Proceedings of the 2020 13th International Pipeline Conference
IPC2020
September 28- October 1, 2020, Calgary, Alberta, Canada

IPC2020-9303

FULL ENCIRCLEMENT ENGINEERED LAMINATED STEEL SLEEVE SYSTEM FOR REPAIRS AND AUGMENTATION OF PIPELINES

THE ENGINEERING DEVELOPMENT, VALIDATION TEST RESULTS, AND IMPLICATIONS FOR MITIGATION OF BOTH STRESS AND STRAIN DEPENDENT INTEGRITY THREATS

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ABSTRACT

A full encirclement thin layer steel laminated sleeve system has been designed, developed, and optimized for pipeline integrity management applications. Development goals included the elimination of thixotropic concerns as well as the exclusion of the degradation of material properties of composite repairs. Elimination of cyclical fatigue of welded repairs and safety concerns associated with hot work were also considerations. The use of thin layer steel with a modulus matched to base pipe and steel's homogenous isotropic properties enable axial calculations and evaluation of strain-based concerns. The thin layer steel laminated design results in extremely high fracture toughness and promotes intrinsic mitigation of potential future third party damage. The resulting system has demonstrated the reliable engineering data and analysis required for pipeline repairs and demonstrates applicability for the augmentation of existing pipes without defects.

An Engineering Critical Assessment (ECA) has been completed. This ECA follows the industry's precedents of ASME B31G and ASME PCC-2 Article 4 type assessments and provides operators with greater functionality. This ECA has been named the Leewis Augmentation Analysis (LAA) and is presented, reviewed, and discussed.

Third party full scale ASME PCC-2 style burst testing has been completed. The results are presented. Highly instrumented tests were also conducted to determine an effective modulus of elasticity of the installed system as well as a determination of any delay in system acceptance of load. As installed, an effective modulus of 14 million psig (96526.60 MP)a with loading in layer 3 of the laminate at only 50 micro strain is reviewed. Long term creep and cyclical fatigue testing of the steel/adhesive laminate is presented and reviewed. 10 million cycles at 50% of ultimate lap shear has been achieved, which exceeds current industry practice by several orders of magnitude. The classic metal loss defect mitigation principle is reviewed and updated in light of these available technical advances. Finally, the implications for mitigation of both stress and strain dependent integrity concerns is discussed

1. INTRODUCTION

A review of the open literature related to various pipeline repair methods published over the last several decades could lead one to conclude that operators and stakeholders are not dissatisfied with their repair options. However, if one reviews the literature closely, one can identified several topics that seem to offer opportunities for improvement.

In 2010, Leewis and Laughlin introduced a stylized graphical depiction of the stress-strain response of various repairs. They suggested that the initial response of a repair system was in fact the most important portion of the curve to consider[1]. Additionally, in a second technical paper from 2010, Laughlin and Leewis utilized previously reported cyclical data from a respected researcher to demonstrate that at least some composite repairs display rather significant thixotropic behaviour manifested in the form of change in strain observed during testing performance[2]. Perhaps the industry's most familiar knowledge and experiences are discussed in PRCI's Pipeline Repair manual[3]. Welded steel sleeves are well discussed. This compendium utilizes a factor as low as 15% for the strain shared by a properly installed welded steel sleeve and cautions are presented regarding cyclical performance of the requisite welds. More recently, Alexander et al[4] showed that a welded steel sleeve, installed as an integral part of a laboratory-based evaluation could be poorly installed and provide much less effective cyclical performance than expected. That same paper also provides evidence that the caution described in the PRCI Repair manual related to cyclical performance of welds is quite reasonable, as the ultimate limiting parameter of welded steel sleeve repairs may well be cracks originating with the weld. In 2018, Rau and Laughlin[5] reviewed the potential concerns and limitation of both welded steel sleeves and composite repair options within the context of long-term integrity threat mitigation.

Some three decades ago, the Gas Research Institute (GRI) managed a development program for a composite sleeve system.

One of the deliverables was an Engineering Critical Assessment (ECA) to be used to assess the metal loss defects that could be effectively repaired via the installation of a composite sleeve[6]. This methodology has proven to be effective and conservative. More recently, ASME PCC-2[7] documents an assessment method to determine the required thickness of a repair system. These methods are not completely mutually exclusive as both can trace their derivation back to a two term Barlow Equation. A key engineering parameter is the determination of an appropriately conservative failure stress for the reinforcement.

Today, The Leewis Augmentation Analysis[8] (LAA) has been created. The LAA follows the precedents established by GRI and ASME PCC-2. The LAA provides the pipeline operator opportunities to integrate their preferred defect assessment methods. In addition to a metal loss defect Engineering Critical Engineering Assessment (ECA), a design factor change ECA has also been created. A third ECA for strain dependent concerns is in process.

2. Discussion of Pipe Repair Mechanics

This section of the paper has been developed to provide the reader with an understanding on the mechanics associated with reinforcing sleeves, with a primary emphasis on composite reinforcing technologies. Provided below are two discussions that provide the framework for this discussion. The first section provides an explanation on how stiffness of the reinforcing sleeve, expressed as the product of elastic modulus and thickness, dictates the level of stress reduction that takes place in the reinforced pipe. The second section addresses the topic of "effective modulus" that is critically important for relating the constitutive properties of the reinforcing material to its overall bulk, or effective modulus.

