TECHNICAL REPORT

DNV RESEARCH AND INNOVATION

METHOD FOR QUALIFICATION OF COMPOSITE REPAIRS FOR PIPELINES: PATCH REPAIRS AND CONSIDERATIONS FOR CATHODIC PROTECTION

REPORT NO 2009-9332

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DET NORSKE VERITAS

TECHNICAL REPORT

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Summary:

While the mechanical properties of composite repairs for pipelines have been investigated extensively, the performance of the entire metal-composite system has not been addressed with regard to corrosion of the substrate, water intrusion at the composite-metal interface, cathodic disbondment behaviour, and adhesion loss. Both commercial and generic products were tested in this work. Commercial products generally outperformed the generic products, and to protect confidentiality, most figures include only photos of generic products for illustrative purposes. ASTM standards for coatings have been adapted for this work. The procedures address adhesion with the substrate in addition impact and cathodic disbondment resistance, and the data presented within this document is intended to be illustrative to support the validity of the methods.

This document concludes with recommended procedures for qualifying composite repair materials for metallic pipelines and pressure vessels, and identifies methods to evaluate their long term performance on cathodically protected metallic surfaces in wet conditions. This work was conducted with funding from the Pipeline and Hazardous Materials Safety Administration (PHMSA) and internal funding from DNV Research and Innovation. Funding from PHMSA extended from mid 2008 to end of 2009.

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1 CONCLUSIVE SUMMARY

Composites have seen increased usage for reinforcement of metallic structures in structural, marine, and underground conditions. While the mechanical properties of composites have been investigated extensively, the performance of the entire metal-composite system has not been addressed with regard to corrosion of the substrate, water intrusion at the composite-metal interface, and adhesion loss on the metal surface or within the composite itself. In this work we have investigated the influence of corrosive environments on the performance of composite repair systems with specific case studies on pipelines. These studies are intended to be applicable to all composite repairs – patch or full circumference – on pipelines and pressure vessels.

This document concludes with recommended procedures for qualifying composite repair materials for pipelines and pressure vessels, and identifies methods to evaluate their long term performance on cathodically protected metallic surfaces in wet conditions. ASTM standards have been adapted from coating evaluations to include composite evaluations. The procedures address two dimensions of composite repair performance: it must first demonstrate good adhesion with the substrate, and must also resist impact and cathodic disbondment. The procedures for evaluating composite repairs are as follows:

1. Decide whether the system should be tested in a coated or uncoated condition
2. Perform ASTM G14 – impact testing to simulate field damage
3. Perform ASTM G62 – holiday detection to determine penetration of impact
4. Perform cathodic disbondment via ASTM G95, G8 or G42
5. Inspect

These procedures can be complimented with mechanical tests. Two tests that appear to be effective at qualifying composite repair products are

1. ASTM D4541 – pull-of adhesion test of the polymer resin comprising the resin matrix of the composite
2. Modified ASTM G39 – four point bend of metal plates with composite repair to evaluate strength

The benchtop impact and cathodic disbondment tests provide qualitiative results about the performance of the composite repair product. The mechanical tests indicate how well it bonds with the substrate and how well it reinforces the steel to which it is bonded. Both commercial and generic products were tested in this work, but it should be clarified that commercial products generally outperformed the generic products, and to protect confidentiality, most figures include only photos of generic products for illustrative purposes. Details and results of how these tests are performed are included within.

2 INTRODUCTION

Fiber reinforced composites are now used in many niche applications such as repair or permanent structural reinforcement for pipeline, bridge, and ship structures. Composites offer an alternative to welding with potential savings in time and cost. However, in this rapidly growing field, there are still questions concerning long term performance.

Environmental variables specific to these applications may affect the integrity of the reinforced or repaired member. While the emphasis on composite materials for these applications is strength, in some cases the functionality of the composite as a coating or protective barrier must also be considered. Impacts, cathodic protection, and electrolytes corrosive to the substrate will inevitably combine to form conditions that affect the performance of the composite itself. Degradation of the polymer matrix and adhesion loss defeat the function of the composite, and if the substrate is cathodically protected, cathodic disbondment (CD) may be a concern. Evaluation of composite reinforcements under cathodic disbondment conditions is essential for a prediction of long term performance. Cathodic protection (CP) is a measure taken to protect metals that are in service in corrosive conditions. For pipelines, there are established guidelines for these systems for most soils. [2] A possible consequence of cathodic protection is cathodic disbondment of the coating and possibly the composite repair, which could lead to enhanced corrosion of the substrate metal in the disbonded region depending on the coating type and soil conditions.

In studies of coating disbondment, it has been found that the disbondment mechanism begins with the formation of an alkaline environment by cathodic reduction of dissolved oxygen in water 2. Generated alkalinity in CP conditions can react with organic polymers that are used in the adhesive layer or mastic in a process called saponification to disbond the coating at the interface between coating and metal at a defect. [3, 7] The degree of alkalinity is highest near the defect site because the cathodic potential tends to be the most negative at this location and the concentration of oxygen is the highest. The alkaline formation is cyclic and self supporting as the disbondment around the defect grows and encourages a propagating disbondment region expanding from the defected area. [4] Since fiber reinforced composites rely on similar adhesives and polymers for matrix materials, the mechanism of cathodic disbondment applies to this system as well, whenever cathodic protection is applied to composite-repaired structures. Depending on the impact strength, damage tolerance, and the polymer matrix, cathodic disbondment can pose a threat to cathodically protected structures reinforced with composite repairs.

In past research for pipeline repairs, it was found that the strength of a polymethyl methacrylate resin matrix reinforced with glass fiber (E-glass) was sufficient to reinforce a pressurized pipe such that under extreme loads, the repaired region would exceed the strength of the pipe elsewhere. [5] In that work it was noted that the composite had adequate strength and was expected to be a sound anti-corrosion coating, however the polymer matrix alone offered marginal corrosion protection. It was recommended that an additional coating be applied over the composite repair. Mechanical strength of the repair was emphasized in that research, however the combined effects of mechanical damage to the composite and cathodic protection and damage were not considered in depth.

For pipelines in particular, mechanical damage is not only a concern; it is inevitable. Statistics indicate that over 43% of pipeline damage is due to either excavation damage or human error. Additional risks account for another 20% of damage events. Therefore composite materials are expected to perform in an environment where at least 63% of failures are related to some kind of external force or imposed condition that is outside the expected design limits of the material. [6] By these statistics, composites will endure the same events that affect the performance of coatings. After a defect (such as an impact) has been incurred, moisture in the environment and a cathodic current combine to create conditions favorable for cathodic disbondment. While it has been shown the composites can certainly be designed strong enough to reinforce pressurized pipes and vessels, the performance of the composite as a coating has received less attention. It is important to understand if and how quickly the composite material properties degrade in service. For example, water uptake has been shown to degrade a composite's strength up to saturation. [8] A composite material's properties may be appropriate at the time of the repair, but an adequate expectation of the lifetime must include an understanding of possible degradation modes.

It should also be mentioned that in all of the previous work for composite repairs, a full encirclement sleeve has been the focus of the work. Only in a few instances have patches been mentioned as a viable repair. An ASME standard emphasizes full circumference sleeves rather than patches, though there are products available that are advertised as patches and are suggested for pipeline repair. [9] An ISO document, in particular, briefly mentions strength of materials considerations regarding patches, but provides no additional information. [10] Besides informal discussions, information about the use of composite patches is sparse. In China, for instance, carbon fiber is used extensively for structural reinforcement and repair, but there is a dearth of printed material on usage and results from those applications. The ASME and ISO standards for composite repair address the use of patches specifically but only in a limited fashion with general statements about their use on large pipes. Patches are mentioned for use when it is impractical for the repair to encompass the full circumference of the component, and the ISO standard recommends that patches be limited to large diameter (greater than 600 mm) pipework. In addition it is recommended that the patch extend the same distance in axial and circumferential directions.

