard requires the adhesive bond to be stronger than the lap-shear strength between the laminate and the metal substrates and with minimum shear strength of 580 psi (4 MN/m^2).

The short-term shear strength of the adhesive between the laminate and the steel pipe is evaluated in the ASTM D3165 test [43]. In this test, the lap-shear strength is measured when the specimen is gripped and subjected to tension load. The tests are performed in both the axial and circumferential directions at design temperature.

B.7) Long-term lap shear performance:

Where evidence of long-term durability of the adhesive bond is required, the ASME PCC-2 requires performing 1,000-hour long-term lap shear strength at the design temperature. The average lap shear strength determined from this test shall be at least 30% of the values from the short-term lap shear tests determined at room temperature.

B.8) Hydrostatic Loading tests:

The load-carrying capacity of the repair system depends on the efficiency of the load-transfer mechanism between the pipe and the repair at low-strain levels. Hydrostatic pressure tests are performed on pipe samples with the repair system to evaluate the load-carrying capacity of the system.

The ASME PCC2 describers a short-term survival test method in Appendix III to demonstrate that a Type A defect can be repaired using the repair system. The test applies pre-determined test pressures at the repair system on defected pipe specimen. The purpose of this test is to demonstrate the integrity of a structural repair up to the yield level of the original pipe.

B.9) Long-term Performance Tests:

The ASME PCC-2 specifies three test methods for determining the long-term strength of the Repair System, namely:

- Survival tests, where the repair system is subjected to a period of 1,000 hour sustained load. This test is performed on pipe sections of minimum diameter 4 inch (100 mm) and the internal pressure is applied to reach the required long-term strength.
- Regression testing, based on ASTM D1598 [44] where a series of tests on the repair system are performed on specimens subjected to sustained pressures of different values and the time at which the repair laminate shows signs of deterioration is recorded. The results are extrapolated to the long-term strength based on the ASTM D2992 [45] standard practice.
- Coupon tests, based on regression testing of representative coupons followed by confirmation of long-term coupon test results with survival testing.

B.10) Cyclic Loading Tests:

Cyclic loading tests are commonly used to simulate pressure changes of incompressible liquids in liquid and petroleum pipelines. The ASME PCC2 procedure requires considering cyclic loading in the risk assessment of the repair if the predicted number of pressure cycles is more than 7,000 over the design life.

B.11) Performance under External Loads:

Repair systems can be subjected to flexural (bending) stresses when pipes are under heavy overburden loads without sufficient support from the underlying soil. Several ASTM testing procedures such as ASTM D6416 [46] and ASTM D2412 [47] address the determination of flexural stresses of pipes and composites. These procedures do not directly address the configuration and loading mechanism of pipes with composite repairs and, consequently, modifications are required to accommodate one or several of these procedures for the evaluation of the repairs under external loads.

B.12) Cathodic Protection of Composite Repair:

In catholically-protected pipelines, hydrogen gas caused by the cathodic current is formed at the location the holidays. This formation may result in the development of a disbondment force between the composite and carrier pipe. The long-term disbondment force can ultimately cause delimitation or damage to the repair.

The ASTM G8 [48] and ASTM G95 [48] testing procedures are used to evaluate the susceptibility of pipeline coatings to disbondment under an imposed electrical current. The ASTM G8 requires the use of full pipe specimens while ASTM G95 utilizes an attached cell which can test over a specific area.

B.13) Long-Term Degradation of the Composite:

Thermoset polymers are generally compatible with a wide range of environments. The ASME PCC-2 requires the suitability of the repair system to the service environment, based on the following considerations:

- When required, the repair system shall be protected from UV exposure, water, and damaging chemicals.
- The repair system is compatible with aqueous and hydrocarbon environments at the qualification temperature. Consideration needs to be given when the environment is strongly acidic ($pH<3.5$), strongly alkaline ($pH>11$), or is a strong solvent.
- When the compatibility of the Repair System is unknown, the supplier shall demonstrate the environmental compatibility of the composite polymer.

If no compatibility data is available, specific environmental testing is required. Results from tests according to one of the following test procedures, ASTM D543 [50], ASTM C581 [51], ASTM D3681 [52], or equivalent, comparing the exposure of the specific environment at the design temperature shall be performed.

When erosion is the cause of the degradation process of the substrate material, the repair system should also survive the erosion environment for the specified repair lifetime.

4. Mechanical Properties of Composites

A) Tensile Strength of the Composites

A.1) Short-Term Tensile Tests:

The evaluation of the tensile strength of the composites was performed using two different testing procedures; namely, tensile tests using flat samples as per ASTM D3039 [34] and tensile tests using split disk method as per ASTM 2290 [53].

The ASTM D3039 is commonly used to determine the design tensile strength, strain and modulus of the repair laminates. The test was performed on specimen size of 1 inch wide and 10 inches long. The tension force was applied at a strain-controlled rate of 1% per minute. The strains were measured in the tests using extensometers attached to the specimens to mitigate the possible slippage of the specimen at the clamps. Figure 14 shows the test specimen in the tensile loading frame.

Figure 14 - ASTM D3039 tensile test specimen

The sample size used in the ASTM D2290 tests was 1.0 inch wide and was wrapped around split discs of 2.5 inch diameter. It consisted of two-ply composites wrapped with the bonding material. The samples were notched to reach failure between the two halves of the discs. The loading mechanism in this test resembles the state of stresses developed in the laminates around the pipe. Figure 15 shows the test specimen.

The tensile tests were performed on two composite materials, namely, glass woven fiber with impregnated resin and Carbon-glass fiber composite. The results of the two testing procedures are shown in Figure 16 and Figure 17 for the glass fiber and carbon fiber composites, respectively.

Figure 15 - ASTM D2290 tensile strength Test

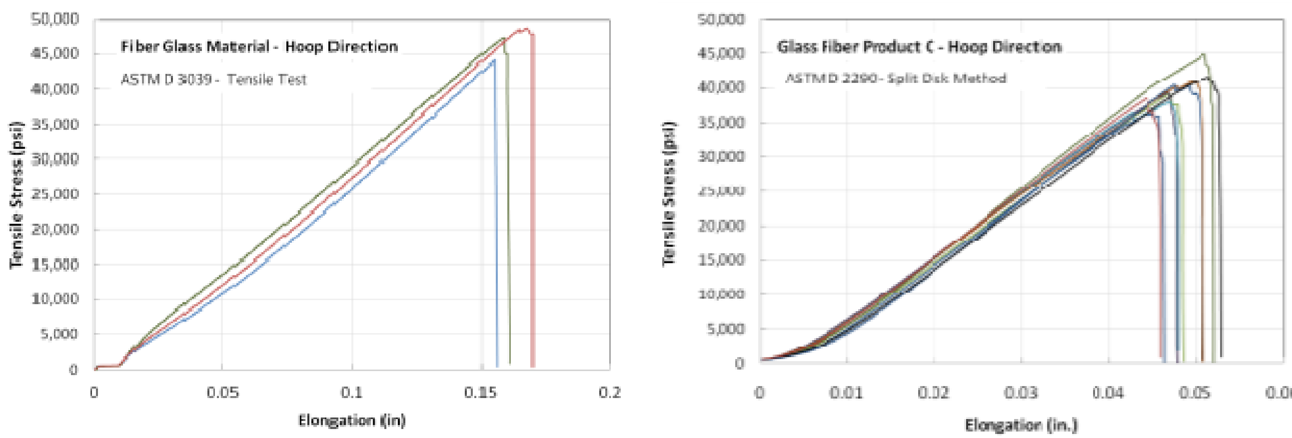


Figure 16 - Tensile test results for the glass fiber product

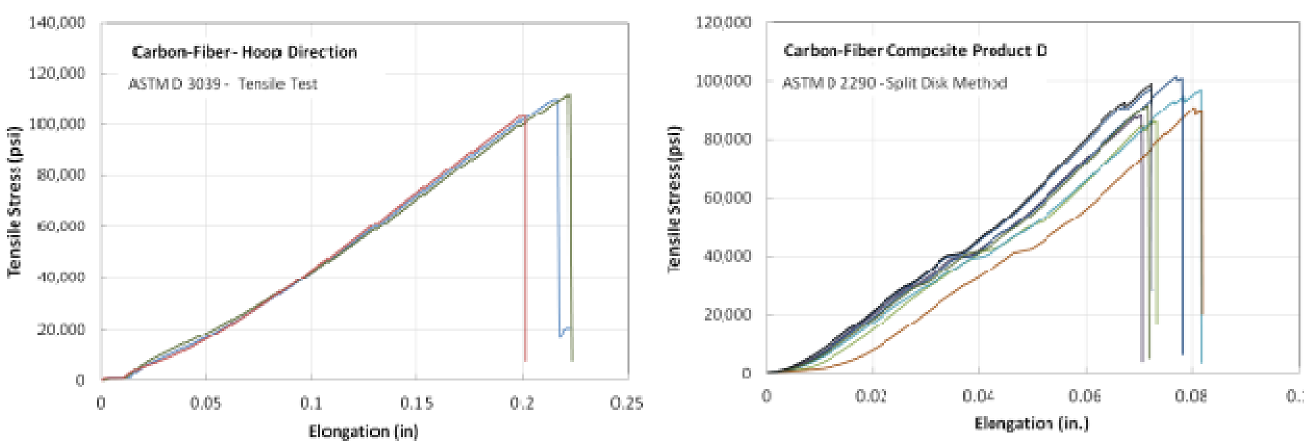


Figure 17- Tensile test results for the carbon fiber product

The figures show repetitive results for both tests. However, the two test methods are associated with different sample sizes and boundary conditions; which makes it difficult to compare the results. The tensile strength results of the split disk method (ASTM 2290) were typically about 10 percent lower; however, it has much lower elongation at failure. Although the split disk method represent a state of stress closer to the field condition, it is difficult to calculate accurate strains from the tests results due to the small initial length of the strained part of the specimen.

A.2) Long term tensile tests:

The long-term tests were performed at elevated temperatures for 1,000 hours. The tests were performed on the glass fiber and carbon fiber composites at tensile loading levels of 30 and 60 percents of the ultimate short-term tensile loads of the material. These tests were performed at the TRI Environmental, Inc. and the testing report is presented in **Appendix A**.

The tests were conducted using a multi-station lever action creep frames which are housed inside environmental chambers as shown in Figure 18. The tests were performed at constant elevated temperature of 140^{o}F (60^{o}C). The fiberglass specimens were clamped using aluminum plate clamps and the tabs of the Carbon specimens were cast in epoxy and post-cured for 12 hours. The epoxy block was then clamped using aluminum plate clamps. The strains were measured with LVDTs.

Each specimen was allowed to reach equilibrium at the prescribed temperature prior to testing. The specimens were then ramped to the specified percentage of their ultimate strength and were held until failure or 1,000 hours. The results of the creep testing are shown in Table 5.

Figure 18 - Creep testing frame and sample in environmental chambers

For the analysis of the long-term strength tests at elevated temperatures, a procedure was developed for predicting the service life stresses based on rate process approach. This procedure is described in detail in the following section.

Table 5 - Results of Creep Tests at Elevated Temperature

Product	No. of Tests	Test Temperature (^{o}F / ^{o}C)	Applied Load (%Tmax)	Time to rupture (Hour)
Glass fiber	3	140 / 60	30	>1000
Glass Fiber	3	140 / 60	60	>1000
Glass Fiber	1*	140 / 60	60	18.7
Carbon Fiber	1	140 / 60	30	>1000
Carbon Fiber	1	140 / 60	60	>1000
Carbon Fiber	1*	140 / 60	60	158

* Sample failed in slippage at the clamps

B) Bonding Strength of the Composites

B.1) Short-Term Testing of Bonding Strength:

The adhesive used in the composite repair system is a critical component that not only bonds the repair to the pipe, but also bonds the individual layers of the repair to one another (i.e., laminates, fibers, weaves, mesh, etc.). If this bond is not adequate, load will not be effectively transferred from the pipe to the repair system.

The short-term shear strength between the laminate and the steel pipe is evaluated in the ASTM D3165 test [43]. In this test, the lap-shear strength is measured when the specimen is gripped and subjected to tension load as shown in Figure 19. The tests are performed in both the axial and circumferential directions at design temperature. The ASME PCC-2 requires a minimum shear strength value of 580 psi for the adhesive bond in the lap shear tests.

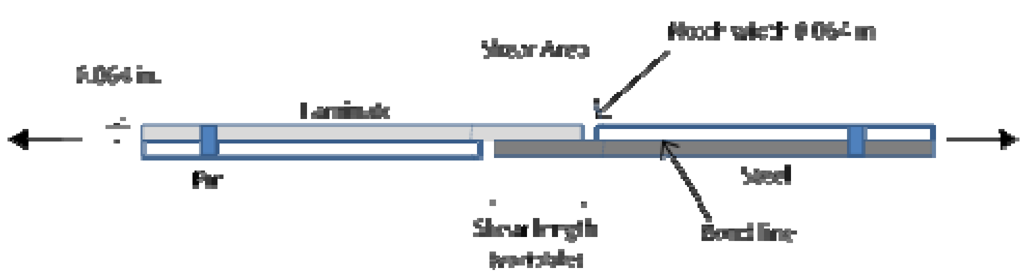


Figure 19 - Schematic of lap-shear test specimen

Alternatively, shear tests were performed in this project to evaluate interlaminate adhesive strength of the composite. These tests were performed on accordance with ASTM D3039 [34]. The standard was modified to apply shear loads rather than tensile loads on the test samples.

The test specimen consisted of two metal plates bonded to two plys of the composite material. A piece of thin Teflon sheet separated the layers with a 0.75-inch diameter hole to allow for the adhesive bonding between the two layers. Figure 20 shows a schematic and a cross section of the test specimen. This design configuration ensured uniform distribution of the shear load at the interface, reduced the chance of peal back, and promoted an adhesive shear failure between the layers without disturbing the laminates.

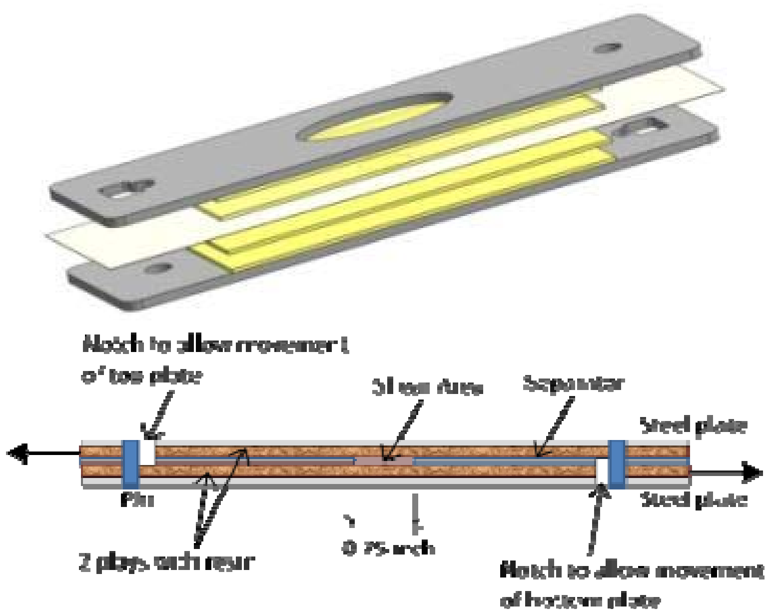


Figure 20 - Schematic and a cross section of the shear test specimen

Figure 21 shows the test sample in the shear test. The tests were performed on samples previously immersed in liquid at 70°F, 105°F, and 140°F. At each of these temperatures, the short-term strength was used as a baseline for determining long-term loads.

The results of the tests performed on 7 composite repairs are shown in Table 6. The results of tests show the significant effect of temperature on reducing the bonding strength in the samples. However, the repair systems had higher short-term shear strengths than the minimum requirement of 580 psi at the test temperature of 105°F. The short-term results were used to determine the loading levels of the samples in the long-term bonding strength tests.

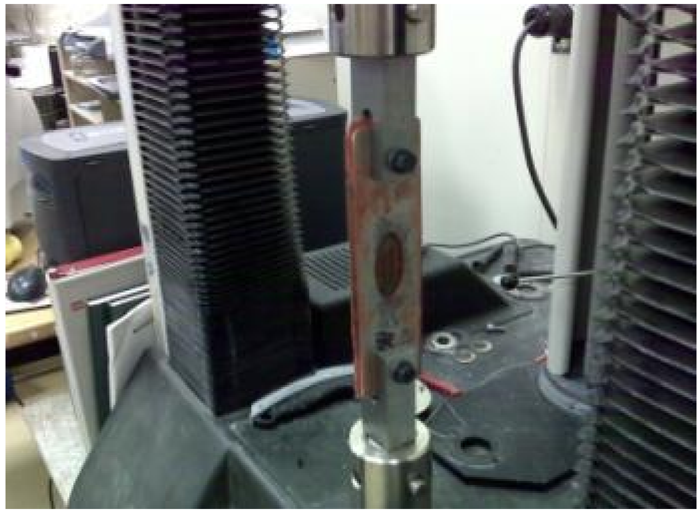


Figure 21 - Composite sample for short-term testing of the adhesive bond

Table 6 - Results of Short-Term Testing of the Adhesive Bond

	Product Code	Description	Short-term Shear (psi)		
			70°F	105°F	140°F
1	U	Glass-Woven fiber with water-activated urethane resin	2,366	1,483	672
2	C	Glass-woven fiber with epoxy resin	3,067	1,554	276
3	Z	Woven carbon fiber with epoxy resin	5,122	2,950	931
4	H	Glass-woven fiber with water-activated resin	2,467	1,551	955
5	A	Woven carbon fiber with epoxy resin	4,032	1,640	779
6	P	Fiber-glass with polyurethane resin	2,847	1,972	945
7	J	Glass-woven fibers with resin	4,096	2,792	1,203

B.2) Long-Term Bonding Strength Testing Procedure:

A testing procedure was developed in the co-funding research project to evaluate the long-term interlaminate adhesive strength of composite repairs [54]. The procedure was modified from the ASTM 2919 [55] and ASTM D2294 [56]. A summary of the testing procedure and results were published in a conference paper and it is shown in **Appendix B**.

The samples used in the long-term tests were identical to the ones in the short-term tests. The loading frames consisted of lever arms with static loads applied at the arms as shown in Figure 22. The weights applied to the samples were calculated as percentages of the short-term shear strength.

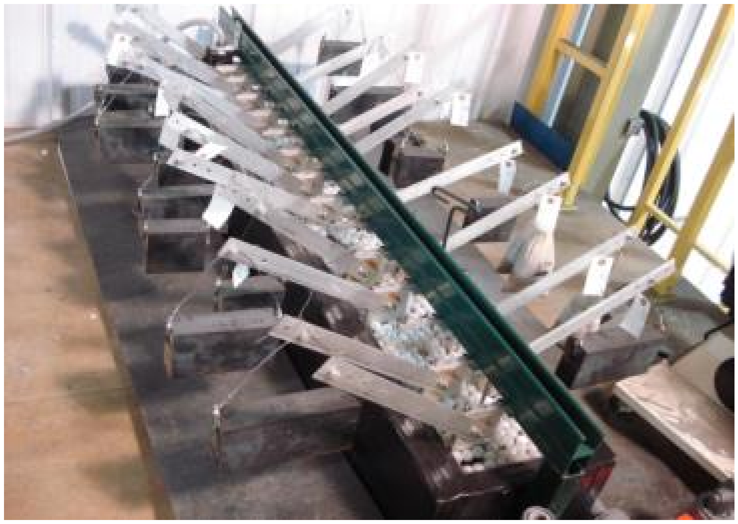


Figure 22 - View of the loading frames in temperature-controlled containers

B.3) 1,000-Hour Test Results of the Adhesive Bond:

The ASME Standard PCC-2 requires long-term shear strength to be determined for repairs where evidence of long-term durability of the adhesive bond is required. As per the standard, this test is to be carried out following immersion in water (or other relevant medium) at minimum design temperature of 40^{o}C (104^{o}F) for 1,000 hour. The average lap shear strength determined from this test shall be at least 30% of the values from the short-term tests.

The results of the samples loaded to failure at 1,000 hours are shown in Table 7 for temperature 105^{o}F. With the exception of one product, the results show that the 1,000-hour shear strengths of the repairs were higher than the 30% values of their short-term strength.

Table 7 - Results of 1,000-Hour Shear Tests

	Product Code	Short-term Shear (105^{o}F)		1,000-hour shear at 105^{o}F, psi
		(psi)	30% Strength	
1	U	1,483	445	724
2	C	1,554	466	421
3	Z	2,950	885	1,830
4	H	1,551	465	1,179
5	A	1,640	494	815
6	P	1,972	591	1,175
7	J	2,792	838	2,000

B.4) 10,000-Hour Long-Term Tests on the Adhesive Bond:

Although the ASME PCC-2 standard requires performing 1,000-hour tests to evaluate the long-term performance of the composite, the prediction of the life expectancy of the repair requires performing tests for longer durations. The shear tests were performed at 10,000 hours at various temperatures to allow for extrapolating the results and predicting the long-term strength values.

The tests were performed with the samples immersed in water tubs at the various loading levels and temperatures of 70°F, 105°F and 140°F. As per ASTM D2992 [57], the samples were loaded in an effort to create a failure profile with a minimum number of samples failures between each testing durations as shown in Table 8. Typical results of the long-term bonding strength tests at elevated temperatures are shown in Figure 23 and Figure 24.

Table 8 - Required Failure-Point Distribution per STM D2992

Hours to Failure	Failure Points
10 to 1,000	at least 4
1,000 to 6,000	at least 3
after 6,000	at least 3
after 10,000	at least 1
Total	at least 18

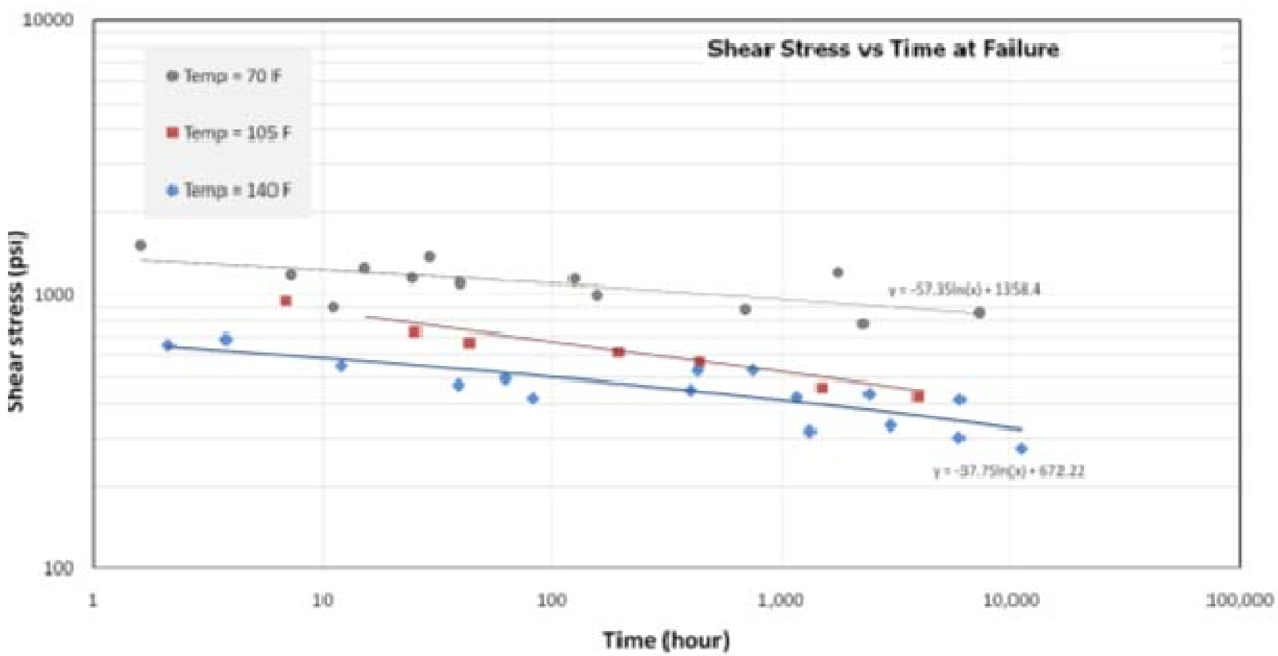


Figure 23 - Long-term bonding strength of composite U at various temperatures

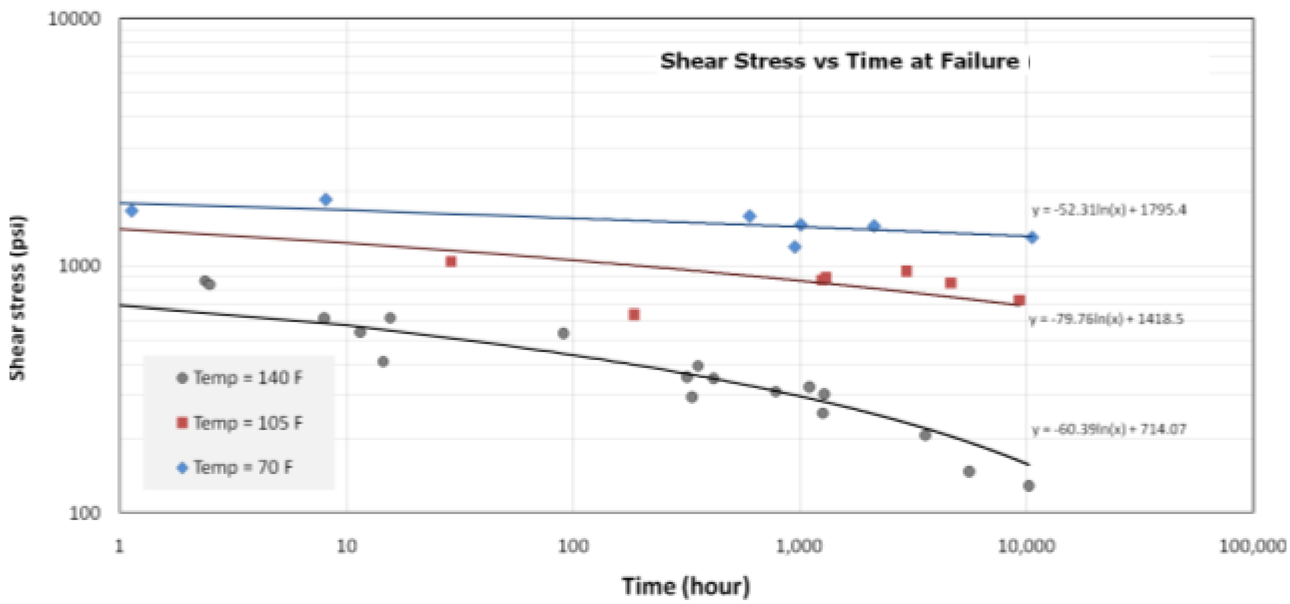


Figure 24 - Long-term bonding strength of composite H at various temperatures

B.5) Prediction of the Long-Term Adhesive Strength:

The results of 10,000-hour long-term tests were extrapolated to predict the shear strength at longer durations. Two procedures were used for the estimation of the 20-year shear strengths of the composites, namely:

- The first procedure is based on the direct extrapolation from the 10,000-hour curves established for each product at 70°F. This procedure assumes that the predicted performance and the corresponding best-fit curves do not drastically change at longer time intervals.
- The second procedure is based on the methods used of thermoplastic materials. These materials are assumed to exhibit accelerated creep at longer time intervals (i.e., at 100,000 hours). This accelerated creep can be predicted from elevated temperature tests using the rate process theory.

The second extrapolation procedure is based on the rate process method in ASTM D2837 [58]. This approach is further described in detail in various publications [59, 60] and a summary of the process from these two references is as follows:

The basic assumption of the extrapolation process is that the kinetics of the adhesive bond strength is in line with the rate process theory where temperature accelerates the failure process due to shear.

The following rate process based equation has been found to well model the experimentally established relationship between time to failure, magnitude of the applied stress, and the temperature:

$$\text{Log } t = A + B/T + C (\log \delta)/T \quad (1)$$

Where, t = time to fail, hours, T = absolute temperature (°R),

δ = applied stress, psi, and A, B, and C = experimentally established coefficients.

The temperature shift is explained graphically in Figure 25. The validation process of the applicability of the rate process theory is as follows:

- In accordance with ASTM D2837, the material is evaluated at the base temperature of 73°F as shown in Line a-a' in Figure 25. The stress-time curve is extrapolated to estimate the stress that results in failure at the 100,000 hour intercept (Point I).
- At the elevated temperature of 140°F, a brittle failure line (line b-b') is established.
- Determine the log average of Point II on the line which results in a brittle-like failure (a failure with no visible sign of deformation) in the range of 100 to 500 hours. Similarly, establish points at failure times between 1,000 to 3,000 hours for Point III. In the experimental program, points II and III were established with failure points less than the six test points recommended in ASTM D2837.

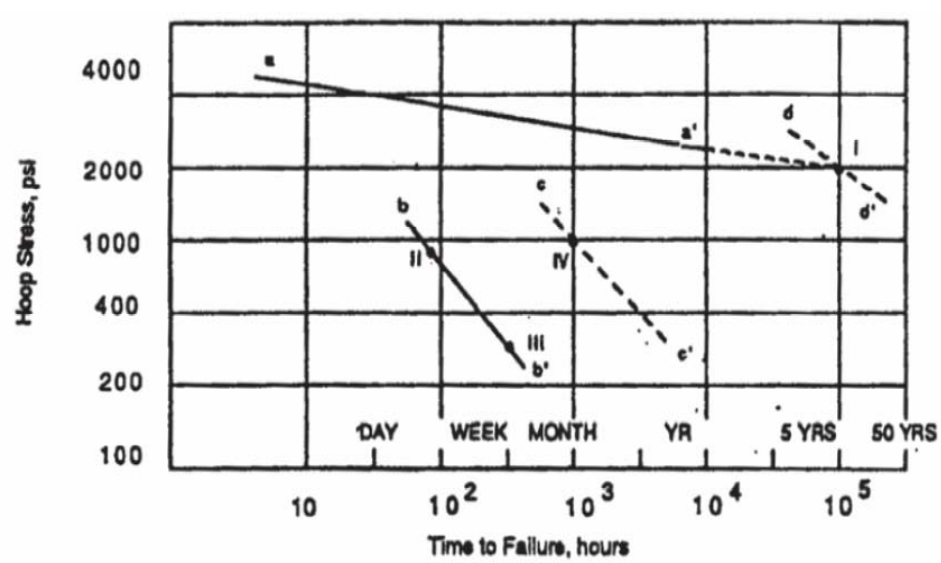


Figure 25 - Temperature effect on the long-term performance of thermoplastic material

- Calculate the coefficients A, B, and C of equation $\log t = A + B/T + (C/T) \log \delta$, from the failure points I, II, and III.
- The underlying theory in ASTM D2837 assumes that the downturn or 'knee' will occur after 100,000 hours. Therefore, the worst case assumes that the 73°F knee will occur at 100,000 hours, which is indicated by line dd'.
- To confirm that the 73°F knee is at or beyond this worst case situation, select a temperature at least 15°C lower than Condition I and at similar stress level. This is indicated as Point IV and line cc'. In the experimental program, Point IV was tested at temperature 105^{o}F.
- Apply the rate process equation to mathematically predict failure time for point IV. If the experimental result meets or exceeds this predicted time, the hypothesis that the knee occurs at or beyond 100,000 hours has been confirmed independently and the ASTM D2837 procedure is validated.

It should be noted that this process was established for thermoplastic material and it is a conservative approach for the thermoset polymers commonly used in composites. Table 9 shows the predicted 20-year bonding strength of the composites from the best-fit curves and the rate process approach.

Table 9 - Predicted 20-year Bonding Strength of the Composites

	Product Code	Short-term Shear (70^{o}F), psi	10,000-hour shear (70^{o}F), psi	20-year (best- fit), psi	20 years (rate process), psi
1	U	2,366	1,129	1,050	910
2	C	3,067	537	480	464
3	Z	5,122	3,125	2,910	1,657
4	H	2,467	1,586	1,516	1,318
5	A	4,032	2,046	1,950	1,888
6	P	2,847	1,956	1,750	1,671
7	J	4,096	2,332	2,285	1,981

5. Repair Performance under Hydrostatic and External Loading

A) Long-Term Performance under Hydrostatic Loading

The evaluation of the repair systems included performing hydrostatic pressure tests on seven commercially available composite repairs using 8-inch and 16-inch diameter pipes. The testing procedure was developed in the co-funding research project [33]. In these tests, controlled gouges and dents were applied to the pipe samples and then repaired by the various composites. Without applying the repair, the damage would have caused failures at burst pressures of about 70 percent of the pipes Specified Minimum Yield Strength (SMYS). The application of the composite repair was performed by the manufacturers at the GTI facility. After repair, the pipes were subjected to incremental hydrostatic pressure up to 100 percent SMYS. The pressure was then increased to 120 percent SMYS and was kept for 1,000 hours.

The seven products in the testing program are shown in Table 10. Most of the composite repair manufacturers develop their own design procedures to determine the required number of layers based on pipe and damage characteristics. The manufacturers' designs were compared with the design requirements of the ASME PCC-2 standard [31]. The evaluation shows that the numbers of wraps of the repair systems are generally more conservative in the ASME PCC-2 standard than the ones provided by the manufacturers.

Table 10 - Composite repair systems in the testing program

	Composite	Elastic Modulus of Composite (psi)
A	Integrated Woven Fiberglass	3.01E+06
B	Glass woven fabric impregnated with water-cured urethane resin	2.78E+06
C	Woven glass fiber with 2-part epoxy resin	2.00E+06
D	Woven carbon-fiber material	9.72E+06
E	Non-woven glass fiber and epoxy resin	2.09E+06
F	Woven carbon-fiber material	8.44E+06
G	Glass fiber with epoxy-based resin	4.40E+06

The preparation of the test samples for hydrostatic burst tests consisted of the following steps:

- Prepare and cap the pipe specimens: The pipe specimens used in the testing program were grades X42 and X52 and had nominal diameters of 8 and 16 inches and wall thickness of 0.25 inches. The pipes were capped and two threaded inlets were welded at the ends of the pipes to allow for applying the hydrostatic pressure. Figure 26 shows a schematic of the test pipe sample.

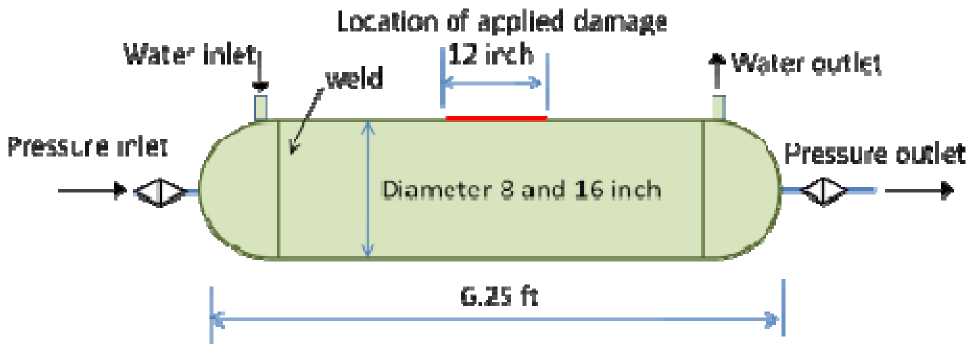


Figure 26 - Schematic of the hydrostatic pressure test specimen

- Machine a longitudinally-oriented gouge into the wall thickness of the pipe using a v-shaped cutter while the pipe is unpressurized: A 90-degree gouge was applied to a depth of 0.1 inch in the 0.25-inch thick pipes, which is 40 percent of wall thickness (Figure 27). The lengths of the gouge was 12 inches which is greater than (6 $\sqrt{Dt}$) *of* the pipe sample. As such, the defect can be considered to be representative of a long defect.
- Pressurize the pipe to a pre-determined pressure level: The pipes were placed in the loading machine and hydrostatic pressure was applied to reach a hoop stress equals 40 percent SMYS of the pipe material.
- Apply dent while the pipe is pressurized: A rounded disc was used to apply a vertical dent to the pipe. After applying the vertical dent, the dent disc was moved horizontally to cause a dent length of 12 inches above the gouge (Figure 28). A pressure release tank was connected to the pipe during this process to maintain constant internal pressure by accommodating the excess volume of water displaced from the pipe during pipe denting.

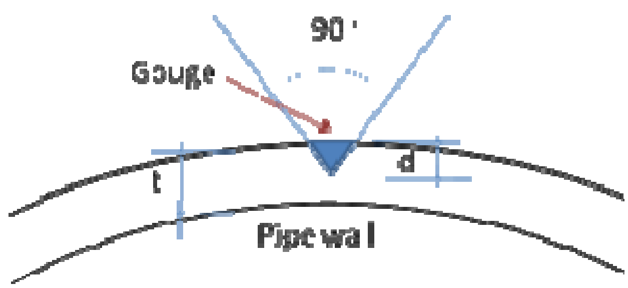


Figure 27 - Schematic of the gouge geometry in the pipe samples

Figure 28 - Application of dent on the pipe sample

- After the application of the gouges and dents, the pipes were grinded to the bottom of the gouges to obtain a smooth transition from the damaged section to the original surface. The surface was grinded to meet NACE 2/SA2.5 near-white metal finish with about 4-mil anchor profile as shown in Figure 29.
- After denting, pipe pressure was released to 0 psig and the dent depth was measured using a straight edge. The remaining pipe wall thickness was measured using a digital ultrasonic thickness gauge.

Figure 29 - Surface preparation for the composite repair application

The application of the composite repairs on the pipes was performed by the manufacturers at the GTI lab. The repair consisted of applying the load transfer filling material. After it was set, the composite wraps were applied over the damaged area. Figure 30 shows the application of the composite carbon wrap on the pipe samples.

Figure 30 - Application of the carbon wrap on the 8-inch pipe

The pipe samples were subjected to hydrostatic pressure of 120 percent SMYS and were kept for 1,000 hours in a controlled temperature container. All the pipe samples carried the pressure without leakage. Figure 31 shows the pressurized pipe samples in the test chamber.

Figure 31 - Pipe samples in the 1,000-hour pressure test

B) Evaluation of the Composites under External Loads

B.1) Testing for Flexural Strength:

Repair systems can be subjected to bending stresses when pipes are under heavy overburden loads over cavities or wet ground without sufficient support from the underlying soil. The ASME PCC2 and the API 15S Recommended Practice [61] require that the manufacturer should specify the maximum external pressure which a pipe should be exposed.