2.1 Pipe Stress Reduction

The elastic modulus for materials used in reinforcing systems plays a central role in determining the magnitude of strain reduction achieved in the reinforced pipe. Repair systems, including those that use steel and composite materials, reduce strain by sharing loading applied to the pipeline. As an example, the Barlow-type equation provided below is used to calculate hoop stress in the pipe considering the elastic moduli and geometry of both the pipe and reinforcing sleeve.

$$\sigma_{pipe} = \frac{P\,D}{2\,t_{pipe}\left(1+\frac{E_{sleeve}t_{sleeve}}{E_{pipe}t_{pipe}}\right)} \quad (1)$$

Where:

P Internal pressure

D Pipe outside diameter

t Wall thickness (subscripts denoting pipe, p, or sleeve,s)

E Elastic modulus (subscripts denoting pipe, p, or sleeve,s)

An appreciation of the preceding equation is critical for understanding the magnitude of stress (or strain) reduction provided by a reinforcing sleeve. To provide perspective concerning the relationship between pipe-sleeve stiffness and pipe reduction, Table 1 includes multiple repair combinations considering variations in elastic modulus and thickness. As noted, the greater the stiffness of the sleeve relative to the pipe stiffness, the greater the reduction in pipe stress.

Also included, Figure 1 plots pipe hoop stress ratio as a function of the sleeve-to-pipe modulus to stiffness ratio, considering stiffness ratios up to 2.0. Listed below are several noteworthy observations made in reviewing the data presented in Table 1 and plotted in Figure 1.

- For comparison purposes, multiple reinforcing materials are included in the presented calculations. These values are based on representative composite repair technologies evaluated over the past 20 years.
- **Scenarios 3 and 7:** It is possible for a low modulus E-glass system to have an equivalent stiffness as a low modulus carbon system; however, in this scenario the thickness of the E-glass (2tpipe) must be four (4) times that of the carbon system (0.5 tpipe).
- **Scenario 11:** If the moderate carbon material is used and it has a thickness equal to the pipe material, the stress in the reinforced pipe is reduced by 40%. This is a significant level of stress reduction for a relatively thin level of reinforcement.
- **Scenario 14:** Although not the primary purpose of this paper, data are included considering steel as the reinforcing material (i.e., Type A steel sleeve). If the thickness of the steel sleeve and pipe are the same, the stress in the reinforced pipe is one-half the stress in an unreinforced pipe (as expected).

Table 1: PIPE HOOP STRESS AS A FUNCTION OF REINFORCING SLEEVE STIFFNESS

Reinforcing Scenario	Sleeve Modulus (Msi / GPa)	Thickness Ratio (t_{sleeve} / t_{pipe})	Stiffness Ratio $(E\cdot t)_{sleeve}$ / $(E\cdot t)_{pipe}$	Pipe Stress Ratio σ_{pipe} / $\sigma_{nominal}$ (1)	Notes
1	2.0 / 14	0.5	0.03	0.97	Low modulus E-glass
2	2.0 / 14	1.0	0.07	0.94	Low modulus E-glass
3	2.0 / 14	2.0	0.13	0.88	Low modulus E-glass (2)
4	4.5 / 31	0.5	0.08	0.93	Moderate modulus E-glass
5	4.5 / 31	1.0	0.15	0.87	Moderate modulus E-glass
6	4.5 / 31	2.0	0.30	0.77	Moderate modulus E-glass
7	10.0 / 69	0.5	0.17	0.86	Low modulus Carbon
8	10.0 / 69	1.0	0.33	0.75	Low modulus Carbon
9	10.0 / 69	2.0	0.67	0.60	Low modulus Carbon
10	20.0 / 138	0.5	0.33	0.75	Moderate modulus Carbon
11	20.0 / 138	1.0	0.67	0.60	Moderate modulus Carbon
12	20.0 / 138	2.0	1.33	0.43	Moderate modulus Carbon
13	30.0 / 207	0.5	0.50	0.67	Steel sleeve material
14	30.0 / 207	1.0	1.00	0.50	Steel sleeve material
15	30.0 / 207	2.0	2.00	0.33	Steel sleeve material

Notes:

(1) The nominal hoop stress ($\sigma_{nominal}$) is the stress calculated assuming nominal values for pipe diameter and wall thickness based on Barlow's equation (i.e., PD / $2t_{pipe}$).

(2) Data highlighted in RED are discussed specifically in the body of the paper as noteworthy points.

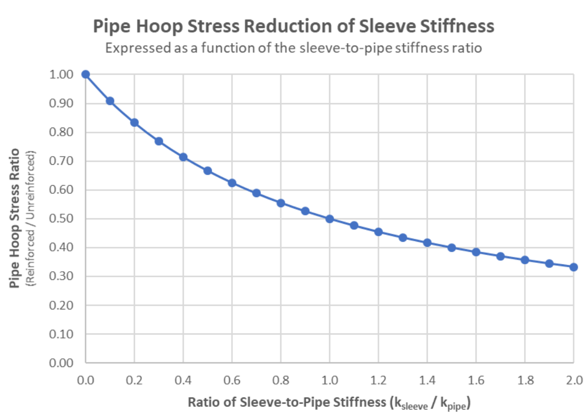

FIGURE 1: PIPE HOOP STRESS RATIO VERSUS PIPE-TO-SLEEVE STIFFNESS RATIO

2.2 Effective Modulus

The effective modulus of a laminate composite reinforcing system differs from the material-specific elastic modulus of the composite lamina (i.e., a laminate is material formed of thin sheets adhesively-bonded together, while lamina is a very thin layer of material). This section of the paper has been prepared to address confusion in the pipeline industry concerning the subject of the effective modulus, especially in terms of layered technologies such as the various rigid composite sleeves commercially available.