The US DOT regulations permit the use of composites provided that certain guidelines are followed, and 49 CFR Parts 192 and 195 were amended to allow the use of composites generically, assuming the repair is one that "reliable engineering tests and analyses show can permanently restore the serviceability of the pipe". [16] The ASME PCC-2 standard indicates that the repair system shall demonstrate resistance to cathodic disbondment if it is to be employed on cathodically protected surfaces. In addition, it is recommended that the composite system show resistance to low velocity (5 Joule) impacts. [9] As the standard correctly assumes that impacts and cathodic disbondment are threats to the integrity of the composite repair, a composite repair must have additional qualifications beyond mechanical reinforcement; it must also endure its external environment.

When the DOT regulations 49 CFR Parts 192 and 195 were amended to allow the use of composites, there were only a few composite manufacturers actively marketing their products toward pipeline operators. Extensive research industry and federal research qualified the strength of composite full encirclement repairs at that time, and efforts were taken to confirm that these materials did not significantly shield cathodic protection. Environmental degradation tests, however, considered service temperatures in relation to the glass transition temperature of the matrix, the stiffness of the composite and load transfer, external loads, cyclic loading, fire resistance and electrical conductivity. Accelerated tests of the composite repairs were conducted in elevated temperature baths. Independently, the lap shear strength of the steel-composite bond was tested and long term water uptake was also tested against the mechanical strength. [5] Until recently, there has been only minor emphasis on cathodic disbondment in service environments and its potential effect on repair integrity. Since most composite repairs are full encirclement repairs, adhesion to the metal surface is considered secondary to the cohesive strength of the composite itself since. For full wrap repairs, the primary function is to contain the tendency of the pipe to strain or expand when pressurized and prevent bulging at the repair location.

In addition, there has been mention of partial encirclement repairs, or patches - such as what is mentioned in the ISO standard – but few (if any) companies have demonstrate their use in North America. [10] Besides uses of patches in unregulated applications or in experimental product development, there has not been extensive work on this type of repair. Of particular interest is the concept of a patch repair which can be applied without full excavation of the pipe. Such a repair would require a "keyhole" be prepared near the damaged region of the pipe, but without the extensive excavation necessary to perform a full encirclement repair. Less material and time are needed for this type of repair which could offer cost savings. Patches are also relevant for pressure vessels where a full wrap is perhaps impractical, as pressure vessels typically have large diameters. For this reason, the ISO standard specifically states that patches are likely better suited only for pipes with large diameters, and equations to estimate the load transferred from the steel pipe to the composite are cited in the standard.

Therefore the state of the art in composite repair of metallic pressurized pipes and vessels is mostly full circumference wraps composed of either pre-preg or wet-wrap products applied in the field. Patches are more common for pressure vessels that are themselves constructed from composite materials, but it is acknowledged that a composite patch may be appropriate for large diameter metallic pressure vessels and piping. The expertise required to evaluate the mechanical strength of these systems is accessible and well practiced in the ASME and ISO standards. As far as strength and mechanical properties are concerned, composite repair of metallic pressure vessels is fairly well understood. However, the effects of the external environment on composite materials and the consequential effect on mechanical strength could perhaps benefit from more study.

There are two phases described in this work. First, investigations of cathodic disbondment performance of composite materials are described with the pertinent results. Second, finite element analysis (FEA) models are constructed of composite repairs (both patch and wrap scenarios) on pipeline structures in order to analyze stress distributions and their possible effect on adhesion with the substrate.

3 MODELS OF A COMPOSITE REPAIR PATCH

Finite element analyses were performed to study the radial and shear stresses acting on a hypothetical composite patch repair and the hoop stress acting on the repaired pipe itself. FEA is an established numerical technique to calculate the stresses in structural members, which cannot be easily performed using closed form equations. The modeling requires the use of specialized software, as it relies on the solving of hundreds of mathematical equations for each model. The calculation necessary to determine the load transfer from the steel to composite is relatively straightforward using closed form equations, but only provided a full encirclement repair is assumed. Toutanji and Dempsey calculated the circumferential bending stresses incurred by soil loads and traffic. [15] The geometry of the patch and pipe FE model are shown in Figure 8.

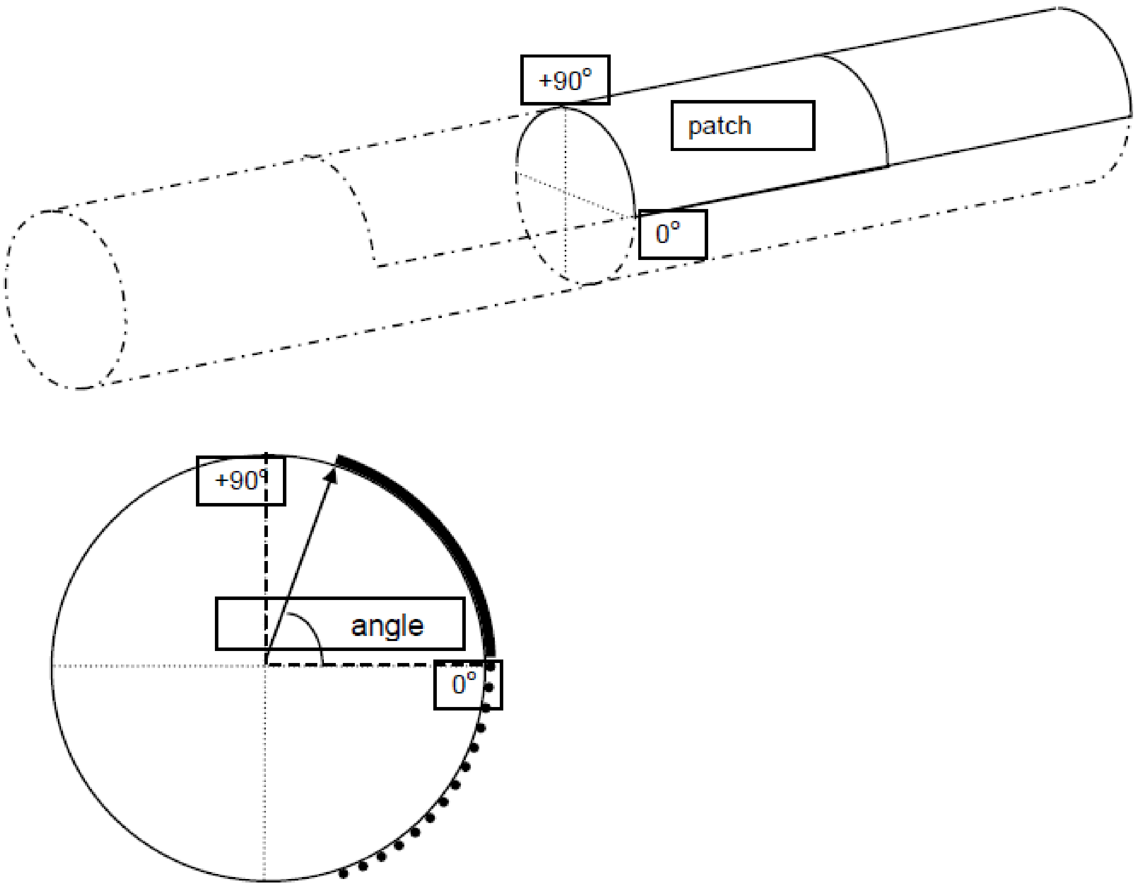


Figure 1 The geometry of the "quarter model" corresponds to the dimensions shown.