Several ASTM standards are used for determining the flexural resistance to outside loads. These standards include ASTM D747 [62], ASTM D790 [63], ASTM D6272 [64], and ASTM D7264 [65]. The ASTM D747 measures the force and angle of bend of plastics in a cantilever beam and the loading scheme in this standard does not replicate the loading condition which the repair may be subjected to in the field. The ASTM D790 utilizes a three-point loading system applied to a simply supported beam. The flexural strength from this test method is generally not applicable to materials that do not break or that do not fail in the outer surface of the test specimen within the 5.0 percent strain limit.

The ASTM D6272 test method is more suited for materials that do not fail within the strain limits imposed by test method D790. It utilizes four-point bending where the maximum axial fiber stress is uniformly distributed between the two loading points. Similarly, procedure A of the ASTM D7264 uses three-point loading system and procedure B uses four-point loading. The major difference in this test method is its use of a standard span-to-thickness ratio of 32:1 versus the 16:1 ratio used by Test Methods D 790 and D6272.

Additionally, crush resistance under external load may be characterized using the parallel plate test ASTM D2412 [66]. The impact resistance of the repair should also be specified if field conditions demonstrate the need for such resistance. Where it is necessary, a performance-based test should be devised such as the impact testing procedure in ISO 3127 [*8*].

B.2) Testing Procedure:

The flexural resistance of the composites was evaluated in four-point loading tests according to the ASTM D6272 standard procedure. The specimens consisted of the fiber glass composite wrapped in 4 layers around 2-inch diameter HDPE pipes. The pipe flexural resistance was determined first without the composite and the value was subtracted from the results.

The composite pipe specimens were 36 inches long and they conditioned for 24 hours and placed in the four-point flexural loading machine (Figure 32).The tests were performed at a constant strain rate of 0.4 inch/min until a maximum displacement of 3 inches or failure. Figure 33 shows the failed composite specimen under flexural bending. The results of the tests are shown in Figure 34.

B.3) Composite Resistance to External Loads:

The equivalent distributed soil pressure which results in a bending stresses equal to the ones obtained from the four-point loading can be calculated from the bending moment diagrams shown in Figure 35.

Figure 32 - Composite sample under four-point loading test

Figure 33 - View of the composite sample after breakage in flexural test

The results of the bending tests in Figure 34 show an average maximum flexural resistance of 961 lb-ft. A distributed soil pressure (w) of 855 lb/ft per linear foot will approximately result in an equivalent flexural resistance.

To resist this external pressure, the minimum repair thickness, t_{min} is given by [32]:

$$t_{min} = D\left[\frac{3(1-\upsilon^2)P_e}{2E_c}\right]^{1/3} \qquad (2)$$

Where, D is the pipe diameter, P_e is the applied external pressure (w) on the composite, E_c is the tensile modulus of the composite laminar in the circumferential direction (psi), and v^2 is defined as $(v_{ca}{}^2 . E_a/E_c)$. The value of v_{ca} is the Poisson's ratio for the composite laminate in the circumferential direction, and E_a is the tensile modulus of the laminate in the axial direction.

The substitution of the equivalent soil pressure (w) into equation 1 results in a minimum required thickness of 10 layers. This requirement is larger than the actual number of layers in the test specimens (4 layers), resulting in a factor of safety of about 2.5.

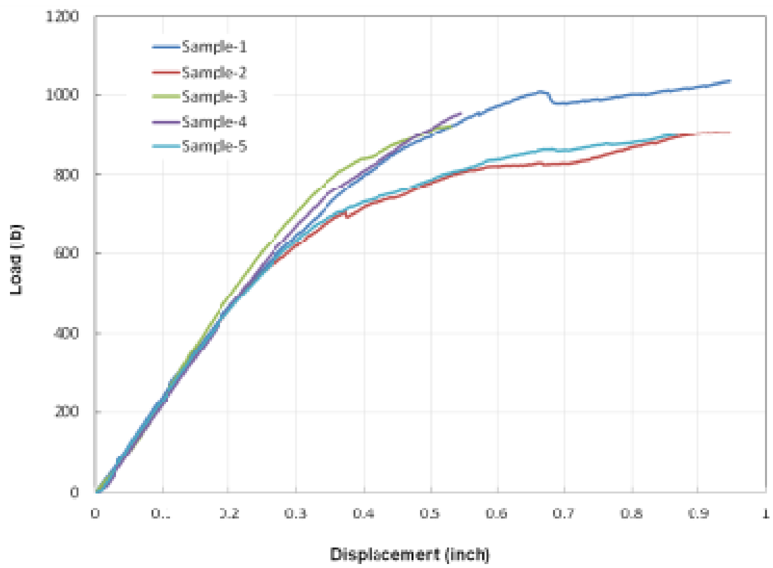


Figure 34 - Results of four-point flexural tests on the glass fiber composite

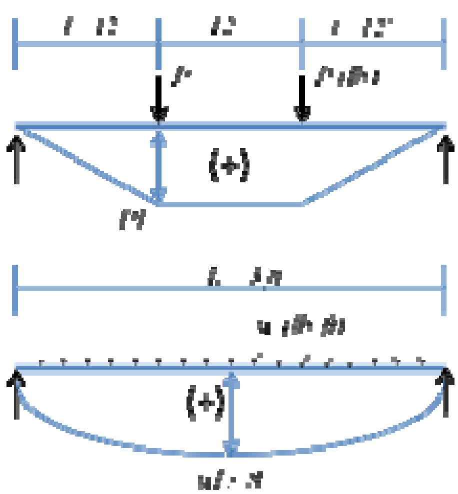


Figure 35 - Moment diagram in 4-point tests and equivalent moment under soil pressure

6. Repair Performance under Cyclic Loading

A) Introduction

Long-term hydrostatic pressure tests are appropriate for simulating the loading conditions of natural gas pipelines. Alternatively, cyclic loading tests are commonly used to evaluate the repairs in liquid transmission pipes commonly subjected to a cyclic pressure loading during operation.

The ASME PCC2 procedure for the design of composite repair systems [31] requires considering cyclic loading in the risk assessment of the repair if the predicted number of pressure cycles is more than 7,000 over the design life. In this case, the allowable strains used in the design equations shall be de-rated by the factor, f_c, given by:

$$f_c = \sqrt{\left[R_c^2 + \frac{1}{2.888\text{Log}\,(N) - 7.108}\,(1 - R_c^2)\right]}$$

Where R_c is the cyclic loading severity, defined as the minimum cyclic load (P_{min}) divided by the maximum cyclic load (P_{max}), and N is the number of cycles over the design life of the system.

The following sections present a testing procedure for the cyclic loading tests and the estimations of the fatigue life from the experimental data.

B) Testing Composites under Cyclic loading

The sample preparation for cyclic loading tests followed the same procedure used for hydrostatic tests and it mainly consisted of:

- Prepare pipe sample: The pipe diameter to wall thickness ratio, D/t is an important factor which represents the actual field parameters under investigation. Typical pipe samples with ratios ranging from 25 to 100 are commonly tested. The samples used in the testing program were grade X-42 with 8-inch diameter and a wall thickness of 0.25 inches (i.e., D/t ratio of 33). The samples were caped and for the pressure applications.
- Apply controlled mechanical damage on the pipe samples: The selection of the anomaly type determines the range of pressure loads to be applied to the samples and to achieve failure. A metal loss of 40% of wall thickness on a 10-inch by 6-inch area was applied on the sample to simulate corrosion damage. Figure 36 shows a schematic of the metal loss area and Figure 37 shows the application of the metal loss on the pipe surface.
- Apply the repair: Samples were repaired with two composite repair systems, namely glass-fiber and carbon fiber composites.
- Table 11 shows the properties of the composites and Figure 38 shows the installation of the glass fiber composite on the specimen.

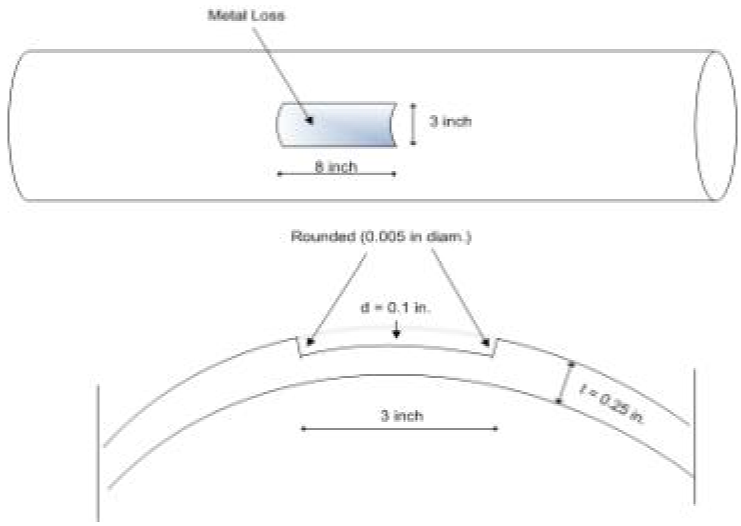


Figure 36 - Schematic of the metal loss in the pipe sample

Figure 37 - Machining of the sample to simulate metal loss

- Apply cyclic loading tests: The tests were performed with the samples inside a concrete enclosure (test chamber) shown in Figure 39-(a). A computer-controlled loading system was used for applying the cyclic loads and storing the data as shown in Figure 39-(b) and (c).

Table 11 - Properties of the composites in the cyclic testing

	Glass fiber composite	Carbon Fiber composite
Hoop Tensile Strength (psi)	54,000	100,000
Tensile Modulus (psi)	3,595,000	11,320,000
Layer Thickness (inch)	0.013	0.018

(a) Application of the filling material

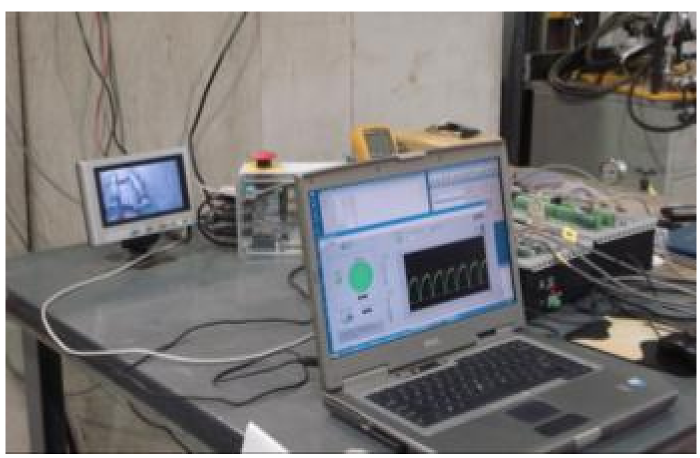
(b) Application of the composite wrap

(c) View of the control and composite-repair samples

Figure 38 - Installation of the composite repair on the samples

(a) View of the pressure test chamber and hydraulic system

(b) The pressure test chamber and equipment



(c) View of the data control and monitoring screen of the test chamber

Figure 39 - The cyclic testing equipment

The cyclic loading was applied with P_{min} = 400 psi and P_{max} = 1,800 psi, these values are equivalent to 15 and 72 percents of the pipe SMYS. The loads were applied at a rate every 15 seconds as shown Figure 40. The tests were performed up to 100,000 cycles. No failure occurred at the samples tested.

Strain gages were installed on the surface of pipe samples tested with and without the composite repair. A view of the strain gages is in Figure 41 and Figure 42. The results of the strains measured at these pipes are shown in Figure 43. The figure shows significantly lower circumferential strains on the pipe surface in the composite repair samples. Further details on the cyclic testing procedure are presented in **Appendix C.**

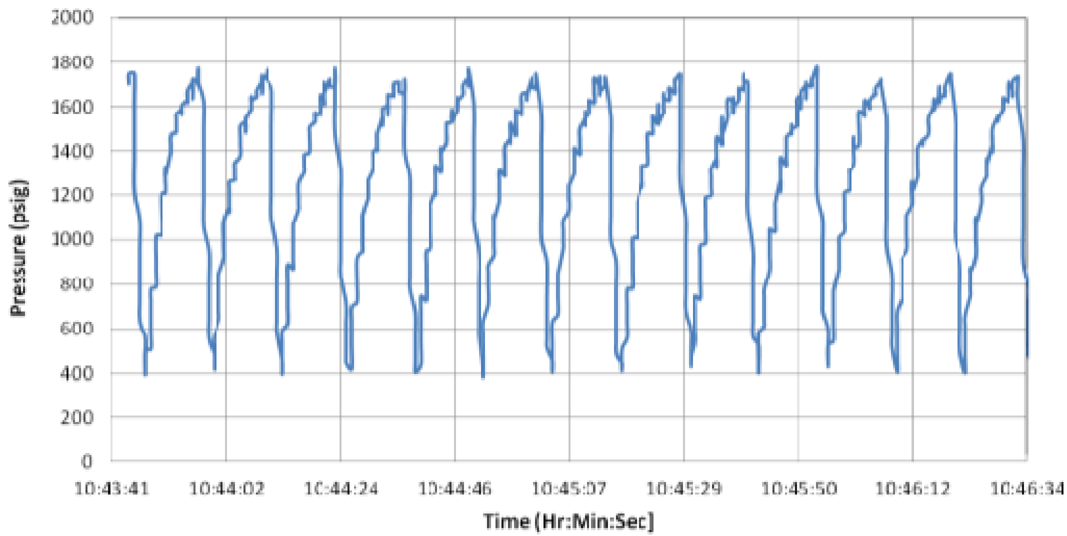


Figure 40 - View of the cyclic loading scheme in the test

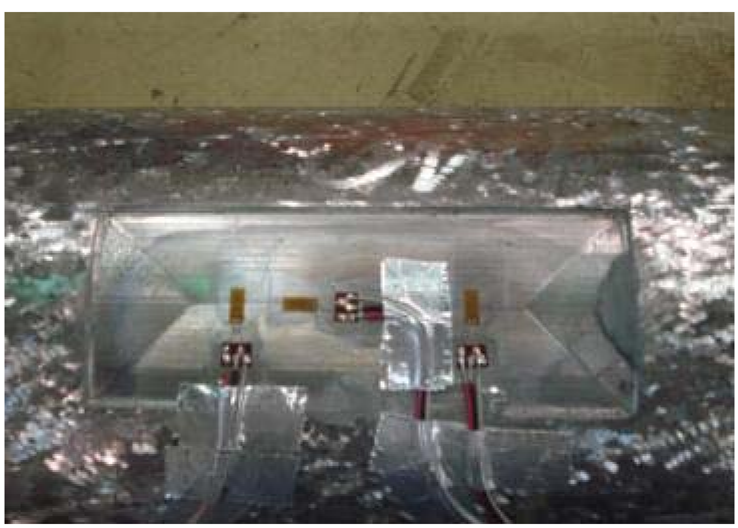


Figure 41 - Strain gages installed on the pipe sample

Figure 42 - View of the fiber-glass and carbon composite repairs

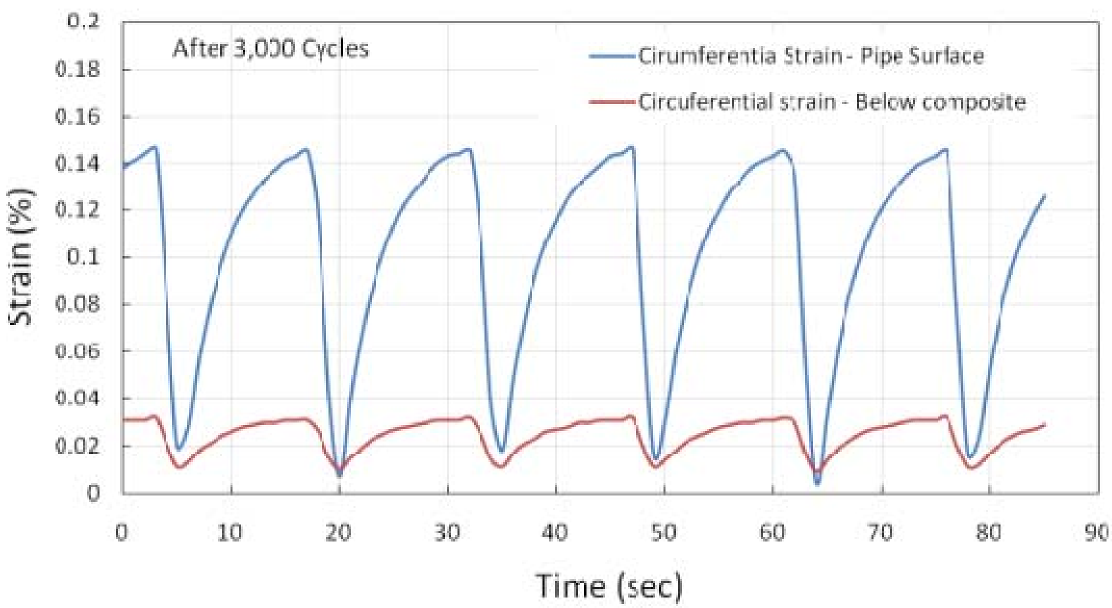


Figure 43 - Strain gages measurements on samples with and without repair

C) Estimating the Fatigue Life from Experimental Data

The estimation of the fatigue performance of the repair was performed by the project consultant: Stress Engineering Services, Inc. (SES), Houston, TX. It utilizes a database of published test results on various composite repairs and establishes a procedure for estimating the long-term life expectancy of the repairs of pipes subjected to mechanical damage (i.e., dents and gouges). The consultant report is presented in Appendix C.

The estimation of the fatigue life of the repaired pipeline system from the experimental data is estimated by dividing the number of experimental cycles to failure by the appropriate safety factor, as follows:

$$Remaining\ Design\ Cycles = \frac{Experimental\ Cycles\ to\ Failure}{Fatigue\ Design\ Factor}$$

The Fatigue Design Factor typically ranges between 10 and 20. The ASME Boiler & Pressure Vessel Code employs a safety factor of 2 on stress and 20 on experimental fatigue data to establish a design life, whichever generates the lower fatigue life [67].

The remaining design cycles are then converted to the number of years for an actual pipeline service life. The procedure is outlined in C based on the analysis recommended by the project consultant: Stress Engineering Services, Inc. (SES). The procedure is based on previous work performed by SES [68] and is summarized as follows:

- Covert the operation pressure data from the field into a format that counts the number of pressure cycles for each pressure range. An example output of such pressure data is in the histogram plot shown in Figure 44.
- Use Miner's rule to combine the numbers of pressure cycles for the different pressure ranges to an equivalent number of cycles at the selected pressure. For example:

$$N_{350} = N_{25}\left[\frac{350\ psi}{25\ psi}\right]^{-3.74} + N_{75}\left[\frac{350\ psi}{75\ psi}\right]^{-3.74} + \dots \tag{3}$$

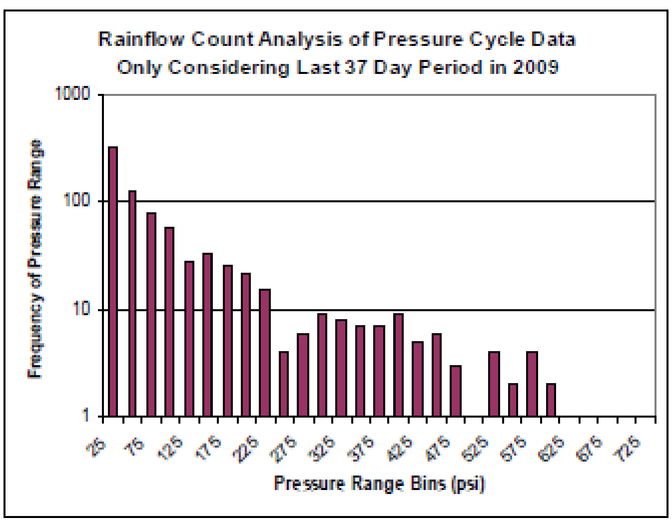


Figure 44 - Example of the frequency of pressure cycles (After SES Report, Appendix C)

- The equation can be used to convert the data from the experiment pressure range to the equivalent number of cycles at the field operating pressure. It is useful for applying test results to pipeline operation. Further details about the selection of the exponential parameter (-3.74) in the equation are presented in the Appendix.

To apply the results to a gas pressure system which operates at 200 annual cycles with pressure range of 36% SMYS, the test data must be converted into an equivalent number of cycles for a pressure range equal to 36% SMYS.

Using Miner's Rule, the repaired samples that were cycled at 36% SMYS have a 73,488 equivalent number of cycles when converted from the 72% SMYS data.

The remaining design life is calculated by dividing the experimental fatigue lives by 200 annual cycles, results in about 367 remaining years of service.

An example of using the above procedure is as follows: A product tested at 110,000 cycles to failure at a pressure range of 72% SMYS.   What is the 'Remaining Years of Service' in a system which operates at 400 annual cycles with a pressure range at 36% SMYS?

- From experimental results: the Design Cycles equals 5,500 when a Fatigue Design Factor of Safety = 20 is applied.
- Convert the test data into an equivalent number of cycles for a pressure range equal to 36% SMYS. Using Miner's Rule, the repaired samples that were cycled at 36% SMYS would have a 73,488 equivalent number of cycles when converted from the 72% SMYS data.
- The remaining design life is calculated by dividing the experimental fatigue lives by 400 annual cycles, resulting in about 183 years of service.

7. Cathodic Disbondment of Composite Repairs

A) Introduction

For composite-repairs on pipes with cathodic protection, the applied electric potential on the pipe surface may cause a loss of the bond between the pipe material and the repair. This may occur if holidays reach the pipe surface through the composite wrap or when existing ones have effective electrolytes underneath the repair.

The ability to resist the disbondment is a desirable quality for the repair. The localized disbondment, however, is not necessarily an indication of a loss of the repair general performance. The ASME PCC-2 standard for the non-metallic composite repair systems [31] states that:

- For repairs to components that are cathodically protected, it may be required to demonstrate that the repair will not disbond due to the cathodic protection system.
- ASTM G8 [48] shall be used to demonstrate that the repair will not be susceptible to disbondment under an imposed electrical current.

The ASTM G8 test method covers accelerated procedures for determining the characteristics of the coating systems in catholically-protected steel pipes and it is applicable to composites with some modifications. This method however requires the test specimen to be submerged in electrolyte solution during the test.

The ASTM G95 test method [49] is more applicable to composite repairs since it is intended to facilitate testing when it is impractical to submerge or immerse the specimen. In this method, a test cell is cemented to the surface of the pipe specimen in a configuration such as flat plate and small diameter pipe.

The cathodic disbondment tests were performed on composite repairs using the ASTM G95 test method. The testing procedure evaluated the disbondment areas of pre-set holes in pipes when subjected to an electric potential of 3V DC in a solution. The procedure specifies the use of a razor to remove the disbonded coating and identify the disbondment areas. In the composite testing, the procedure was modified to allow for the removal of the much thicker disbonded wrap without damaging the adjacent sections.

B) Testing Procedure

The testing procedure consisted of using a transparent plastic tube over the holiday. The tube is sealed to the test sample surface with a waterproof sealing material. The cylinder is 4.0 inch in diameter with a sufficient height to contain the electrolyte (Figure 45). The test cell was installed on the surface of a repaired 8-inch diameter pipe with wall thickness of 3/16-inch as shown in the figure.

The composite samples inspected for unintentional holidays and a 0.125 inch holiday was created in the repair, drilled until it has fully reached the steel pipe. The test cells were installed on the holidays and was filled with a solution of distilled water and combined with 3 percent by mass of sodium chloride.

An anode assembly was placed in the cell at a distance of one inch above, and a half inch offset to the holiday. The anode assembly consisted of a platinum wire which provided the current path to the solution. A positive 3V DC potential was then created from the platinum anode to the steel pipe by connecting the positive lead to the platinum wire, and the negative lead to the steel pipe. The voltage of each test cell was recorded twice a week using a copper-copper sulfate reference electrode. A view of the test setup is shown in Figure 46.

Figure 45 - Installation of the test cells on the composite samples

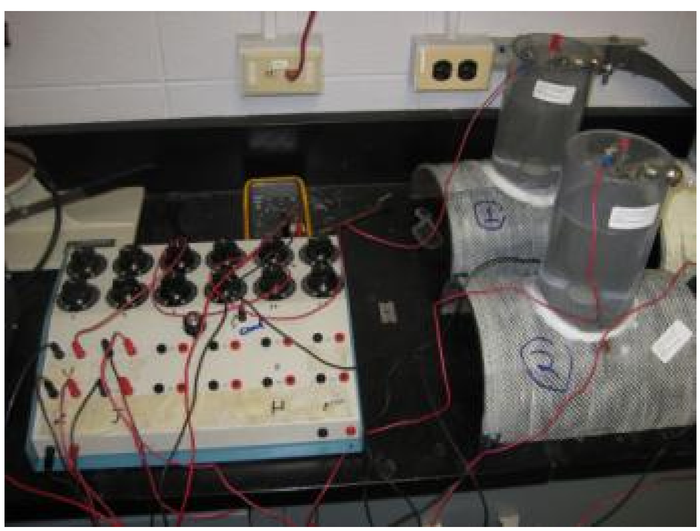


Figure 46 - View of the cathodic disbondment testing assembly

C) Measurement of the Disbonded Area

Two procedures were evaluated for the removal of the thick composite wrap and determining the size of the disbonded area. Procedure A was applied to seven commercially-available composite repair systems and it consisted of cutting a cross-section of the pipe sample and exposing the disbonded area for digital measurements. Procedure B was applied in this project and it evaluated two composite pipe materials with glass fiber and carbon fiber. This procedure consisted of introducing a dye to the electrolyte and exposing the dyed area on the surface to quantify the disbondment.

C.1) Procedure A:

In this procedure, the pipe samples were cut to 2 inch by 2 inch square sections around the test holiday. The composites were then inspected to evaluate their adhesion with the steel. Some of the samples exhibited the disbondment between the composite and the steel pipe. In these samples, the disbonded areas were measured and the samples were cut to inspect their cross-section areas. Other samples exhibited the disbondment between the laminates. In these samples, the laminates were carefully detached down to the lowest layer of primer. The samples were then cut to inspect their cross-section areas.

The exposed sections were photographed and measured to determine the disbondment area for each sample. Table 12 shows the disbondment area measurements of the seven composite products using this procedure. The images taken for the disbondment area and the cross-sections of the samples are shown in Figure 47.

Table 12 - Measured Cathodic Disbondment Areas – Procedure A

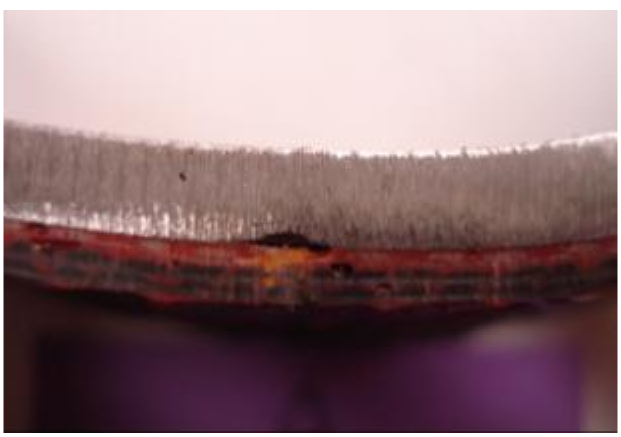
Product Code	Product Type	Disbonded Area, $inch^2$
U	Glass fabric with urethane resin	0.126
C	Glass fabric with epoxy resin	0.033
Z	Carbon-fiber with epoxy resin	0.055
H	Glass fiber with water-cured polyurethane	0.144
A	Carbon fiber with epoxy resin	0.026
P	Glass fiber with urethane resin	0.385
J	E-Glass fiber with urethane resin	0.019

Sample U

Sample C

Sample Z

Sample H



Sample A

Sample P

Figure 47 - Cross-sections of the holidays in the samples

C.2) Procedure B:

In this procedure, a dye solution was used as an electrolyte in order to measure the approximate disbonded area underneath the composite (Figure 48). This procedure is similar to other work to evaluate cathodic disbondment of composites [69]. The procedure was applied to fiber glass and carbon composites with limited success due to the difficulty in measuring the dyed area after the removal of the composite from the surface. Table 13 shows the results of measurements of the disbonded area in the carbon fiber composite using this procedure.

Figure 48 - View of the test assembly with dyed electrolyte

Table 13 - Measured Cathodic Disbondment Areas – Procedure B

	Product Type	Disbonded Area, $inch^2$	
		Sample 1	Sample 2
	Carbon fabric with urethane resin	0.51	0.65

Electrolyte = 3% wt. NaCl in de-ionized water
Cell diameter = 4 inch, Electrolyte depth = 5 inch
Initial holiday diameter = 0.125 inch
Test duration = 90 days

D) Evaluation of Composites Disbondment

The ability to resist cathodic disbondment is a desirable quality for the repair. However, localized disbondment does not necessary mean a loss of the carrying capacity of the composite. The ASTM procedure does not specify maximum disbondment limit for the qualification against cathodic disbondment. When comparing the disbondment of the composite repairs to those of the pipeline coatings, larger disbonded areas were measured in the composites and the size was highly dependent on the quality of the pipe surface preparation during composite installation.

Cathodic disbondment tests on composite repairs may be performed using the ASTM G95 testing procedure as it is more applicable to composite repairs than ASTM G8. The results of the tests may be used to compare the performance of composite materials. The results varied significantly between the products; with the highest disbondment radius about four times the radius of the composite with the lowest disbondment.

Procedure A of cutting the pipe cross section to quantify the disbonded area using digital imaging provided more consistent results than the use of the dye in Procedure B. This is mainly due to the loss of the dye footprint during the process of removing the composite layers.

The Canadian Standard Z245.20 [70] specifies 8.5 mm (0.3 inch) for the cathodic disbondment of FBE coating. Their qualification requirements, shown in Table 14, are based on tests performed for 28-day tests at room temperature as opposed to the ASTM G95 test of 90-day duration.

Table 14 - Qualification requirements of the Canadian Standard [70]

Test	Acceptance criteria		Number of test specimens	Test method
	System 1A	System 1B		
Thermal characteristics	Meets manufacturer's specification	Meets manufacturer's specification	3	Clause 12.7
Cure — ΔTg	≤ 5 °C	≤ 5 °C	3	Clause 12.7
24 h cathodic disbondment at 65 °C	6.5 mm maximum radius	6.5 mm maximum radius	3	Clause 12.8
28 d cathodic disbondment at 20 °C	8.5 mm maximum radius	8.5 mm maximum radius	3	Clause 12.8
28 d cathodic disbondment at 65 °C	20 mm maximum radius	—	3	Clause 12.8
28 d cathodic disbondment at 95 °C	—	20 mm maximum radius	3	Clause 12.8

Note: System 1A: single-layer FBE with glass transition temperature less or equal
System 1B: Single-layer FBE with glass transition temperature larger than 110°C

8. Environmental Durability of the Repairs

A) Introduction

This chapter addresses the environmental factors that may affect the post-construction service life of a composite repair system. It covers the selection of the test methods which are recommended for evaluating the effect of the specific environment that the repair system is exposed to. These tests were performed on typical composite repair systems with glass fiber and carbon fiber to evaluate the applicability of the test methods and the durability of the composite material.

The requirements for the durability of the composite repair systems are provided in the industry specifications and standards, including the ASME PCC-2 [31] and ISO/TS 24817 [32] standards. These two standards are similar with respect to repair system qualification requirements and references are made in the two standards regarding the need for chemical resistance testing.

The ASTM standards D543 [50], C581 [51], D3681 [52], and ISO 10952 [71] are listed in these standards for assessing the composites performance. Ultraviolet light exposure from sunlight is also listed as a concern for some service environments but no specific test method is recommended. The following are the specific requirements for the environmental compatibility of the composites as listed in ASME PCC-2:

When required by the service environment, the repair system shall be protected from UV exposure (e.g., sunlight), water, and damaging chemicals, either as an inherent characteristic or by the application of coating or mechanical barrier.

The qualification of the repair system shall ensure that it is compatible with aqueous and hydrocarbon environments at the qualification temperature. In general, thermoset polymers are compatible with a wide range of environments but consideration needs to be given when the environment is strongly acidic (pH $\leq$3.5), strongly alkaline (pH $>$11), or is a strong solvent.

When the compatibility of the repair system is not available, then specific environmental testing is required from one of the following test procedures, ASTM D 543, ASTM C 581, ASTM D 3681, ISO 10952, or equivalent.

When erosion is the cause of the degradation process, then the repair system should demonstrate that despite this potential loss of laminate material, the repair should survive for the specified repair lifetime.

B) Environmental Durability Testing Procedures

The composite repair system shall be protected from surface conditions and damaging chemicals that may exist in the environment. The qualification of the repair system may include the following requirements:

- Chemical resistance,
- Ultraviolet light deterioration,
- Temperature stability,
- Oxidation Resistance,
- Abrasion resistance, and
- Stress cracking.

B.1) Chemical Resistance:

The ASTM D543 and C581 test methods are commonly used to evaluate the chemical compatibility of the composite repair system. The two methods are similar in that they involve exposing material samples to the chemical environment of interest for sustained periods and then determining whether that exposure has caused any meaningful changes in the sample properties. The ASTM C581 method uses flat test samples immersed in the solution of interest. The ASTM D543 test also immerses flat test samples, but offers the additional option of subjecting samples to constant strain by placing them in a fixture which introduces bending while they are immersed. With either method, samples are tested after the chemical exposure to quantify any changes. Flexural bend and tensile testing are the preferred evaluation methods. Many chemical interaction effects are more active at elevated temperatures and D543 tests can be conducted in environmental chambers.

The immersion of cut test samples is potentially a shortcoming of ASTM D543 and ASYM C581 in that the cut edges and reinforcing fibers of the samples are exposed to the fluid. This may create a path for chemical attack and fluid penetration along the fibers which would not normally exist. In actual service, the edges of the cured material are usually sealed with resin. An alternate chemical resistance test which exposes just the face of a sheet specimen is in ASTM D4398. This method clamps the sheet to a cylindrical test chamber which is filled with the chemical solution of interest. The equipment required for this method is rather more complex than the one needed for ASTM D543 or ASTM C581. The ASTM D3681 and ISO 10952 standards are designed for testing pipe test sections and they are less suitable for this application.

For the evolution of the effect of the specific environment that the repair system is exposed to, it is suggested that 3 or 4 chemicals which commonly exist in the soil environments around the pipelines be tested. Safety, flammability and volatility of the test chemicals can have important ramifications on the effort and cost required to conduct testing of this type. It will be important to have specific information on the chemicals, temperatures, test duration, and sample size before performing these tests.

B.2) Ultraviolet Exposure:

The ASTM G154 [72] addresses the outdoor exposure of nonmetallic components to ultraviolet light. The procedure uses a fluorescent UV light and water apparatus to reproduce the weathering effect which occur when materials are exposed to sun light and moisture in actual usage. Other tests used for evaluating the effect of outdoor exposure include ASTM D5970 [73] and D4355 [74] for geotextile polymers. Both tests also expose the samples to moisture and heat in a Xenon Arc type apparatus.

B.3) Temperature Stability:

The ASME PCC-2 standard specifies that the repair system should not be used above the service temperature limit of (T_g -36^{0}F), where T_g is the glass transition temperature of the composite polymer. The glass transition temperature is the temperature region where an amorphous material changes from a glassy phase to a rubbery phase upon heating, or vice versa if cooling.

Several standard testing methods may be used to the determination of the thermal stability of the composite material; including ASTM E831 [37], ASTM E1640 [38], and ASTM D6604 [39]. The ASTM E831 standard is used to determine the T_g by the Thermo-Mechanical Analysis (TMA). The TMA is a thermal analysis technique which measures dimensional changes with temperature. In TMA, a probe is placed on a sample surface and the movement of the probe is measured as the sample is heated or cooled. With a load applied to the probe, a combination of modulus changes and expansion of the sample are observed.

B.4) Oxidation Resistance:

Several ASTM standards, including D3895 [75], E1858 [76], and ASTM E537 [77] are used to determine the oxidation resistance of the material by the Differential Scanning Calorimetry (DSC) method.

The DSC is a thermal analysis technique which measures the temperature and heat flow associated with transitions in materials as a function of temperature and time. If a sample and an inert reference are heated at a known rate, the temperature difference between the sample and the reference is directly related to the differential heat flow. Such measurements provide quantitative and qualitative information about physical and chemical changes that include endothermic/exothermic processes or changes in heat capacity.

Specific information that can be obtained from the DSC procedure, including the glass transition temperature, melting point, crystallization time and temperature, heats of fusion, oxidative stability, and thermal stability. A complementary technique used to determine if oxidation has occurred is to measure the Oxidative Induction Time (OIT) using DSC. The OIT is defined as the time to the onset of oxidation of a test specimen exposed to an oxidizing gas at an elevated isothermal test temperature. This measurement provides parameters associated with the long-term stability of polymers. A very short OIT is indicative that the material has already been oxidized.

B.5) Abrasion:

There are many different approaches to evaluating abrasion resistance in the industry. Typical abrasion tests use various types of sliding blocks, rotating abrasive wheels, drums, or falling abrasive grit. The resistance to abrasion is greatly affected by the condition of the test, such as the type of the abrading material, the load applied on the specimen, and the duration and the number of loading cycles. For this reason, abrasion tests may be used as index type tests for the quality acceptance of the material.

The major issues to consider in selecting the appropriate abrasion method include determining the characteristics of abrasion which are of concern for the intended application, whether the method fairly represents the damage likely to occur in service, and how repeatable the method is. Examples of standard testing procedures are the ASTM D4886 [78] and D4060 [79] test methods to determine the abrasion resistance using sand paper or sliding block method. However, the consistency and type of the surface texture of the composite material will be factors in determining the effectiveness of these testing methods.

B.6) Stress Cracking:

Many polymer materials are known to have a susceptibility to the development of cracking caused by the combined presence of sustained stress, chemical exposure, and elevated temperature. The ASTM D5397 [80] method places small "dog bone" test specimens in a heated fluid bath with the appropriate chemicals and creates stress in the form of a hanging weight tensile load applied through a force-multiplying lever arm. This method can be adapted to composite pipe materials but the strength of most composites is expected to be much greater than the polyolefin membranes for which the standard was designed.

The suitability of using an open, heated, fluid bath for the chemical solution will depend on the test temperature to be used and the nature of the chemicals. Sustained stress tests tend to be more aggressive than sustained strain tests since there is no opportunity for the material to relax. Sustained strain tests are, however, generally easier to perform. The ASTM D543 for chemical resistance is often used with sustained loads to produce stress cracking.

C) Environmental Durability Test Results

C.1) Chemical Resistance:

The chemical exposure of fiber glass and carbon composite samples was performed in accordance with ASTM D543. Six specimens of each composite type were tested in tensile tests after exposure to various chemicals solutions for 1,000 hours. Figure 49 shows the composite samples conditioned for the chemical resistance tests.

The chemical tests used 10% solutions of the following:

- Gasoline,

- Fertilizer grade 10-10-10,
- Sodium Hydroxide NaOH, and
- Hydrochloric acid HCI.