It is possible to empirically-derive the effective modulus of the composite reinforcing system using results from a pipe sample test where strain gages are installed on the pipe beneath the composite repair materials. Essentially, the strain reduction provided by the composite repair system is proportional to the effective modulus of the composite material. The previous equation is rearranged to isolate the modulus of the reinforcing material as shown below. By using actual measurements of stresses measured in the reinforced pipe using strain gages (σ_{pipe}), the effective modulus of the reinforcing system can be calculated.

$$E_{sleeve} = \frac{E_{pipe}}{t_{sleeve}} \left(\frac{P\,D}{2\,\sigma_{pipe}} - t_{pipe} \right) \quad (2)$$

One of the tests specified in ASME PCC-2 is the 1,000-hour test. Although not required for compliance with the PCC-2 standard, most current leading composite repair technologies use this test as a means for establishing their long-term tensile strength used to determine the design thickness of their system. Per ASME PCC-2, the 1,000-hour test involves the reinforcement of three (3) pipe samples with thin layers of composite materials, typically on the order of 0.2 inches (5 mm). The pipe samples are pressurized to levels that exceed the ultimate tensile strength of the reinforced pipe samples in order to achieve elevated stress levels in the composite. These stress levels are then held for 1,000 hours. Upon successful completion of the 1,000-hour period without loss of pressure or delamination of the composite, the long-term design strength is determined.

To support the 1,000-hour test work, dating back to as early as 2006, Alexander[9] recommended to composite manufacturers that a fourth "sacrificial" pipe sample be tested. This sample was fitted with strain gages beneath the composite system and pressurized to failure. The concept allowed the lab to pressurize at least one sample to failure while the three remaining 1,000-hour samples would be pressurized to a safe pressure level. The additional benefit is the ability to back-calculate effective modulus of the repair system, which is the subject of this discussion.

Data were extracted from the "sacrificial" 1,000-hour tests of three different composite repair technologies. Strain gages installed beneath the composite layers were used to calculate the stress in the pipe during pressurization at 2,000 psig (13,790 KPa). It is worth noting that all of the systems from which data were extracted have undergone extensive testing and have been among the top performing composite repair technologies evaluated over the past 10 years in reinforcing corrosion damage and dent features; additionally, the carbon-epoxy system has been used to successfully reinforce planar defects and crack-like features. This statement is not made for commercial purposes, but to validate the acceptability of using these technologies in calculating their effective moduli.

Included in Table 2 are information relating to the following:

- Product type
- Reported “lamina” elastic modulus
- Pipe stress on the steel surface beneath composite reinforcement based on strain gage measurements during the 1,000-hour test
- Calculated effective modulus

TABLE 2: CALCULATED EFFECTIVE MODULUS VALUES FOR DIFFERENT REPAIR TECHNOLOGIES

Product Type	Composite Thickness Inches (mm)	Pipe Stress psi (MPa)	Reported Lamina Modulus Msi (GPa)	Calculated Effective Modulus Msi (GPa)
E-glass epoxy (wet wrap)	0.190	31,680 (218.4)	4.2 (29.0)	4.3 (29.6)
E-glass polyester(pre-coiled)	0.195	31,500 (217.2)	5.5 (37.9)	4.6 (31.7)
Carbon epoxy (wet wrap)	0.165	36,000 (248.3)	9.7 (66.9)	12.3 (84.8)

It is not recommended that too much be drawn from this observation, but the most important facet of this finding is that the stiffness values as reflected in the effective moduli for these E-glass and carbon systems are able to significantly reduce stresses in the reinforced pipe. Another important observation is that layered systems will have a reduced stiffness when comparing the effective modulus for the “bulk” system to the “individual” lamina modulus. This is to be expected as the adhesive that is bonding the layers has a certain level of compliance (or elastic give) that acts to reduce the overall stiffness of the system. In conclusion, absent actual test data, it is inappropriate to assume that the effective modulus is equivalent to the lamina modulus, especially for layered technologies.

Several plots are provided to illustrate how composite reinforcing materials reduce strain in non-corroded and corroded pipelines. Figure 2 plots the data used to calculate the effective modulus values listed in Table 2, showing hoop strain in the pipe beneath the composite material as a function of internal pressure. The slope of the plotted line is proportional to the effective modulus, where the carbon-epoxy system has the greatest stiffness of all the plotted reinforcing technologies. Because there were no defects in these pipe samples the plotted data curves never cross (i.e., intersect). The failure pressures for the three reinforced samples exceeded 4,000 psig (27,579 KPa).