Figure 2 is a contour plot of the hoop stress in the 3D model of the steel pipe with a full encirclement composite repair sleeve. The model is a quarter-model of the pipe and repair, so horizontal (X-Z) and vertical (X-Y) mirror symmetry planes can be assumed, as illustrated previously in Figure 1. The left side (open end) of the model represents the reinforced section of pipe. The stress in both the reinforced section of pipe and the composite repair are less than in the un-reinforced section of pipe. Stress in the composite is lowest in regions near the center of the repair, far from the edges. . The low stress in the reinforced section of pipe is indicated by the gradient to be lowest near the outer diameter. The higher stress in the un-reinforced section of the pipe is indicated by the gradient to be maximum near the inner diameter and is comparable to the calculated nominal hoop stress one would expect in an undamaged pipe. In addition, there is a reduction in hoop stress in the un-reinforced section of pipe near the axial edge (right side) of the composite repair. This is due to the geometry and internal loading. The model is appropriate to consider the generic stress distribution in a steel pipe with full encirclement sleeve.

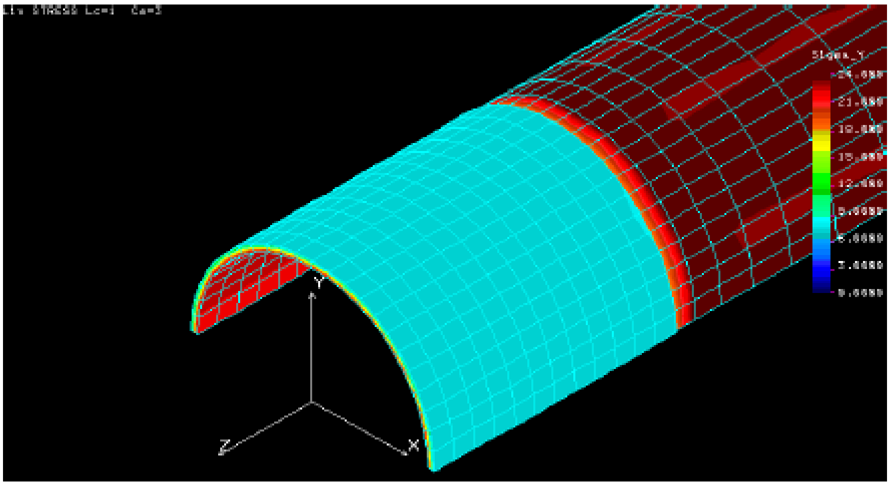


Figure 2 A contour plot of the hoop stress in one of the 3D steel pipe-composite repair models with a full encirclement repair. Stress is measured in ksi.

Figure 3 is a contour plot of the hoop stress in the 3D model of the steel pipe with a partial (50%) encirclement composite "patch." It can be seen from the model that the stress in the composite repair is less than in the non-reinforced section of the pipe. The hoop stress is not uniform in the repair. Reinforcement is maximized in the center of the repair patch because the stress in the pipe is lowest in this region, i.e. a large proportion of the stress has been transmitted to the composite. The lower right region of the figure is the center of the patch, considering model symmetry. The stress decreases near the circumferential edge (upper left, edge parallel to pipe axis). This edge of the repair patch is a free surface and transmits zero stress in the hoop direction. This is important as it affects the stress distribution in the steel pipe. Any composite material that does not transmit stress is not contributing to reinforcement of the steel pipe and not directly effective in the repair. In addition, the section of zero stress in the composite repair must be compensated for by the steel pipe itself. The patch causes the stress distribution in the pipe to exceed the stresses elsewhere in localized areas near the patch edge. Therefore the application of the patch must account for these stresses and the operating pressures of the pipe.

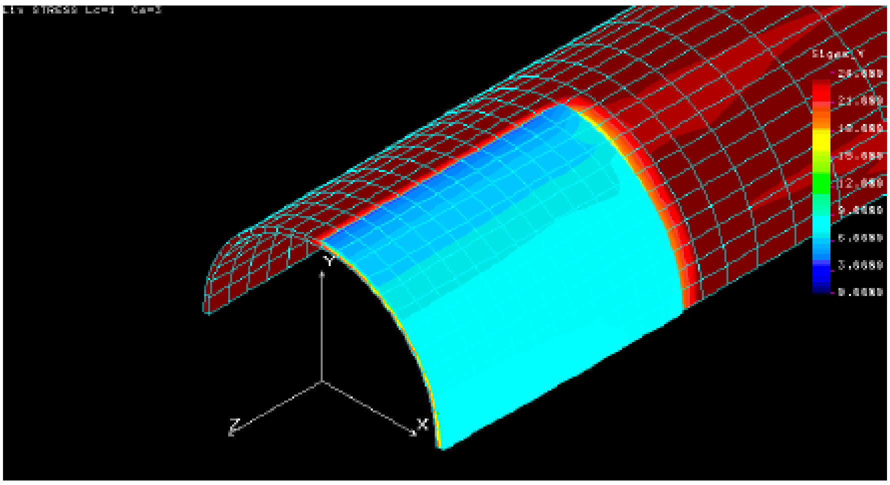


Figure 3 A contour plot of the hoop stress in one of the 3D steel-pipe composite repair models, with a partial (505) encirclement repair. Stress is measured in ksi.

Figure 4 is a magnified view of the contour plot of the hoop stress in the 2D transverse section model. There is a complex hoop stress distribution near the circumferential edge (left side) of the composite repair. There is a transition of maximum hoop stresses from the internal surface of the reinforced pipe to the external surface on the un-reinforced pipe. This is due to the particular combination of geometry and internal loading. Of particular interest is the stress concentration in the un-reinforced section of pipe near the edge of the composite repair. This stress is higher than the nominal hoop stress in the un-reinforced section of pipe. This indicates that a pipe with only partial encirclement repair would require a decreased internal pressure to compensate for this stress concentration. It should also be noted that the stress distribution is inverted along the contour of the pipe circumference such that there is a resulting bending moment at the patch edge. The transition in hoop stress distribution from the reinforced to un-reinforced sections of pipe contributes to a region of high shear stress in the center of the pipe wall near the circumferential edge of the composite repair.

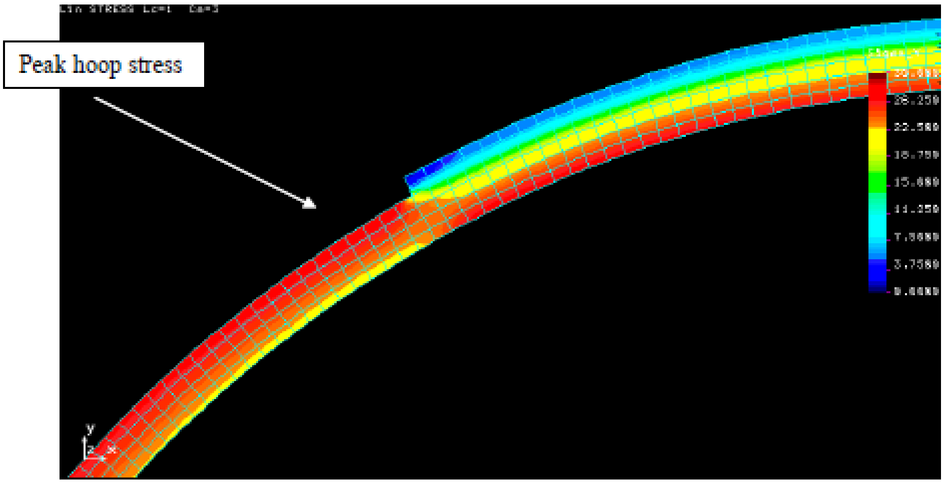


Figure 4 A contour plot of the hoop stress in one of the 2D transverse section steel pipe composite repair models, with a partial 92.3) encirclement repair (magnified). Stress is measured in ksi.