At the end of the exposure time, specimens were conditioned for a minimum of 40 hours in accordance with ASTM D618 [81] and subsequently tested in tensile tests in accordance with ASTM D638 [82]. The results of the tensile tests are shown in **Appendix D**.

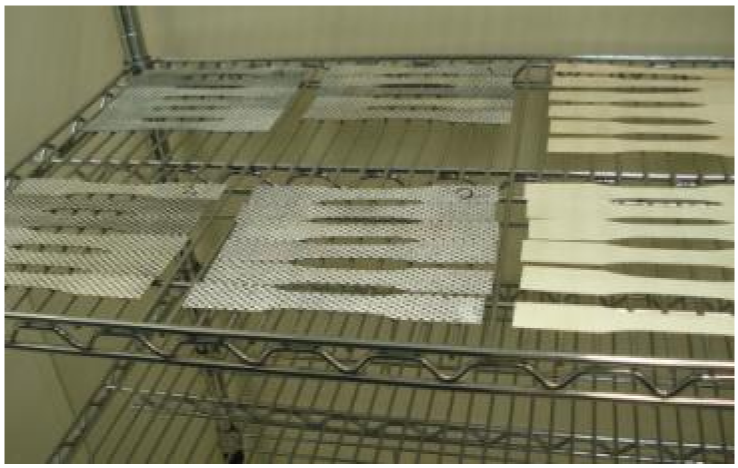


Figure 49 - Conditioning the tensile samples for chemical exposure tests

C.2) Ultraviolet Exposure:

UV aging of the composite specimens was performed using a UV light chamber (Figure 50) in accordance with ASTM G154 using UVA lamps. The test cycles alternated between UV exposure (4-hours at 60^{o}C) and condensation (4-hours at 50^{o}C) for duration of 282 hours. Figure 51 shows the UV-Aged fiber glass and carbon composite samples with the original samples shown in the background for comparison. At the end of the exposure, the specimens were conditioned for a minimum of 40 hours and subsequently tested in accordance with ASTM D638. Figure 52 shows the UV-aged carbon specimen in a tensile test.

The results of the tensile tests of the specimens after the chemical and UV exposures are shown in Table 15 and

Table 16 for the glass fiber and carbon composites, respectively. The results in Table 15 show that the model p-values for the NaOH and HCI are less than 0.05. The low p-values indicate high probability that the effect of these chemicals on the glass fiber composite is significant. Similarly, the results of the HCI exposures show significant effect on the tensile strength of the carbon composite. Figure 53 and Figure 54 show the results of the statistical t-test for the fiber glass and the carbon samples, respectively.

Figure 50 - The UV light testing chamber

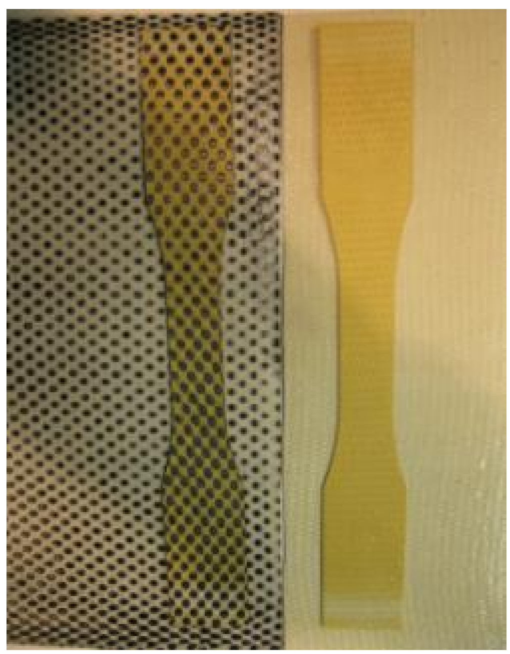


Figure 51 - The UV-aged samples against the original samples in the background

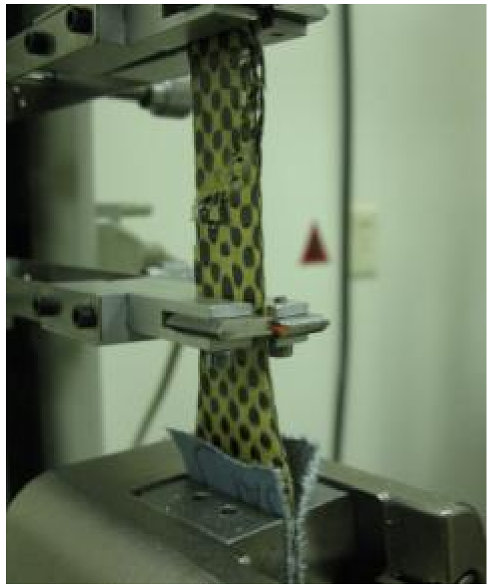


Figure 52 - Tensile test of UV-aged specimen

Table 15 - t-test for Strength of the Glass Fiber Test Groups

T-test for Independent Samples Note: Variables were treated as independent samples					
	Mean - Group 1	Mean - Group 2	t-value	df	p
Control- vs. UV Aged, Strength (psi)	45971.43	44110.00	1.07537	9	0.310189
Control- vs. Gasoline, Strength (%)	45971.43	48207.97	-1.47001	10	0.172306
Control- vs. Fertilizer, Strength (psi)	45971.43	46583.03	-0.39863	10	0.698542
Control- vs. NaOH, Strength (psi)	45971.43	40916.18	3.09026	9	0.012924
Control- vs. HCI Acid, Strength (psi)	45971.43	12625.57	21.3905	10	0.000000

Table 16 - t-test for Strength of the Carbon Test Groups

T-test for Independent Samples Note: Variables were treated as independent samples					
	Mean - Group 1	Mean - Group 2	t-value	df	p
Control- vs. UV Aged, Strength (psi)	98605.52	85501.00	3.71295	9	0.00482
Control- vs. Gasoline- Strength (%)	98605.52	88115.94	2.3673	9	0.04209
Control- vs. Fertilizer- Strength (psi)	98605.52	89313.00	2.01552	9	0.07466
Control- vs. NaOH- Strength (psi)	98605.52	90704.37	2.11522	10	0.06051
Control- vs. HCI Acid- Strength (psi)	98605.52	84489.07	3.83222	10	0.00331

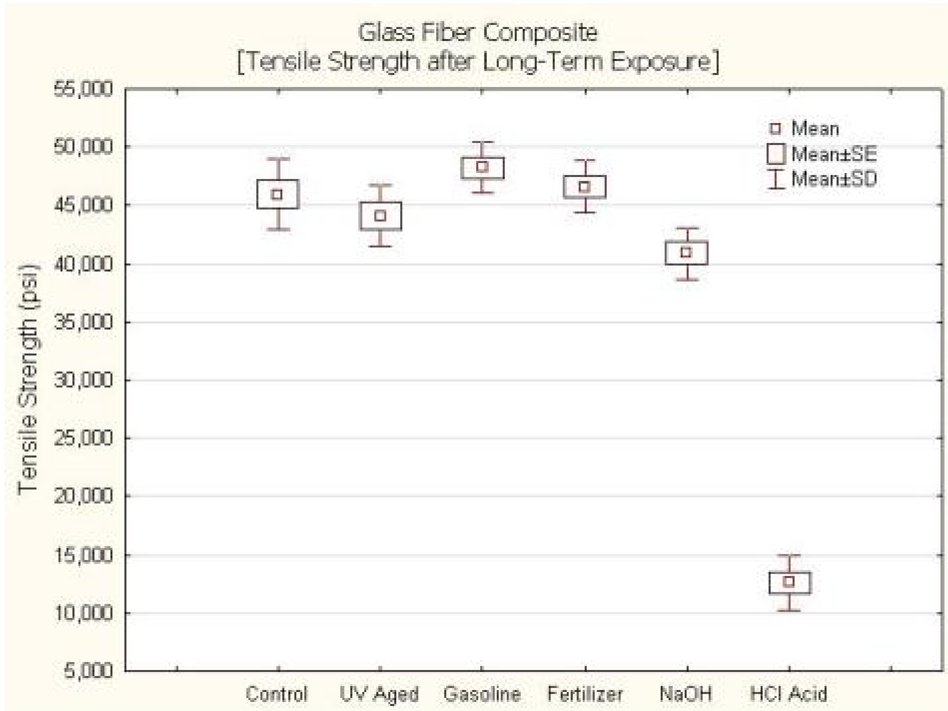


Figure 53 - Statistical mean values of the tensile strength of the glass fiber samples

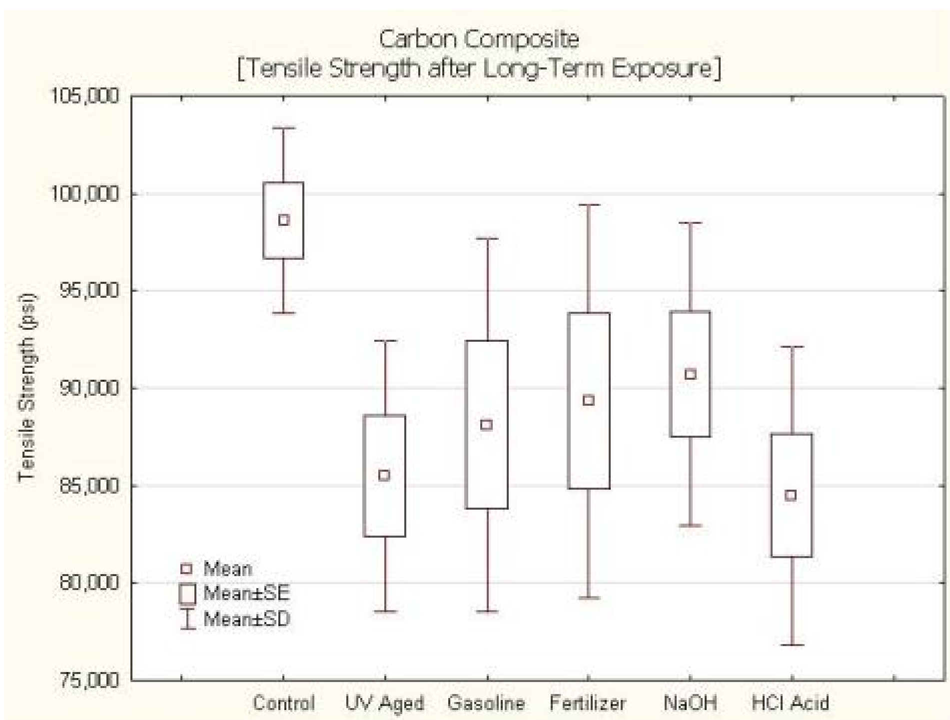


Figure 54 - Statistical mean values of the tensile strength of the carbon samples

C.3) Temperature Stability:

Figure 55 shows the TMA-2940 thermo-mechanical analyzer used in the determination of the glass transition temperature of the composite polymer. The results of the change of the samples dimensions with temperature are shown in Figure 56 and Figure 57 for the glass fiber and carbon composites, respectively.

Figure 55 - The thermo-mechanical analyzer

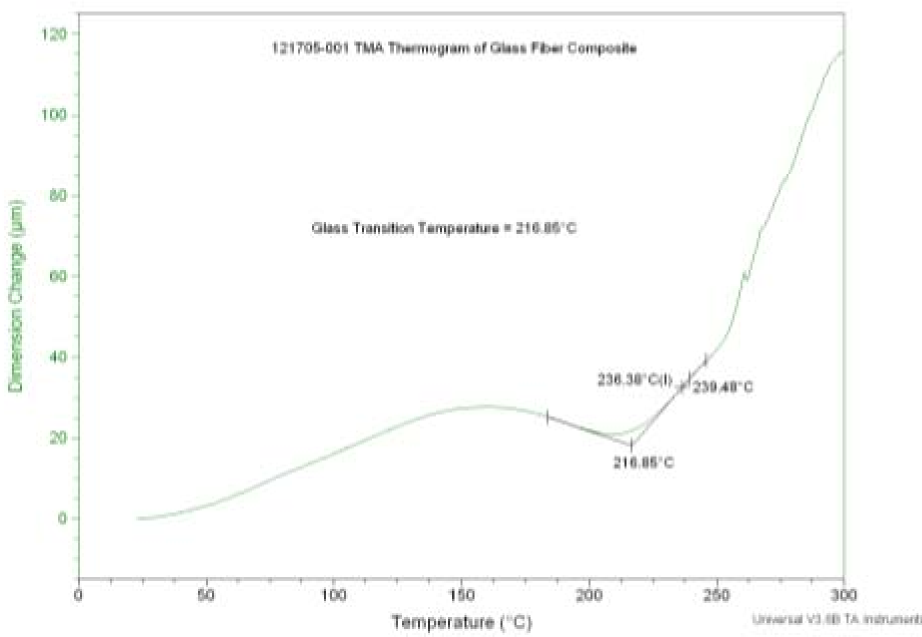


Figure 56 - TMA analysis for the of the T_g of the glass fiber

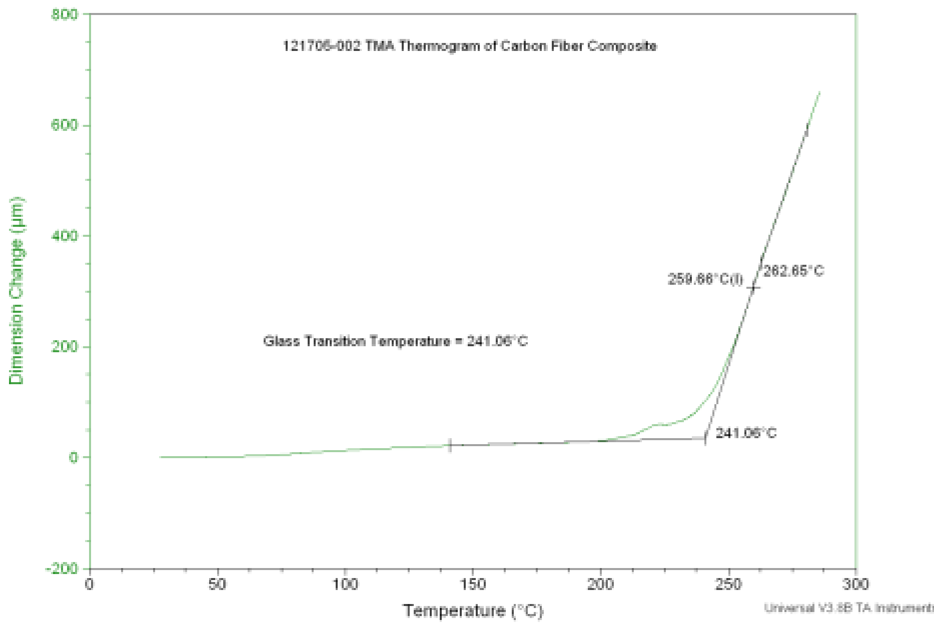


Figure 57 - TMA Analysis for the of the T_g of the carbon fiber

C.4) Oxidation:

Oxidative induction time for the materials was determined in accordance with ASTM D3895. The Differential Scanning Calorimetry (DSC) was measured using the DSC-2920 differential scanning calorimeter shown in Figure 58. The results of the heat flow with time are shown in Figure 59 and Figure 60 for the glass fiber and carbon composites, respectively. The Oxidative Induction Time (OIT) for both composites is shown in the figures and can be used in the quality control of the composite products, based on the polymer design requirements.

Figure 58 - differential scanning calorimeter Device

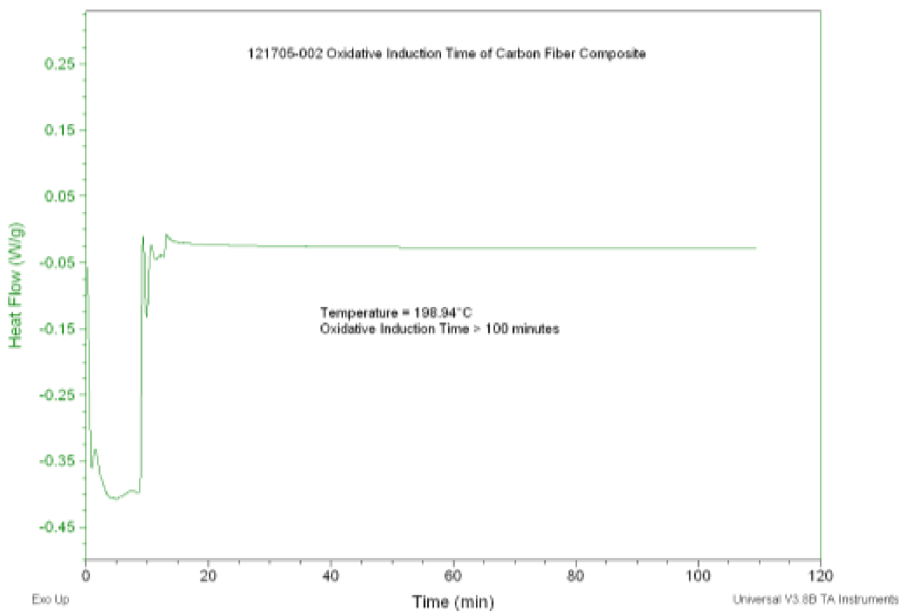


Figure 59 - Oxidative Induction Time for the fiber glass composite

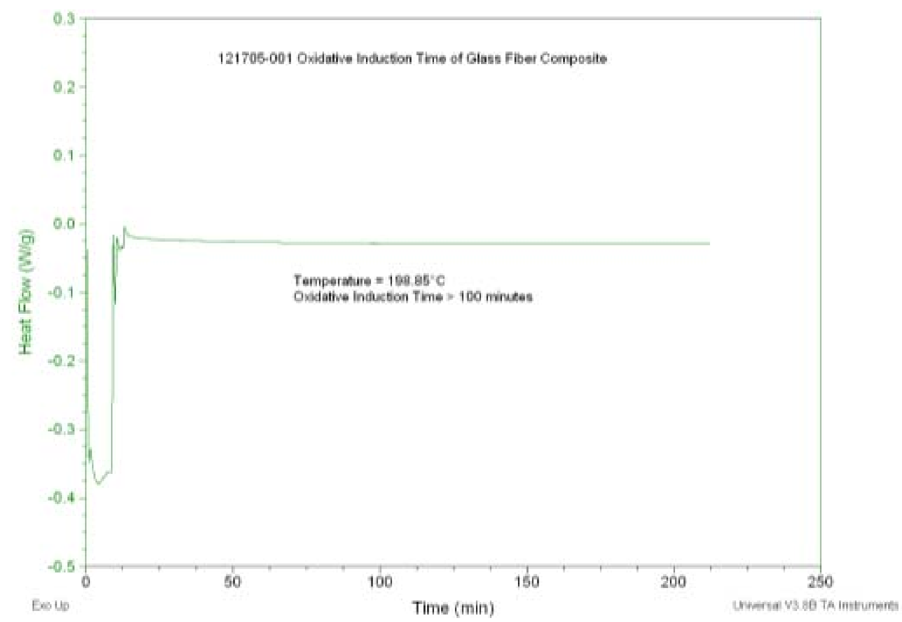


Figure 60 - Oxidative Induction Time for the carbon Composite

C.5) Abrasion Tests:

The composite resistance to abrasion should demonstrate that it survives for its specified lifetime despite the potential loss of laminate material. However, it is difficult to simulate the actual field conditions which cause the loss of the surface material in lab tests. For this reason, abrasion tests are performed under accelerated conditions as index parameters.

Abrasion tests were performed on two composite products with fiber glass and carbon laminates. The test method was modified from ASTM D4060 to utilize a straight abraser rather than and rolling wheel abraser. The tests used the “Taber Linear Abraser” device shown in Figure 61, with an H-22 coarse abraser. A load of 1,600 g (3.52 lb) was applied on the top of the abrading head and tests were performed with applying a linear stroke length of 2 inches for 3,000 cycles.

Six specimens were tested for each product as room temperature and the results of the tests are shown in Figure 62. The results show higher abrasion resistance of the carbon fiber than the fiber glass at the same testing conditions. The results are commonly used for quality control and to compare the abrasion resistance between several products.

Figure 61 - The Taber linear abraser device

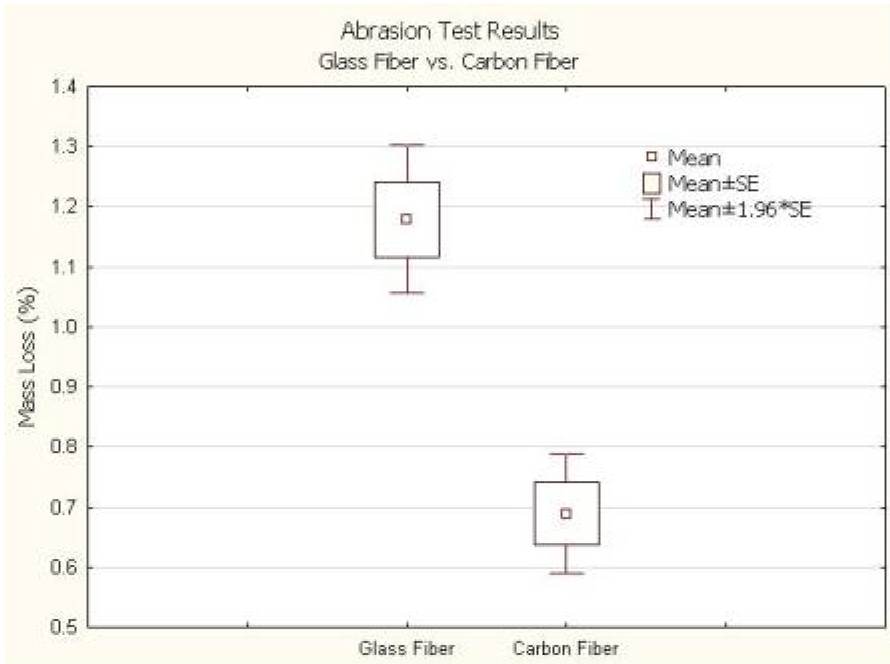


Figure 62 - Results of abrasion tests on the Glass and carbon Fibers

9. Guidelines for the Selection of the Composite Repair Systems

A) Risk Assessment

This section provides guidelines for the selection and application of the composite repair systems. Prior to the application of such repair, the assessment of the defect should be completed to identify the need for the repair, remaining strength of the defected pipe, and selection of the appropriate repair options. Such assessment should be performed in accordance with relevant industry standards, including:

a) Design and performance of oil and gas pipeline systems such as ASME 31.4 [83] and ASME 31.8 [2], and the welding of pipelines [84],

b) Integrity management programs such as ASME B31.8S [4], API 1160 [85], NACE SP 0502 for the direct assessment of external corrosion [86],

c) Fitness for service practices such as API 579 [87].

Several repair methods are currently applied to permanently restore serviceability of transmission pipes. These methods include full-encirclement steel reinforcing sleeves and composite wrap material. A wide variety of composite materials are used in pipeline repair systems. They mainly consist of glass and carbon fiber reinforcement in a thermoset polymer (e.g., polyester, polyurethane, and epoxy) matrix. The long-term performance of these repairs depends on a combination of engineering tests and qualifications of the following elements of the repair:

a) Structural component and interaction of the repair system with the carrier pipe,

b) Surface preparation and application of repair method (e.g.; curing of the composite systems).

There are two potential failure modes for composite repair systems. The first failure mode is a consequence of overloading the composite laminate or wrap. In some instances, the substrate will fail before the composite wrap resulting in a higher load transfer from the substrate and a burst failure of the composite. The second model is the loss of bonding strength and delamination of the composite laminate from the substrate. Accordingly, the design process should involve the two modes of failure to ensure that the composite laminate is not overloaded and that it remains bonded to the substrate.

Additionally, a risk assessment prior to any application should be performed to assess all the potential hazards such as surface preparation of a pressurized pipeline [88]. Other repair design considerations include the evaluation of the external loads, fatigue, fire, electrical conductivity and cathodic disbondment.

The ASME PCC-2 [31] evaluates the design of composite repair systems based on the defect type, namely:

i) Type A Design Case: In this case, the original pipe (substrate) is not leaking, thus requiring structural reinforcement only. Within this design case there are three design methods:

- Pipe allowable stress: The remaining strength of the substrate is included in the design where the yielding of the pipe may or may not be included,
- Repair laminate allowable strains: The remaining strength of the original pipe in not included in the design and the repair is assumed to carry all the loads.
- Repair laminate allowable stresses determined by performance testing: In this method the design is based on long-term performance data of the repair system.

ii) Type B Design Case: In this design case, the substrate is designed for the requiring structural reinforcement and the sealing of through-wall defects (leaks). This type of defect was not a part of the testing program in this project and this design case is not addressed in this report.

B) ASME PCC-2 Design Procedures for Composite Repair Systems

B.1) Repair Laminate According to the Pipe Allowable Stress:

This design method is appropriate if the contribution of the substrate is included in the calculation for the load carrying capability. When the yield strength of the substrate is the criterion for determining the thickness of the repair, the minimum remaining wall thickness (t_s) of the steel substrate when un-reinforced is defined as:

$$t_s = \frac{p_s D}{2s} \qquad (4)$$

Where, p_s is the Maximum Allowable Operating Pressure (MAOP) for the component with the defect, D is the pipe diameter, and s is the yield strength (SMYS) of the pipe material.

The maximum strain (ε) of the substrate and composite combination is given by:

$$\varepsilon = \frac{pD}{2\left(E_c t_{\min} + E_s t_s\right)} \qquad (5)$$

Where p is the internal design pressure, E_c is the tensile modulus of the composite laminate in the circumferential direction, E_s is the tensile modulus of the pipe material, and t_{min} is the minimum repair thickness.

Accordingly, the yield strength (s) in the pipe substrate is:

$$s = \frac{pDE_s}{2\left(E_c t_{\min} + E_s t_s\right)} \qquad (6)$$

Substituting for t_s from Equation (4) into Equation (6) gives:

$$2s\left(\frac{E_c}{E_s}t_{\min}+\frac{p_s D}{2s}\right)=pD \tag{7}$$

Rearranging the equation gives:

$$t_{\min}=\frac{D}{2s}.\left(\frac{E_s}{E_c}\right).\left(p-p_s\right) \tag{8}$$

Equation (8) is the minimum repair thickness for the hoop stress due to the internal pressure as defined in Section 3.4.3.1 of the ASME PCC-2.

Alternatively, when the design of the composite is carried out with the assumption that the underlying pipe substrate does not yield, then the substrate pipe carries no further load after yield and any further load is assumed to be carried solely the composite. Therefore the extra strain, ($\varepsilon_{plastic}$) carried by the composite after yield is given by:

$$\varepsilon_{plastic}=\frac{(P-P_{yield})D}{2E_c t_{\min}} \tag{9}$$

Where, P_{yield} is the internal pressure of the pipe substrate at yield.

The elastic strain, ($\varepsilon_{elastic}$) within the composite laminate is given by:

$$\varepsilon_{elastic}=\frac{(P-P_{live})D}{2\left(E_c t_{\min}+E_s t_s\right)} \tag{10}$$

Where, P_{live} is the pipe internal pressure during repair. Equating the total strain (the sum of Equations 9 and 10) to the design allowable strain of the composite (ε_c), the thickness of the repair can be derived from the following equation:

$$\varepsilon_c=\frac{PD}{2E_c t_{\min}}-s\frac{t_s}{E_c t_{\min}}-\frac{P_{live}D}{2(E_c t_{\min}+E_s t_s)} \tag{11}$$

Equation (11) is used in Section 3.4.3.2 of the ASME PCC-2 to determine the minimum repair thickness (t_{min}) in this case by an iteration procedure.

B.2) Design Based on Repair Laminate Allowable Strains (3.4.5):

The use of this design method is appropriate when the contribution of the substrate is to be ignored in the calculation for load carrying capability. Accordingly, this method is over conservative and results in a much larger repair thickness.

The circumferential (hoop) strain in the composite laminate is defined by:

$$\varepsilon_c = \frac{pD}{2\,t_{\min}\,E_c} - \frac{\upsilon_{ca}\;F}{\pi D\;t_{\min}\,E_c} \tag{12}$$

Where υ_{ca} is Poisson's ratio of the composite laminate in the circumferential direction and F is the sum of the axial tensile loads on the pipe substrate.

Rearranging Equation (12) results in:

$$t_{\min} = \frac{1}{\varepsilon_c}\left(\frac{PD}{2}\frac{1}{E_c} - \frac{F}{\pi D}\frac{\upsilon}{E_c}\right) \tag{13}$$

Equation (10) is the minimum repair thickness for this design case as defined in Section 3.4.4 of the ASME PCC-2.

It should be noted that the thermal expansion coefficients for composites are different than those for the steel pipe substrate. Accordingly, the effect of differential thermal expansion between the repair laminate and the substrate shall be considered in the determination of the strain limit (ε_c) of the composite. ASME PCC-2 lists allowable values for these strains based on the composite thermal expansion coefficient and the design temperature of the system.

B.3) Repair Laminate Thickness Determined by Performance Testing:

This design method is appropriate if long-term performance data are available. The minimum repair thickness of the laminate for circumferential stresses in the pipe is defined as [31]:

$$t_{\min} = \frac{p\,D}{2}\left(\frac{1}{f\,.s_{lt}}\right) \tag{14}$$

Where s_{lt} is the 95% lower confidence limit of long-term strength of the composite determined by performance testing and f is a service factor equals 0.5 for 1,000-hour test data and 0.75 for the design life data.

B.4) Determination of the Length of Repair:

The axial length of the repair must be greater than the axial extent of the stress caused by the defect to ensure adequate stress transfer between the composite laminate and the substrate. The ends of the repair should ideally be tapered to a 5:1 ratio. The minimum length of the repair L_{min} is defined as:

$$L_{\min} = L_{defect} + 5\sqrt{\frac{D\,t}{2}} \tag{15}$$

Where, L_{defect} is the length of the defect.

C) Web-Based Program for the Selection of the Repair System

A web-based computer program was developed to provide the repair thickness and properties of various composite systems which are used in the repair of pipelines. The properties of the repair systems in the computer program were evaluated in this project and in the tests performed in the co-funding research projects [33, 54]. These tests included the tensile and shear strength of the material, the long-term performance in 1,000-hour hydrostatic tests, and the long-term bond strength between the laminates. Other material properties of the composite systems were obtained from the manufacturers' data according to standard ASTM testing procedures.

The output of the computer program is the thickness of the repair system expressed in terms of number of layers (wraps) of the laminates and the axial length of repair. Identifying the repair thickness by the number of layers is a better representation of the correct amount of reinforcement since higher resin content during the installation on site can result in thicker repairs.

The computer program addresses the repairs of various types of defects which include:

- Metal loss due to external corrosion where structural integrity is compromised,
- External damage, such as dents and gouges, and
- Manufacturing or fabrication defects.

According to ASME PCC-2, composite systems may also be applied to other types of defects (such as cracks and leaks) under certain conditions. However, these types of defects were not evaluated in this project and are not in the scope of the computer program.

The computer program addressed the repair of longitudinal pipe sections subjected to circumferential (hoop) stress due to internal hydrostatic pressure. For the repair of other piping systems and for pipes subjected to other loading conditions, the user should refer to ASME PCC-2 and other appropriate standards.

The design equations presented in the program addressed the repair of 'Type-A' damage (Non-leaking Pipe) with a loss of wall thickness less than 80% of the original pipe wall thickness. These equations were presented in the previous section according to the following design methods of the ASME PCC-2 standard:

- Component Pipe Allowable Stress: The design method in this section includes the contribution of the original pipe in the calculation for load carrying capability and assumes that the pipe substrate yields.
- Repair Laminate Allowable Strains: The design method in this section ignores the contribution of the original pipe for load carrying capacity and uses short-term material properties.

Repair Laminate Allowable Stresses Determined by Performance Testing: This design method uses performance data based on long-term failure test results.

A summary of the scope and limitation of the computer program is also listed in the main web page of the program as shown in Figure 63.

The 'Data Entry Page' of the computer program lists eight composite systems in the left menu bar (Figure 64). These composite systems are commonly used in the repair of liquid and gas transmission lines and they include five composite systems with fiber-glass laminates and three composites with carbon fiber laminates.

The data entries should be entered according to certain formats and ranges for each field. An error message will be displayed if the user enters a non-numerical value or values outside the acceptable range of the property. A sample data entry is provided when the user clicks on 'Run Example' button as shown in Figure 64.

An example of the output data of the program is shown in Figure 65. The output lists the repair thicknesses AND LENGTH according to the various design options in the ASME PCC-2 standard. The number of composites layers is based on the minimum required thickness, which is commonly calculated from the option of including the contribution of the original pipe in the calculations.

Figure 63 - The main page of the program

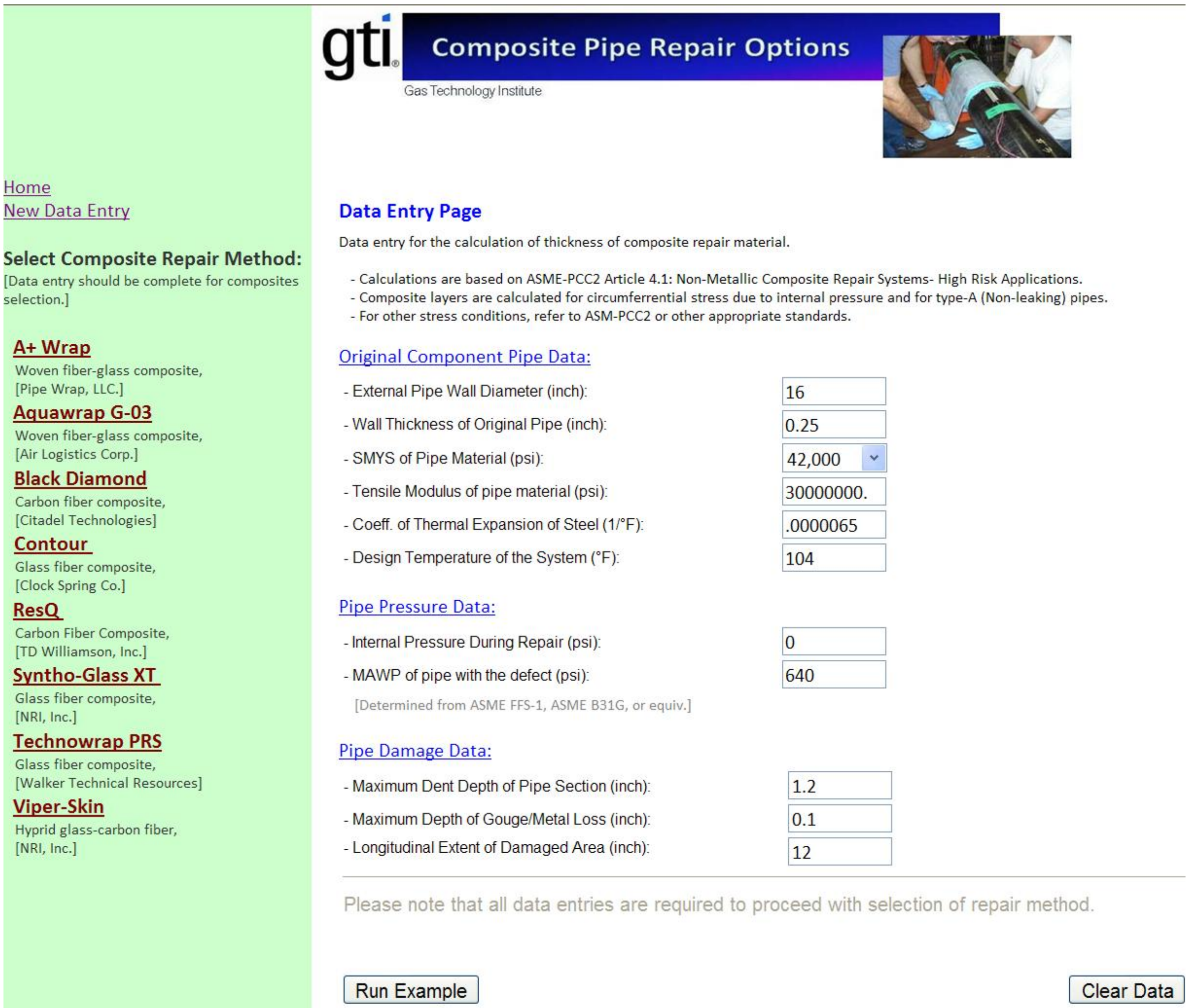


Figure 64 - Example of the data entry page of the program

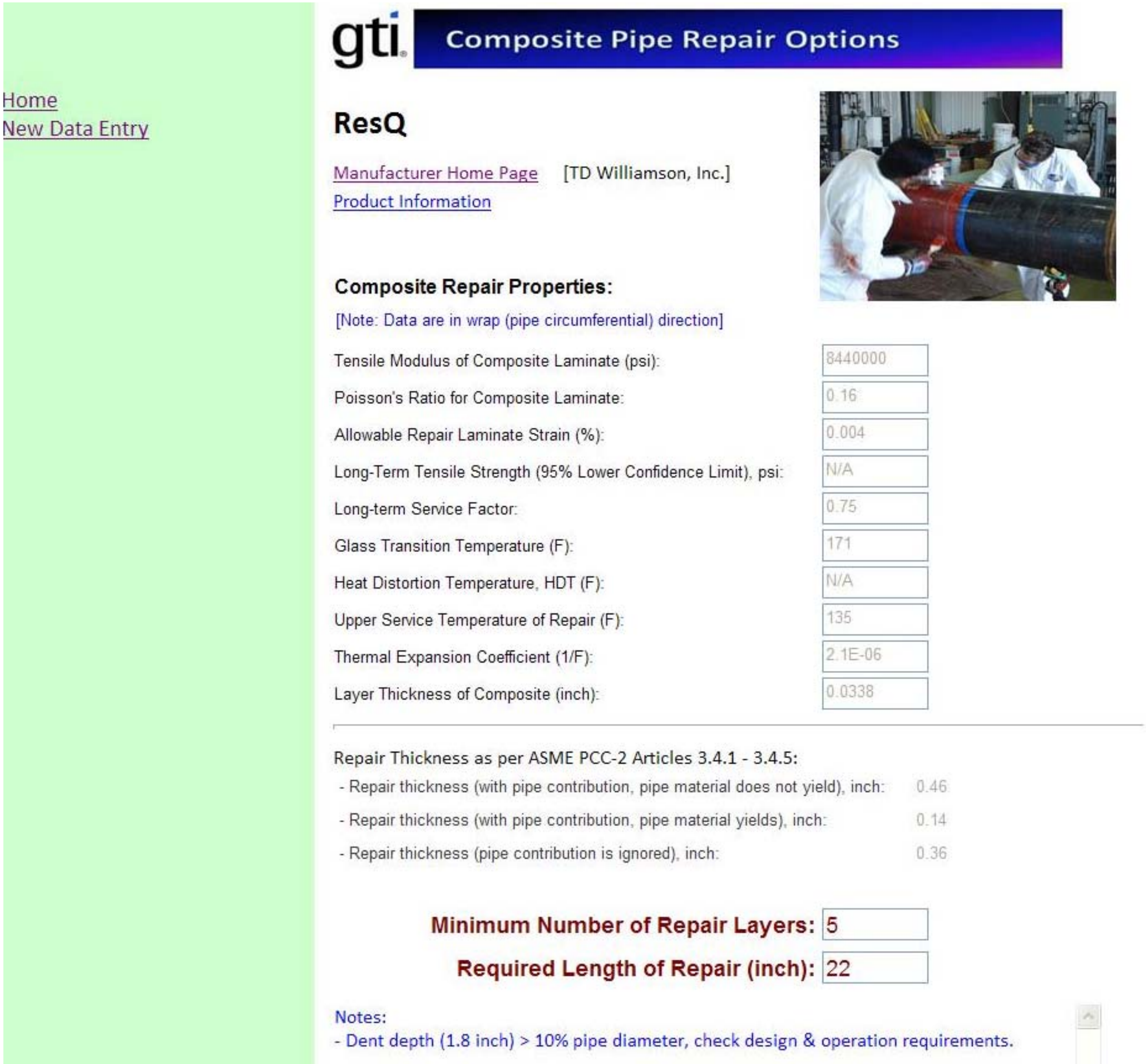


Figure 65 - Example of the data output of the program

D) Parametrical Evaluation of the Input Data

A parametrical study was carried out using the computer program to evaluate the effect of the various design parameters on the strength of the composite, and consequently, the number of layers required for the repair. The parameters included pipe diameter, pipe wall thickness, SMYS of the pipe material, internal pipe pressure during repair, metal loss, and the design temperature. The effect of these parameters was investigated on four fiber-glass and three carbon composites, the composites had various tensile modulus and laminate (ply) thicknesses as shown in Table 17.