The other included plot is Figure 3 that plots hoop strain as a function of internal pressure for strain gages located in a 75% deep corrosion feature reinforced with an incompressible filler as the missing wall plus the E-glass / epoxy and carbon / epoxy systems (same systems included in Table 2 and Figure 3). In addition to burst testing, 75% corrosion fatigue samples were fabricated, and pressure cycled from 36% to 72% SMYS. In addition to burst failure occurring outside the repairs, both systems were able to achieve cycles to failure in excess of 250,000 cycles before leaks developed in the repairs. In reviewing the data plotted in Figure 3 there are several noteworthy observations:

- Hoop strain measured in the thinned pipe membrane region beneath the filler material and composite material is an extremely important measurement in terms of quantifying the magnitude of strain reduction and performance of the composite reinforcement. The hoop strains at 72% SMYS for the carbon system and E-glass were 1,7700 and 3,000 με, or respectively not quite twice that and about three times that of the bare pipe.
- At 100% SMYS, the hoop strain increases for both systems to 3,000 and 5,000 με, or respectively 2.5 times and 4 times the strain in the bare pipe.
- At elevated pressure levels gross plasticity forms in the base pipe. At a certain pressure level, the composite system begins to internally realigned to provide support and starts to take on a larger percentage of the load. Graphically, this is reflected in the inflection point of the strain measurements taken in the corroded region of the pipe samples. The pressure level at which this occurs is determined by the fibers aligning giving this change in the bulk or effective modulus of the composite material.
- At extremely high pressure levels the strain in the base pipe is no longer elastic and increases disproportionately to increasing pressure levels until plastic bulging failure occurs. This is observed in the different slopes associated with the curves plotted in Figure 3; the reinforced data sets have a markedly less slope when compared to the data for the unreinforced base pipe as the reinforcement system provides support and limits the plastic deformation of the thin steel membrane at the bottom of the simulated corrosion.

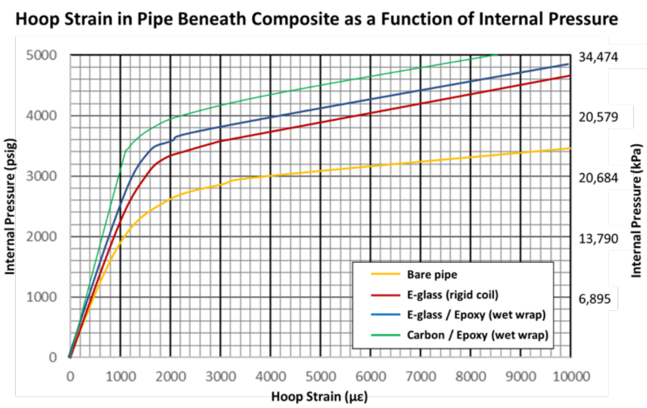

FIGURE 2: REPRESENTATIVE PLOT SHOWING DATA USED TO CALCULATE EFFECTIVE MODULUS

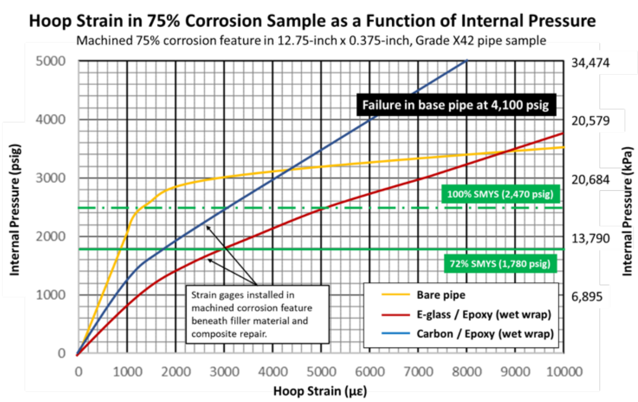

Figure 3: HOOP STRAIN FOR COMPOSITE REINFORCED 75% DEEP CORROSION FEATURE

3. Development objectives and targets for an improved system

The engineering development of the full encirclement engineered laminated steel sleeve system targeted several specific areas:

- Stress Strain Response - The delay in the stress-strain response is detrimental to repair performance. Minimizing this delay would be beneficial. These benefits may not be obvious in a short-term single event burst test but would become obvious in cyclical performance testing.
- The Modulus of Elasticity - The Effective modulus of elasticity of the reinforcement system is a key performance indicator for effective restraint: the higher the better.
- The Elimination of Degradation Over Time - For composites systems, thixotropic changes associated with fiber architecture or resin/fiber positions would cause significant changes in restraint. Short-term testing may provide results that provide a false sense of security regarding effective mitigation of these issues. Composites are known to display a degradation of properties with time. To address the strength considerations, care must be taken to over design the repair so that the initial properties remain sufficient enough (with safety factor) to guarantee effective long-term performance. The change in bulk modulus topic has not been well addressed on the open pipeline literature. It seems intuitively obvious that the constituent components and architecture choices of thixotropic composites will be key variables within the context of a degradation function for the modulus response. Cyclical testing program have displayed the change in strain during accelerated testing of non-metallic composite repair systems.
- Fit Up Concerns - For welded steel sleeve systems, the fit up associated with conforming to potentially out of round pipe ovality, pipe long seams or girth welds, as well as a similar set of concerns for the sleeve sections suggest that minimization of fit up issues would be tremendously beneficial to performance.