Figure 5 is a plot of the nodal hoop stresses calculated along the external surface of the pipe for six different models as a function of location along the circumference of the pipe. The data in Figure 5 corresponds to the angular coordinate geometry in Figure 1. The data points on the right side of the plot represent an average hoop stress, effectively an average of the stresses borne by the steel pipe and the composite repair. The data points on the left side of the plot represent the hoop stresses along the external surface of the un-reinforced section of pipe. Note that the length of the right and left sections vary with circumferential extent of repair. The grey dashed line indicates the nominal hoop stress in an equivalent un-reinforced pipe. There is a fluctuation in the stresses in the un-reinforced pipe that can be disregarded. These fluctuations are due to a slight faceting of the pipe model, as flat elements are made to conform to a circular geometry. The figure shows that partial circumference reinforcement of a pipe with a composite repair will lead to stresses greater than the prescribed nominal hoop stress near the circumferential limit of the patch. Elsewhere the reinforcement provides adequate strength such that the hoop stress is below the nominal hoop stress without reinforcement.

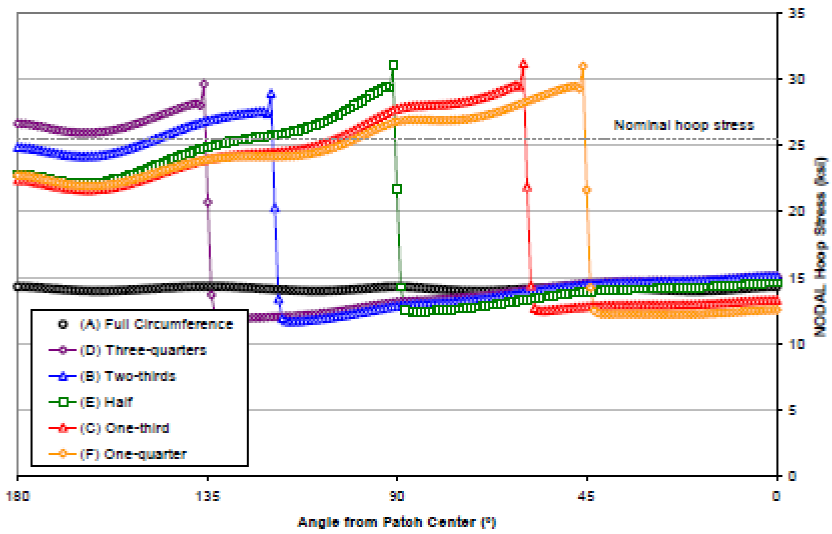


Figure 5 A plot of the nodal hoop stresses calculated along the external surface of the pipe model of six different models, as a function of location along the circumference of the pipe.

4 TESTING PROGRAM

Since strength is the main emphasis for composite repair, the performance of the entire metalcomposite system has not been extensively addressed with regard to corrosion of the substrate, adhesion loss, and cathodic protection. Standards tend to acknowledge that cathodic disbondment (CD) should be considered for these repair systems, but as of now little effort has been taken to specify in detail how the present cathodic disbondment standards – which were developed in a coatings context – should be adapted to consider the specific properties of composite materials.

For composite materials, cathodic disbondment tests are so far an adaptation of the ASTM standards for cathodic disbondment (CD) of coatings. However, there are some specific considerations for composites that the coatings standards were never designed to consider. One specific distinction is that the imposed defect on the coating for these tests is a simulated holiday. The intention of the ASTM CD standards is to assess the performance of a coating assuming the worst case scenario - when a coating is applied in the field, a thin area of the coating will result in a pinhole-like defect that exposes metal and may later allow water ingress and coating disbondment. These kinds of defects are often unavoidable as the field conditions are much less controlled than any lab environment. Bubbles formed during curing and rock punctures during backfill can cause these defects. The spirit of the ASTM CD standards is to determine how the coating will resist cathodic disbondment if these pinhole defects are present.

However, composite repairs on pipelines have a component structure that is distinctly different from coatings, yet these repairs are implicitly expected to serve the same function as a coating. A drilled defect creates a precise penetration in a coating that will act as the controlled defect site for accelerated disbondment testing according to ASTM CD standards, but the shortfall in this approach with regard to composites is that there are few field conditions that will result in a pinhole-like defect. The conditions that cause a puncture or tear in a coating will cause an impact and micro-fracture cracks in a composite. A composite is generally much more durable than a coating and can withstand much greater impact energy. The composite system is more resistant to impact, thicker, has greater cohesive integrity, and its cured resin matrix is often stronger than a coating. But composites are more prone to brittle fracture than coatings which are typically more malleable. If cathodic disbondment is to be tested for a composite system, a drilled defect is unrealistic; an impact is more relevant to field conditions.

Therefore the ASTM CD tests (such as G8, G95, and G42) should be precluded by modified impact testing per ASTM G14. Another ASTM test, G62, can be used to detect conductivity at the impact site, i.e., determine if the impact has reached bare metal. This paper follows that approach and presents the results.

This work investigates the influence of corrosive environments on the performance of composite repair systems for pipelines. Earlier in this work, FEA models were used to evaluate a composite patch for pipelines in order to understand the stresses involved. The effect of impacts, cathodic protection, long term immersion, and soil corrosivity have been investigated by monitoring variables related to potential and conductivity of the electrolyte. [17, 18] And finally, the mechanical properties are tested via four point bends on specimens intentionally exposed to ASTM cathodic disbondment tests and the results are presented here. In addition to four point bend tests, the performance of these repairs has also been evaluated in a modified ASTM G8 cathodic disbondment test with the addition of high pressure cyclic loading. By monitoring these variables, loss of adhesion and integrity in the composite-metal system is addressed.

To evaluate the performance of these materials in their expected field operating conditions, several testing methods were combined by using established ASTM techniques from coatings, adapted for composite materials with modifications where applicable. The testing program consisted of multiple phases. The benchtop tests include preliminary cathodic disbondment tests (ASTM G95), adhesion tests (ASTM D4541), impact tests (ASTM G14), and penetration/conductivity tests after impact (ASTM G62). Pull-off adhesion measurements of the composite resin were taken separately per ASTM D4541. Controlled environment testing in soil boxes was performed according to ASTM G8. The cyclic loading tests were actually a modified ASTM G8 test using actively pressurized vessels instead of pipe sections. The four point bend tests evaluated specimens that had already been impacted per ASTM D4541, conductivity tested by ASTM G62, and cathodically disbonded by ASTM G95. Loading guidelines for the four point bend tests were consistent with ASTM G39 for a larger specimen. The specimens in buried service are connected to an actual operating cathodic protection system on an operating pipeline, but the specimens are not part of an operating pipe – they are separate from the pipe itself and they do not contain flowing media or pressure.

4.1 Impact and Cathodic Disbondment Tests

The effect of impact and subsequent water exposure at cathodic potentials was examined. Steel plates measuring 4" (~10 cm) square were laminated with either E-glass or carbon fibers in varied resin materials. The plates were manufactured by hand lay up of multiple layers of fiber and curative materials. The plates were sand blasted prior to application of the composite according to NACE No. 2/SSPC-SP10 which is routinely used in the field. [11] A test matrix was developed for plates with 1-3 layers of fiber reinforced polymer matrix subjected to three levels of impact with increasing intensity, as shown in Table 1. The description and results shown here are representative examples from the original test matrix. While proprietary information is not revealed here, it can be said that Product A is commonly used for the manufacture of composite pipe (non-metallic), and Product B is commonly used for sandwich epoxy construction of structures like skis, snowboards, and aircraft wings.

Table 1 Resin and hardener types used in the testing program.

Product Generic Name	Resin	Hardener	Product Description
A	Polyester styrene monomer resin	MEK peroxide in dimethyl phthalate	E-glass, 3 layers
B	Multifunctional acrylic based monomer resin	Modified amine mixture and diphenylopropane	Carbon Fiber, 3 layers
C	Proprietary	Proprietary	Carbon fiber with insulating layer
D	Proprietary	Proprietary	E-glass carbon fiber hybrid

Impact tests were performed via ASTM G14. [12] The impact testing apparatus used a weight dropped from a fixed and recorded height. The weight tip was hemispherical. The weight was dropped down a tube such that impacts with the surface were uniform and repeatable. Since the desired goal was to test the specimens for penetration, a tup with a weight of 5.51 kg (12.1 lbs) was dropped from heights near 3 m to impact the specimens. The tup diameter is 15.875 mm and has a hemispherical tip as shown in. The tup impact was typically repeated 4 times, and ASTM G62 was performed after each impact.