Table 17 - Properties of the Composite Repairs

Material		Ply Thickness (inch)	Tensile Modulus (psi)
Fiber-glass	A	0.022	3,010,000
Fiber-glass	B	0.0155	2,780,000
Fibre-glass	D	0.013	3,595,000
Fiber-glass	E	0.0197	4,400,000
Carbon	K	0.018	11,320,000
Carbon	L	0.0193	9,720,000
Carbon	M	0.0338	8,440,000

D.1) Pipe Diameter:

Table 18 shows the properties and operation parameters of the pipe sizes in the parametrical study. The pipe wall thicknesses were constant for all diameters and the corresponding maximum working pressures (MAWP) were calculated as 0.72 of the maximum pressures of these pipes. The computer runs were performed with no internal pipe pressure during repair and with metal loss of 80 percent of the pipe wall thickness.

The number of layers for these operating parameters is shown in Figure 66. The results show no effect of the pipe diameter on the number of layers. This is due to the fact that the increase of the pipe diameter corresponded to a decrease in its operating pressure as shown in Table 18; thus resulting in no change of the stresses in the composites. The low number of layers of composite E in comparison to the other fiber-glass composites of similar ply thickness is mainly due to its higher tensile modulus.

Table 18 - Properties of the Pipe Diameters Analysis

Diameter	**4**	12	**24**	**32**
Thickness	0.25	0.25	0.25	0.25
SMYS	42,000	42,000	42,000	42,000
Design Temp	104	104	104	104
MAWP	3,780	1,260	630	473
P internal	0	0	0	0
Metal Loss	0.2	0.2	0.2	0.2

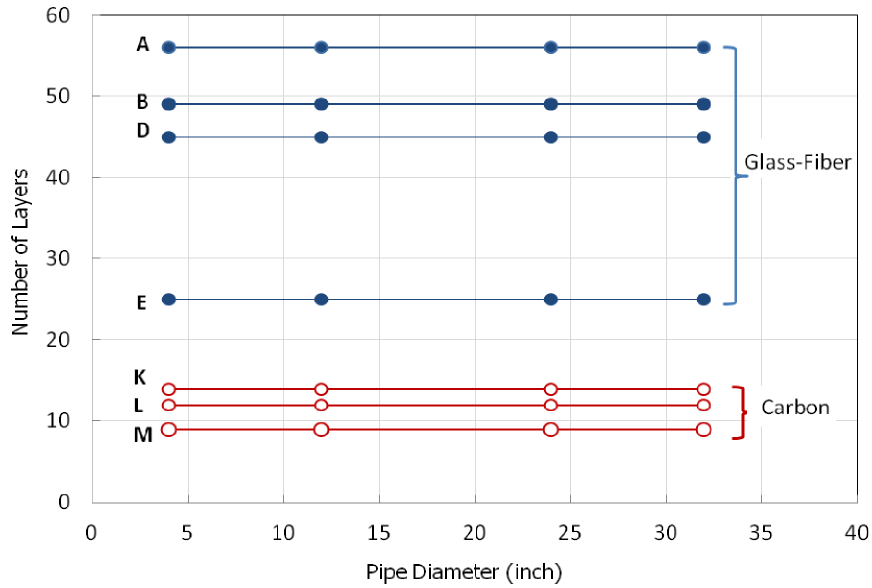


Figure 66 - Number of layers for various composite materials

D.2) Pipe Material Yield Strength (SMYS):

Table 19 shows the properties and operation parameters of the pipes in the parametrical study. The SMYS of the pipe material varied from 35,000 to 70,000 psi and the corresponding maximum working pressures (MAWP) were calculated as 0.72 of the maximum pressures of these pipes. The computer runs were performed with no internal pipe pressure during repair and with metal loss of 80 percent of the pipe wall thickness.

The variation of the number of the composite layers with the change of the pipe yield strength is shown in Figure 67. The results show a significant increase of the number of composite layers for high yield pipes. An evaluation of the operational constraints related to installing a large number of layers and the associated costs may be performed for the repair of pipes with high yield strength.

Table 19 - Properties of the Pipe SMYS Analysis

Diameter	12	12	12	12
Thickness	0.25	0.25	0.25	0.25
SMYS	**35,000**	**42,000**	**52,000**	**70,000**
Design Temp	104	104	104	104
MAWP	1,050	1,260	1,560	2,100
P internal	0	0	0	0
Metal Loss	0.2	0.2	0.2	0.2

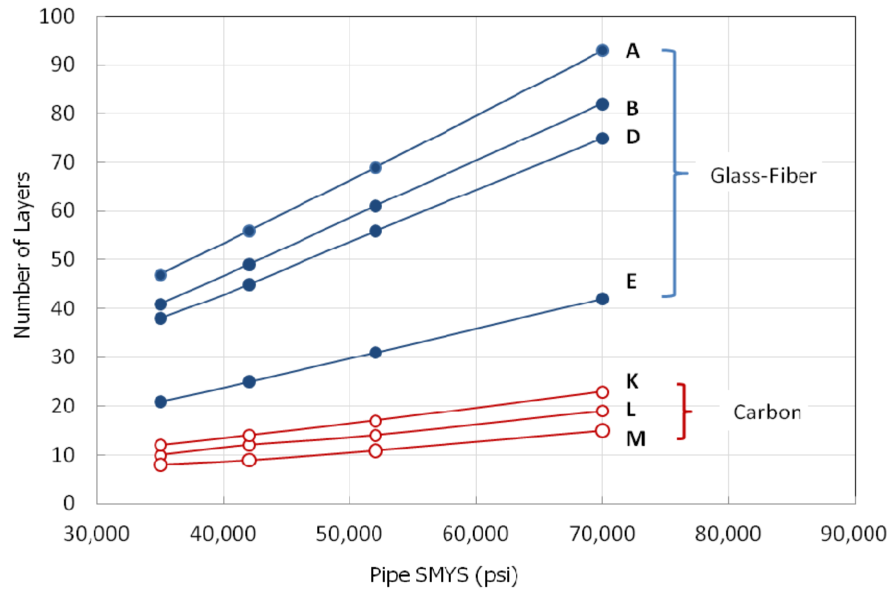


Figure 67 - Change of the repair thickness with pipe yield strength SMYS

D.3) Pipe Wall Thickness:

The properties and operation parameters of the pipes with various wall thicknesses are shown in Table 20. The pipe wall thickness varied from 0.25 to 0.5 inches with a constant pipe diameter of 24 inches. The corresponding MAWP was calculated as 0.72 of the maximum pressure. The computer runs were performed with no internal pipe pressure during repair and with metal loss of 80 percent of the pipe wall thickness.

Similar to the effect of pipe SMYS, the number of composite layers increases with the increase in pipe wall thickness (Figure 68). This is due to the high pressures of the thick-walled pipes which are transferred to the composites due to metal loss.

Table 20 - Properties of the Pipe Thicknesses Analysis

Diameter	24	24	24
Thickness	**0.25**	**0.375**	**0.5**
SMYS	42,000	42,000	42,000
Design Temp	104	104	104
MAWP	630	945	1,260
P internal	0	0	0
Metal Loss	0.2	0.3	0.4

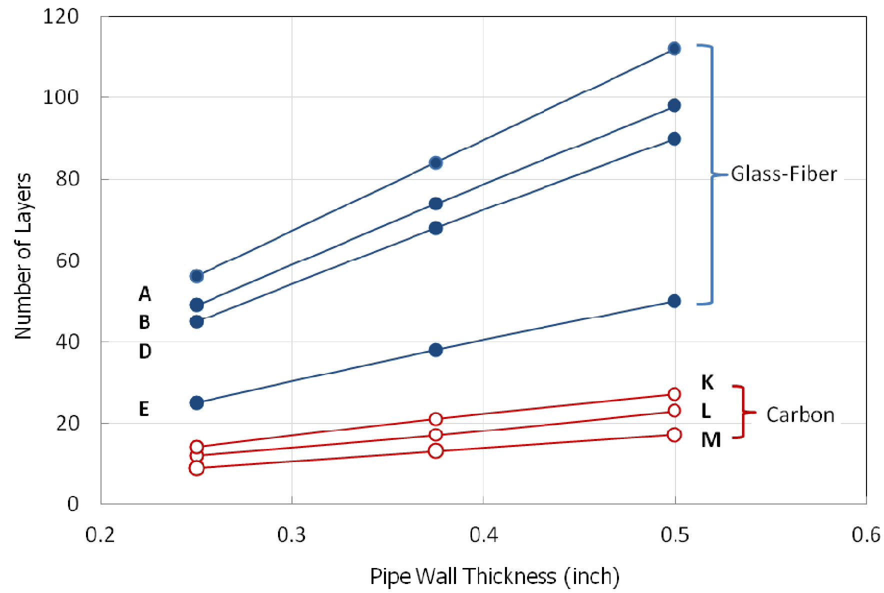


Figure 68 - Change of the repair thickness with pipe wall thickness

D.4) Pipe wall loss:

The properties and operation parameters of the pipes with various metal losses are shown in Table 21. The pipe metal loss varied from 20 to 80 percent of the pipe wall thickness in a constant pipe diameter of 12 inches. The computer runs were performed with no internal pipe pressure during repair. The number of composite layers increases with the increase of the pipe wall loss as shown in Figure 69.

Table 21 - Properties of the Metal Loss Analysis

Diameter	12	12	12	12
Thickness	0.25	0.25	0.25	0.25
SMYS	42,000	42,000	42,000	42,000
Design Temp	104	104	104	104
MAWP	1,260	1,260	1,260	1,260
P internal	0	0	0	0
Metal Loss	**0.05**	**0.1**	**0.15**	**0.2**

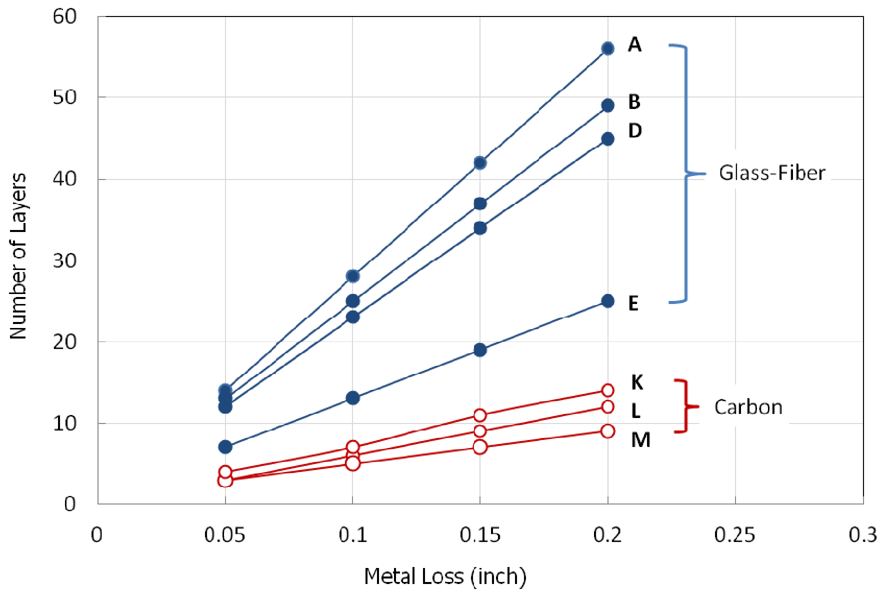


Figure 69 - Change of the repair thickness with pipe wall loss

D.5) Pipe Repair Pressure:

Composite repairs are commonly applied on live lines with the pipe internal pressure (P_{live}) at its operational level or reduced by about 20 percent as a safety procedure during repair. The properties and operation parameters of the pipes with various operating pressures during repair are shown in Table 22. The pressures varied from zero pressure to 100 percent of the MWAP of the pipe line.

The number of the composite layers decreased with the increase of pipe repair pressure as shown in Figure 70. The stresses in the composite repair decrease at high pressures during repair since the increase in P_{live} results in a decrease in the elastic strains of the composite as shown in Equation 7.

Table 22 - Properties of the Pipe Pressure Analysis

Diameter	12	12	12
Thickness	0.25	0.25	0.25
SMYS	42,000	42,000	42,000
Design Temp	104	104	104
MAWP	875	1,260	1,260
P internal	**0**	**630**	**1,260**
Metal Loss	0.2	0.2	0.2

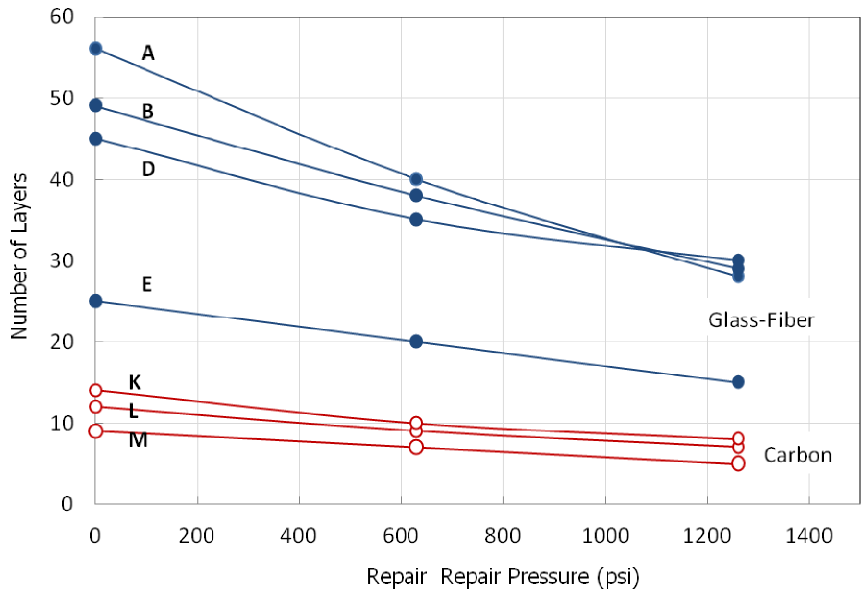


Figure 70 - Change of the composite thickness with pipe repair pressure

D.6) Pipe Operating Temperature:

The strength and stiffness of composite materials is a function of temperature. As the temperature is increased both the composite strength and stiffness reduce. Significant reductions in these properties occur as the temperature approaches either the glass transition or heat distortion temperature of the resin in the matrix material. Temperature de-rating factors are used in the design methodology for service temperatures greater than 104^{O}F [31]. The de-rating factors are used in the determination of the composite.

The properties and operation parameters of the pipes to evaluate ethe effect of temperature are shown in Table 23. The temperatures varied from 32^{O}F to 250^{O}F. The stresses in the composites were highly dependent on the thermal expansion coefficient of the repair material and the results in Figure 71 show general increase of the number of layers with the increase in temperature.

Table 23 - Properties of the Pipe Temperature Analysis

Diameter	12	12	12	12
Thickness	0.25	0.25	0.25	0.25
SMYS	42,000	42,000	42,000	42,000
Design Temp	**32**	**72**	**104**	**250**
MAWP	1,260	1,260	1,750	1,260
P internal	0	0	0	0
Metal Loss	0.2	0.2	0.2	0.2

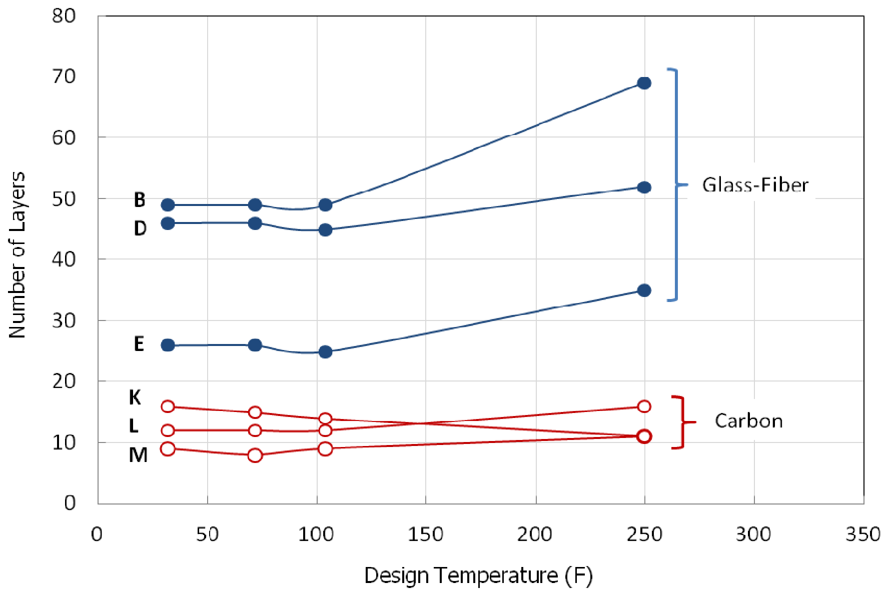


Figure 71 - Change of the composite thickness with temperature

10. Summary and Conclusions

The selection of the appropriate pipe repair method is a challenging task due to the wide range of metallic and composite repair products in the market, the variety of their characteristics, and the various parameters that affect the repair's long-term serviceability.

The option of pipe replacement is generally a conservative and safe one since the damaged pipe section is removed and replaced. However, it requires service interruption and appropriate procedures for welding and inspection. Several research projects have investigated the use of metallic sleeve repairs. For the option of leak repairs using type B sleeves, similar welding and inspection procedures are required when the sleeve is installed while the pipe is in-service. Although steel sleeves are widely used, long-term problems still exit resulting from improper installation and corrosion.

Composite systems were investigated in this report for the permanent repair of liquid and gas transmission and distribution pipelines with corrosion and mechanical damage (i.e., dents and gouges). Prior to the application of the repair the following steps should be considered:

- An assessment of the defect should be completed to identify the need for the repair, remaining strength of the defected pipe, and selection of the appropriate repair options. Such assessment should be performed in accordance with relevant industry standards.
- Determination of the short and long-term properties and performance of the repair, its interaction with the carrier pipe under the expected internal and external loads, and its long-term durability in the pipe environment.
- An evaluation of the surface preparation procedures. Pipe grinding should be used on the damaged area to produce smooth surface and remove the harmful stress concentration of defects and micro cracks. If cracks in the defected are not entirely removed, an alternative repair technique should be applied.
- Qualification of the installers and the installation procedure (e.g.; number of layers, application of the adhesive, and curing of the composite systems).
- A risk assessment to assess all other potential hazards such as surface preparation of a pressurized pipeline, fire and electrical hazards, and cathodic protection of the system.

A parametric study using the Design-of-Experiment (DoE) methodology was performed to model the pipe-composite repair at various material properties and loading conditions. The results of the study provided an understanding of the influencing properties which is further investigated in the experimental program. The most significant parameters which affect the performance of the repair are the pipe and the repair tensile modulus, applied pressure, and pipe size. On the other hand, the size of the damage and the Poisson's ratio of the wrap have no significant effect on the stresses in the pipe-composite system.

There are two potential failure modes for composite repair systems. The first failure mode is a consequence of overloading the composite laminate or wrap. The second model is the loss of bonding strength and delamination of the composite laminates. The report investigated the testing requirements to determine the properties relevant to both failure modes. These testing requirements included the following:

- Short-term tests: Including tensile strength, tensile modulus of the composite, shear strength at the pipe-composite interface, and the interlaminate shear between the composite laminates.
- 1,000-hour tests: Including the tensile strength of the composite, interlaminate shear strength, and the hydrostatic pressure tests on pipe samples with composite repair. The results of these tests are used with the appropriate safety factors in the design of the composite system.
- 10,000-hour tests: The results of these tests at elevated temperatures were extrapolated to predict the service life strengths of the composites. The rate process procedure was presented and used to extrapolate the 20-year bonding strengths of the composites. The results provided a comparative analysis and demonstrated the significant effect of temperature on the bond strength of the composites.

A testing procedure and analysis were developed to evaluate the composite repairs under internal hydrostatic loading, cyclic loading, and external bending loads. The ASME PCC-2 standard for repair of pressure equipment and piping was used for the estimation of the stresses from the bending test results.

Guidelines for evaluating the effects of cyclic pressure on the performance of composite repairs were presented. In particular, a testing procedure was established to provide a consistent protocol so that meaningful test results are generated to permit the assessment of composite technologies. Additionally, guidance is provided on interpreting and applying the test results to quantify the long-term performance and to establish a useful service life condition for the repair system.

The ability to resist cathodic disbondment is a desirable quality for the repair. Cathodic disbondment tests on composite repairs were performed using the ASTM G95 testing procedure as it is more applicable to composite repairs. When comparing the disbondment of the composite repairs to those of the pipeline coatings, larger disbonded sizes were measured in the composites. The disbondment was highly dependent on the quality of the pipe surface preparation during composite installation.

The composite repair system should be protected from surface conditions and damaging chemicals that may exist in the environment. Tests were performed to evaluate the environmental compatibility of the repair systems with respect to the following:

- Chemical resistance to gasoline, fertilizer, sodium Hydroxide, and hydrochloric acid,
- Ultraviolet light deterioration,
- Temperature stability,
- Oxidation Resistance,
- Abrasion resistance, and
- Stress cracking.

In general, composite repair systems consisting of glass and carbon fibers with thermoset polymers demonstrated high resistance to temperature and oxidation. These systems were also compatible with a wide range of environments. However, exposure to high acidic environment significantly reduced the strength of this material.

Most of the composite repair manufacturers develop their own design procedures to determine the required number of layers based on pipe and damage characteristics. The manufacturers' designs were compared with the design requirements of the ASME PCC-2 standard. The evaluation shows that the numbers of wraps of the repair systems are generally more conservative in the ASME PCC-2 standard than the ones provided by the manufacturers.

The ASME PCC2 design procedure was implemented in the web-based program: Composite Pipe Repair (CPR). The program can be accessed at the web address:

http://gasapps.gastechnology.org/cprguide

The web program is a public domain and an access is provided to the users when they click on the posted link and request a user ID and a password.

The program provides the properties and design parameters of the composite repair methods, the number of layers, and the length of repair for a given damage on the pipe surface; providing that appropriate DOT regulatory requirements and applicable industry standards are observed.

A parametrical study was carried out using the computer program to evaluate the effect of the various design parameters on the strength of the composite, and consequently, the number of layers required for the repair. The results demonstrated the increase of the number of composite wraps with the increase of pipe pressure and wall thickness. The number of composite layers also increased for the pipes with high yield strength (SMYS). The web program was accordingly limited to yield strength up to 70,000 psi since the use of higher yield strength pipes required impractically larger number of wraps for most of the repair systems.

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[END OF REPORT]

Appendix A – Accelerated Tensile Creep Tests

September 7, 2012

Mr. Khalid Farrag
Gas Technology Institute
1700 S. Mount Prospect Rd.
Des Plaines, IL 60018

Email: khalid.farrag@gastechnology.org

Re: Elevated Temperature Creep Testing

Dear Mr. Farrag:

TRI/Environmental, Inc. (TRI) is pleased to present this final report for accelerated creep testing. All work was registered and performed under TRI log number E2280-63-05. The following sections describe the work and present the results.

INTRODUCTION

Objective

The objective of this effort was to determine the long term tensile strength of composite materials using elevated temperature conventional creep tests.

MATERIAL AND TEST EQUIPMENT

Material

The materials tested were prefabricated fiberglass and carbon composite dogbones identified as NF 4-18 and NC 4-18 respectively.

Equipment

- Testing platforms: Instron Model 5583 load frame under computer control and BTI multi-station lever action creep frames.
- Environmental chamber: TRI Model TRI CIP conventional isothermal chamber.

- Extensometers: Epsilon Model SW3542-0200-050-ST; Trans Tek LVDT-dc, Model 0245-0000
- Temperature controller: Omega model 76020; Fuji Electric PXZ-4 temperature controllers.
- Heating/cooling - Electrical/liquid CO_2
- Data acquisition: Instron data acquisition with Bluehill2 software; National Instruments data acquisition & Labview V5.1 software.

RESULTS

Short-term tensile testing was performed using ASTM D 3039, *Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials*, to establish the baseline tensile strength of the specific products being tested. Testing was conducted on an Instron 5583 load frame using Instron self tightening wedge clamps. Strain was measured using an Epsilon extensometer. Individual specimen results and the average ultimate tensile strengths (UTS) for each product are reported in Table 1.

Table 1. Product Tested Tensile Strengths

Product	Tensile Strength (lbs) / Tensile Strain (%)			
	Specimen 1	Specimen 2	Specimen 3	Average (UTS)
Fiberglass	787.3 / 1.14	856.3 / 1.23	866.6 / 1.23	836.8 / 1.20
Carbon	2881.9 / 1.00	3169.2 / 1.07	2708.2 / 0.96	2919.7 / 1.01

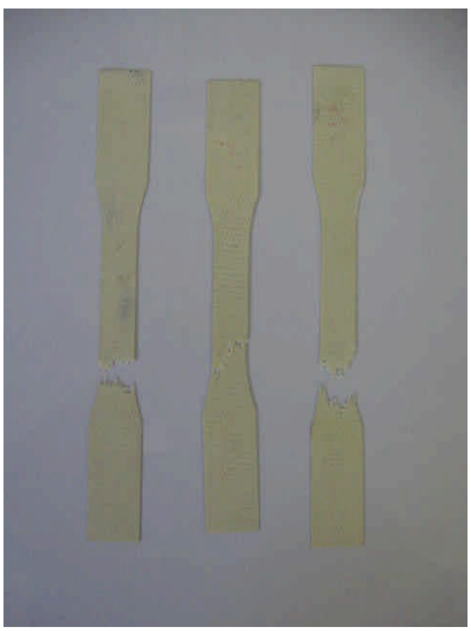
Elevated temperature conventional creep testing was performed using ASTM D 3039 tensile dogbones. Testing was conducted on BT multi-station lever action creep frames. Fiberglass specimens were clamped using aluminum plate clamps. The tabs of the Carbon specimens were cast in epoxy and post-cured for 12 hours. The epoxy block was then clamped using aluminum plate clamps. Strain was measured with a Trans Tek LVDT.

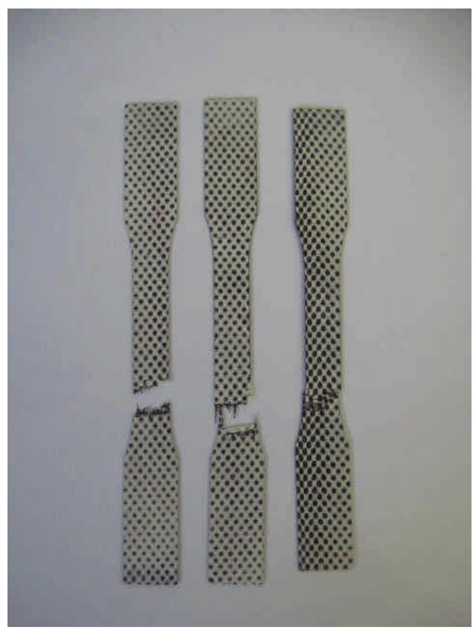
Each specimen was allowed to reach equilibrium at the prescribed temperature of 60^{o}C prior to test initiation. Specimens were then ramped to the specified percentage of UTS and then held at that load until failure or 1,000 hours. Results of the creep testing are reported in Table 2. Short-term tensile stress/strain and creep strain curves may be found in the attached graphs.

Table 2. Creep Results

Product	Test Temperature (^oF / ^oC)	Applied Load (% UTS)	Time to Rupture (hrs)
Fiberglass	140 / 60	30	>1000
Fiberglass	140 / 60	30	>1000
Fiberglass	140 / 60	30	>1000
Fiberglass	140 / 60	60	18.7
Fiberglass	140 / 60	60	>1000
Fiberglass	140 / 60	60	>1000
Fiberglass	140 / 60	60	1061
Carbon	140 / 60	30	>1000
Carbon	140 / 60	60	>1000
Carbon	140 / 60	60	158

PHOTOS

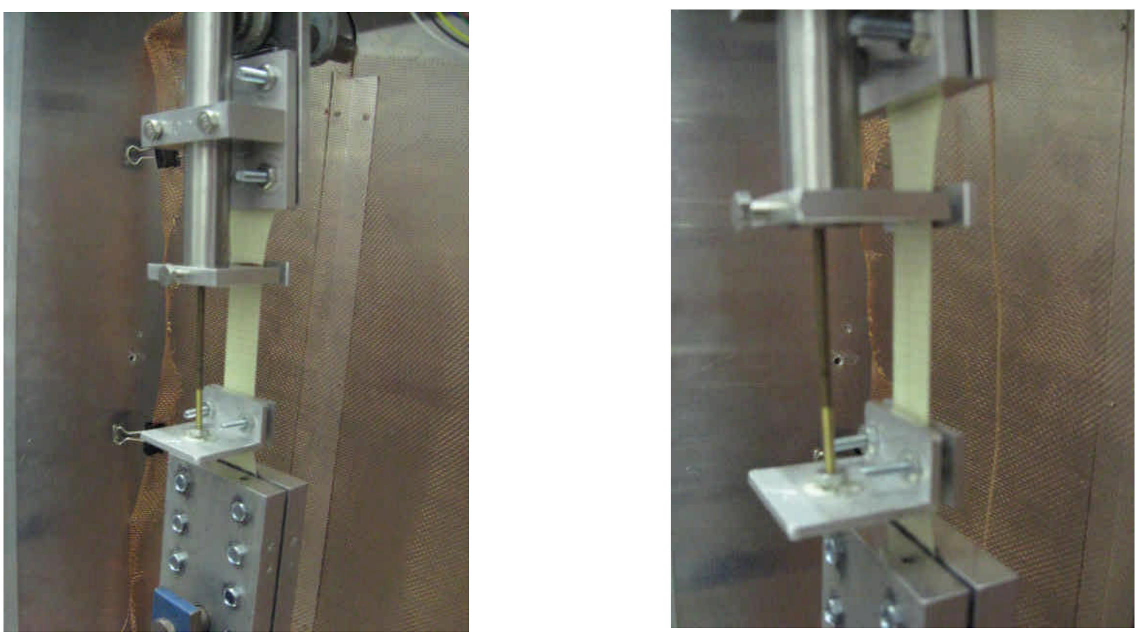




Figures 1 & 2. Short-Term Tensile Ruptures for Fiberglass and Carbon

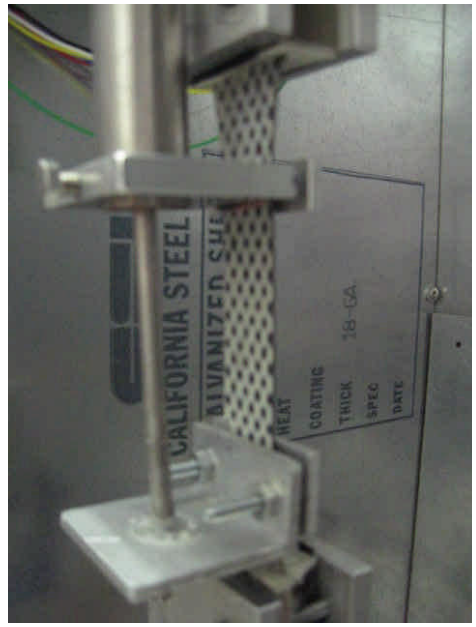
Figure 3. Conventional Creep Frames

Figure 4. Inside of Creep Chamber

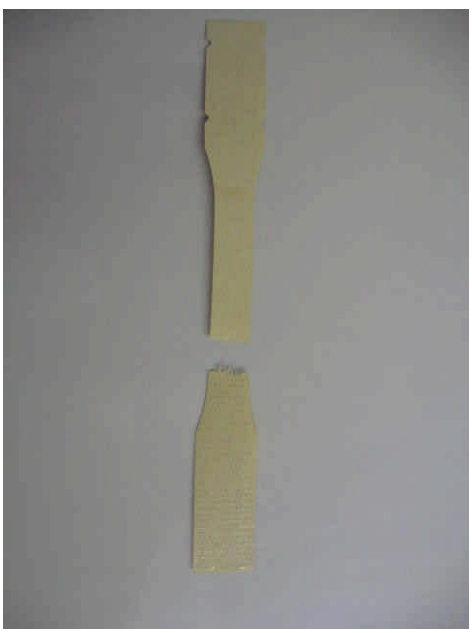


Figures 5 & 6. Typical Fiberglass Creep Specimens

9063 Bee Caves Road / Austin, TX 78733 / 512-263-2101 / FAX 263-2558 / 800-880-TEST



Figures 7 & 8. Typical Carbon Creep Specimens



Figures 9 & 10. Creep Ruptures for Fiberglass and Carbon at 60% UTS

Figures 11 & 12. Epoxy Block and Plate Clamp for Carbon Creep Tests

CONCLUSION

TRI is pleased to be of service to this work effort. If you have any questions or require any additional information, please contact me at Jnelson@tri-env.com or telephone to 512 263 2101.