After evaluating these targets, the concept of the laminated steel sleeve system was born. The use of steel eliminated the any concerns in the change in repair system properties with time. The thickness of the system's steel layers was a design variable with thin layers offering the mechanism to best handle various fit up issues with existing line pipe. The grade of steel can also be a design variable to adjust performance outcomes.
Prototype development focused on multiple areas:

- Steel layer thickness
- Yield strength of steel
- Lap shear of potential adhesive systems
- Performance on mild steel substrate with specific interest in cyclical and shock loading performance
- Compressive strength or compressive modulus of filler material
- Bond thickness of adhesive systems
- Various operator appeal topics associated with ease of installation and use of components

A cross section of the laminate design was set to approximately 70% steel and 30% adhesive. The volume ratio was easily controlled via simplified installation methods and adhesive dispensing technology. Failure considerations for the engineered steel laminate involved the limits of either the steel strength member (yield) or a failure of the adhesive system. For the adhesive system, the lap shear strength, creep and cyclical performance, as well as potential degradation from environmental chemical exposure needed to be considered. Adhesive system selection criterion was not trivial but is beyond the scope of this paper. The designers of the subject system elected to utilize a toughened system designed for steel substrate to maximize cyclical performance and resistance to shock of fatigue failure. The selected system has a maximum 180 F, temperature service limit.

As previously mentioned, the laminate thickness is a design variable. A conservative limit has been established for a two-layer minimum. This provides for an abundance of safety factor for the adhesive system and leaves the yield and UTS of the selected steel to be utilized for the input parameter for engineering critical assessment methods.

4. Testing

FIGURE 4: INSTALLATION OF COIL AT TEST FACILITY

The strength of the repair and effectiveness for metal loss defects is a rather straight forward evaluation and follows the long established industry methods. A single event burst test serves as the prove of acceptability for ASME PCC-2 with the target being to return the serviceability and the burst strength back to the original elastic design capacity of the pipe (SMYS). The full scale burst testing was completed by ADV integrity with results discussed below. While conducting that ASME PCC-2 type test, a second system was installed to determine the initial response characteristic and an effective modulus of elasticity with the results also discussed below. The long-term failure of a steel laminated sleeve system would either happen at the failure stress of the utilized steel or via a failure of the adhesive system. To determine the long-term performance of the selected adhesive system, creep and cyclical testing were conducted. To assuage concerns, associate with exposure to potential future leaks of typical pipeline fluids, chemical compatibility tests were also completed.

4.1. Modulus

ADV conducted the burst testing program[10] with a test sample and procedure utilized for ASME PCC-2 Article 4.1, Appendix III, Short Term Spool Survival Test. A second unit was installed on the base pipe, with significant instrumentation intended to provide an empirically derived effective modulus for the system.

The key points of interest within the defect test results:

- MAOP at 72% SMYS = 1780 psig (12.27 MPa)
- Theoretical failure stress (SMYS) = 2470psig (17.03 MPa) (success for ASME PCC-2)
- Actual yield of unrepaired base pipe (proportional limit) = 3175 psig (21.89 MPa)
- Highest pressure achieved = 3885 psig (26.79 MPa)
    - Note: 218% of MAOP, approximately 700psig (4.83 MPa) above actual yield of the unreinforced base pipe, approximately 2000 psig (13.79 MPa) above the bare flaw expected failure)
- The specimens tested were highly instrumented. Two strain gauges were installed within the 77% machined wall loss defect. Based on extensive prior work, ADV has suggested that a Key Performance Indicator be established for the system restraint displayed at 72% SMYS. For the preferred test specimen configuration, this KPI is $\leq$4000 Micro strain. The average of the two strain gauges for this test was 3488 micro strain.

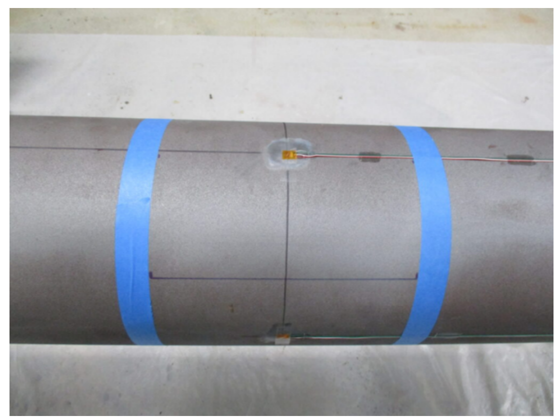

Figure 5: STRAIN GAUGE PLACEMENT ON THE PIPE FOR EFFECTIVE MODULUS

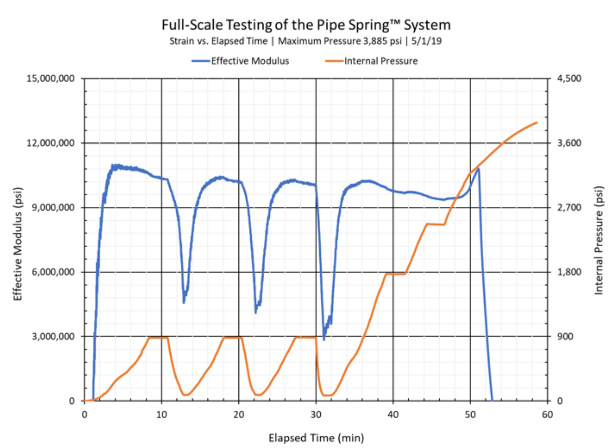

Figure 6: EFFECTIVE MODULUS VIA EQUATION

Summary of the key findings of the effective modulus unit:

- ADV Integrity reported 9.95 MSI (68.60 GPa)

- After adjustment to account for the thickness added via strain gauge wires, 14 MSI (96.53 GPa) is a conservative value for effective modulus
  - Note: the added thickness of the strain gauge wires has two effects
    - a direct mathematical effect
    - an indirect hindrance to the effective modulus.
  - An actual installation without the experimental intrusion of strain gauges and wires should perform better
- The strain gauge at the 3rd layer of the steel lamination consistently indicated the acceptance of load when the unrepaired base pipe was at approximately 50 micro strain.