Figure 6 Hemispherical tup head used for impact per ASTM G14.

A representative impacted specimen is shown in Figure 7, where the E-glass impact is shown in the center of the figure. After impact, the specimen was tested for conductivity per ASTM G62 to determine whether the impact penetrated to the substrate. [13] The conductivity test used a wet sponge at the end of a wand, with a DC voltage applied between the end of the wand and the substrate. The substrate was connected via an electrode clamp. If the impact penetrated the composite material, water from the sponge on the wand created a conductive path into the holiday (defect) and to the substrate. If conductivity was achieved, the system emitted an audible signal. Specimens were tested with this method to assess whether the impact penetrated to the substrate, because visual observation of impact depth can be misleading.

Cathodic disbondment was performed at room temperature via an attached cell method per ASTM G95. [14] The ASTM G95 standard was originally intended for evaluating cathodic disbondment of coatings with drilled holidays. In this case the standard was modified to evaluate CD performance of composite materials (instead of coatings) with an impact site (instead of a drilled defect). An acrylic cell centered about the defect site was affixed to the surface of the composite with a silicone adhesive. Once secured, the cell was filled with a 3% NaCl solution. A platinum wire was inserted into the solution inside a frit, and a 3V DC potential (vs. a saturated calomel reference electrode) was applied between the platinum and the steel plate onto which the composite was adhered. The cathodic disbondment cells are shown in Figure 8.

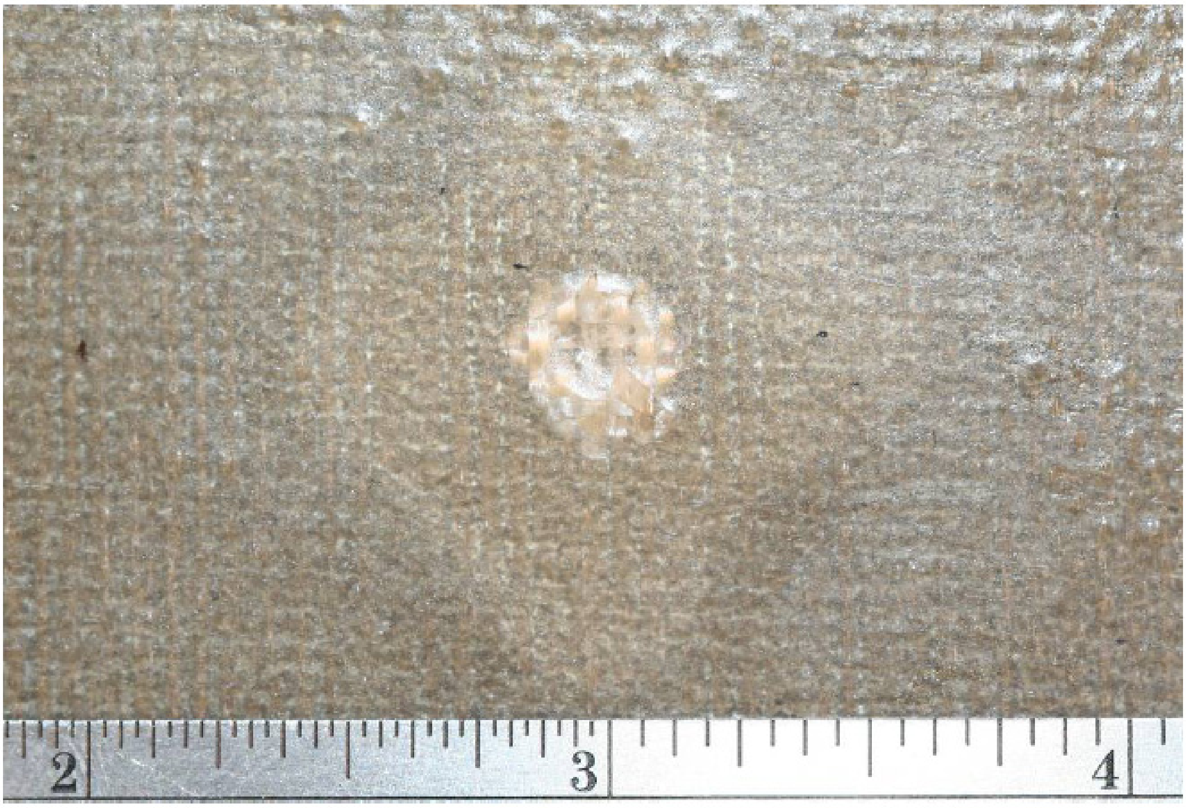


Figure 7 The impact with the glass fiber reinforced polyester caused noticeable deformation around the impact site, as shown in this photograph. Scale is in inches.

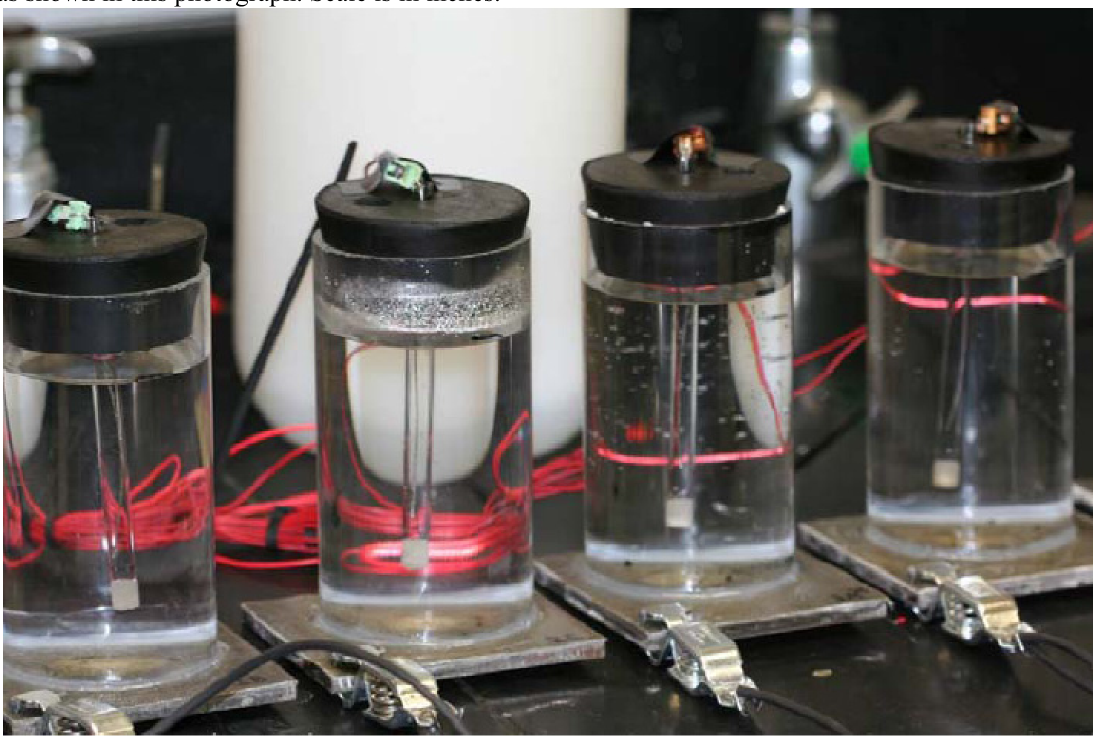


Figure 8 The cathodic disbondment cells are shown in the photo and attached to composite plates via silicone adhesive.