Sincerely,

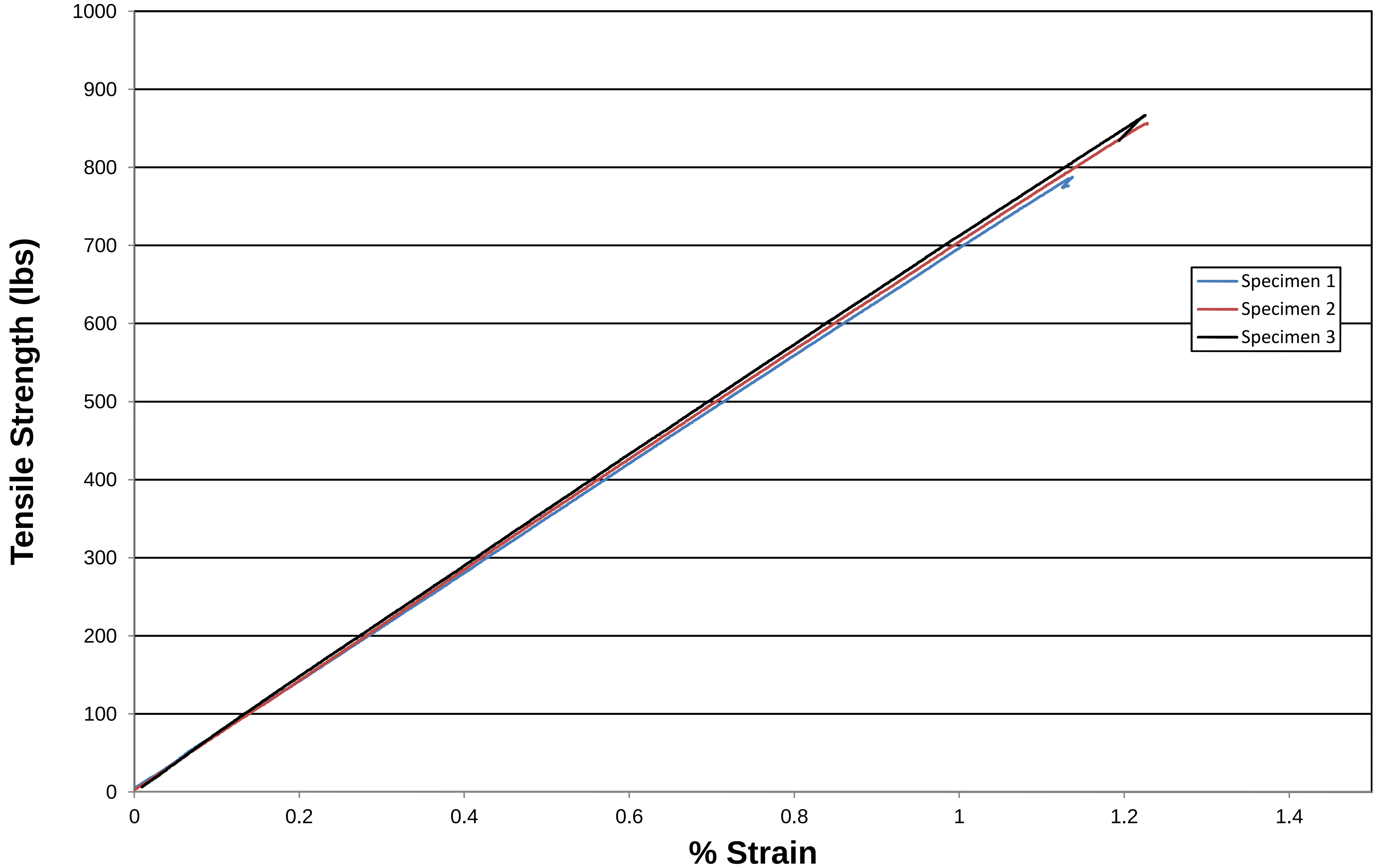
Jarrett A. Nelson
Special Projects Manager
TRI Geosynthetic Services
www.GeosyntheticTesting.com

Attachments

Tensile Test Results - ASTM D3039

TRI Client : Gas Technology Institute

Product: Fiberglass



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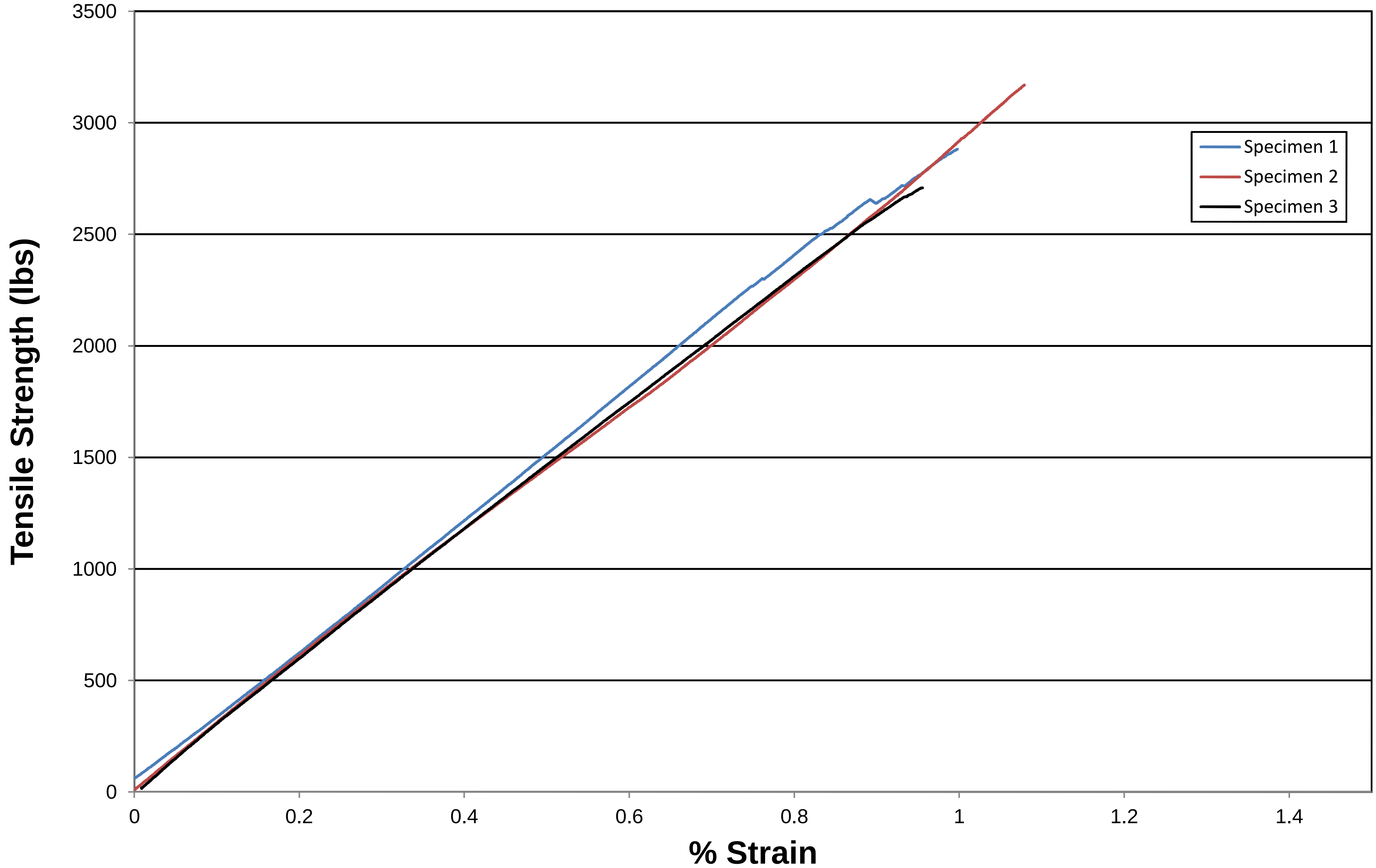
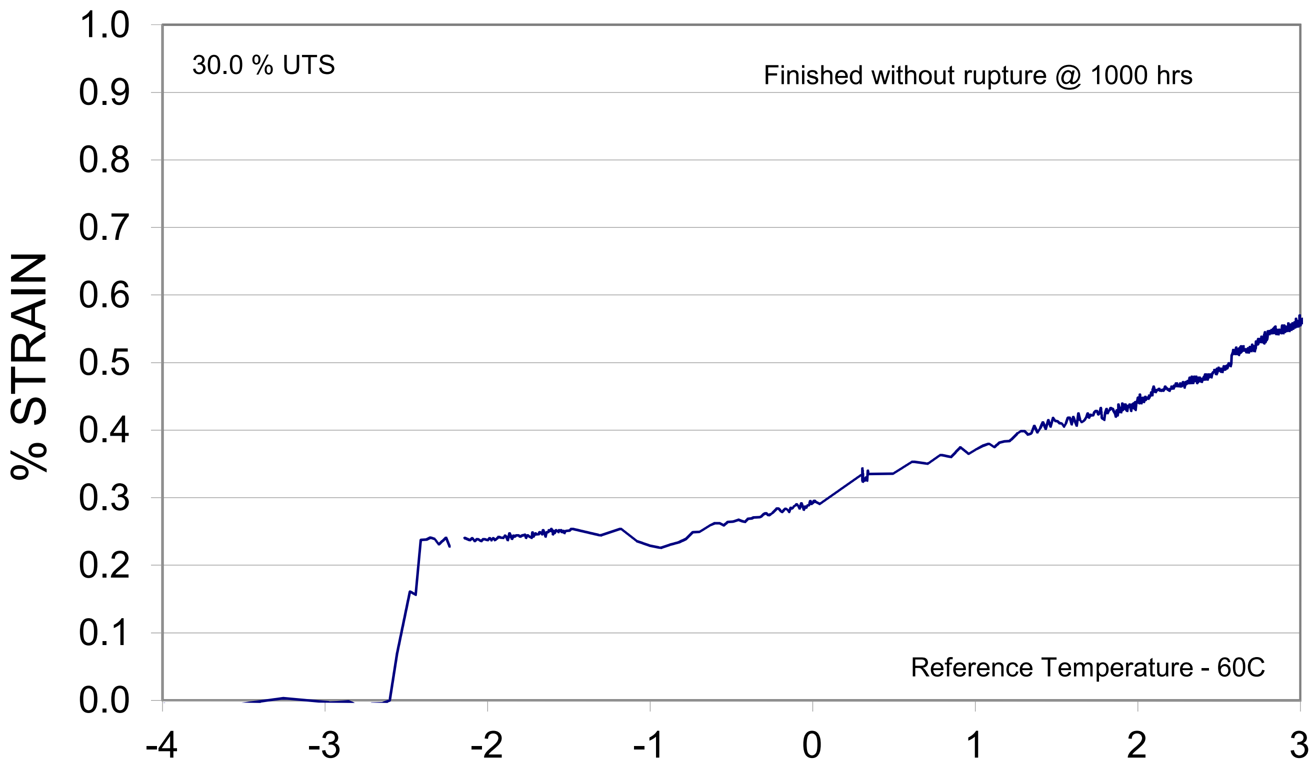
Tensile Test Results - ASTM D3039

TRI Client : Gas Technology Institute

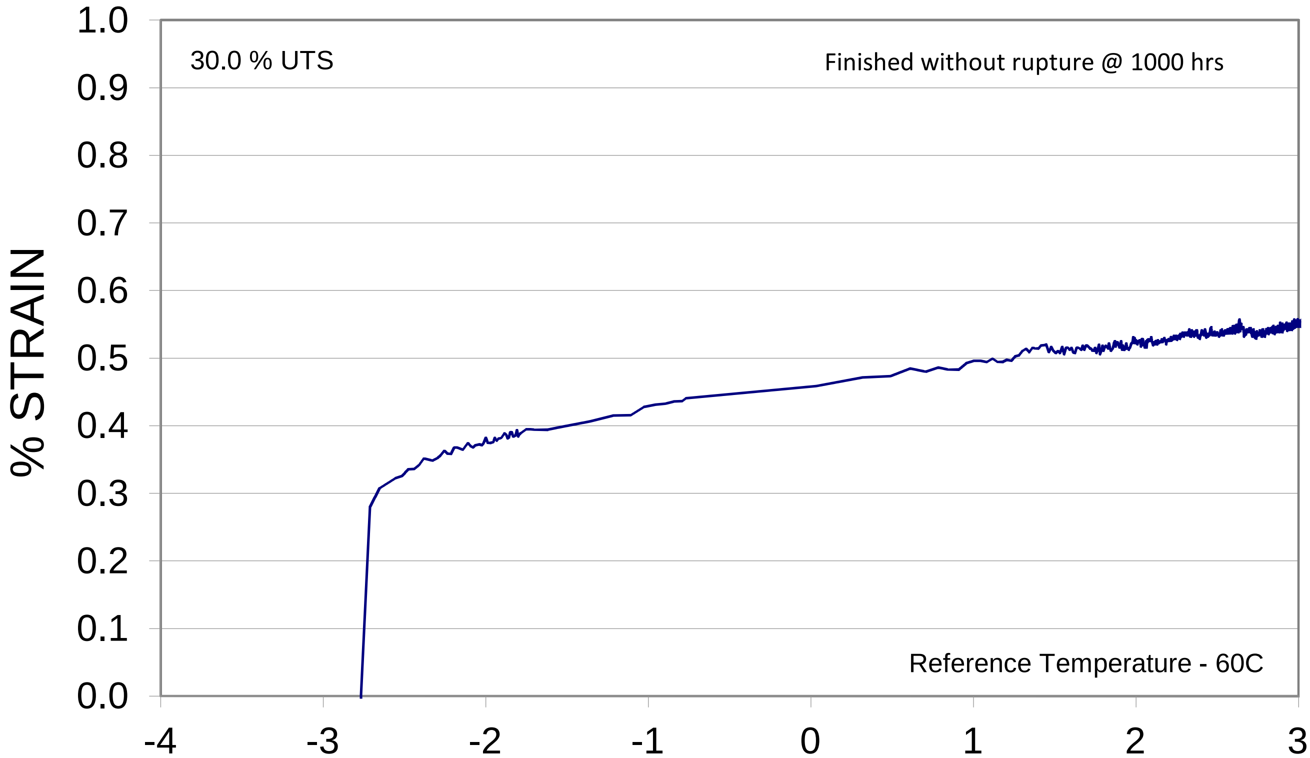
Product: Carbon

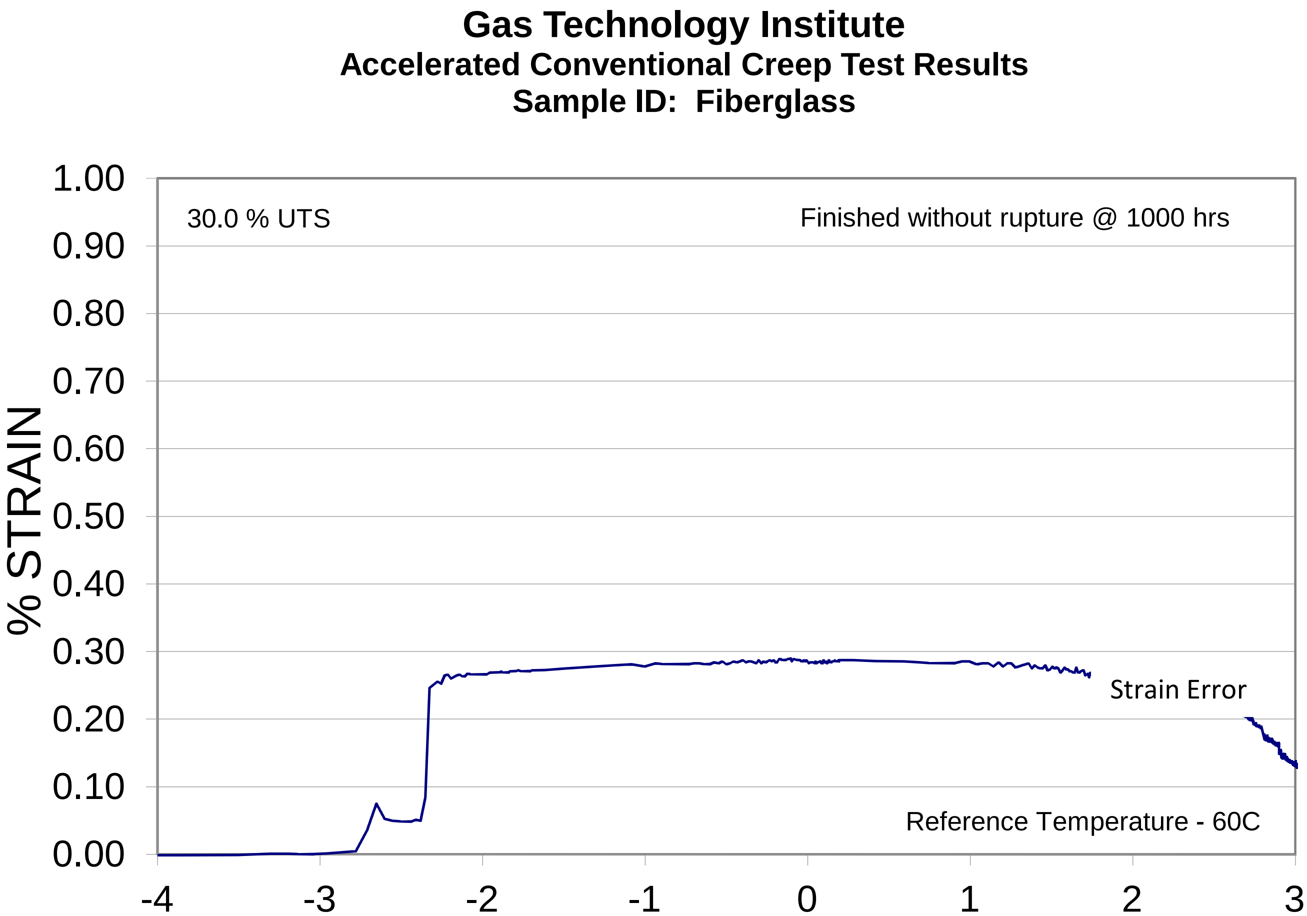


Gas Technology Institute
Accelerated Conventional Creep Test Results
Sample ID: Fiberglass

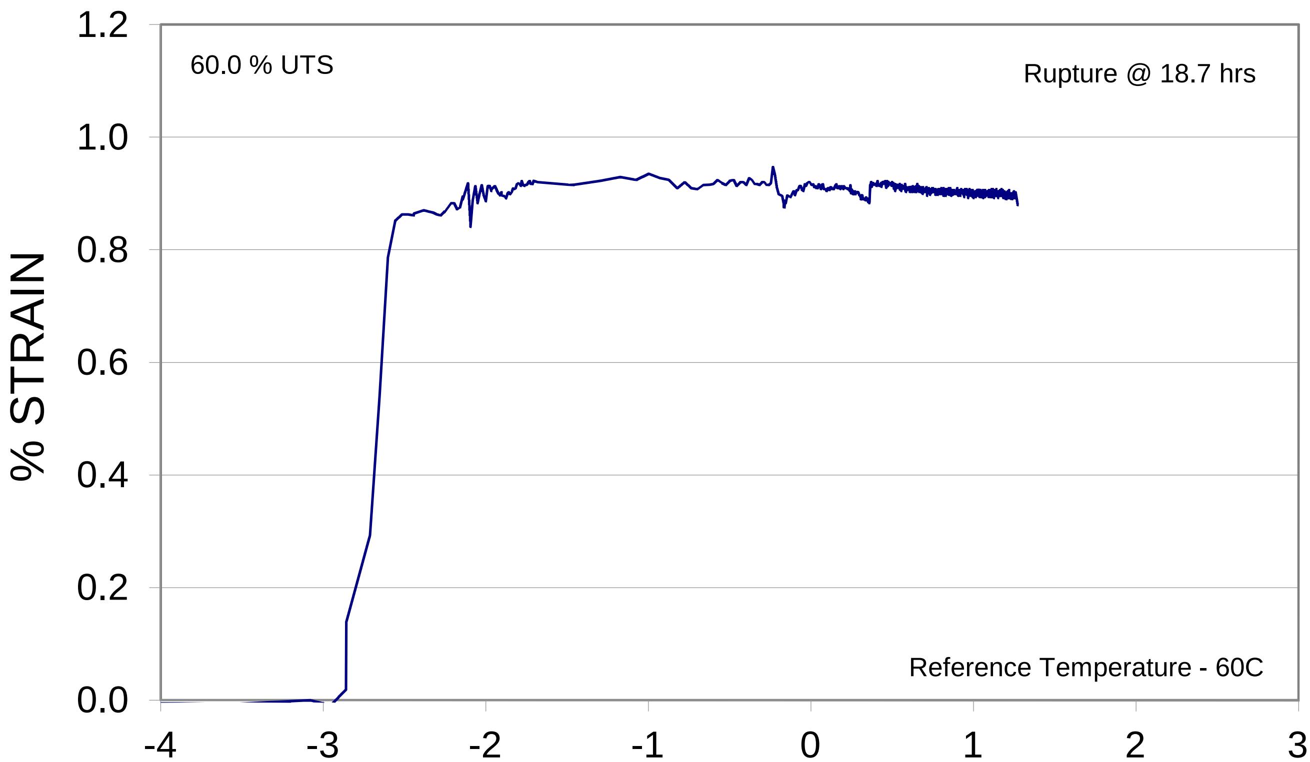


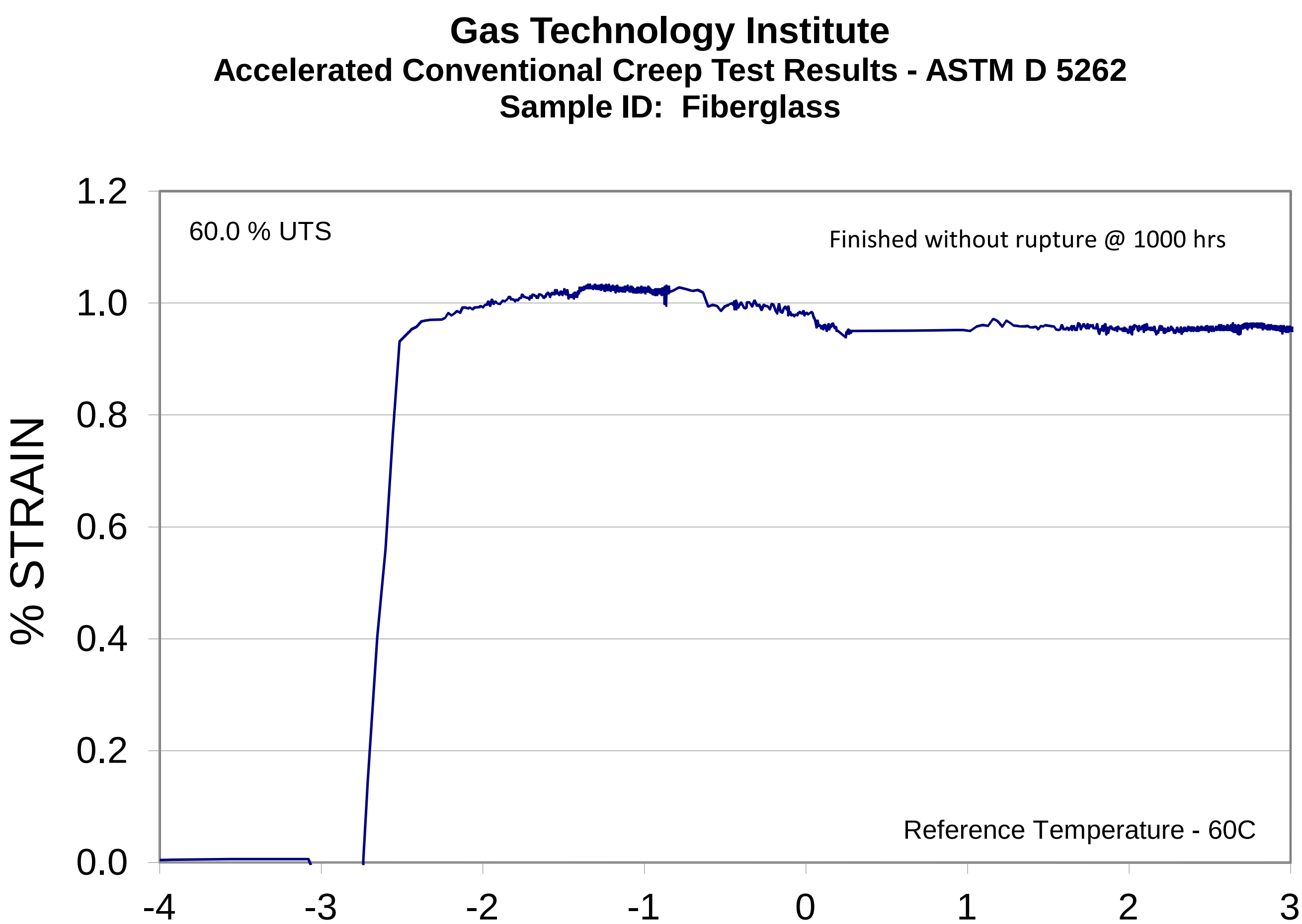
Gas Technology Institute
Accelerated Conventional Creep Test Results - ASTM D 5262
Sample ID: Fiberglass




Gas Technology Institute
Accelerated Conventional Creep Test Results
Sample ID: Fiberglass
30.0 % UTS
Finished without rupture @ 1000 hrs
Strain Error
Reference Temperature - 60C
% STRAIN
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
-4
-3
-2
-1
0
1
2
3

Gas Technology Institute
Accelerated Conventional Creep Test Results - ASTM D 5262
Sample ID: Fiberglass




Gas Technology Institute
Accelerated Conventional Creep Test Results - ASTM D 5262
Sample ID: Fiberglass
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0.8
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0.4
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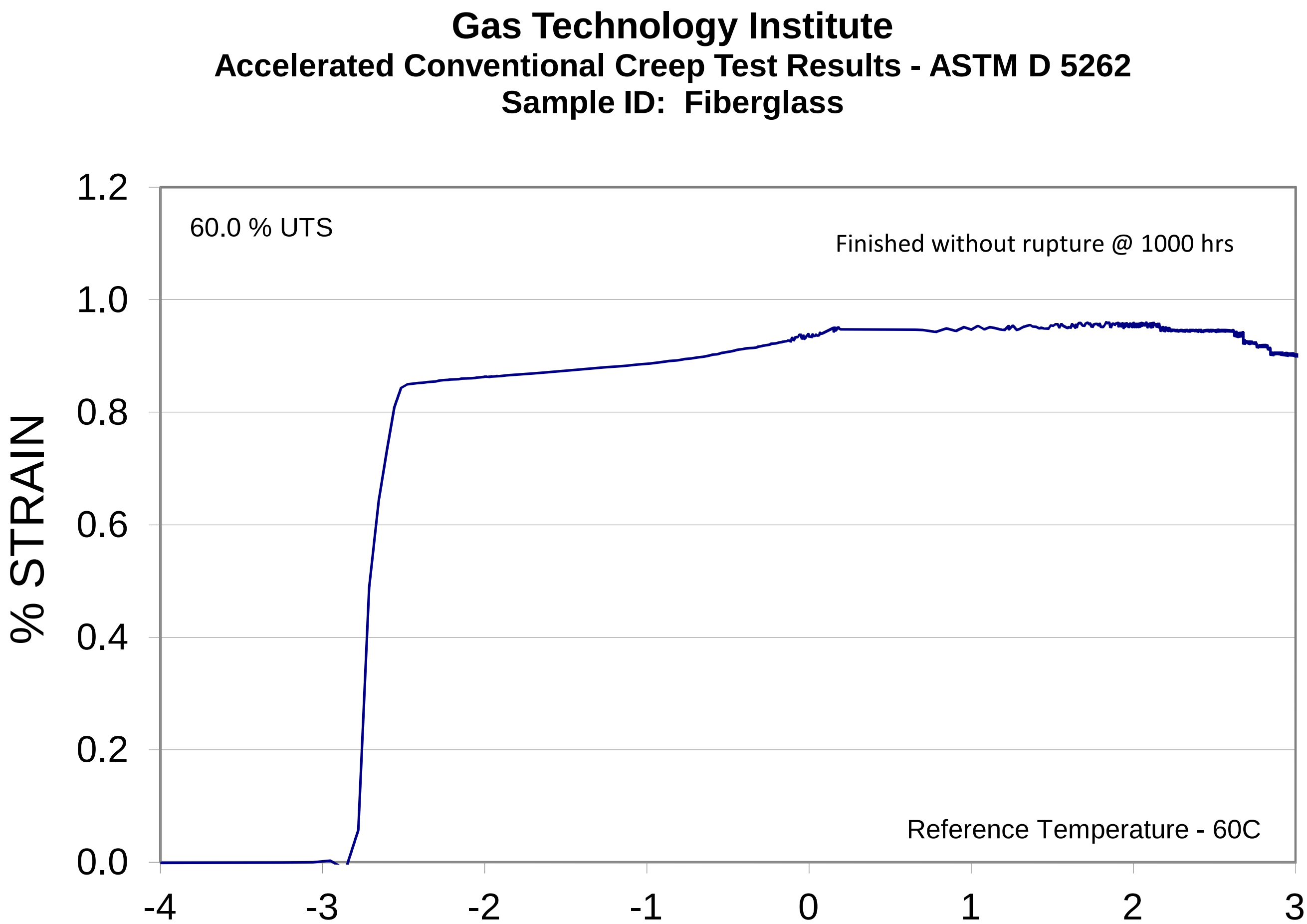
60.0 % UTS
Finished without rupture @ 1000 hrs
Reference Temperature - 60C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Reference Temperature - 60C
% STRAIN
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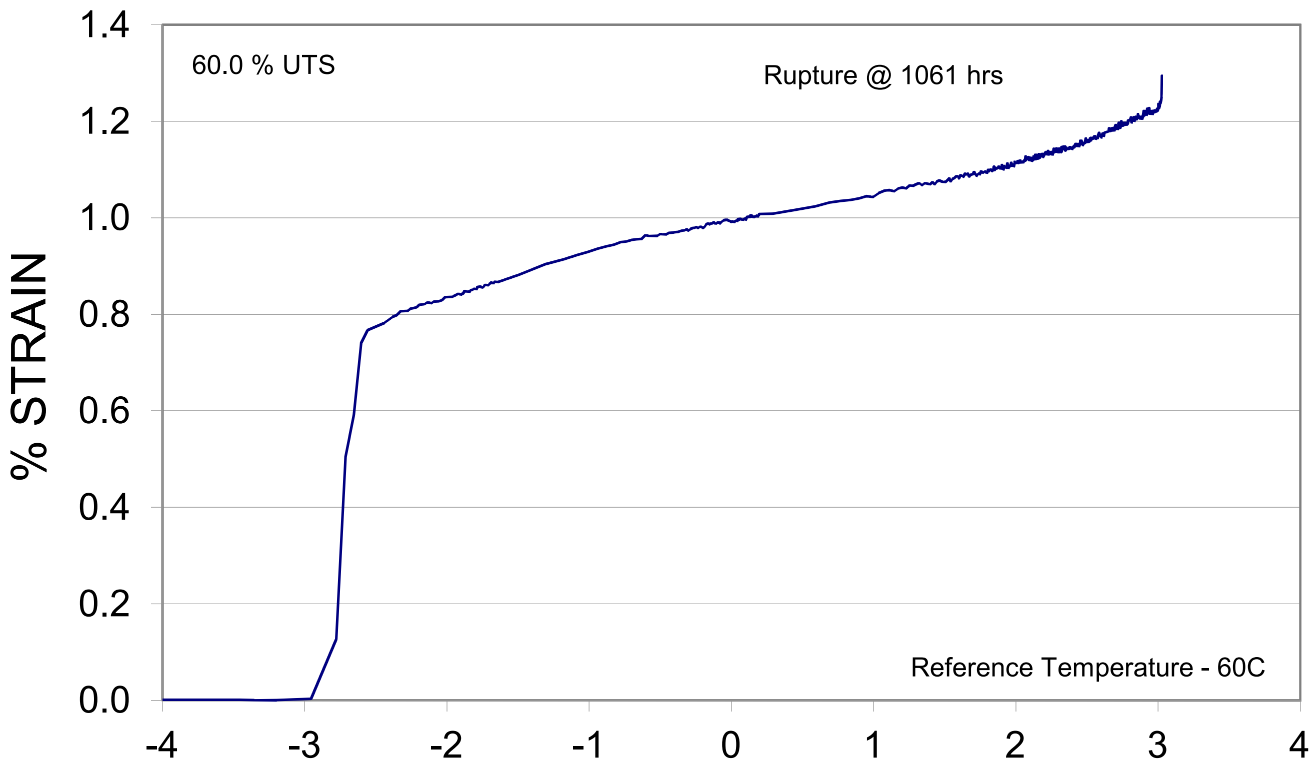
Gas Technology Institute
Accelerated Conventional Creep Test Results
Sample ID: Fiberglass



Gas Technology Institute
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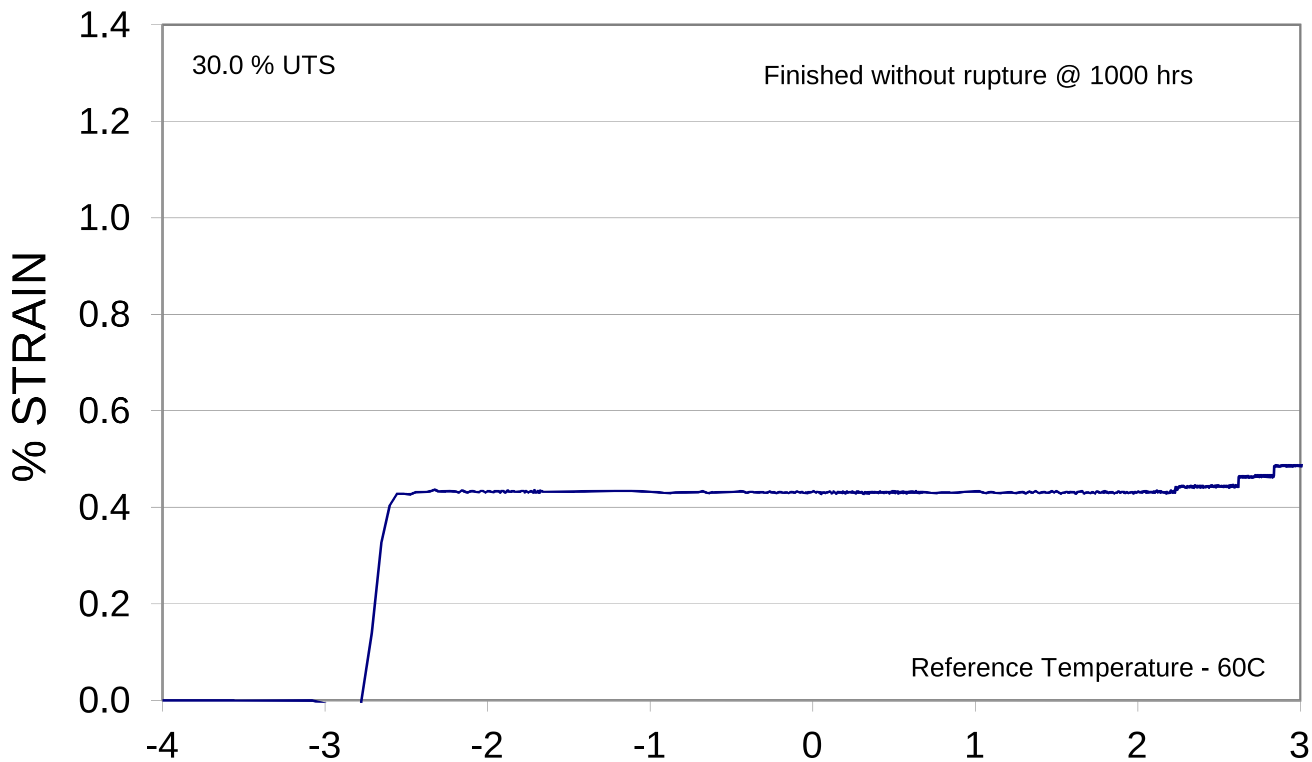

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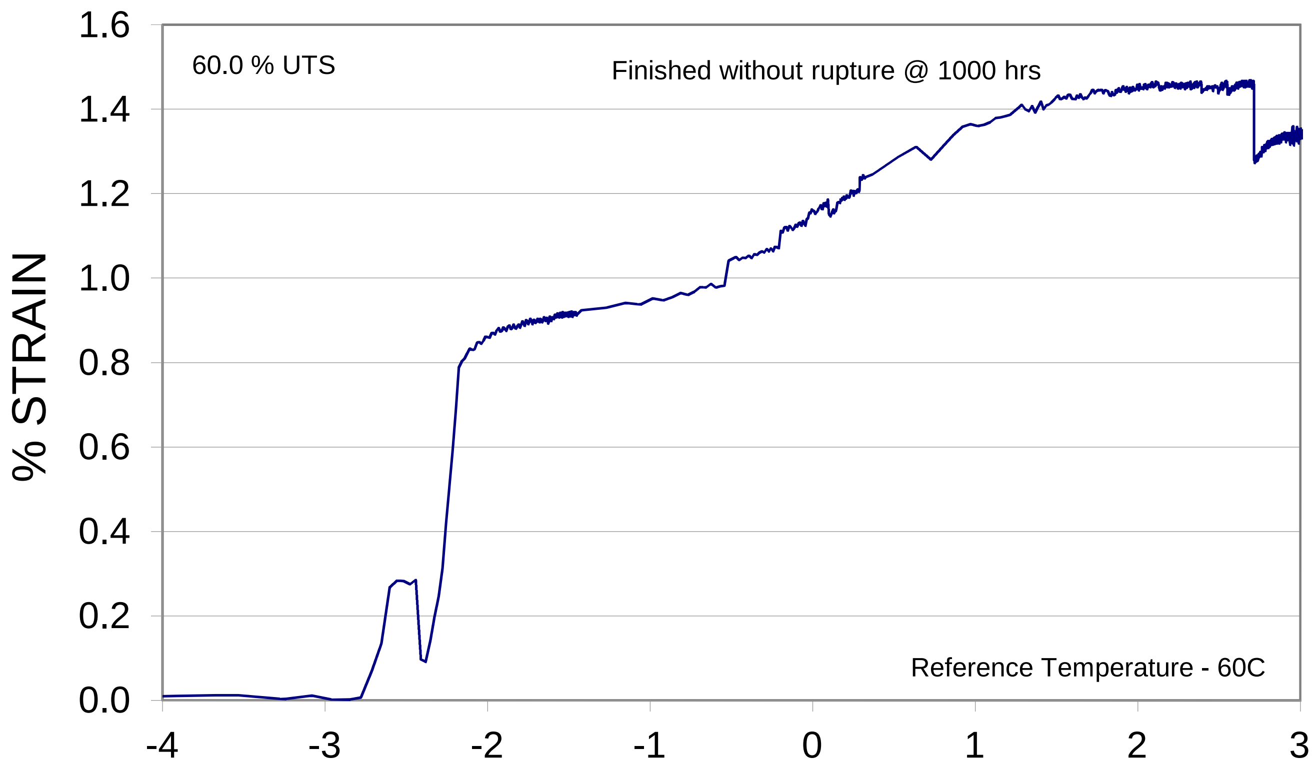

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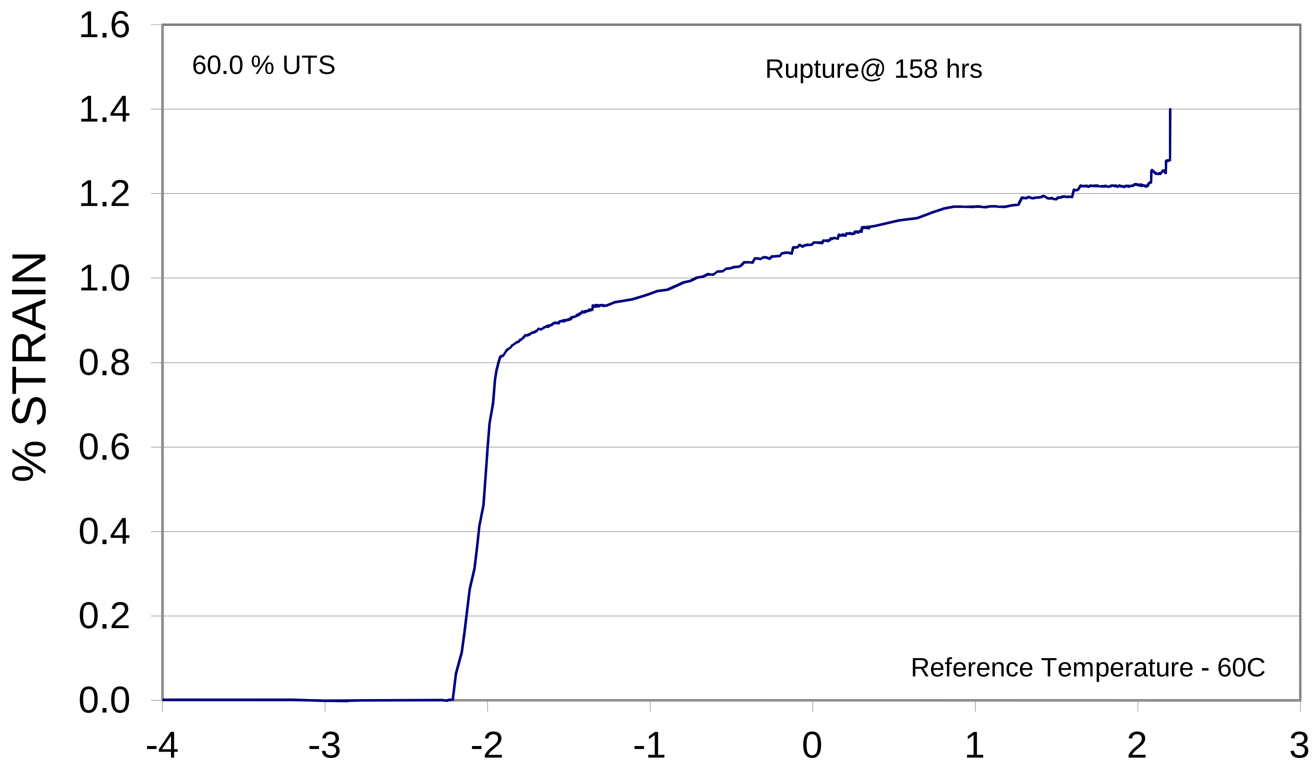

Appendix B – Evaluation of Bonding Strength of Composite Repairs

Proceedings of the 9th International Pipeline Conference
IPC2012
September 24- 28, 2012, Calgary, Alberta, Canada

IPC2012-90071

LONG-TERM EVALUATION OF THE BONDING STRENGTH OF COMPOSITE REPAIRS

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ABSTRACT

The long-term performance of composite repair systems depends on their structural integrity and interaction with the carrier pipe. The adhesives used in the composites are critical components that not only bond the repair to the pipe, but also bond the individual layers of the repair to one another. The durability of the inter-laminate adhesive bond is required to ensure adequate load transfer between the pipe and the composite layers over the predicted lifetime of the repair.