4.2 Pipe Spring™ Testing

Figure 7 shows the location of the A Defect H and B Defect H strain gauges in the simulated corrosion before the repair.

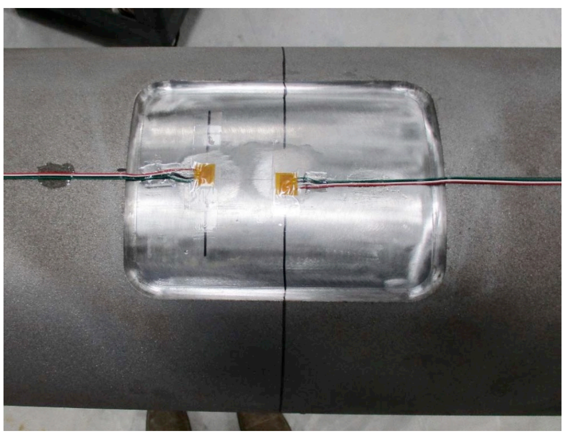

Figure 7: BIAXIAL STRAIN GAUGES IN THE SIMULATED CORROSION DEFECT

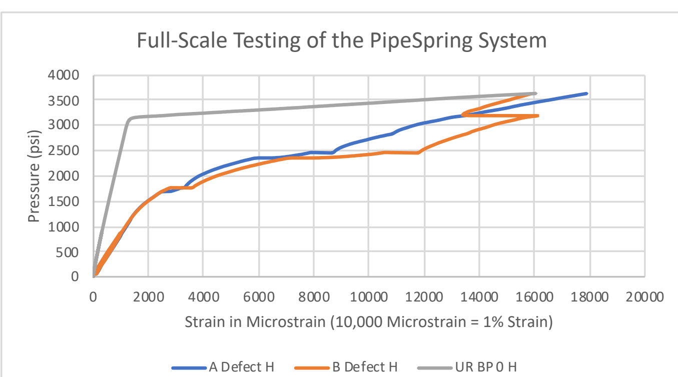

Figure 8: STRAIN IN THE SIMULATED CORROSION WITH PRESSURE GAUGE DATA

Figure 8 displays the control of strain in the thinned section within the simulated metal loss defect for the engineered steel laminated systems tested. Two strain gauges were utilized. Figure 3 provides some comparable data drawn from previous efforts. Strain data for the un-repaired base pipe remote from the defect is shown, this is labeled UR BP 0 H. The nomenclature references unrepaired (UR) base pipe (BP) zero degrees offset from the defect, and hoop direction (H). The two redundant strain gauges are labeled as A Defect H (hoop direction) and B Defect H (hoop direction). Both strain gauges with the simulated defect indicate rather linear and similar behavior until about 1500 psig (10.34 MPa) and around 1700 microstrain. As pressure increases above 1500 psig (10.34 MPa), the strain gauges indicate increased strain with localized differences as thinned sections adjust at varying rates. At MAOP of 1780 psig (12.27 MPa), the average of the two stain gauges is 3450 microstrain, indicating the strain growth is well controlled. These results compare favorably with stiff carbon fiber based systems. As pressure continues to increase above MAOP, localized yielding behavior is displayed within the thinned section, with some relaxation or re-rounding indicated as the system adjusts. The unrepaired base pipe indicates yielding at around 3150 psig (21.72 MPa).

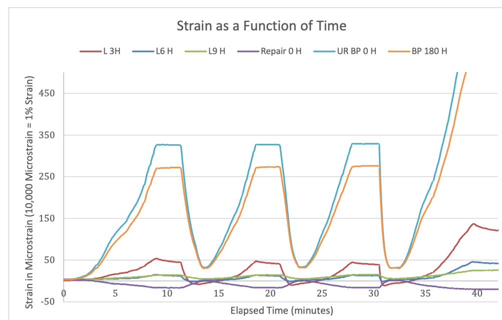

Figure 9: BEHAVIOR AT LOW STRAIN LEVELS

Figure 9 displays the stain as a function of time with a focus on initial response and low strain levels. This data was provided by the second unit installed on the pipe with no simulated corrosion. The strain gauges installed on the third layer of steel with the laminated unit consistently indicate loading through several pressure cycles when the un-repaired base pipe is at only 50 micro strain. This data along with the reasonably linear slope of the strain gauge date for the simulated defect (Figure 8) from the origin to near MAOP indicates that the laminated steel sleeve system is engaged quick quickly and well controls strain.

5. Creep and Cyclical Testing

Within this development project, the long-term performance of the system was considered. The steel chemistry, material properties, and tolerances are well controlled and documented via Material Test Reports (MTR). The reported material properties do not degrade or change over time. The thin layer design results in a very high, effective toughness. For pipeline service, the reported yield point is the appropriate failure stress to utilize for design considerations for the steel component of the system. The most advantageous design is to utilize an adhesive system with sufficient strength, toughness, and resistance to shock and vibration loading to ensure that a system failure can be forced to the steel component. Recent adhesive developments have provided advances. The system selected for the full-scale test provides an abundance of ultimate lap shear tensile strength. A minimum two-layer design has been established to ensure that a conservative safety factor is applied to the joint design considerations.