ASTM G95 was performed for 90 days. The test cell was removed upon test completion, and a dye solution was injected into the impact area in order to measure the approximate disbonded area underneath the composite. The accepted disbondment measurement method for coatings is to mechanically score the coating in a pie-section pattern centered about the defect, remove the loose pieces with a putty knife, and measure the approximate disbonded area. Since composite materials do not “flake” in this fashion, the dye solution was attempted instead with reasonable success.

Specimens with one layer of fiberglass began to fail after 30 days of cathodic disbondment testing. Other specimens failed within the testing period with a maximum time of 90 days. If the specimen passed the ASTM G62 holiday detection test, in most cases it would eventually develop full penetration at the impact site. When failures were observed, the failure was first characterized by leaking of the test solution at the composite-steel interface at the edge of the plate. Subsequent evaluation revealed the dissolution of the polyester matrix in the majority of the exposed area and sometimes beyond, as shown in Figure 9. In most cases, total disbondment was achieved with these generic products. These results are not necessarily representative of all commercial products.

(a)

(b)

Figure 9 Photographic views of generic glass fiber reinforced polyester composites exposed to a cathodic disbondment cell show (a) the entire test area illustrating evidence of dissolution of the polyester matrix with the presence of localized dry firber areas, and (b) a close-up of the polyester matrix dissolved beyond the cathodic cell.

As shown in the figure, the disbondment process led to adhesion loss at both the steel substrate and between layers. This kind of behaviour was evident for all materials that failed the ASTM G62 screening test. All specimens with less than 3 layers of material failed the ASTM G62 test. Few of the specimens passed the G62 qualification procedure, and if a holiday was not initially detected, these specimens eventually developed a fully penetrated holiday during the test. Most began to show failure within 30 days. Some carbon fiber and aramid materials were permitted to run beyond 30 days to investigate longevity and resistance to degradation. It should be noted that carbon fiber is conductive, and even with a thick matrix layer applied first to the substrate, the carbon fiber managed to establish a conductive path with the steel substrate in all cases. As a result, during the ASTM G95 test, the carbon fiber shows evidence of gas evolution in locations besides the impact site. In some cases the resulting dissolution of the matrix was evident in locations besides the impact site. Gas evolution was witnessed at multiple locations on the carbon fiber as shown in Figure 10 (taken during an active test through the acrylic cell).

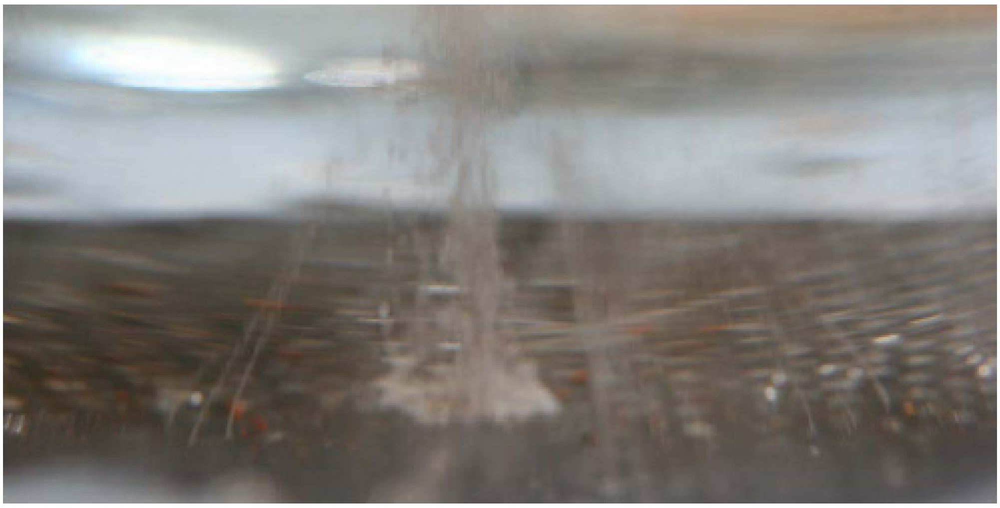
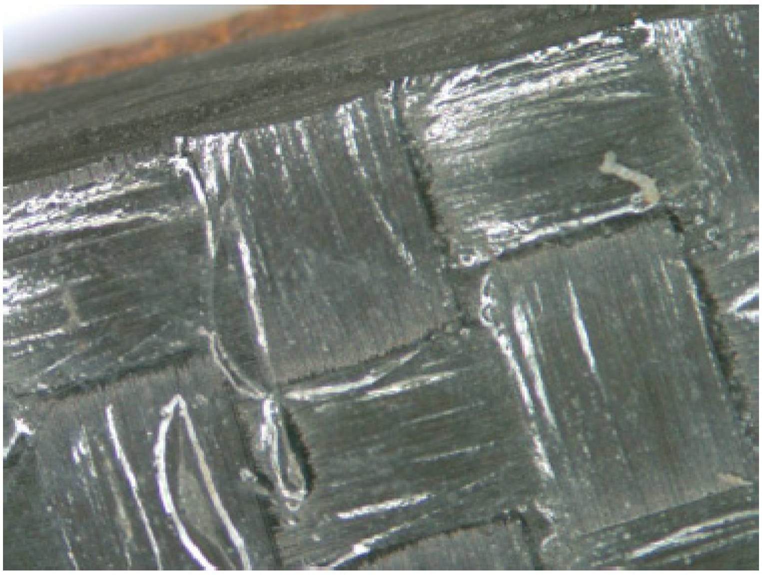


Figure 10 This photo was taken of a carbon fiber CD cell and shows gas evolution at the defect (center) and elsewhere on the carbon fiber surface.

In Figure 11, the degradation of the carbon fiber with product B is shown. The unexposed area (a) exhibits uniform dispersion of the resin matrix and low roughness (as indicated by the high reflectivity of the surface). The exposed area exhibited signs of degradation similar to pitting (b). The surface roughness and opacity increased as time progressed.

a)



b)

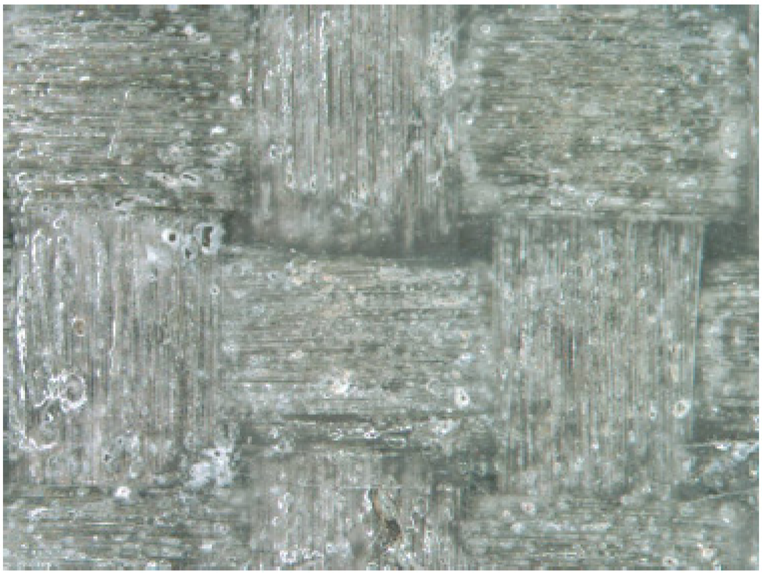


Figure 11 Carbon fiber with product B after nearly 30 days of cathodic disbondment shows a) no defects before, and b) pitting after.

After testing, the CD a representative test solution from a polyester/E-glass specimen was subjected to a standard environmental quality test at an EPA certified laboratory. The results indicated the presence of styrene, alcohols, and carboxylic acid, as well as trace detection of chloroform. In almost all cases the entire exposed area of the attached cell showed evidence of disbondment. In the case of the above figures, a dye was injected into the impact site to determine if a disbondment "pocket" was present around the site. The disbonded area as measured by the dye is shown in Figure 12. The pictured specimen is the same polyester specimen shown in Figure 9. It is evident that the inspection dye penetrated underneath the glass fiber composite and revealed a disbondment "pocket" underneath the composite layers.