A testing program was performed to evaluate the shear strength of the adhesives used in composite repairs. The testing program evaluated the performance of seven commercially-available composite repair systems and it consisted of short-term and long-term shear tests on the adhesives and cathodic disbondment tests on the repair systems. The long-term shear tests were performed for 10,000 hours on samples submerged in a water solution with pH value of 9 and at various loading levels at temperatures of 70^{o}F, 105^{o}F and 140^{o}F.

The results of the long-term tests at elevated temperatures were extrapolated to predict the shear strengths at longer durations. The 20-year shear strengths of the composites were estimated using: (a) direct extrapolation of the best-fit curves and (b) the application of the rate process procedure. The results demonstrated the significant effect of temperature on the bond strength of the composites and provided a comparative analysis to evaluate the long-term shear strength and cathodic disbondment of the composite repair systems.

INTRODUCTION

The long-term durability of the adhesive bond is required, along with other properties such as the laminate tensile strength and modulus, to classify the repair system as a 'temporary' or a 'permanent' repair over the predicted lifetime of the pipeline.

The adhesive used in a composite repair system is a critical component that not only bonds the repair to the pipe, but also bonds the individual layers of the repair to one another (i.e., laminates, fibers, mesh, etc.). If this bond is not adequate, load will not be effectively transferred from the pipe to the repair system.

The ASTM D 3165 Lap-shear test [*1*] has been used to provide a measure of the bond strength between the composite and the pipe surface. This test was modified to mimic the expected stresses and evaluate the shear strength between the composite layers. As a result, the long-term performance of a repair can be assessed using coupon level tests.

The testing program evaluated seven composite repair systems available in the market. The tests consisted of performing short-term and long-term shear tests on the adhesives and cathodic disbondment tests on the repair systems. The testing equipment was developed to allow for long-term testing of the composite samples under accelerated environmental conditions.

Cathodic disbondment tests were performed to evaluate the disbondment area of pre-set holes in pipes with composite repairs when placed in a solution and subjected to an electric potential of 3V DC. The testing procedure allowed for the measurement of the disbondment area in the composite repair.

TESTING PROCEDURE

The test specimen consisted of two layers of composite material bonded to two aluminum plates and separated by a thin layer of fluorinated ethylene propylene (FEP). The composite layers were stacked approximately 1/16-inch thick, separated by the FEP, and then adhered to the aluminum plates. A 0.75-inch diameter hole in the middle of the FEP sheet allowed for the composite materials on both sides to bond to each other with a contact area of 0.44 inch^2. A schematic view of the test samples is shown in Figure 1.

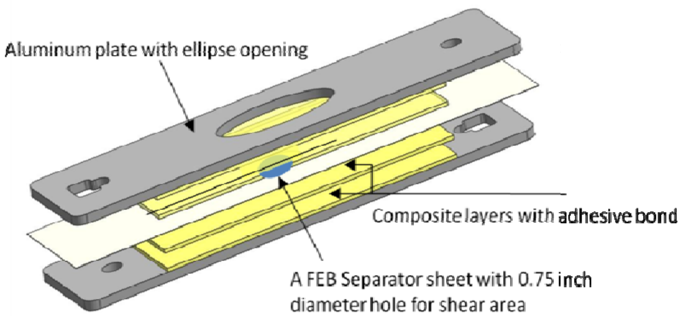

FIGURE 1 - SCHEMATIC VIEW OF THE TEST SAMPLE

As shown in the figure, an ellipse was cut in the plates to allow for the liquid to contact the composite layer. This was done to simulate the immersion of the composite in wet or saturated soil in the field. Figure 2 shows the test specimens of various composites in the testing program.

The surface area between the composite material and the aluminum plate was 30 times larger than the shear area between the composite laminates. This ratio helped promote the failure at the adhesive interface, as opposed to failure between the composite and loading plates.

FIGURE 2 - VIEW OF THE PREPARED TEST SAMPLES

During the shear testing, the specimen was gripped with two pins to apply the shear loading between the plates. In the long-term testing apparatus, these pins were used to transmit the load through the creep frame loading assembly shown in Figure 3.

The long-term testing of the samples was based on the durability testing procedures in ASTM D2919 [*2*] and the creep loading in shear for metals in D2294 [*3*]. The creep loading frame was designed with a high load-lever arm ratio to allow for a relatively lightweight system with small lever arms. A target ratio of 60:1 proved to be the most practical advantage. The maximum required displacement until shear failure for all samples was determined from short-term shear testing and found to be from 0.02 to 0.04 inches. A factor of safety was added to set the maximum displacement of the loading frames to 0.15 inches.

FIGURE 3 - LONG-TERM TESTING FRAMES IN TEMPERATURE-CONTROLLED CONTAINERS

As shown in Figure 3, the tests were performed with the samples immersed in water tubs with pH value of 9 and at various loading levels and temperatures of 70^{o}F, 105^{o}F and 140^{o}F. The pH level was produced by mixing sodium bicarbonate and sodium carbonate in purified water as per ASTM D2990 [*4*].

Long-term shear loads were applied on the frames using rectangular steel sections of variable weights. Bags filled with steel shot were also used to apply lighter loads.

TEST RESULTS

<u>a) Short-Term Tests:</u> These tests were performed at 70°F, 105°F, and 140°F on a minimum of five samples for each product. The short-term strength was used as a baseline for determining the long-term loads. The results

of the short-term shear tests at the three temperatures are shown in Figure 4. The figure demonstrates the significant effect of temperature on the bond strength of the composites.

The ASME Standard PCC-2 Article 4.1 [5] requires the composite to have minimum lap shear strength of 580 psi (4 MN/m^2). At 140°F operating pressure, the results show that most of the repair systems had higher short-term shear strengths than this requirement.

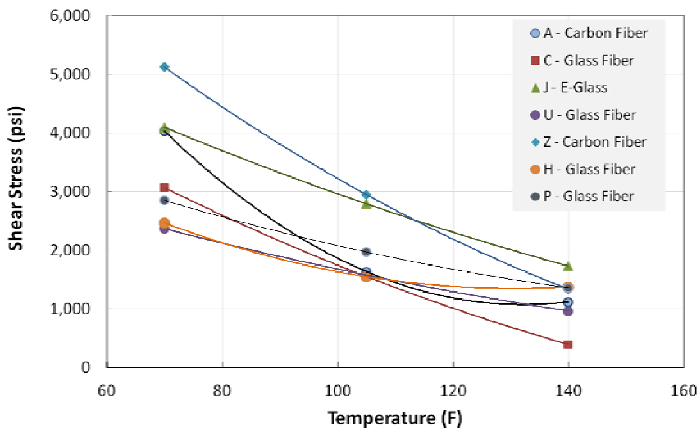

FIGURE 4 - RESULTS OF SHORT-TERM SHEAR TESTS ON THE COMPOSITE SPECIMENS

b) Long-Term Shear Testing: Long-term shear tests were performed for 10,000 hours at various loading levels as percentages of the short-term shear strength results. The specimens were conditioned and tested in water tanks heated to the target temperatures.

As per ASTM D2992 [6], samples for long-term tests were loaded to create a failure profile with at least four sample failures between 10 and 1,000 hours, three between 1,000 and 6,000 hours, three between 6,000 and 10,000 hours, and one after 10,000 hours. This procedure was performed using about 32 samples for each product to obtain the minimum number of samples failing at the specified times as per the ASTM standard.

Figure 5 shows typical results of the long-term shear stress failures of a composite repair product at 70°F, 105°F, and 140°F. The results show a reduction of the shear strength due to accelerated creep of the adhesive at the elevated temperature of 140°F. Such effect of temperature needs to be considered when selecting the types of composites suitable for long-term performance at elevated temperatures.

ANALYSIS OF RESULTS

The ASME Standard PCC-2 Article 4.1 requires the long-term shear strength to be determined for repairs where evidence of long-term durability of the adhesive bond is required. The standard requires that the 1,000-hour shear strength, at a minimum temperature of 40^0C (104^0F), to be more than 30% of the short-term strength.

The 1,000-hour shear strength results on the adhesive bond between the laminates at temperature 105^0F are shown in Table 1. With the exception of one product, the results show that the 1,000-hour shear strengths of the repairs were higher than the 30% values of their corresponding short-term shear strength at the same temperature.

The results for longer durations up to 10,000 hours were used to estimate the long-term performance of the composites. The 10,000-hour results were extrapolated to predict the shear strengths at longer durations. Two procedures were used for the estimation of the 20-year shear strengths of the composites:

The first procedure was based on the direct extrapolation from the 10,000-hour curves for each product at 70°F. Examples of the best-fit equations of these curves are shown in Figure 5.

TABLE 1 - RESULTS OF 1,000-HR TESTS AT 105°F

Code	Product	Short-term shear, psi (105°F)	30% of short-term shear	1,000-Hr shear, psi (105°F)
U	Glass fabric with water-cured urethane resin	1,483	445	724
C	Glass fabric with epoxy resin	1,554	466	421
Z	Carbon-fiber with epoxy resin	2,950	885	1,830
H	Glass fiber with water-cured polyurethane	1,551	465	1,179
A	Carbon fiber with epoxy resin	1,640	492	815
P	Glass fiber with urethane resin	1,972	591	1,175
J	Glass fiber with urethane resin	2,792	838	2,000

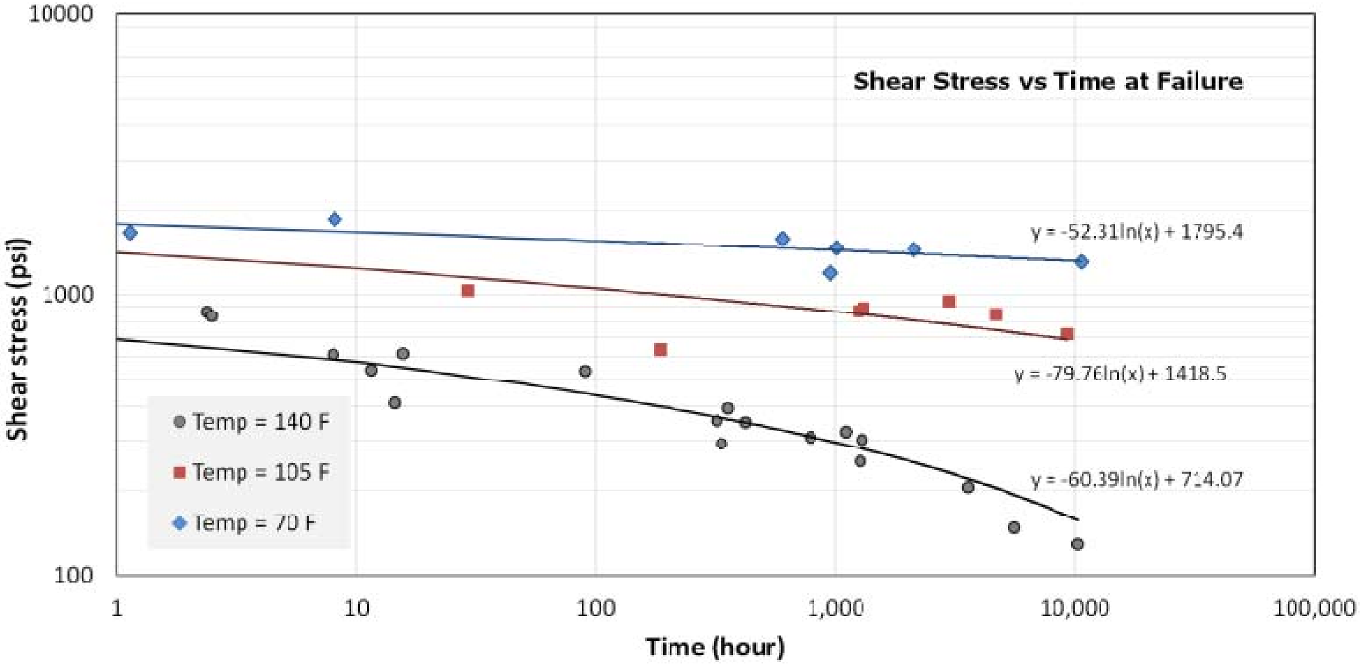

FIGURE 5 - LONG-TERM RESULTS AT VARIOUS SHEAR LOADS FOR THE COMPOSITE

(a) Direct Extrapolation of the Best-Fit Curves: The best-fit procedure assumes that the creep curves do not drastically change at longer time intervals. The 10,000-hour creep results can typically be extrapolated to one-scale on the log-time axis (i.e. to 100,000 hours; or 11 years). The results in Figure 5 show that this extrapolation is also practically reasonable for predicting the 20-year performance (i.e.; to 175,000 hours) for the curves at 70°F.

The extrapolation of the long-term results at 105°F, and 140°F, however, should be performed with caution due the accelerated creep curves at these elevated temperatures.

(b) The Rate Process Procedure: The second prediction procedure was based on the prediction methods used for thermoplastic materials. These materials are assumed to exhibit accelerated creep at longer time intervals (i.e., at or beyond 100,000 hours). This accelerated creep can be predicted from elevated temperature tests using the rate process theory.

The extrapolation procedure of the rate process method is discussed in the ASTM D2837 [*7*] and is applied when temperature accelerates the rate of the material molecular activity. The rate process approach is described in detail in various publications [*8, 9*] and the following equation has been found to well model the relationship between time to failure, applied stress, and temperature:

$$\text{Log } t = A + B/T + C\,(\log \delta)/T \qquad (1)$$

Where, t = time to fail, hours, T = absolute temperature in °R, δ = applied stress, psi, and A, B, and C are experimentally established coefficients.

A validation process of the applicability of the rate process theory is graphically shown in Figure 6 and is as follows:

- The material was evaluated at the base temperature curves of 70°F (similar to line a-a' in the figure). The stress-time curve is extrapolated to estimate the stress that results in failure at the 100,000 hour (Point I).
- A failure line is established at the temperature curves at 140°F (similar to line b-b' in the figure).
- Point II is selected on line b-b' to present a failure point with no visible sign of deformation. This is commonly at the time range of 100 to 500 hours. Similarly, establish Point III at failure time between 1,000 to 3,000 hours.
- Calculate the coefficients A, B, and C of equation (1), from the failure points I, II, and III.

- The underlying theory in ASTM D2837 assumes that a downturn or 'knee' will occur after 100,000 hours. Therefore, the worst case assumes that the 70°F knee will occur at 100,000 hours, which is indicated by line d-d' in the figure.
    - To confirm that the 70°F knee is at or beyond this worst case situation, point IV is selected at a temperature between the base temperature (line a-a') and the one for line b-b', and at similar stress level. This is indicated as line c-c'. In the experimental program, Point IV was selected from the curves at temperature 105°F.

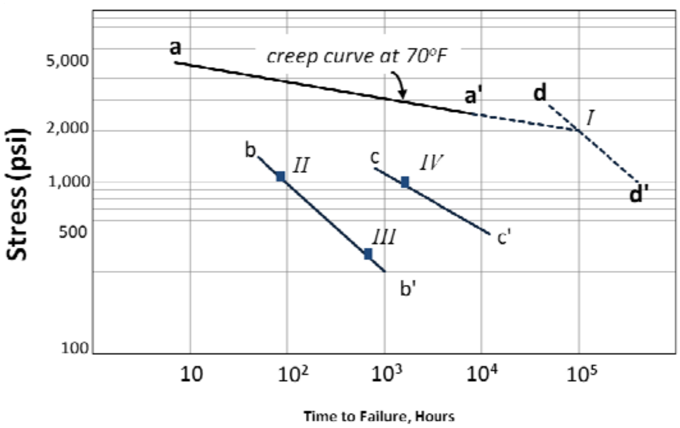

FIGURE 6 - EFFECT OF TEMPERATURE ON THE LONG-TERM PERFORMANCE OF THERMOPLASTIC MATERIAL [*8*]

- The rate process equation (1) was applied to predict failure time for point IV. If the experimental result meets or exceeds this predicted time, the hypothesis that the knee occurs at or beyond 100,000 hours has been confirmed and the rate process equation is valid. If the actual failure time is less than the predicted time, the sample cannot be considered adequate for the extrapolation.

Table 2 shows the results of the application of the rate process on the experimental curves for predicting failure stress at 20 years extrapolation. The results are compared with the direct extrapolation results from method (a) of the best-fit curves.

CATHODIC DISBONDMENT TESTING

The ASTM G95 test procedure [*10*] is used to evaluate the disbondment area of a preset hole in a coated pipe when placed in a solution and subjected to an electric potential of 3V DC. The procedure was modified to allow for the measurement of the disbondment area in the composite repair as opposed to one described for the coating.

TABLE 2 – 10,000-HOUR RESULTS AND EXTRAPOLATED 20-YEAR VALUES FOR 70°F TESTS

Code	Product	10,000-Hr, psi (70°F)	20-year (from best- fit curves), psi	20-year (from rate-process), psi
U	Glass fabric with water-cured urethane resin	1,129	1,050	910
C	Glass fabric with epoxy resin	537	480	464
Z	Carbon-fiber with epoxy resin	3,125	2,910	1,657
H	Glass fiber with water-cured polyurethane	1,586	1,516	1,318
A	Carbon fiber with epoxy resin	2,046	1,950	1,888
P	Glass fiber with urethane resin	1,956	1,750	1,670
J	E-Glass fiber with urethane resin	2,332	2,285	1,980

The test method consisted of attaching a test cell on the surface of a composite repair of an 8-inch diameter pipe with wall thickness of 3/16-inch. A 0.125-inch diameter holiday was created in the composite to the steel pipe surface.

The test cells were then installed on the holidays as shown in Figure 7. The test cells consisted of a four inch diameter clear PVC tube sealed with an adhesive to the outside of the pipe sample. The test cell was filled with a solution of distilled water and combined with 3 % by mass of sodium chloride.

Platinum wires were placed in the cells at a distance of one inch above the holiday which provided the current path to the solution. A positive 3V DC potential was created from the platinum anode to the steel pipe. The voltages of the test cells were recorded twice a week using a copper-copper sulfate reference electrode.

FIGURE 7 - INSTALLATION OF THE TEST CELLS S ON THE COMPOSITE SAMPLES

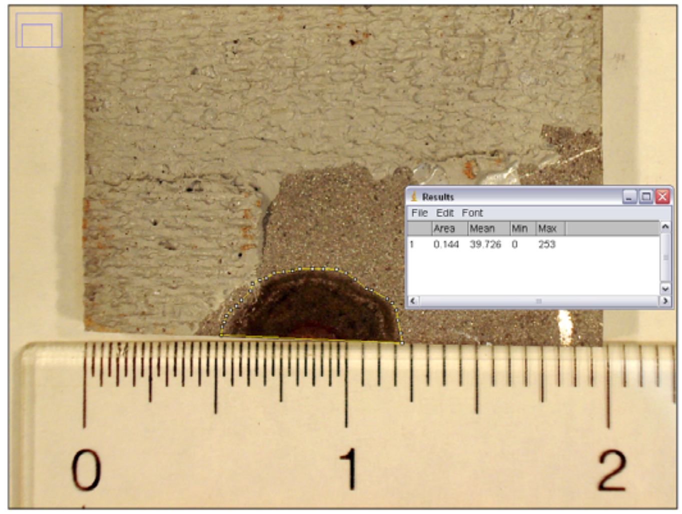

FIGURE 8 - DIGITAL MEASUREMENT OF THE DISBONDED AREA IN A COMPOSITE WRAP

The ASTM G95 specifies the use of a razor to remove the disbonded coating and identify the disbondment areas in two locations. The first location is in the damaged area and the second one is a reference one in an undamaged section of the pipe. In the composite tests, the procedure was modified to allow for the removal of the much thicker wrap without damaging the adjacent sections.

The laminates were carefully detached down to the lowest layer of primer. A razor was used to remove the unsupported resin and define the size of the disbondment. The samples were then cut to inspect their cross-section areas. The exposed sections were photographed and the disbondment area for each sample was digitally calculated as shown in Figure 8. The yellow line shown in the figure identifies the perimeters of the disbandment in the samples.

Table 3 shows the disbondment area measurements of seven composites after 90 days of exposure. Method (A) in the table is obtained from the image analysis, while Method (B) is calculated from the measured radius by assuming that the disbondment is a perfect circle.

The results in Table 3 varied with the type of epoxy and bonding material used in the composite; with the exception of one product with a disbondment of 0.4 inch^2, the maximum values were less than 0.15 inch^2. The ASTM does not specify values for the qualification requirements of cathodic disbondment. However, the disbondment of the composite repairs were comparable to the values measured in fusion bonded epoxy coating.

TABLE 3 - MEASURED CATHODIC DISBONDMENT AREAS OF THE COMPOSITES

Code	Product	Disbonded Area, inch^2 Method (A)	Disbonded Area, inch^2 Method (B)
U	Glass fabric with urethane resin	0.126	0.167
C	Glass fabric with epoxy resin	0.033	0.033
Z	Carbon-fiber with epoxy resin	0.055	0.053
H	Glass fiber with water-cured polyurethane	0.144	0.146
A	Carbon fiber with epoxy resin	0.026	0.028
P	Glass fiber with urethane resin	0.385	0.406
J	E-Glass fiber with urethane resin	0.019	0.015

The Canadian Standard Z245.20 [*11*] specifies 8.5 mm (0.3 inch) for the maximum cathodic disbondment of FBE coating. If we establish a performance criteria for the composite similar to the FBE coating, most of the composites in Table 3 would have acceptable performance below 0.3 inches of disbondment.

Their qualification requirements in the Z245 standard however, are based on tests performed for 28-dayd at room temperature as opposed to the ASTM G95 test of 90-day duration.

DISCUSSION

The performance of composite repair systems varies depending on their fabric and resin types, manufacturing processes, and installation procedure. Their long-term performance depends on several structural and installation requirements which include the following:

- The long-term strength of the reinforcing fabric,
- The long-term shear strength of the adhesive used in the composite,
- Surface preparation, application of repair method, and curing of the composite system.

The long-term strength of the fibers and adhesives should be demonstrated in the material specification sheet provided by the supplier; documenting the material properties as per the requirements of the ASME Standard PCC-2 Article 4.1. Material specifications should also include fabric orientations, minimum ply thickness, and installation procedures, along with the material properties used in design.

The ASME PCC-2 standard specifies 1,000-hour test as a minimum requirement for evaluating the long-term performance of the composite. The prediction of the life expectancy of the repair requires performing tests for longer durations up to 10,000 hours and at various temperatures to allow for extrapolating the results and predicting the long-term strength values.

The 20-year shear strength was estimated from the 10,000 hour test results using direct extrapolation of the best-fit curves and an application of the rate-process procedure for thermoplastics. Although most of the adhesives used in composites are thermoset materials, which may not exhibit downturn knees in their creep curves, the rate process procedure provided a conservative approach for predicting the long-term strength.

The results of the long-term shear strength varied according to the composite fabric and adhesive types. The composites with carbon fibers (products A and Z) had comparable 10,000-hour shear strength. The other composites consisted mostly of glass-woven fabrics impregnated with the resin. With the exception of one product, these composites also had comparable 10,000-hour strengths.

The 10,000-hour tests can be used to qualify the products performance for long-term repairs up to 20 years; providing that they are properly designed and their installation procedure and degradation resistance also satisfy the long-term requirements of the repair.

The test results at elevated temperatures show a reduction of the shear strength due to accelerated creep of the adhesives at temperatures of 105^{o}F and 140°F. Such effect of temperature needs to be considered when selecting the types of composites suitable for long-term performance at elevated temperatures.

The cathodic disbondment results varied between the products with most of the products had disbondment areas of less than 0.15 inch^{2} which is less than the values required in fusion bonded epoxy (FBE) coating as per the requirements of the Canadian standard for coatings.

ACKNOWLEDGMENTS

The research program is sponsored by the U.S. Department of Transportation, Pipeline and Hazardous Materials Safety Administration (DOT-PHMSA) under contract No.DTPH56-10-T-000014 with co-funding from the Operations Technology Development OTD.

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Appendix C – Cyclic Pressure Testing of Composite Repair Systems

Guidelines for Testing Composite Repair Systems Subjected to Cyclic Pressures

PN 1151736

Prepared for
The Gas Technology Institute

Prepared by: ______________________

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Principal

Reviewed by: ______________________

Mr. Ron Scrivner
Staff Consultant

Firm Registration Number is F-195

March 2012

STRESS ENGINEERING SERVICES INC.
an employee-owned company

REV	*DATE*	*DESCRIPTION*	*ORIGINATOR*	*REVIEWER*	*APPROVER*
Final	*3/28/12*	*Revised per client*	*CRA*	*CRA / GTI*	*CRA*
Draft	*2/6/12*	*Issued for client review*	*CRA*	*RWS*	*CRA*

EXECUTIVE SUMMARY

Over the past 20 years composite repair systems have become an integral part of most transmission pipeline companies' integrity management programs. It is rare to find a company operating high pressure gas or liquid pipelines that does not employ composite materials in some capacity to repair their pipelines. The initial use of composite materials was aimed at restoring the integrity of corroded pipe sections; however, it is now commonplace for composite materials to be used to repair and reinforce a wide range of anomalies and features including dents, wrinkle bends, and branch connections. Full-scale testing efforts have been used to quantify the limit state performance of particular composite repair systems. In terms of long-term performance, the importance of full-scale destructive testing cannot be overstated.

This document has been prepared for the Gas Technology Institute. It includes guidelines for evaluating the effects of cyclic pressure on the performance of composite repairs used to reinforce corrosion, dents, and mechanical damage. In particular, a testing procedure is provided to establish the fundamental elements associated with a cyclic loading testing procedure. The intent is to establish a consistent protocol so that meaningful test results are generated to permit the assessment of competing composite technologies. Additionally, guidance is provided on interpreting and applying the test results to establish a useful service life condition, thus helping to quantify the long-term performance for the respective repair system.

In conjunction with the guidance document, a large body of test data supporting the proposed testing protocol is included. Furthermore, example problems are included that translate raw experimental pressure cycle data into estimated years of service (i.e. design life). The design life of a repair is an essential element to consider when restoring the integrity of a damaged pipe section. Integrating data based on full-scale performance testing, along with specified operating conditions for a particular pipeline system, is a proven methodology for evaluating the integrity of a particular repair solution. In using appropriate design margins, operators can proceed with confidence when employing composite materials to reinforce their damaged pipeline systems.

LIMITATIONS OF THIS REPORT

The scope of this report is limited to the matters expressly covered. This report is prepared for the sole benefit of the Gas Technology Institute (GTI). In preparing this report, Stress Engineering Services, Inc. (SES) has relied on information provided by GTI and industry sources. SES has made no independent investigation as to the accuracy or completeness of such information and has assumed that such information was accurate and complete. Further, SES is not able to direct or control the operation or maintenance of client's equipment or processes.

All recommendations, findings, and conclusions stated in this report are based upon facts and circumstances, as they existed at the time that this report was prepared. A change in any fact or circumstance upon which this report is based may adversely affect the recommendations, findings, and conclusions expressed in this report.

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1.0 INTRODUCTION

This guideline document has been prepared by Stress Engineering Services, Inc. (SES) for the Gas Technology Institute (GTI) to address the following two objectives.

1. **Establish a cyclic loa ding testing procedure:** The standard procedure will provide the selection criteria of the testing parameters (e.g., pipe samples size, application of controlled damage, thickness of repair, and range of the cyclic loads). The procedure will identify the effect of these testing parameters on the performance of the composite repairs under cyclic loading.
2. **Analysis of cyclic loading tests:** The analysis will utilize a database of published test results on various types of composite repairs to establish a procedure for estimating the long-term life expectancy of the composites used in the repair of corroded pipe sections and pipes subjected to mechanical damage (i.e., with dents and gouges).

At the present time there has been relatively little guidance developed for the pipeline industry with regards to establishing acceptable operating envelopes for composite repairs subjected to cycle pressure conditions (or other cyclic loading conditions for that matter). In contrast, standards such as ASME PCC-2 and ISO 24817 provide for industry useful information in defining what constitutes an acceptable composite repair design subject to static loads such as internal pressure. One element that adds complexity to the current discussion is that there is no guidance in how to transform experimentally-acquired *cycles to failure* for a given pipeline defect type into meaningful design conditions. For example, if a researcher pressure cycles a particular dent defect 125,000 cycles at a pressure range equal to 72% SMYS, what does this mean in terms of acceptable design (or operating) conditions? We know from experience that it would be inappropriate to take this data and communicate to an operator that an equivalent dent could be expected to have a remaining life of 125,000 cycles at a pressure range equal to 72% SMYS due to the absence of a safety factor. To make matters more complicated, what if we are to consider the performance of the dent considering a less aggressive pressure regime, say 36% SMYS, as opposed to the 72% SMYS pressure range condition? This guideline document seeks to bring clarity to the potential confusion that exists in transforming experimental pressure cycle failure data into design conditions that can be used to define a fitness for purpose condition for a particular pipeline defect type, in particular one that has been repaired or reinforced using a composite repair system.

The sections of this document that follow include a discussion on recommendations in the *Proposed Testing Methods* section that can be used to evaluate via full-scale cyclic pressure testing the performance of composite materials used to repair pipeline defects such as corrosion and dents that are subjected to cyclic pressure conditions. To support the merits of the proposed testing methods the *Previous Experimental Investigations* section has been included that contains data from previous research efforts including actual fatigue failure test data. The *Case Studies* section uses actual operating pressure data from pipelines, including gas and liquid transmission operators, and integrates previous experimental pressure cycle data to establish design conditions. A few closing comments and discussion items are included in the *Closing Comments* section.

2.0 PROPOSED TESTING METHODS

Performance testing is essential for qualifying composite repair systems. While closed-form calculations based on strength of materials concepts are useful for quantifying the geometry of composite repairs (i.e. namely material modulus and thickness of the repair), complex interactions such as those that take place between the pipe, filler material, and composite material require that destructive tests be performed to establish the limit state capabilities for a given repair. For this reason it is essential that testing programs be properly designed to ensure that essential performance variables are addressed. **This section has been included to provide guidance on a testing program whose objective is to evaluate the performance of composite repair systems used to reinforce corrosion, dents, and mechanical damage subjected to cyclic pressure conditions.** Also included in this document is a brief background discussion on the benefits associated with using cyclic pressure testing to qualify the performance of composite repair systems.

2.1 Background on Pressure Cycle Fatigue Testing

Cyclic testing has been used to qualify the performance for piping components, with the most recognized body of work going back to the late 1940s with Markl[1] and his assessment of fittings that included elbows, tees, and mitered joints. In addition to determining the actual fatigue life for a given component, one of the additional benefits is that it is possible to extract a Stress Intensification Factor (SIF) that permits the relative comparison of performance between different components; or as in the case of composite repair systems, competing technologies. For example, if two competing composite repair systems are used to reinforce a given dent geometry subjected to cyclic pressure conditions, it is possible to extract an SIF for each respective system based on the number of cycles to failure. A detailed discussion on this subject is outside the scope of this presentation; however, interested readers are encouraged to consult the paper included in **Appendix B** of this document.

[1] Markl, A.R.C., *Fatigue Test of Piping Components*, Transactions ASME Volume 69, No. 8, March 1947.

One of the other advantages in conducting pressure cycle fatigue tests, especially with regards to composite repair systems, is that it is possible to estimate the remaining life of a repaired pipeline system once a fatigue life has been determined for a particular repaired defect using the pressure history for a particular pipeline. This is an invaluable tool for operators who are often faced with decisions regarding repair or replacement of a given defect or anomaly.

2.2 Elements of the Proposed Testing Program

The proposed program is based on methods that have been employed by SES dating back to the early 1990s. The Pipeline Research Council of the American Gas Association (now known as the Pipeline Research Council International, Inc.) commissioned SES to conduct a testing program to evaluate the severity of mechanical damage in transmission pipelines considering both static and cyclic pressure loading[2]. The deliverables for this body of work, which spanned almost a decade, included fatigue data for a range of mechanical damage defects including dent's having depths up to 15% of the outside diameter of the pipe and gouge depths up to 15% of the pipe's nominal wall thickness. Pipe samples were pressure cycled to failure and the fatigue lives were tabulated. In addition to the experimental work, finite element models were also constructed with the purpose of calculating stress concentration factors (SCFs) for different dent geometries. Once the experimental data were collected, along with the numerically-based SCFs, it was possible to provide operators with an estimated design life for their damaged pipelines using in-the-field measurements or in-line inspection (ILI) data. More recently, SES has used three-dimensional ILI data from high resolution caliper tools to determine SCFs for given dent geometries.

[2] Fowler, J.R., Alexander, C.R., Kovach, P.J., and Connelly, L.M., *Cyclic Pressure Fatigue Life of Pipelines with Plain Dents, Dents with Gouges, and Dents with Welds*, Prepared for the Pipeline Research Council, PR-201-927/9324, June 1994.

Included in this section of the report are details on how to actually conduct a pressure cycle fatigue program. However, before providing details on the test program the following items are presented that provide additional details including the "end objective" of the testing effort.

- The testing program should seek to incorporate real world anomalies and defects. When in doubt, the severity of the defects should be more severe than one might expect in the field, although they should be representative. It is essential that the generated results be conservative in nature.
- Because of the inherent scatter in fatigue testing, there are several critical points of consideration.
    - When possible, seek to test more than one sample having the same defect type (i.e. duplicate samples). Having multiple data points of the same defect type permits one to establish not only upper and low bounds, but establish a confidence level based on the resulting standard deviation of the experimental data.
    - A "tight" error band in the resulting data can be an indication of a well-designed test matrix and set-up. Some of the better pipeline test programs over the past decade have generated consistent fatigue test results, improving confidence from industry in the technical worthiness of the generated data.
    - A safety factor on the fatigue data ranging between 10 and 20 must be applied to every set of data that is generated. For example, if a given set of dents have an average cycle to failure of 100,000 cycles, the appropriate design life for this defect should range between 5,000 and 10,000 cycles (100,000 cycles divided by either 10 or 20). Unlike stresses where safety factors typically range between 2 and 4, fatigue safety factors are generally higher due to increased uncertainties and lower confidence levels in the experimental data.
- The end objective of the testing program is to generate and provide information that can be used to establish a *fit for purpose* condition for the repair of a given defect. Without application in mind for actual pipelines, the proposed effort is little more than an exercise in generating fatigue data.

Provided in **Figure 1** is a flow chart showing some of the essential elements of a pressure cycle test program. Not included in this diagram are the procedures used to evaluate and interpret the pressure cycle fatigue data once it has been generated. Selection of the anomaly type and pipe size (i.e. diameter to wall thickness ratio, D/t) will have profound implications on the results of the program. A well-designed and sufficiently-funded program should seek to have multiple samples for the same defect type. This is critically important to generate meaningful data as there is inherent scatter in any fatigue test. Listed below are some of the important considerations when designing a pressure cycle fatigue test program.

- The anomaly should be representative of defects found in actual pipelines. The manufacturing/installation process used to generate the anomaly should mimic if at all possible the actual process that occurs in the field. An exception to this rule involves corrosion, which is most often installed via machining.
- As part of the anomaly selection process, critical variables associated with that particular anomaly should be identified and integrated into the test program. For example, it is widely-recognized that with regards to plain dents that "dent shape" and its associated curvature are important, along with dent depth. A comprehensive program will integrate a range of variables to determine their impact on reducing pipeline performance.
- When possible, multiple samples of the same defect should be tested. A statistical purist would likely say a minimum of 5 test samples, although it is recognized that the cost associated with sample fabrication typically precludes this from happening. With this being said, SES has had success the past several years testing two or three samples of each anomaly type. If consistent results develop using two samples (i.e. the fatigue lives for the two tests are close), greater confidence is achieved in using the data to make decisions regarding the performance of a particular composite repair system. To cite an example, the PRCI MATR-3-5 study utilized two samples of each defect type that included plain dents, dent in girth welds, and dents in ERW seam welds. The fatigue lives for each test pair tended to be similar, providing confidence in not only the average cycles to failure, but that a consistent test program had been executed (cf. data presented in Table 2 of paper in **Appendix B**)..

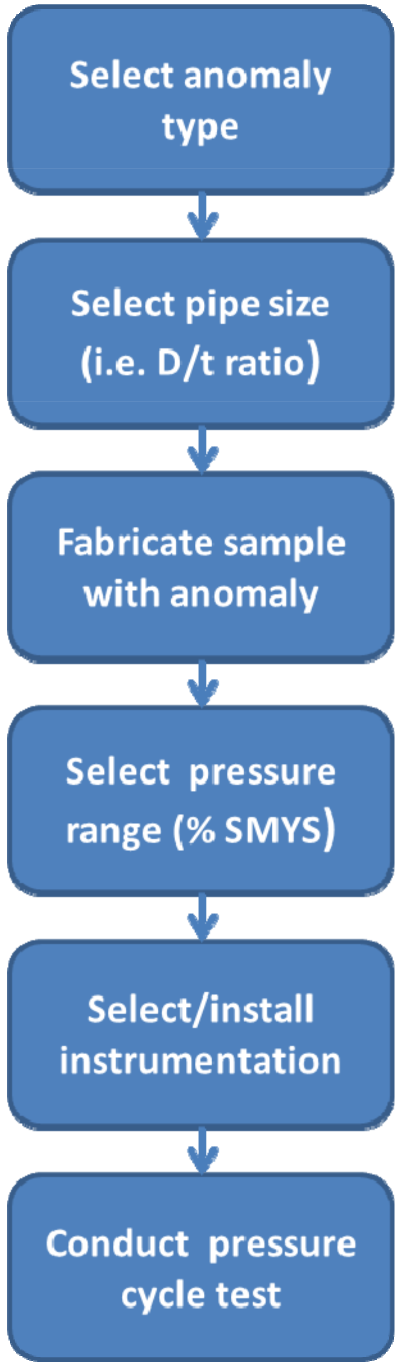

Figure 1 – Flowchart showing elements of a pressure cycle test program

3.0 PREVIOUS EXPERIMENTAL INVESTIGATIONS

Two bodies of work are included in this section of the document that utilized full-scale pressure cycle testing as the basis for establishing the performance of competing composite technologies, including cyclic pressure ranges representative of those found in liquid and gas transmission pipeline systems. This data has been used by numerous operators in making decisions regarding the installation of composite materials used to repair pipeline anomalies similar to those tested. As a point of reference, in 2010 a natural gas transmission pipeline operator used data from the PRCI composite repair dent study (details on this program provided below) as the basis for justifying the use of composite materials in reinforcing a dent located in a girth weld located by in-line inspection. A presentation was prepared for the pipeline company to assist in the decision process and is included in **Appendix A**.