Normal installations on operating pipeline systems would typically see adhesive stresses of well less than 10% of the ultimate lap shear strength. The fatigue and cyclical performance of the adhesive system selected is documented by ITW Performance Polymers[11]. Creep must be considered to ensure long term permanency. Table 1 displays the adhesive results. Cyclical performance is perhaps the area of most appropriate focus. Recent pipeline integrity incidents have been dominated by cyclical fatigue issues which had served to focus the industry's attention. The joint design for actual installations has been kept extremely long (2-layer minimum), and the ultimate lap shear strength is quite high to ensure that the adhesive stress levels are quite modest. 10 million cycles at 50% of ultimate lap shear strength has been achieved. The results are shown in Table 3.

TABLE 3: MA8110 AND MA8120 CREEP DATA

MA8110 and MA8120 Creep Data						
Specimen ID	Width (in)	Length (in)	Max Stress (psi)	Test Duration (hrs)	Creep at Failure (%)	Failure Type
8110-01	1.02	0.977	1506.7	192	0.283	NO Failure
8110-02	1.04	0.971	1501.3	192	0.521	NO Failure
8110-03	1.04	0.953	1508.4	192	0.69	NO Failure
8110-04	1.06	0.973	1504.4	56.3	2.2	100% Cohesive
8110-05	1.03	0.97	1504.6	192	0.427	NO Failure
8120-01	1.05	0.901	1508.4	192	0.517	NO Failure
8120-02	1.04	0.925	1505.1	192	1.01	NO Failure
8120-03	1.04	0.894	1505.6	153	2.56	100% Cohesive
8120-04	1.05	0.899	1511.2	192	0.871	NO Failure
8120-05*	1.04	0.903	1808	2.25	2.21	100% Cohesive
* Improper loading of stress						

TABLE 4: CYCLICAL PERFORMANCE

Adhesive	Max Shar Value at 50% Strength (psi)	Cycles Achieved	Failure Mode
MA8110	2095	10 Million	None – Test Stopped
MA8120	2095	10 Million	None – Test Stopped

6. Augmentation of Existing Pipe

In the pipeline industry, significant amounts of pipe have served well for an extended period of time but lack the traceable verifiable and complete (TVC) documentation that is required by new regulations. In addition, operators may desire to increase the pressure carrying capacity of existing pipe, change design factor, or simply reduce the stress within the existing pipe. Augmentation of the pipe structure with known properties of the engineered steel lamination system provides the opportunity to achieve new operational and regulatory goals. The engineering critical assessment for these purposes is rather straight forward. The steel lamination system provides extremely high effective fracture toughness and intrinsic mitigation of any potential future mechanical damage.

7. Review and update of the Leewis Classic Metal Loss Mitigation Depiction

By 2010, Leewis had published a stylized depiction of the stress/strain response for metal loss defects. The work of the Gas Research Institute to develop and document a composite repair system was the basis for this depiction. Various constituent components and strength member architectures of thixotropic composites had been evaluated. Strength member (fiber) straightening and weave tightening showed a delay in effective response which lead to a "kink" at low stress levels within stress/strain response. It may be important to note that the final version of a commercial product evaluated by GRI employed unidirectional e-glass with no weave or knitted cross threads. This architecture was selected specifically to minimize the "kink" at low stress levels as well as to eliminate as much as possible the concern with continued thixotopic movements within the composite over the expected service life. The classic depiction is shown in Figure 3.

Over the several decades since the development effort which led to this depiction, many specific composite combinations have been tested. Dr Alexanader et al, have been frequent researchers actively involved in these efforts. The fiber to resin ratio of the product tested is a key parameter. The initial fiber position or tension contributes, as does the ratio of voids within the composite. It is now clear that not all carbon fiber weaves will produce the same response, not all glass fiber weaves will produce the same results, tighter weaves produce a higher modulus, more course weaves a lower modulus. Knitted fabric provides results differing from woven fabric. Perhaps most importantly, the method of data collection is a key parameter. Material properties obtained via traditional testing methods produce results significantly different from data obtained by full scale testing on pipe samples. Ovality issues and residual stress from pipe manufacturing process often lead to Effective Modulus values which vary from those obtained from traditional material property testing.

Published data is available for some of these specific combinations of fiber architecture and resin. This data if most often collected in rather short term tests, with long term thixotropic changes ignored. Two updates of the Classic mitigation principle seem appropriate. We need to capture the response before and after thixotropic movement occurs. Figure 8 shows the static short term depiction. Figure 9 indicates the expected longer term depiction.

It may be valuable to communicate several areas of technical interest or concern. Dr. Leewis articulates concerns related to fiber straightening and thixotropic changes during the intended life of a composite repair. He continues to advise that we need to be concerned about the stress strain response under 1000 microstrain, and that the various rates of testing may produce various results. Dr. Leewis also remains concerned regarding degradation of composites during use which result in properties less then obtained by testing done in accellerated conditions. Dr. Alexander suggests that thixotropic changes observed during multiple cyclical testing regimes have not been significant enough to cause great concern. Safety factor within design considerations can be used to keep repairs effective.

Consensus does exists on several important items:

- Higher effective modulus is an advantage.
- Fit up and the elimination in delay of sharing load are key parameters.
- The use of design selections to minimize fit up concerns is beneficial.
- The use of design selections to minimize both initial and long term thixotropic concerns associated with composites is beneficial.
- Blunt features (normal metal loss defects) fail via net section (plastic) collapse. These stress dependent features can be well addressed with less than perfect fit up or the need to quite high modulus repairs.
- Defects that are strain dependent or may fail via fracture may require both excellent fit up and quite high modulus methods for reliable long term mitigation.