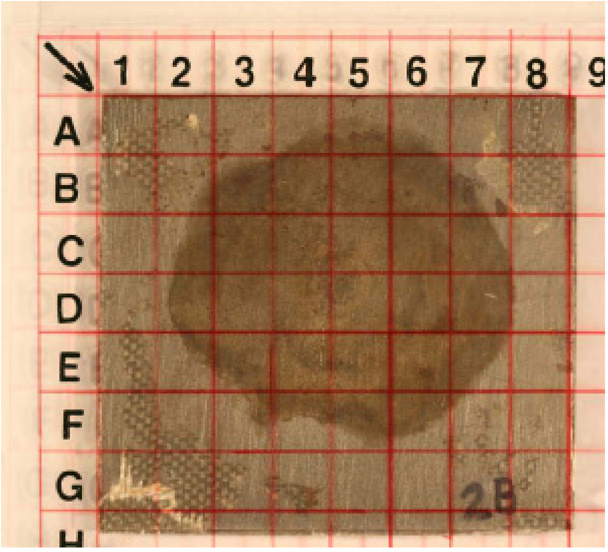


Figure 12 Total disbonded area for 2 layers of fiberglass with polyester matrix.

Carbon fiber specimens showed disbondment behavior similar to the polyester/E-glass specimens. The degree of disbondment ranged from partial to total. Typically the disbonded area was lowest for specimens with more than one layer, and greatest for specimens with only a single layer. An inspection of the disbonded area for carbon fiber with product B is shown in Figure 13.

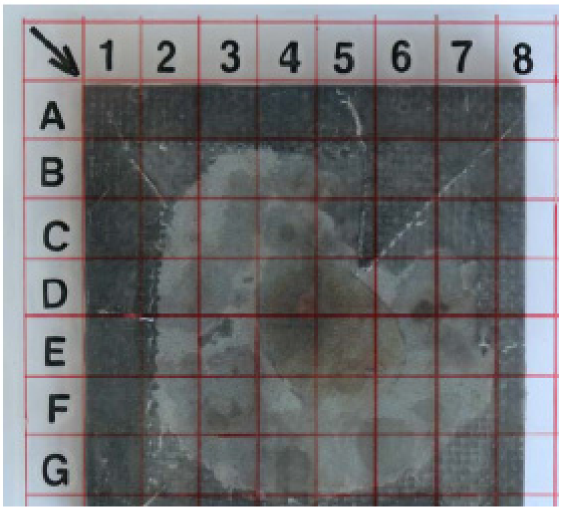


Figure 13 A single layer of carbon fiber in an acrylic matrix after an impact showed near total disbondment.

These tests involved four different epoxy/resin types used in conjunction with E-glass and carbon fiber. This testing program was conducted internally by DNVRI and this research downselected the materials that would be used to qualify a composite repair patch with DOT funding. Two products from these tests were chosen for further evaluation and they are products A and B from Table 1.

4.2 Adhesion and Mechanical Properties

An adhesion testing apparatus which is designed to fulfill the requirements set in ASTM D4541 was used to evaluate the adhesion strength of the resin matrix with the steel itself. The purpose of these tests was to evaluate whether there is a correlation between adhesion strength of the resin to the steel and adhesion strength of the composite system to the steel.

Adhesion measurements were performed with a mechanical dolly adhesion testing apparatus like what is shown in Figure 14.

Figure 14 Pull off adhesion of the matrix alone was measured using a Posi-test pull-off adhesion tester (hand pump not shown).

A four point bend jig was used to evaluate the effect of cathodic disbondment on the strength and performance of the repair, as is shown in Figure 15 and Figure 16. Sets of three specimens per product were tested: 1 control and 2 CD specimens subjected to impact to penetration by ASTM G14, confirmation of penetration by ASTM G62, and cathodic disbondment by ASTM G95. After testing, the subsequent effect of adhesion loss was then translated to the loading behavior of the composite. The role of delamination, adhesion loss at the substrate, and cohesion loss is evident in the load vs. displacement curve and analysis is included in the results.

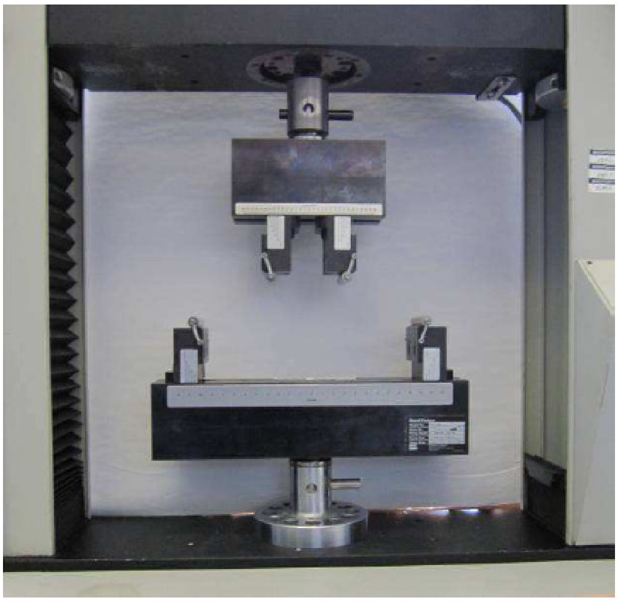


Figure 15 A jig connected to a stress frame was used to bend the 12”x6”x0.1875” plates.

Four point bend specimens were prepared with each of the four products, and in addition blank specimens (virgin steel) were used as a baseline calibration. All specimens that were repaired with a composite were notched with a simulated defect - material was removed using a mill to simulate metal loss. Manufacturers prepared the specimens according to their own specifications. The patch specimens used a body-filler type material to bear the load and transition loading due to “bulging” to the composite. This is a common method for these types of repairs.

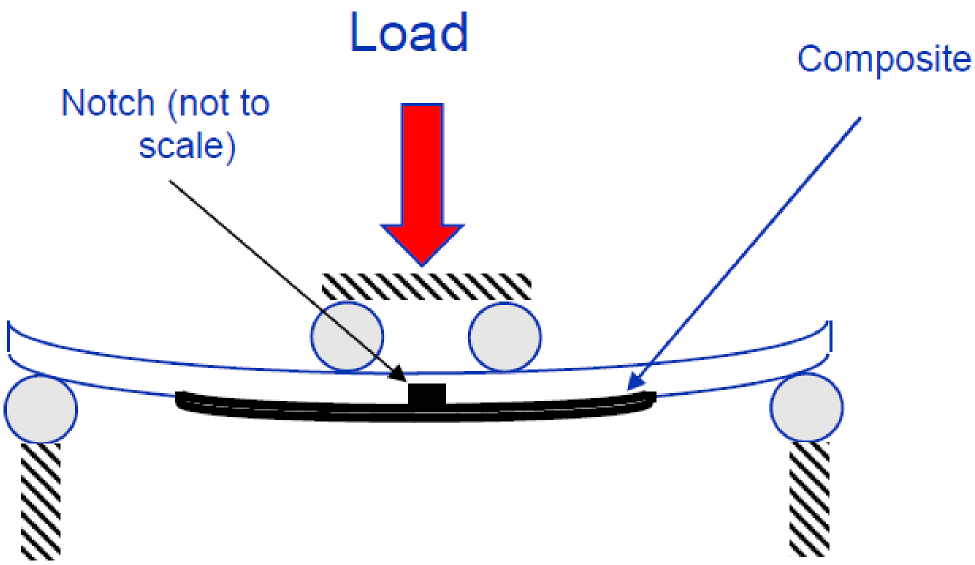


Figure 16 Specimens were notched with a milled defect as is often practiced in burst tests.