3.1 Repairing Corrosion Defects Subjected to Cyclic Pressures

One of the current research programs being sponsored by the pipeline industry is the Pipeline Research Council International's MATR-3-4 study focused on evaluating the long-term performance of composite repair systems in repairing corrosion present in buried pipelines. This program is evaluating 13 different composite repair systems, with some systems being evaluated for up to 10 years. Samples are removed from the test field at designated time periods and burst tested to evaluate their pressure capacity as a function of time. At the current time, burst tests have been completed for sample periods including Year 0, Year 1, and Year 2. **Figure 2** shows the geometry for corrosion defects used in the PRCI MATR-3-4 study. Note that the corrosion depths include 40, 60, and 75% of the pipe's nominal wall thickness (each composite system was tested to evaluate its ability to repair this range of corrosion levels).

One element of the study includes the samples being pressure cycled 900 times per year at a pressure range equal to 36% SMYS, as well as four annual blow downs per year (i.e. 72% SMYS pressure range). Prior to starting this test program, concerns were communicated to the composite manufacturers about the possibility of having in-field leaks of their systems, especially the 75% deep samples. SES recommended that each composite manufacturer complete a pressure cycle test of their system using this particular sample geometry. Several manufacturers recognized the value of this recommendation and agreed to perform the test. As a result, starting in 2007 SES conducted pressure cycle tests on composite materials used to repair 12.75-inch x 0.375-inch, Grade X42 pipe samples having 75% deep corrosion. The samples were pressure cycled at 36% SMYS until failure. Although the original concept for this effort was to support PRCI MATR-3-4 study, in and of itself this particular test has become a benchmark performance test for the current competing composite technologies.

Provided below are results for nine different composite repair systems that have been tested to date. The average number of cycles to failure for the data presented below is 281,247 cycles, although the average for the E-glass and carbon systems is 195,140 cycles.

- E-glass system: 19,411 cycles to failure –
- E-glass system: 32,848 cycles to failure
- E-glass system: 129,406 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
- E-glass system: 259,537 cycles to failure –
- Carbon system (Pipe #4): 532,776 cycles (run out, no failure)
- Hybrid steel/Epoxy system: 655,749 cycles to failure
- Hybrid steel/E-glass Urethane system: 767,816 cycles to failure –

Three products, denoted as *CL*, *CM*, and *CH*, have been selected for use in the case studies included in a subsequent section of this document. The “C” term designates corrosion as the anomaly of interest; whereas “L”, “M” and “H” correspond to the low, medium, and high fatigue life (i.e. cycles to failure) results, respectively.

As noted in the preceding data there is a wide range of performance associated with the competing composite technologies. Barring the hybrid systems that integrated steel as a reinforcing element, all other composite repair systems are currently being used by pipeline companies to reinforce high pressure transmission pipelines. This is somewhat disturbing when considering that an order of magnitude difference exists when comparing the fatigue lives of Product CL and Product CM.

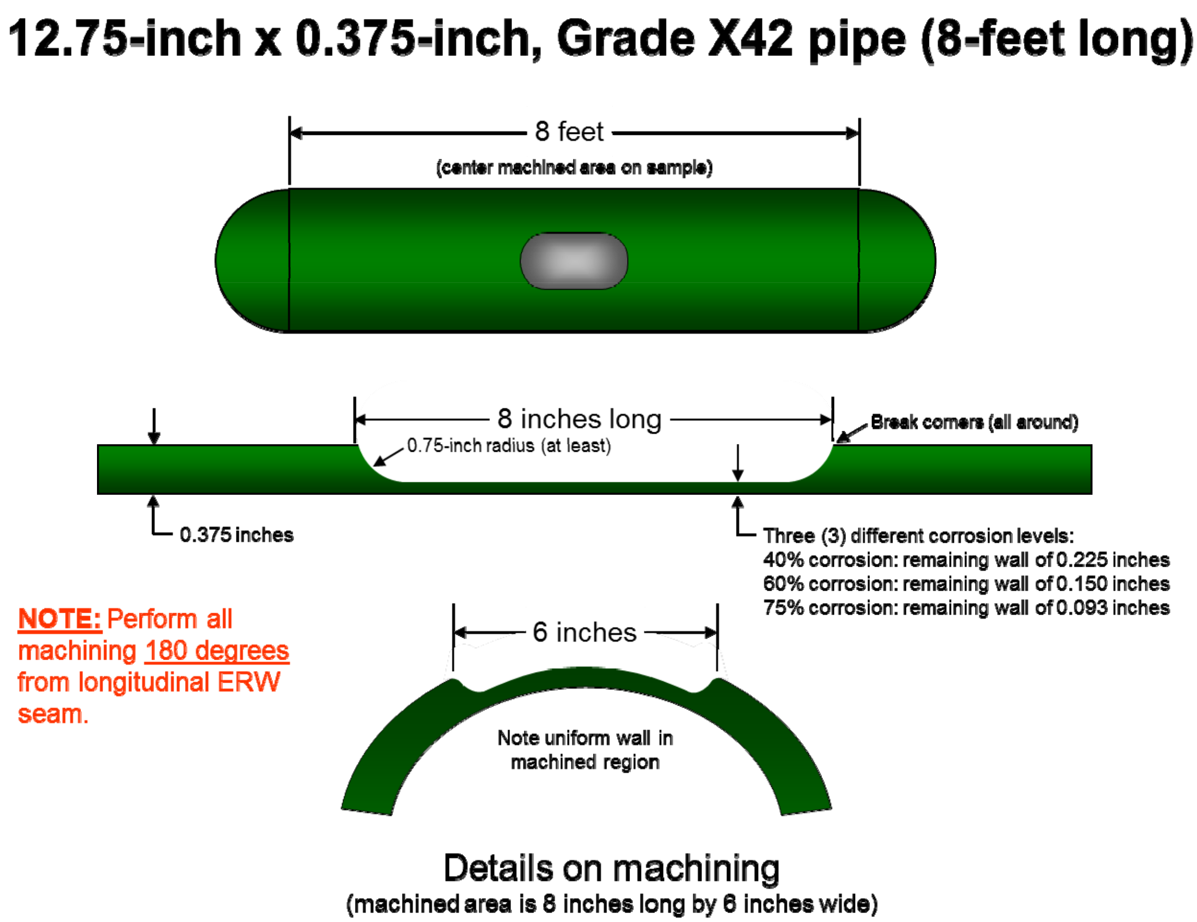

Figure 2 – Geometry for corrosion defects in PRCI MATR-3-4 stud

3.2 Repairing Dent Defects Subjected to Cyclic Pressures

As with the data presented previously for pressure cycle testing on corroded test samples, a similar test program was completed for dents repaired using composite materials. However, the dent program presented in this document was a formal Joint Industry Project co-sponsored by the Pipeline Research Council International, Inc. (PRCI) and composite manufacturers in testing nine (9) different composite repair systems that included the following configurations:

- Two (2) rigid coil system (one E-glass & one steel)
- Three (3) carbon systems
- Four (4) E-glass systems (both epoxy and urethane resins)

The composite dent repair study, known as PRCI's MATR-3-5 program, involved the repair of 12.75-inch x 0.188-inch, Grade X42 pipe material in which defects were installed that included plain dents, dents in girth welds, and dents in the ERW seam. Six dents (2 of each dent type mentioned previously) were tested in a 28-ft long sample for each of the tested composited repair systems, along with an unrepaired test sample. This configuration resulted in a total of 62 tested dents (several extra samples were tested by one manufacturer to improve their performance, i.e. number of cycles to failure). Additionally, one set of dents were tested evaluating the repair performance of steel sleeves, although results are not presented in this document. Strain gages installed in the dented region (in the unrepaired samples and beneath the repairs) and were used to quantify the level of reinforcement provided by each composite repair system. **Figure 3** is a schematic diagram showing the configuration for the test samples. **Figure 4** plots the cycles to failure for each of the tested systems. A run-out condition of 250,000 cycles was established for the program, although one manufacturer wanted to run to failure and the ERW seam failed at 358,470 cycles (before their repaired samples failed).

Included in **Appendix B** is a copy of a paper presented at the International Pipeline Conference on the MATR-3-5 dent study and includes specific details on this particular research program.[3]

[3] Alexander, C., and Bedoya, J., "Repair Of Dents Subjected To Cyclic Pressure Service Using Composite Materials," Proceedings of IPC2010 (Paper No. IPC2010-31524), 8th International Pipeline Conference, September 27 – October 1, 2010, Calgary, Alberta, Canada.

A comment is made regarding the repair of mechanical damage using composite materials. Although testing results for mechanical damage testing are not specifically included in this report, similar results are to be expected when considering the repair of dents. **SES has always recommended that the repair of dents with gouges (i.e. mechanical damage) should involve the removal of gouges, scratches, and other crack-like features by grinding.** A research program sponsored by the Gas Research Institute (GRI) in the late 1990s demonstrated that when gouges are removed by grinding, composite materials can be used to repair mechanical damage.[4] Since that time period similar testing has been conducted on four other composite repair systems that confirmed the conclusion of the GRI research that composite material can be used to repair mechanical damage.

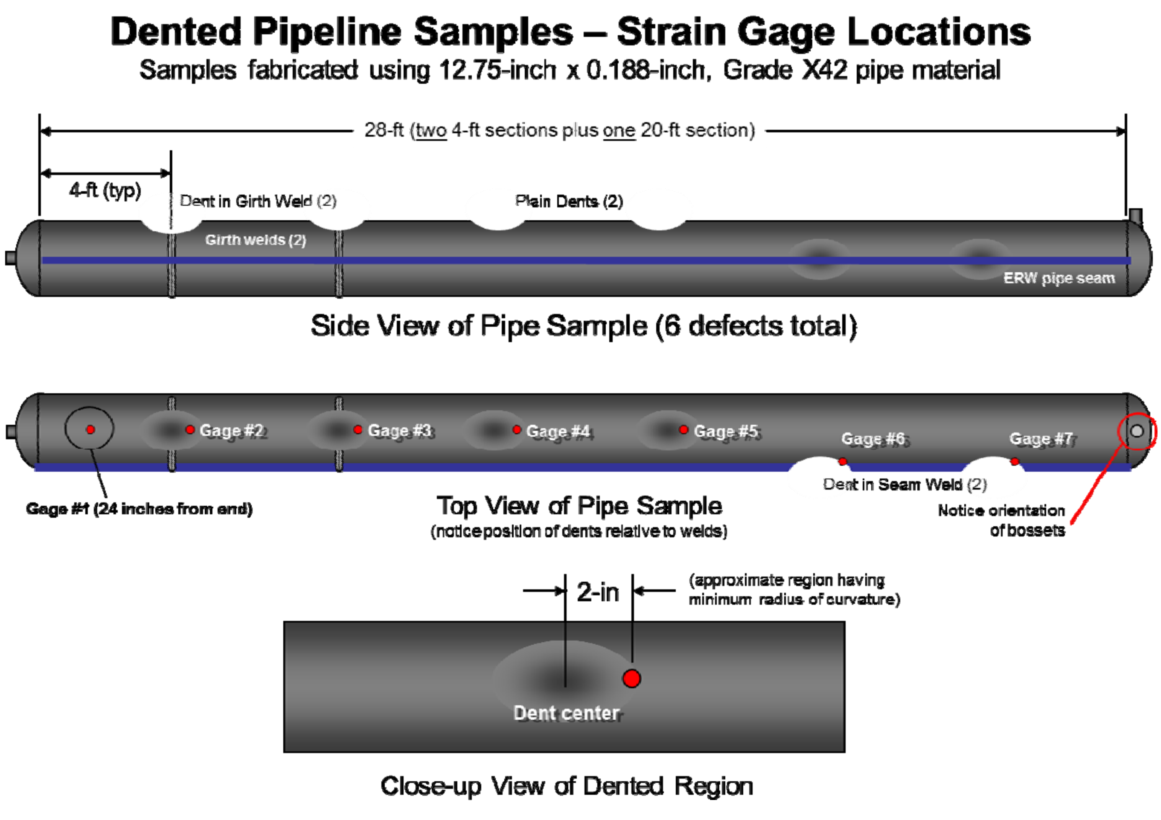

Figure 3 – Diagram showing set-up for the PRCI MATR-3-5 dent samples

[4] Alexander, C.R., *Evaluation of a Composite System for Repair of Mechanical Damage in Gas Transmission Lines*, Prepared for the Gas Research Institute, Chicago, Illinois, GRI-97/0413, December 1998.

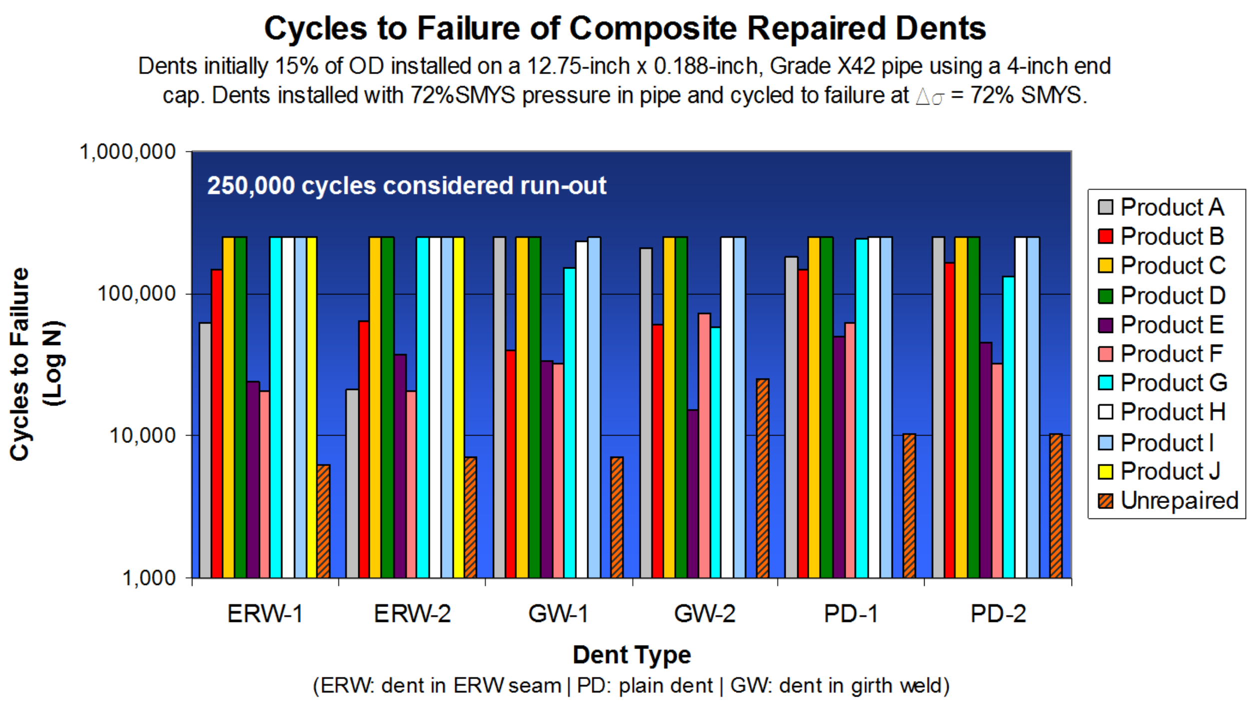

Figure 4 – Pressure cycle to failure results for the PRCI MATR-3-5 dent samples

Listed below are the average cycles to failure for each of the respective tested repair products (six dents tested per product). Note that the run-out condition for this study was designated at 250,000 cycles, while the average value for all data is 161,778 cycles.

- Unrepaired – 10,957 cycles
- Product A – 162,308 cycles
- Product B – 104,581 cycles
- Product C – 250,000 cycles
- Product D – 250,000 cycles
- Product E – 34,254 cycles
- Product F – 40,017 cycles
- Product G – 180,369 cycles
- Product H – 247,075 cycles
- Product I – 250,000 cycles
- Product J – 250,000 cycles

As was done previously, three samples have been selected for use in the subsequent case studies. The "D" denotes dents with the second letter designating the low, medium, and high conditions based on the respective cycle lives. As observed in the above data, composite repair systems are in general an effective means for increasing the fatigue lives over the unrepaired dents by at least one order of magnitude.

4.0 APPLICATION AND CASE STUDIES

The testing methodology presented previously is an essential part of the guidelines presented in this document. The short-term product or deliverable of the testing process includes fatigue results involving the repair of a given defect using a particular composite repair system. The "immediate" terminology is included to remind the reader that the end result of the overall assessment process is not test data. Rather, the end objective is to provide the pipeline industry with a means for evaluating the overall performance of composite repair systems in reinforcing anomalies and defects. To address this issue, this section of the report has been prepared to provide guidance in how to meaningfully transform the experimental data into information that can be used by operators in making decisions on the integrity of composite-reinforced pipelines.

The sections that follow include several pieces of information. The first section discusses how to convert the experimental data into a format that can be used in conjunction with actual pipeline pressure history data. The subsequent sections include actual operating pressure data from liquid and gas transmission pipeline operators, along with the fatigue data presented previously (e.g. repair of corrosion and dents), to estimate the remaining service life for reinforced pipe sections.

4.1 Conversion of Experimental Fatigue Data

As discussed previously in the *Elements of the Proposed Testing Program* section of this document, before experimental fatigue data can be used in assessing the severity of actual pipeline defects it is necessary that appropriate fatigue design factors (i.e. factors of safety) be used. For purposes of this discussion, the resulting fatigue life will be referenced as the *remaining design life* and is calculated by dividing the **experimental cycles to failure** by the **fatigue design factor**. Design factors on fatigue data typically range between 10 and 20. As an example, the ASME Boiler & Pressure Vessel Code employs a safety factor of 2 on stress or 20 on experimental fatigue data to establish a design life, whichever generates the lower fatigue life.[5]

[5] *Criteria of the ASME Boiler & Pressure Vessel Code for Design by Analysis in Sections III and VIII, Division 2*, The American Society of Mechanical Engineers, New York, 1969.

The range of fatigue design factors are a function of the exponents employed by the various fatigue curves, which include several factors including standard deviation of the data set and material response to cyclic loading. Recognizing there is an inherent scatter in fatigue data, the selection of the design factor should be based on confidence in the predicted behavior of the dent. For a relatively smooth dent a design factor on the order of 10 is acceptable. Conversely, a mechanical damage defect where the gouged material has been removed by grinding (e.g. say 35% of the pipe's nominal wall thickness), a conservative design factor on the order of 20 is more appropriate. When in doubt, a more conservative design factor should be used.

Hence, the remaining design life can be calculated by dividing the experimental fatigue life by a number between 10 and 20. As an example, consider a plain dent that has 100,000 cycles to failure at a stress range of 36% SMYS. The resulting remaining design life is 10,000 cycles (i.e. 100,000 cycles / 10). What is missing in this discussion, but will be highlighted in detail using case studies in the following four sections, is how to convert the remaining design life into an actual pipeline service life. This obviously requires a working knowledge of the pipeline's pressure history. Provided in **Figure 5**, **6**, and **7** are a series of graphs and tables based on the pressure performance of a liquid transmission pipeline operated by Shell Pipeline Company. This data was presented previously in a paper presented at the 2010 International Pipeline Conference on Calgary[6]. **Figure 5** includes raw data collected over a 37 day period that was considered to be representative of the pipeline's actual service condition. This data was processed using a rainflow counting algorithm to generate data presented in the histogram shown in **Figure 6**.

Figure 7 shows a spreadsheet that was developed to calculate an equivalent number of cycles for the pressure spectrum provided by the pipeline operator. This spreadsheet used the processed data presented in the histogram, in conjunction with Miner's Rule, to calculate an equivalent number of cycles for a specified pressure range. As noted in **Figure 7**, the *Target Cycle Pressure Range* was selected to be 350 psi. The number of cycles at each pressure bin shown in **Figure 6**

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[6] Alexander, C., and Jorritsma, E., *A Systematic Approach for Evaluating Dent Severity in a Liquid Transmission Pipeline System*, Proceedings of IPC2010 (Paper No. IPC2010-31538), 8th International Pipeline Conference, September 27 – October 1, 2010, Calgary, Alberta, Canada.

is converted into an equivalent number of cycles assuming a pressure range of 350 psi. The end result is that for a pressure range of 350 psi, this particular pipeline cycles 1887 cycles per year. This type of information can be used to convert the remaining design life for a given composite into estimated *years of remaining service*. Using the previous example with the remaining design life of 10,000 cycles, the estimated years of remaining service would be 5.3 years (i.e. 10,000 cycles / 1,887 cycles per year).

Appendix C includes a detailed discussion on the process that was used to evaluate the Shell data and is applicable to evaluating pressure history data for other pipeline systems.

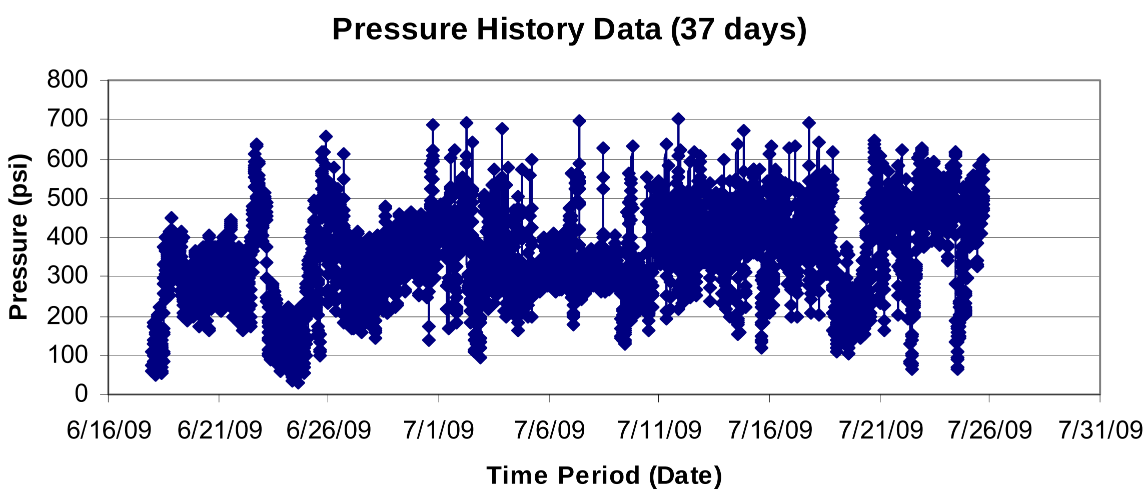


Figure 5 – Pressure data from liquid transmission pipeline system

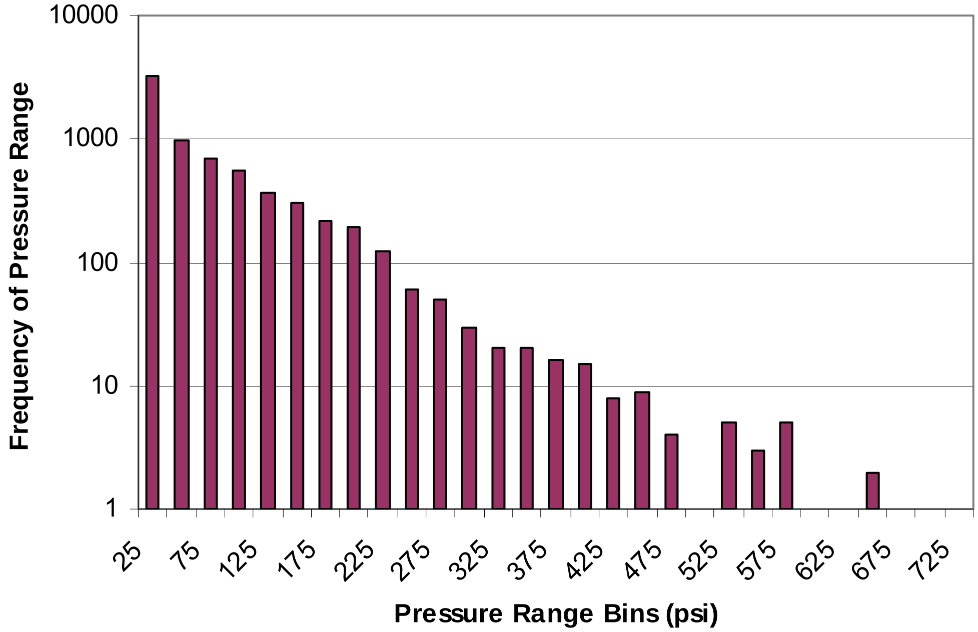
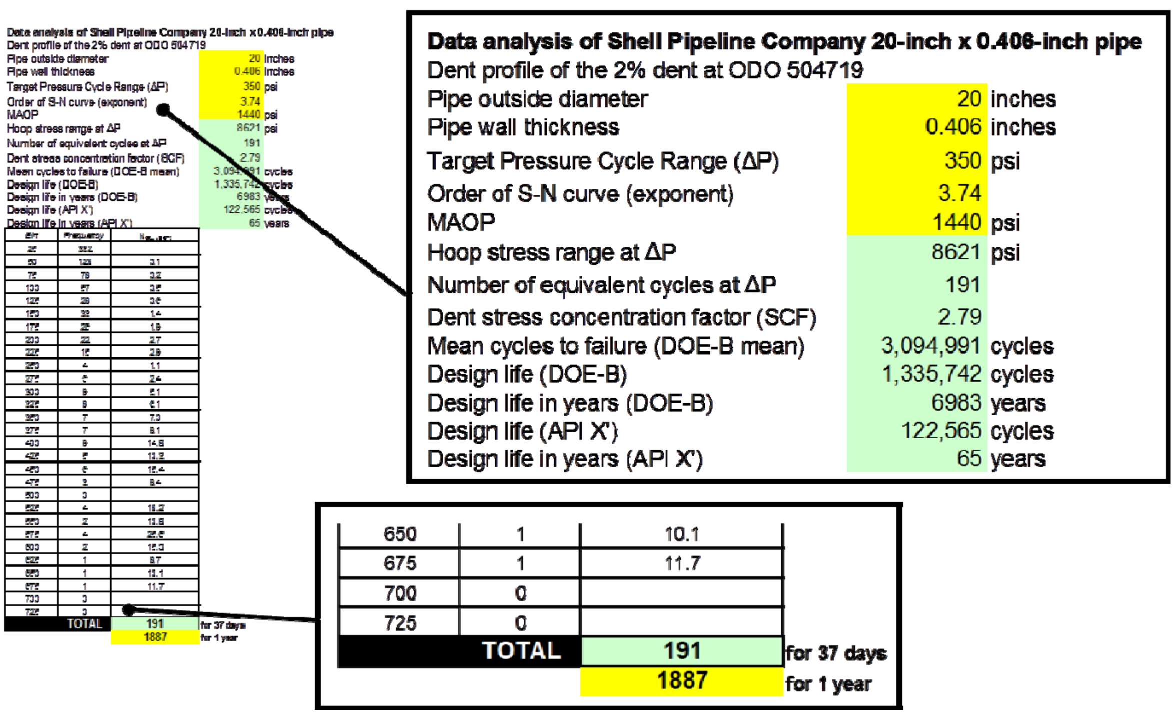


Figure 6 – Histogram of processed data from liquid transmission pipeline



Data analysis of Shell Pipeline Company 20-inch x 0.406-inch pipe		
Dent profile of the 2% dent at ODO 504719		
Pipe outside diameter	20	inches
Pipe wall thickness	0.406	inches
Target Pressure Cycle Range (ΔP)	350	psi
Order of S-N curve (exponent)	3.74	
MAOP	1440	psi
Hoop stress range at ΔP	8621	psi
Number of equivalent cycles at ΔP	191	
Dent stress concentration factor (SCF)	2.79	
Mean cycles to failure (DOE-B mean)	3,094,991	cycles
Design life (DOE-B)	1,335,742	cycles
Design life in years (DOE-B)	6983	years
Design life (API X')	122,565	cycles
Design life in years (API X')	65	years

650	1	10.1	
675	1	11.7	
700	0		
725	0		
	TOTAL	191	for 37 days
		1887	for 1 year

Figure 7 – Spreadsheet used to calculate an equivalent number of cycles

4.2 Case Studies Integrating Test Results with Operating Pressure Histories

The sections that follow provide the estimated remaining years of service for both liquid and gas transmission pipelines. Liquid transmission pipelines typically experience more pressure cycles than gas transmission pipelines and this is reflected in the data presented in this document. Additionally, three (3) repaired corrosion samples and (3) repaired dent samples are considered. Considering all possible combinations, a total of 18 different sample configurations are considered in this presentation.

4.2.1 Case Study #1: Gas Pipeline with 75% Corrosion

Gas pressure condition: <u>50 annual cycles</u> with pressure range of <u>750 psi</u> (36% SMYS)

The composite-repaired **CORROSION** samples were cycled at 36% SMYS and had the following number of cycles to failure:

- Product CL - E-glass system: 19,411 cycles to failure
- Product CM - E-glass system: 259,537 cycles to failure
- Product CH - Hybrid steel/E-glass Urethane system: 767,816 cycles to failure

To convert the experimental fatigue life into a resulting remaining design life, a fatigue design factor of 10 is introduced. Additionally, the 505 cycles per year value is considered in the calculations. Therefore, the remaining design life in *years* is calculated by dividing the experimental fatigue lives by 500 (i.e. 50 cycles per year x 10 safety factor). The following remaining design lives are calculated for the selected three repair configurations.

- Product CL – 39 estimated remaining years of service
- Product CM – 519 estimated remaining years of service
- Product CH – 1,536 estimated remaining years of service

No consideration of prior service has been made. The effects of prior service will act to reduce the estimated remaining life. As observed in the above data, there is a considerable difference in the estimated remaining years of service when comparing Product CL and Product CH.

4.2.2 Case Study #2: Gas Pipeline with Plain Dent

Gas pressure condition: 50 annual cycles with pressure range of 750 psi (36% SMYS)[7]

The 36% SMYS pressure cycle condition will be used as this was the pressure range employed during the experimental dent work. However, as shown below, the experimental study testing dents involved a cyclic pressure range equal to 72% SMYS. The three selected composite-repaired **DENT** samples that were cycled at 72% SMYS had the following cycles to failure:

- Product DL – E-glass system: 34,254 cycles to failure
- Product DM – E-glass system: 161,308 cycles to failure
- Product DH - Hybrid steel/epoxy: 250,000 cycles to failure

Because the samples were cycled at 72% SMYS, and the gas pressure range conditions are provided at 36% SMYS, the test data must be converted into an equivalent number of cycles for a pressure range equal to 36% SMYS. This is commonly done using Miner's Rule, a method for converting cycle numbers between data at different stress ranges. In 1945, M. A. Miner popularized a rule that had first been proposed by A. Palmgren in 1924.[8] The rule, variously called *Miner's rule* or the *Palmgren-Miner linear damage hypothesis*, states that where there are k different stress magnitudes in a spectrum, S_i ($1 \le i \le k$), each contributing $n_i(S_i)$ cycles, then if $N_i(S_i)$ is the number of cycles to failure of a constant stress reversal S_i, failure occurs when:

$$\sum_{i=1}^{k} \frac{n_i}{N_i} = C$$

C is experimentally found to be between 0.7 and 2.2. Usually for design purposes, C is assumed to be 1. This can be thought of as assessing what proportion of life is consumed by stress reversal at each magnitude then forming a linear combination of their aggregate. The above relation is

[7] At a pressure range of 72% SMYS the number of annual cycles was determined to be approximately 3; however, to demonstrate how to convert experimental fatigue data from one stress range to another this value is not included in the calculations. As will be shown, the results for both approaches are essentially the same.
[8] http://en.wikipedia.org/wiki/Fatigue_(material)

used to transform fatigue data (i.e. cycles to failure) collected at a stress range equal to 72% to data at a stress range equal to 36% SMYS. Considering a fourth order relationship between the applied stress range and fatigue life, the number of cycles at a stress range of 36% SMYS is 16 times the number of cycles at a stress range of 72% SMYS ($[72\% \text{ SMYS} / 36\% \text{ SMYS}]^4 = 16$).

The composite-repaired **DENT** samples that were cycled at 36% SMYS (converted from the 72% SMYS data presented above in multiplying by 16) have the following "equivalent" number of cycles to failure:

- Product DL – E-glass system: 548,064 cycles to failure
- Product DM – E-glass system: 2,580,928 cycles to failure
- Product DH - Hybrid steel/epoxy: 4,000,000 cycles to failure

As expected, there is a significant increase in the fatigue life when operating at a pressure spectrum with a lower pressure range. As was done previously, the remaining design life is calculated by applying a fatigue design factor of 10 to the experimental cycles to failure. Additionally, a 20 year design life is considered in the calculation. Therefore, the resulting remaining design life in terms of *years of service* is calculated by dividing the experimental fatigue lives by 500 (i.e. 50 cycles per year x 10 safety factor). Therefore, the following remaining design lives are calculated considering the three repair configurations.

- Product DL – 1,096 estimated remaining years of service
- Product DM – 5,162 estimated remaining years of service
- Product DH – 8,000 estimated remaining years of service

4.2.3 Case Study #3: Liquid Pipeline with 75% Corrosion

Liquid pressure condition: 250 annual cycles with pressure range of 600 psi (36% SMYS)
Liquid pressure condition: 20 annual cycles with pressure range of 1,200 psi (72% SMYS)

The above data sets are based on actual pressure data from a liquid transmission pipeline. The data are for two different pressure conditions on the same pipeline and should not be considered to occur concurrently. As observed, the increased pressure range (i.e. 1,200 psi) results in one order of magnitude decrease in the number of cycles as compared to the lower pressure range conditions (i.e. 250 cycles at the 600 psi pressure range). Miner's Rule can be used to combine multiple pressure range/cycle count conditions; however, in the case of the above data a combined single value is not appropriate. The 36% SMYS pressure cycle condition (250 cycles per year) will be used in the following calculations as this was the pressure range employed during testing of the corrosion samples.

The composite-repaired **CORROSION** samples that were cycled at 36% SMYS had the following cycles to failure:

- Product CL - E-glass system: 19,411 cycles to failure
- Product CM - E-glass system: 259,537 cycles to failure
- Product CH - Hybrid steel/E-glass Urethane system: 767,816 cycles to failure

Once again, to convert the experimental fatigue life into a resulting remaining design life a fatigue design factor of 10 is introduced. As done previously, a 20 year design life is considered in the calculations. Therefore, the remaining design life in years is calculated by dividing the experimental fatigue lives by 2,500 (i.e. 250 cycles per year x 10 safety factor). It is noted that this value is five times greater than the factor presented previously for the gas transmission pipeline. Therefore, the following remaining design lives are calculated considering the three repair configurations.

- Product CL – 8 estimated remaining years of service
- Product CM – 104 estimated remaining years of service
- Product CH – 308 estimated remaining years of service

In considering the above data, the values are one-fifth the results calculated for the gas transmission pipeline. This is to be as expected as mentioned previously in that liquid transmission pipelines tend to experience more pressure cycles than gas transmission pipelines.

4.2.4 Case Study #4: Liquid Pipeline with Plain Dent

Liquid pressure condition: 250 annual cycles with pressure range of 600 psi (36% SMYS)

Liquid pressure condition: 20 annual cycles with pressure range of 1,200 psi (72% SMYS)

The 72% SMYS pressure cycle condition will be used for the calculations as this was the pressure range employed during the experimental dent work. Note that this is different than the 36% SMYS pressure range considered previously for the three other case studies.

The composite-repaired **DENT** samples cycled were cycled at 72% SMYS included the following cycles to failure:

- Product DL – E-glass system: 34,254 cycles to failure
- Product DM – E-glass system: 161,308 cycles to failure
- Product DH - Hybrid steel/epoxy: 250,000 cycles to failure

To convert the experimental fatigue life into a resulting remaining design life the fatigue design factor of 10 is once again introduced. Additionally, a 20 year design life is considered in the calculations. There, the remaining design life in years is calculated by dividing the experimental fatigue lives by 400 (i.e. 20 cycles per year x 10 safety factor). Therefore, the following remaining design lives are calculated considering the three selected repair configurations.

- Product DL – 86 estimated remaining years of service
- Product DM – 403 estimated remaining years of service
- Product DH – 625 estimated remaining years of service

In reviewing the plain dent fatigue lives, the preceding values are approximately one-thirteenth the results calculated for the gas transmission pipeline. This is to be as expected, as mentioned previously, in that liquid transmission pipelines tend to experience more pressure cycles than gas transmission pipelines.

4.3 Discussion on Case Study Results

Determining how to best utilize experimental work for making decisions regarding pipeline operations is not a simple matter. As presented, it is essential that appropriate safety factors, or fatigue design factors, be employed. Safety factors on ultimate tensile strength for pipelines are typically on the order of 2 or 3 when considering static pressures; however, because of the inherent scatter in fatigue data much larger factors of safety are required. As discussed previously, safety factors on cycles to failure need to be more on the order of 10 to 20. Although some might argue that safety factors of this magnitude are too conservative, the risks and consequences associated with pipeline failures necessitate that a conservative position be taken.

The case studies that have been presented provide the reader with examples in how to apply experimental findings to actual pipeline damage. When SES is provided with in-line inspection (ILI) data from which finite element models are constructed to calculate stresses in a dent, it is common for previous experimental data to be integrated into the assessment process. This effort is done to ensure that an appropriate level of conservatism has been provided to the operator in order for them to make appropriate decisions regards the future service of the dent in question. **Figure 8** shows dent profiles for six dents, along with ILI data used to construct a finite element model. Several comparisons were made between the experimental and analytical results, including the dent profile and the resulting stress concentration/intensification factors. Integrating information from both analytical and experimental sources improved confidence in the proposed course of action that included leaving the dent damage in service. **Figure 9** includes two photographs showing failures for two dents tested in a PRCI program. Note that the cycle to failure data for these two samples are included in **Figure 8** for Samples #9 and #10.

One item not specifically addressed thus far in this document concerns the design of the composite repair system itself. In the experimental studies SES has typically relied on the composite manufacturers to design their own repair systems, meaning that they assumed responsibility for determining the appropriate thickness and composite architecture of their repairs. Systems that performed best were typically those companies who had qualified their systems to meet the requirements set forth in the ASME PCC-2 and ISO 24817 standards. The key to the long-term success of a composite repair system is to ensure that the design stress is well below the short-term tensile strength of the composite material itself, with safety factors typically ranging between 5 and 7. For example, consider Product CM listed previously, an E-glass epoxy system that had 259,537 cycles to failure. This system has historically performed well in repairing corrosion, dents, and other anomalies. When operating at 72% SMYS, this system has a safety factor of approximately 6 on the short-term tensile strength based on actual inter-layer strain measurements. When safety factors of this magnitude are employed, the composite material has adequate strength to accommodate a certain level of degradation that is to be expected when dealing with polymers that serve as the matrix for most conventional composite repair systems.