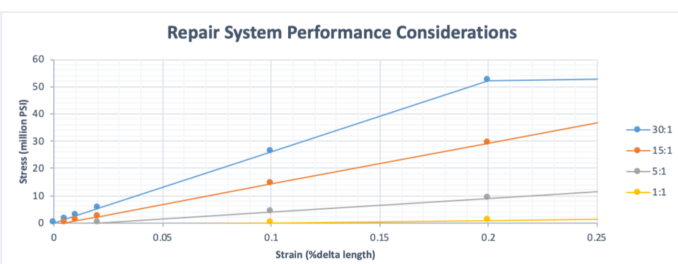

Figure 10: REPAIR SYSTEM PERFORMANCE CONSIDERATIONS

Figure 10 represents the idealized proposed conceptual context for consideration of these issues. The 30:1 line represents pipe steel, X52 in this case. The change in slope is displayed to occur at .2% strain. We have ignored the nonlinear behavior expected above the proportional limit (perhaps around .14% strain). The 15:1 line represents the results obtained for the laminated steel sleeve system. Loading is displayed at least by 50 microstrain in the unrepaired base pipe and there is a slope of around 15 million psig (103,4 GPa). The rise in effective modulus observed was extremely quick. We have included no change in slope near the origin. The 5:1 line represents a published data point for a unidirectional e-glass pre-cured laminated system. Loading is displayed at 200 micro strain and a slope around 5 million psig (34.5 GPa). The 1:1 line represents a low modulus repair, with loading delayed until 1000 micro strain. Not shown is a line for various wet applied composite repairs including various woven carbon fiber strength member products. The effective modulus for these have been reported to be around the 15 million psig (103.4 GPa) range. Data related to the strain level where effective load is shared is often not reported as ASME PCC-2 calls on ASTM D3039 which disregards data below 1000 micro strain. Also not displayed are welded steel sleeve repair options. The effective modulus of the welded steel systems significantly depends on fit up considerations between the base pipe and the sleeve and the related installation issues.

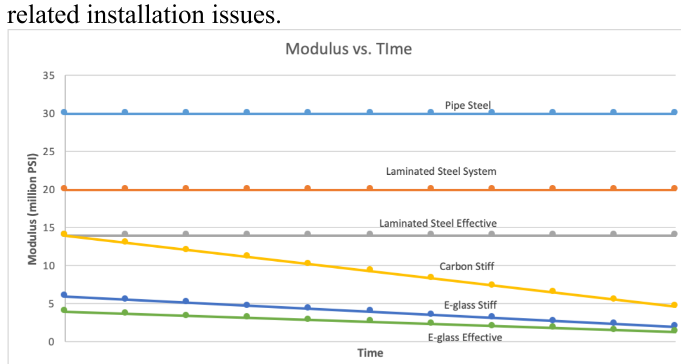

Figure 11: PROPOSED CHANGES IN MODULUS DURING SERVICE

The pipe steel line is approximately 30 million psig (206.8 GPa). The material properties of steel will not change, this line displays the modulus as horizontal and it is consistently at approximately 30 million psig (206.8 GPa). The laminated steel sleeve system is displayed at a horizontal line at about 20 million psig (137.9 GPa). The system was tested for effective modulus as applied to normal pipe and reported an effective modulus of around 14 million psig (96.5 GPa). A single line is displayed for stiff carbon fiber based composite systems. The line is displayed losing modulus over time as thixotropic changes with the composite plus in the "incompressible" filler that make up the repair system, result in lower values after during long term service (no scale applied to the rate of the degradation in modulus). Stiff e-glass based systems are displayed with an initial effective modulus of around 5 million psig (34.5 GPa). An effective modulus line is also shown for these stiff e-glass based systems. The slopes are decreasing as thixotropic and degradation effects will result in lower modulus over time for every repair system. In light of the results, Dr. Alexander has suggested a thinner and stiffer adhesive system might be preferential in complex strain dependent situations.

8. Conclusions

The full encirclement engineered laminated steel sleeve system has demonstrated the reliable engineering test and analysis required for use by regulated pipelines in the United States.

- Effective response within 50 micro strain of the unrepaired base pipe (in layer 3) indicates a significant ability to mitigate strain dependent concerns.
- The effective modulus of elasticity, adjusted for the thickness of strain gauge wires intruding on the system, is conservatively set at 14 million psig (96.5 GPa)
- Cyclical and creep performance of the adhesive system is typically several orders of magnitude better than the expected life of the pipe system. 10 million cycles at 50% of ultimate lap shear stress, with actual installations typically operating at less than 10% of lap shear capacity, represents an extremely significant improvement in long term performance. This performance effectively eliminates the projected lifetime limit of the repair as an integrity threat.
- ADV Integrity reports that: "The results of this test successfully demonstrate that the Pipe Spring™ system can restore structural integrity of a damaged pipe with 75% wall loss corrosion defect. The Pipe Spring™ succeeded in restoring the damaged pipe pasts its theoretical failure pressure. The Pipe Spring™ system is not a true non-metallic repair, but this test sample and procedure mirrors the pipe sample configuration for ASME PCC-2, Article 4,1, Appendix III, Short Term Spool Survival Test."

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