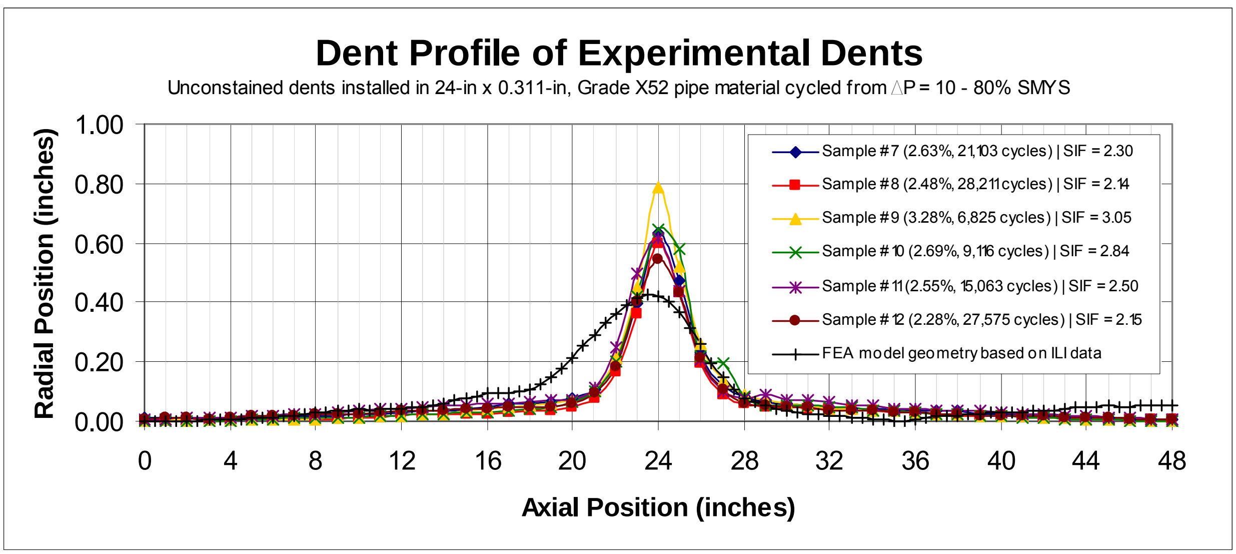


Figure 8 – Analytical versus experimental dent profiles in pipe

Figure 9 – Photographs of dents from PRCI test samples

5.0 CLOSING COMMENTS

This document was prepared for the Gas Technology Institute to provide guidance on using composite materials to reinforce pipeline anomalies subjected to cyclic pressures. Of particular interest was the development of a cyclic loading procedure, along with a methodology for estimating the long-term life expectancy of composite materials used to repair of corrosion and dents.

In this presentation SES specifically included bodies of work from prior studies that involved fatigue data for composite materials used to repair corrosion and composite materials. It is entirely within the realm of sound engineering to integrate full-scale testing, along with actual operating pressure data, to make an assessment on the future performance of damaged pipelines using composite materials. Experience has shown that those systems that have performed best possess several common characteristics. The first is the fact that their design stress is well-below the short-term tensile strength of the composite material, with safety factors ranging between 5 and 7. The second factor, although less documented, is the presence of stiff load transfer materials that ensure load is transferred from the damaged pipe section to the composite material, while minimizing the levels of strains that are generated in the reinforced steel section.

A relatively large body of data has been presented within this document supporting the proposed methodology. The key to properly utilizing composite materials to reinforce and repair damaged pipelines subjected to cyclic service requires full-scale destructive testing to establish the limit state fatigue life, while also integrating actual operating pressure histories. When information associated with these two requirements is integrated, operators can determine with confidence the safe operating envelope for composite-reinforced damaged pipelines.

APPENDIX C – CALCULATING EQUIVALENT PRESSURE HISTORY DATA

Calculating Equivalent Pressure History Data

SES used the pressure cycle data to estimate the remaining life of the dented region of the pipeline. The CRUNCH [9] software package was used to perform a rainflow count analysis on the Shell pressure spectrum. The purpose in completing this exercise is to convert the random pressure cycle data into a meaningful format that permits the generation of a single equivalent pressure cycle data value using Miner's Rule for an assumed pressure range. The steps involved in this process are as follows.

1. Use CRUNCH to convert the raw pressure spectrum data into a file format that counts the number of pressure cycles for a given set of pressure range bins (e.g. 25 psi, 75 psi, etc.). An example pressure data set from the 37 days period ranging from June 18, 2009 to June 25, 2009 is shown in **Figure C1**.
2. Use the pressure bin data calculated in Step #1 to make a histogram plot as shown in **Figure C2**. This particular figure shows data for the three different periods of time considered in this study.
3. Using Miner's Rule, calculate a single equivalent pressure cycle value for an assumed pressure range. **Figure C3** shows results for the Shell-provided data set. As noted in this figure, the resulting number of cycles for a pressure range of 350 psi was calculated to be 1,887 annual cycles. This selection of this pressure range is not critical to the calculated results, but is necessary to provide the Miner's Rule sum. In the spreadsheet shown in **Figure C3** the number of design cycles even when this pressure range is changed. Note that the exponent employed for the Miner's Rule sum is 3.74, which is the same value used in the API X' curve.
4. See the example equation provided below showing how Miner's Rule is used to combine numbers of pressure cycles for different pressure ranges as listed in **Figure C3**.

$$N_{350} = N_{25}\left[\frac{350\text{ psi}}{25\text{ psi}}\right]^{-3.74} + N_{75}\left[\frac{350\text{ psi}}{75\text{ psi}}\right]^{-3.74} + \ldots$$

5. Using an assumed S-N design fatigue curve (e.g. the API X' curve used in this study), calculate the design cycles for the assumed pressure range (e.g. 350 psi) and the calculated dent SCF based on finite element modeling (e.g. 2.79). Note that the SCF has been multiplied by the hoop stress range, which results in a single design fatigue life, which was 122,565 cycles considering the API X' design fatigue curve.
6. Using the calculated fatigue life results from Step #4 and the annual cycle count from Step #3, the estimated remaining design life in "years" of the pipeline can be calculated (e.g. 65 years in this particular case).

Note in **Figure C3** the difference in results between the design fatigue lives calculated using the API X'[10] and the DOE-B[11] curves. It is the author's opinion that the DOE-B mean cycles to failure curve is well-suited for calculating empirical data (i.e. cycles to failure), while the design margin associated with the API X' design curve makes it better-suited for establishing a remaining life based on design conditions. There is nothing significant about the selection of the

[9] CRUNCH USER'S GUIDE by Marshall L. Buhl, Jr., National Wind Technology Center, National Renewable Energy Laboratory, Golden, Colorado, revised on October 15, 2003 for version 2.9.
[10] API RP 2A, *Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms*, American Petroleum Institute, 01-Jul-1993.
[11] Offshore Installations: Guidance on Design and Construction, ISBN 0 11 411457 9, Publication 1984.

two particular fatigue curves, other than the fact that they have been successfully used to estimate the number of cycles to failure for dents subjected to cyclic pressure testing.

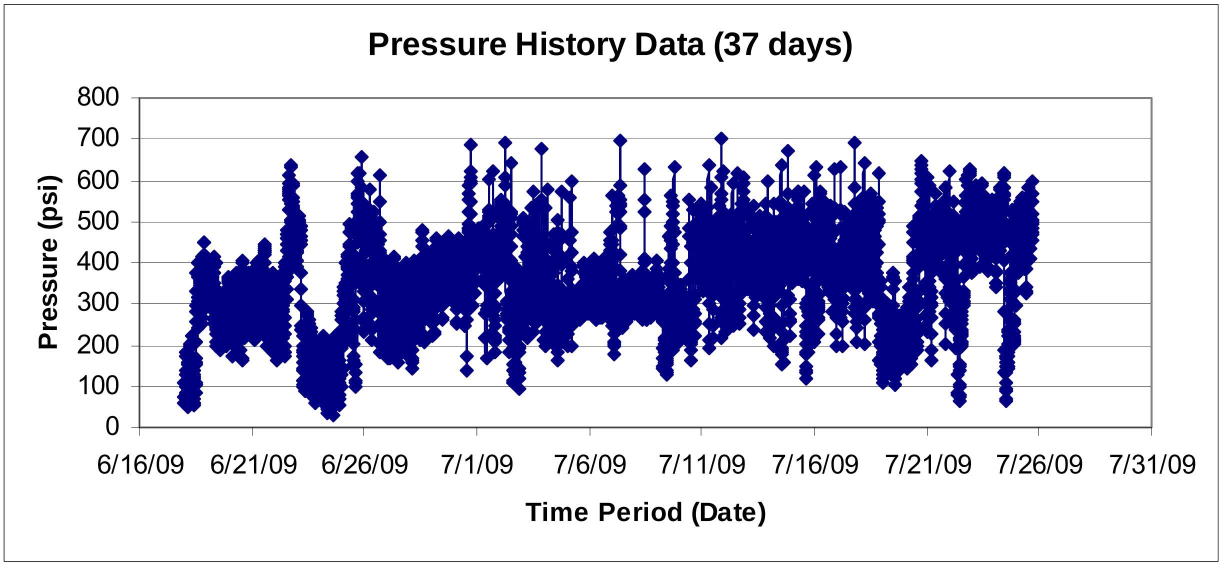


Figure C1 – Historical Pressure History Data for 6/18/09 to 7/25/09
(Last 37 days of the provided Shell pressure cycle data)

Note in **Figure C2** the significant difference that exists in viewing the histograms associated with the three following periods of time.

- July 25, 2008 to July 25, 2009 (all provided data)
- June 18, 2009 to July 25, 2009 (last 37 days of the provided data)
- July 25, 2008 to June 17, 2009 (provided data less last 37 days)

While the estimated cycles to failure is primarily a function of the stress range in the dented region of the pipe, the remaining years of service is determined based on the assumed pressure cycle conditions. A more aggressive pressure cycle condition will result in a shorter remaining life. Provided below in **Table C1** are results using the pressure data considering two different stress concentration factors (calculated using finite element analysis for given dents) and three different periods of time. As noted in this table, if one considers the pressure cycle condition prior to June 18, 2009 for the SCF = 2.79 the estimated remaining life is 3,011 years; however, if one considers the more aggressive pressure cycle condition since June 18, 2009 the estimated remaining life is reduced to 65 years.

Table C1 - Design Life as a Function of Operating Period and SCF
(Miner's Rule assessment uses exponent of 3.74 from the API RP2A X' curve)

SCF = 2.79			SCF = 4.24		
All year (7/25/08 - 7/25/09)	**Last 37 days** (6/18/09 - 7/25/09)	**Year minus last 37 days** (7/25/08 - 6/17/09)	**All year** (7/25/08 - 7/25/09)	**Last 37 days** (6/18/09 - 7/25/09)	**Year minus last 37 days** (7/25/08 - 6/17/09)
306 years	65 years	3,011 years	64 years	14 years	629 years

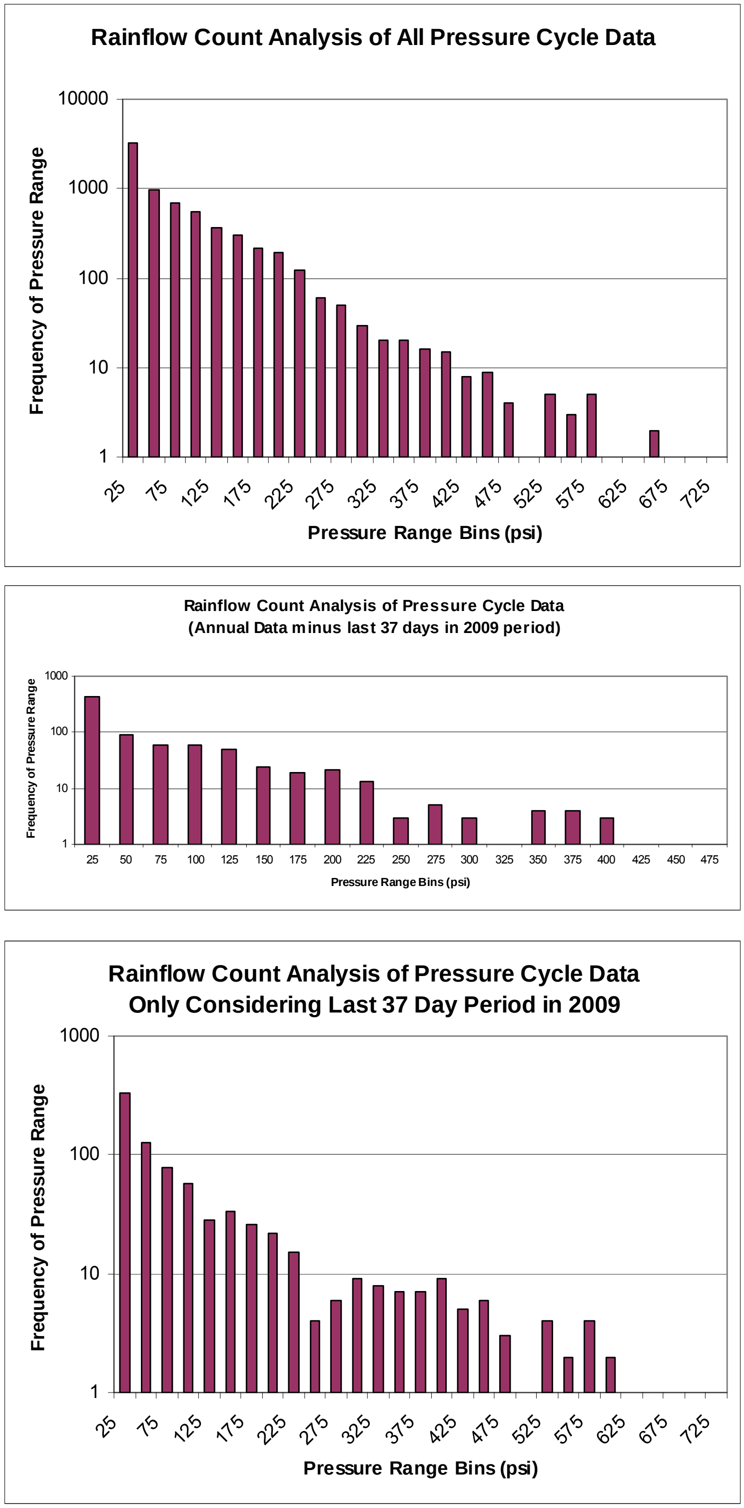


Figure C2 – Pressure Cycle Histograms for three time periods

Data analysis of Shell Pipeline Company 20-inch x 0.406-inch pipe

Dent profile of the 2% dent at ODO 504719

Pipe outside diameter	20	inches
Pipe wall thickness	0.406	inches
Target Pressure Cycle Range (ΔP)	350	psi
Order of S-N curve (exponent)	3.74	
MAOP	1440	psi
Hoop stress range at ΔP	8621	psi
Number of equivalent cycles at ΔP	191	
Dent stress concentration factor (SCF)	2.79	
Mean cycles to failure (DOE-B mean)	3,094,991	cycles
Mean design cycles (DOE-B)	1,335,742	cycles
Mean design years (DOE-B)	6983	years
Mean design cycles (API X')	122,565	cycles
Mean design years (API X')	65	years

Bin	*Frequency*	$N_{equivalent}$	
25	332		
50	128	0.1	
75	78	0.2	
100	57	0.5	
125	28	0.6	
150	33	1.4	
175	26	1.9	
200	22	2.7	
225	15	2.9	
250	4	1.1	
275	6	2.4	
300	9	5.1	
325	8	6.1	
350	7	7.0	
375	7	9.1	
400	9	14.8	
425	5	10.3	
450	6	15.4	
475	3	9.4	
500	0		
525	4	18.2	
550	2	10.8	
575	4	25.6	
600	2	15.0	
625	1	8.7	
650	1	10.1	
675	1	11.7	
700	0		
725	0		
	TOTAL	**191**	**for 37 days**
		1887	**for 1 year**

Figure C3 – Data Analysis Showing Calculated Results
(Tabulated data same as histogram plotted in Figure C1)

APPENDIX D – Chemical Degradation Test Results

List of Figures

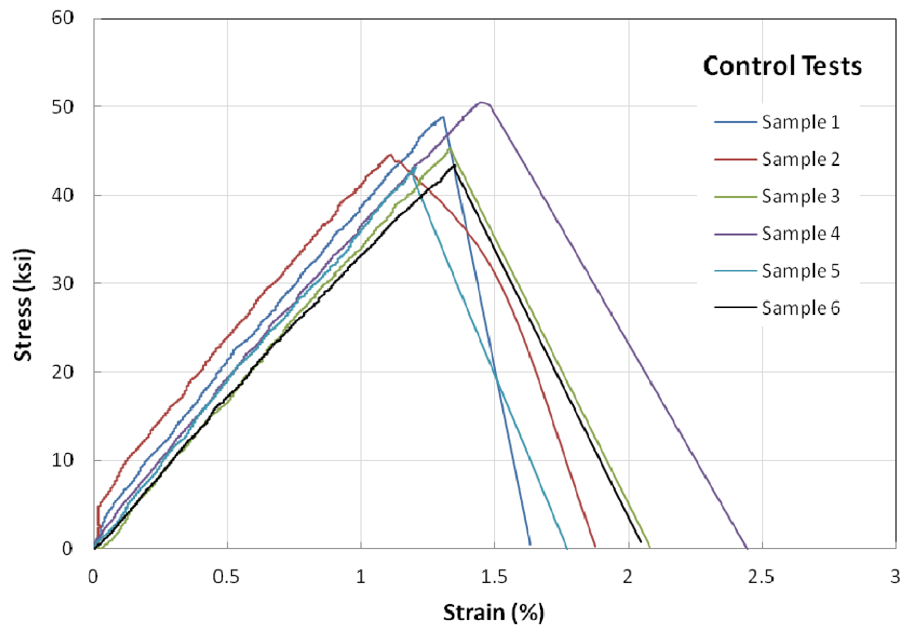


Figure A-1 Fiber Glass Tensile Tests – Control Samples

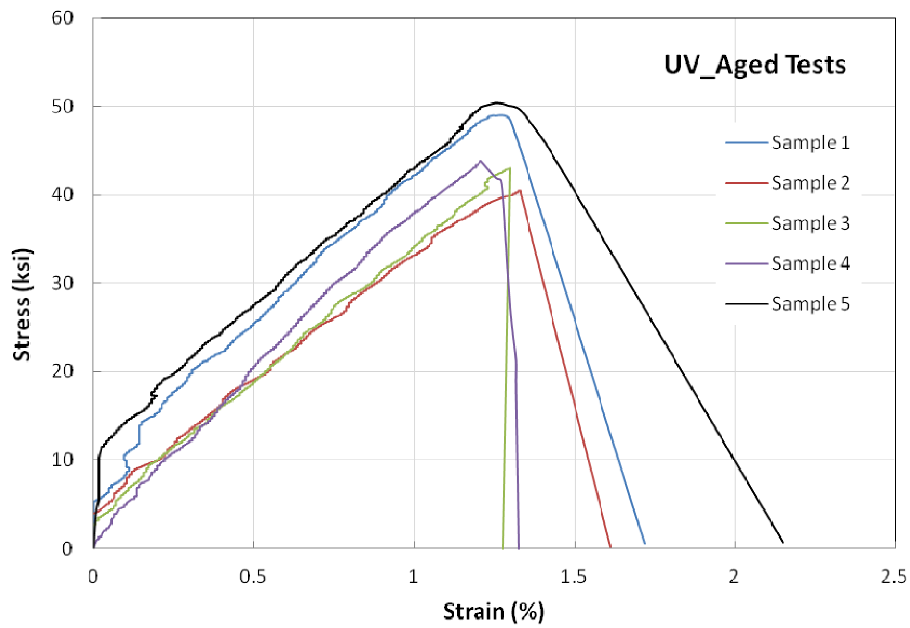


Figure A-2 Fiber Glass Tensile Tests – UV Aged Samples

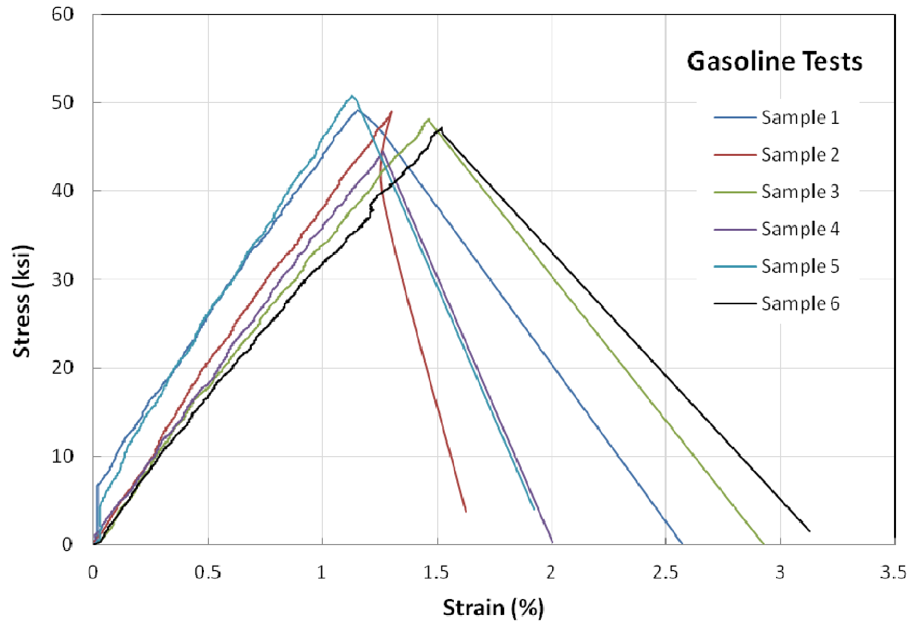


Figure A-3 Fiber Glass Tensile Tests – Gasoline Tested Samples

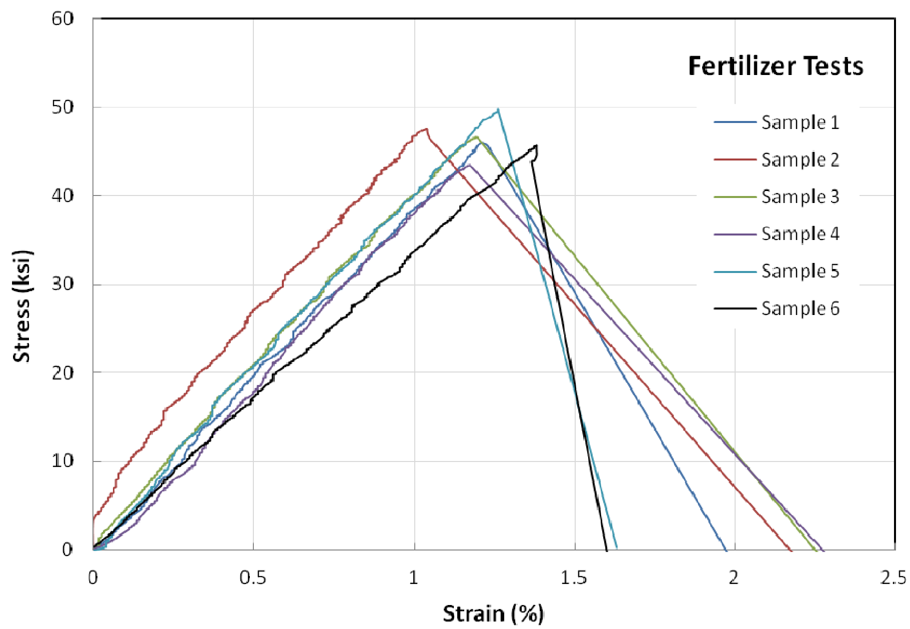


Figure A-4 Fiber Glass Tensile Tests – Fertilizer tested Samples

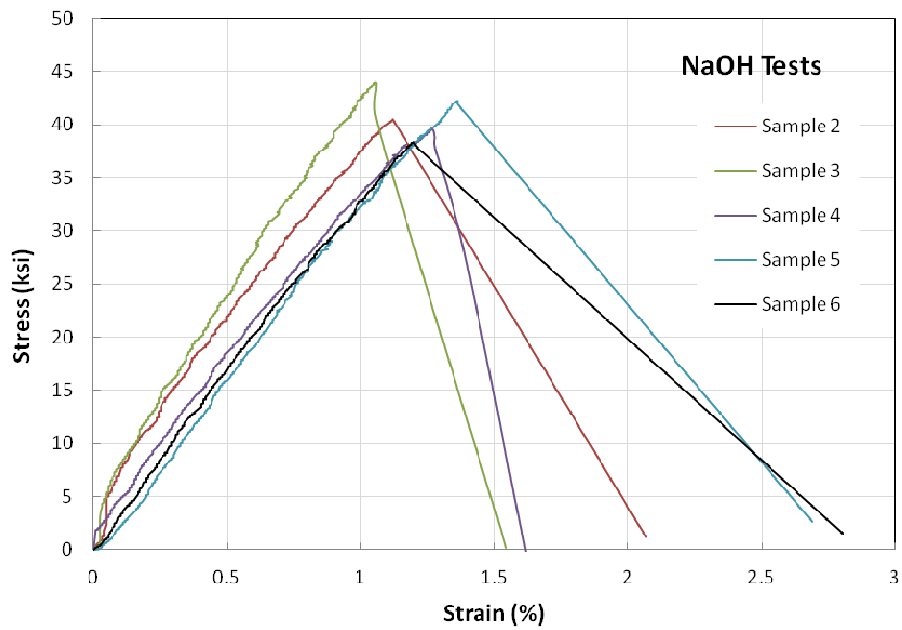


Figure A-5 Fiber Glass Tensile Tests – Sodium Hydroxide Tested Samples

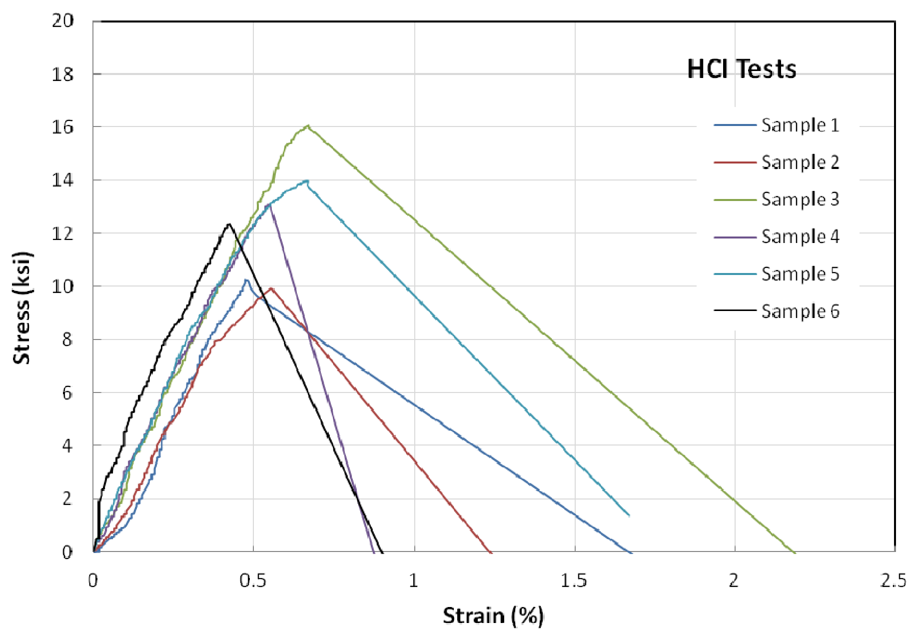


Figure A-6 Fiber Glass Tensile Tests – Hydrochloric Acid Tested Samples

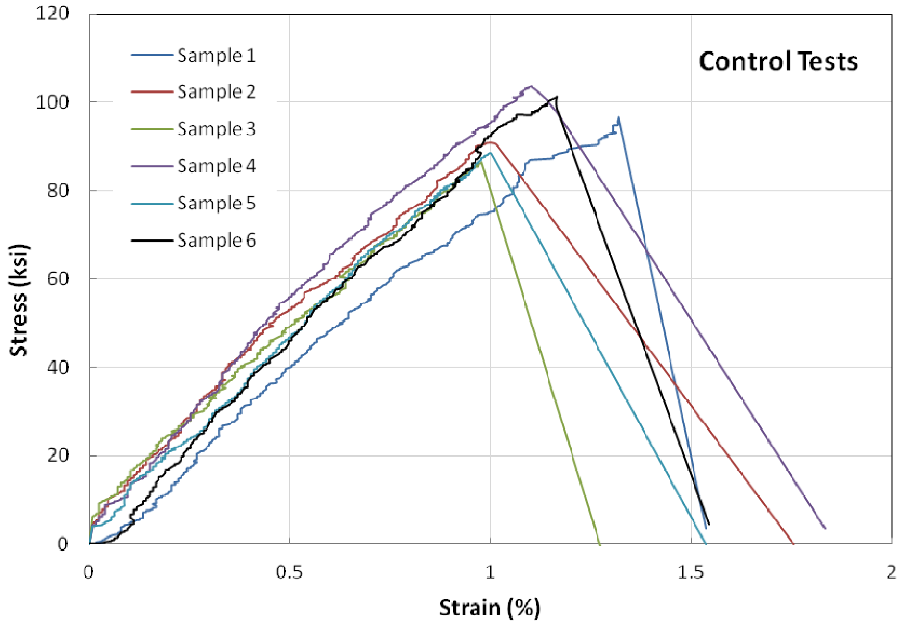


Figure A-7 Carbon Tensile Tests – Control Samples

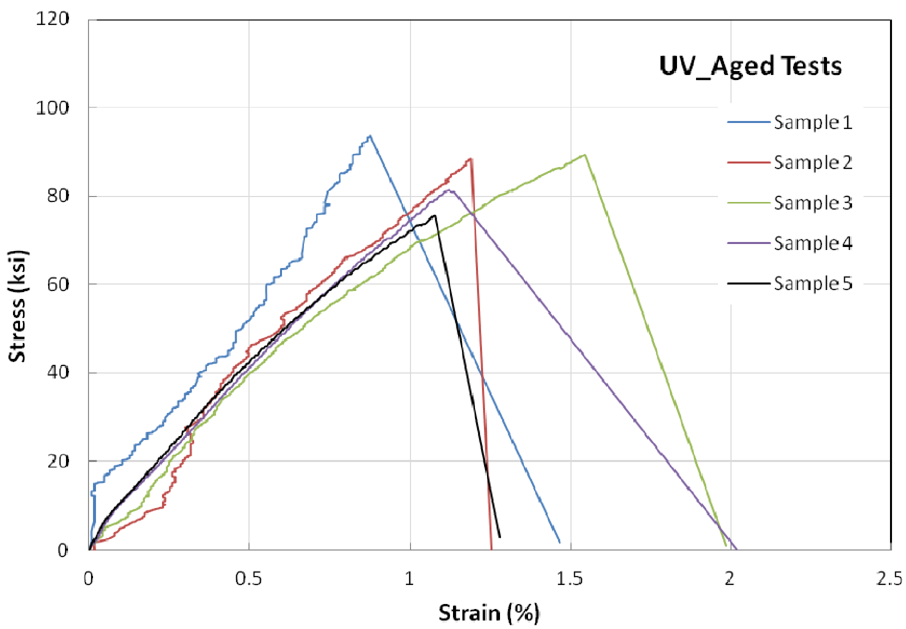


Figure A-8 Carbon Tensile Tests – UV Aged Samples

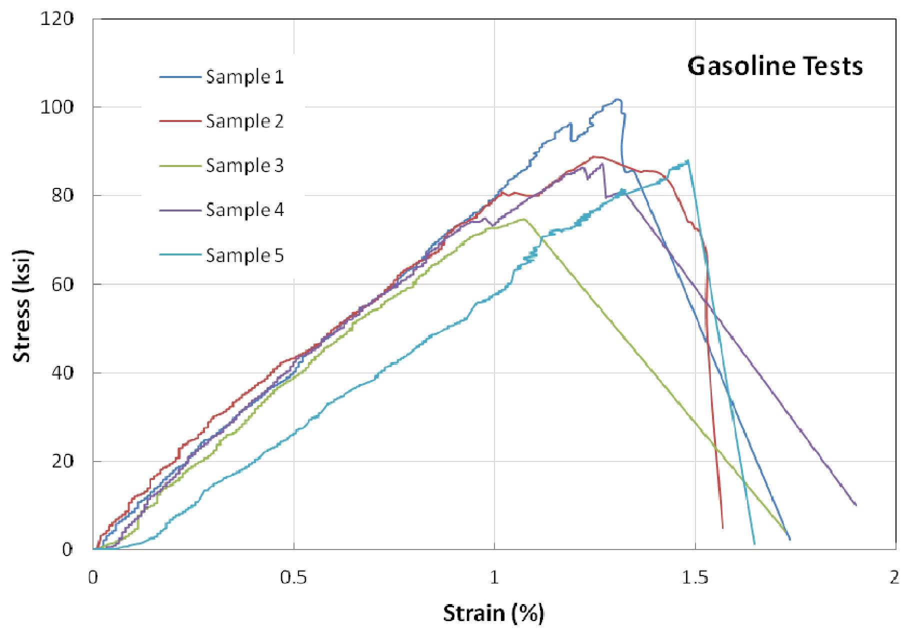


Figure A-9 Carbon Tensile Tests – Gasoline Tested Samples

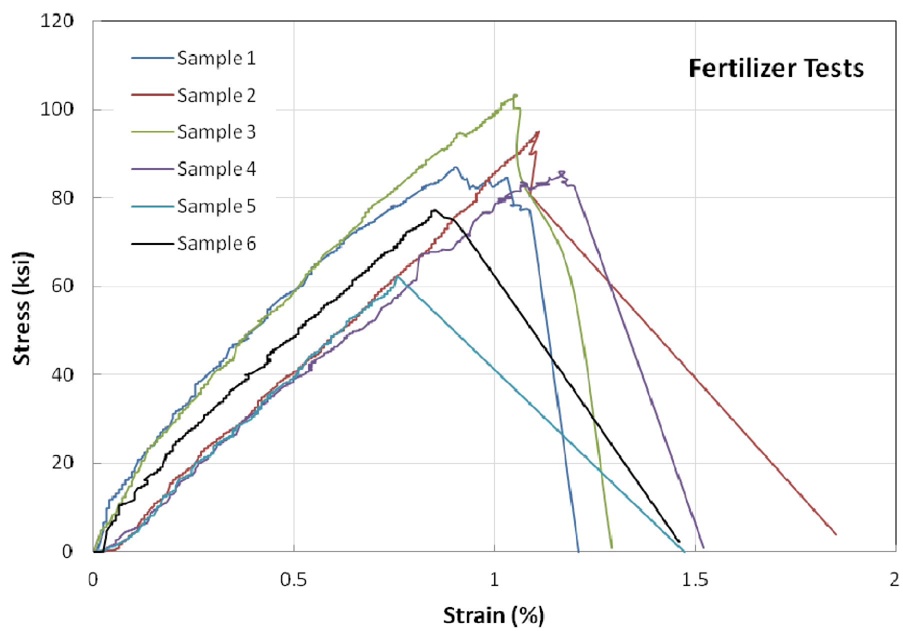


Figure A-10 Carbon Tensile Tests – Fertilizer Tested Samples

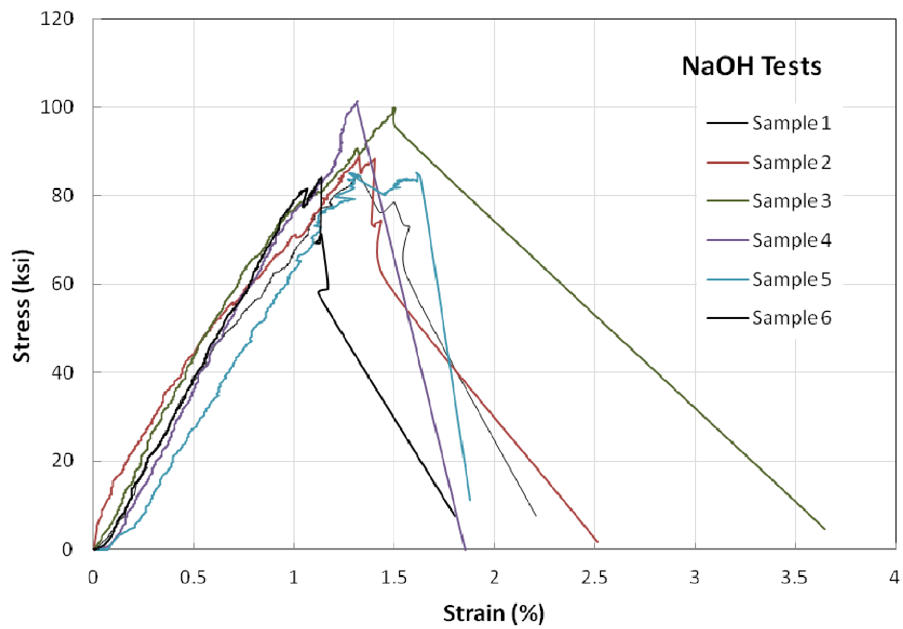


Figure A-11 Carbon Tensile Tests – Sodium Hydroxide Tested Samples

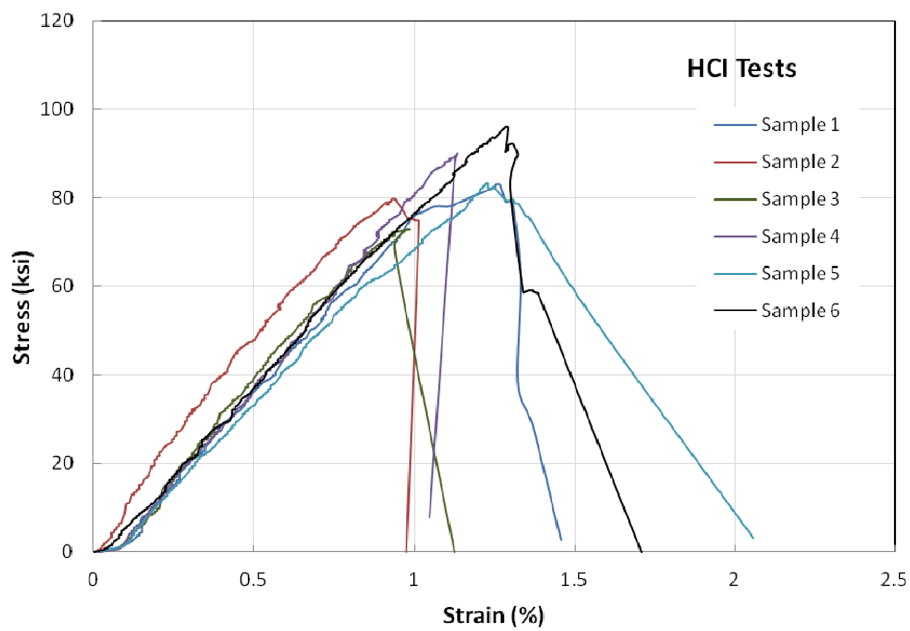


Figure A-12 Carbon Tensile Tests – Hydrochloric Acid Tested Samples