Baseline load data was taken from the virgin steel specimens with no defects. This load curve was used as the comparison between all specimens. The % load or % deflection for each remaining specimen was measured against this calibration curve. This enabled the fair comparison according to the DOT language, allowing a direct comparison which determine whether the repair is one that “reliable engineering tests and analyses show can permanently restore the serviceability of the pipe”. The baseline load curves are shown in Figure 17. I nthe figure, the notched specimen can only bear about 75% of the load of the virgin steel specimen. The target for a repair is to restore the load bearing capability of the specimen to the virgin steel stress-strain curve.

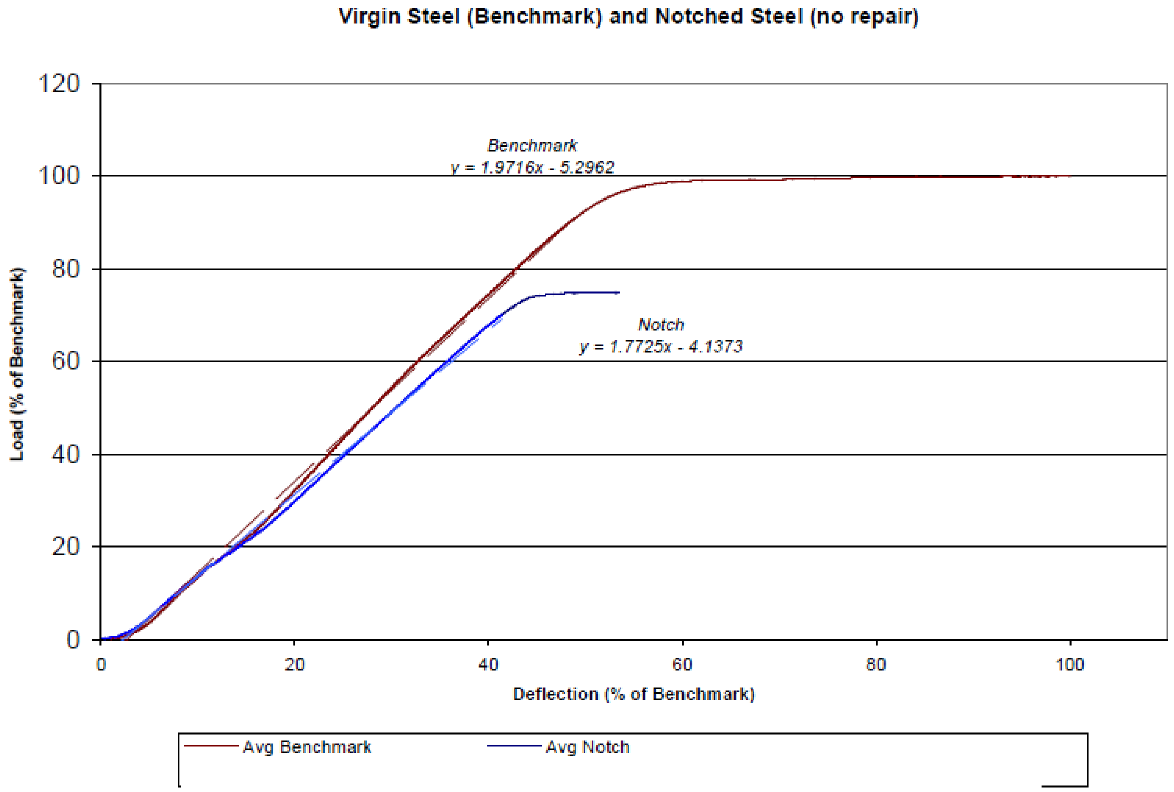


Figure 17 Baseline load (%) vs. deflection 9%) for virgin and notched steel.

An example of the adhesion failure mechanism is shown by Figure 18 and Figure 19. In Figure 18, due to reduced specimen thickness at the point of maximum stress, the modulus for the notched specimen (green, fine dashed) is less than the baseline specimen (brown, dashed). In the Product A composite repair case (red, solid), however, it can be shown that the modulus is near the benchmark steel until adhesion is gradually lost. The cathodically disbonded specimen performed similarly to the notched steel, indicating that this patch repair did not successfully restore the serviceability of the pipe steel after being subjected to the cathodic disbondment tests.

Product B shows a sudden drop in load in Figure 19 corresponding to delamination of the product from the metal surface. It can be seen that delamination occurs several times as the specimen is loaded. Once the composite is separated from the steel, the response behavior is similar to the notched specimen, which is the same base metal. Product B is also an odd case because the disbondment specimen performed better than the control specimen, perhaps indicating that the control specimen had some defects that prohibited it from performing better than its disbonded counterparts.

In the figures, the linear fit to the elastic portion of the curve has a slope that is proportional to the quotient of % load and % extension, so in this way it is directly proportional to the stiffness or modulus and is treated as such.

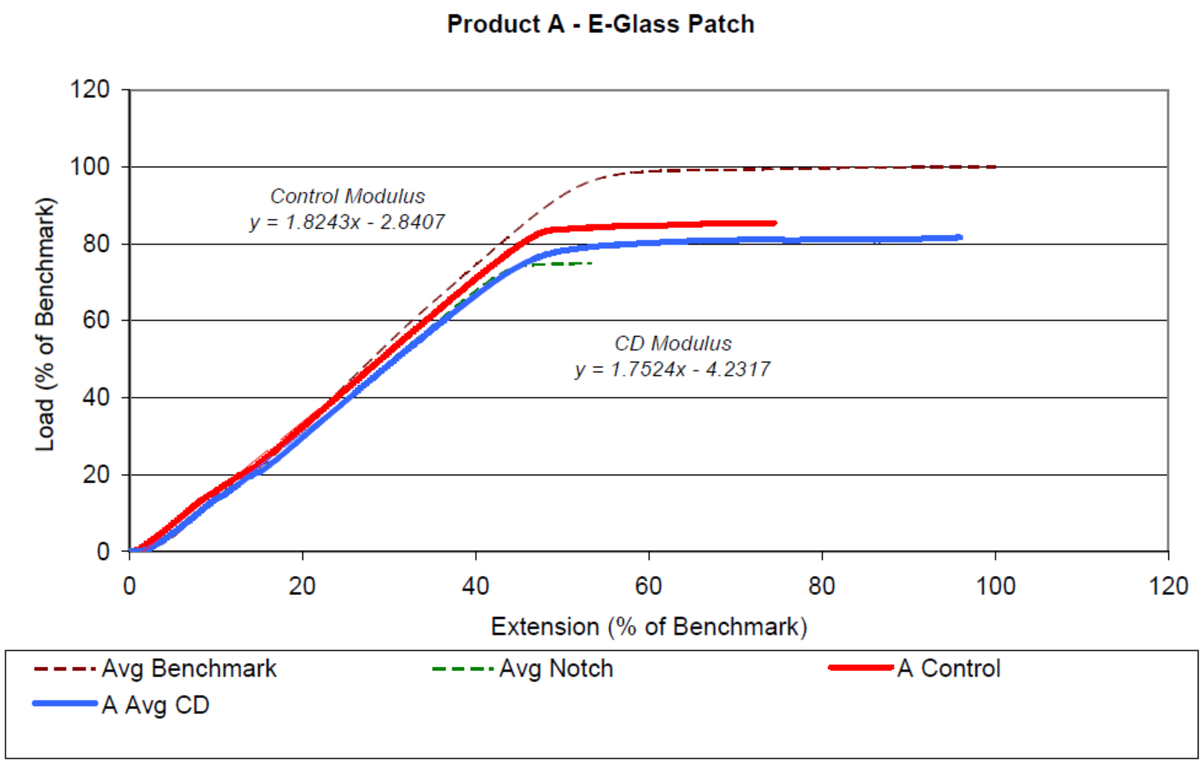


Figure 18 Product A exhibited strength similar to the benchmark virgin steel, but was susceptible to cathodic disbondment which led to behavior similar to the notched steel.

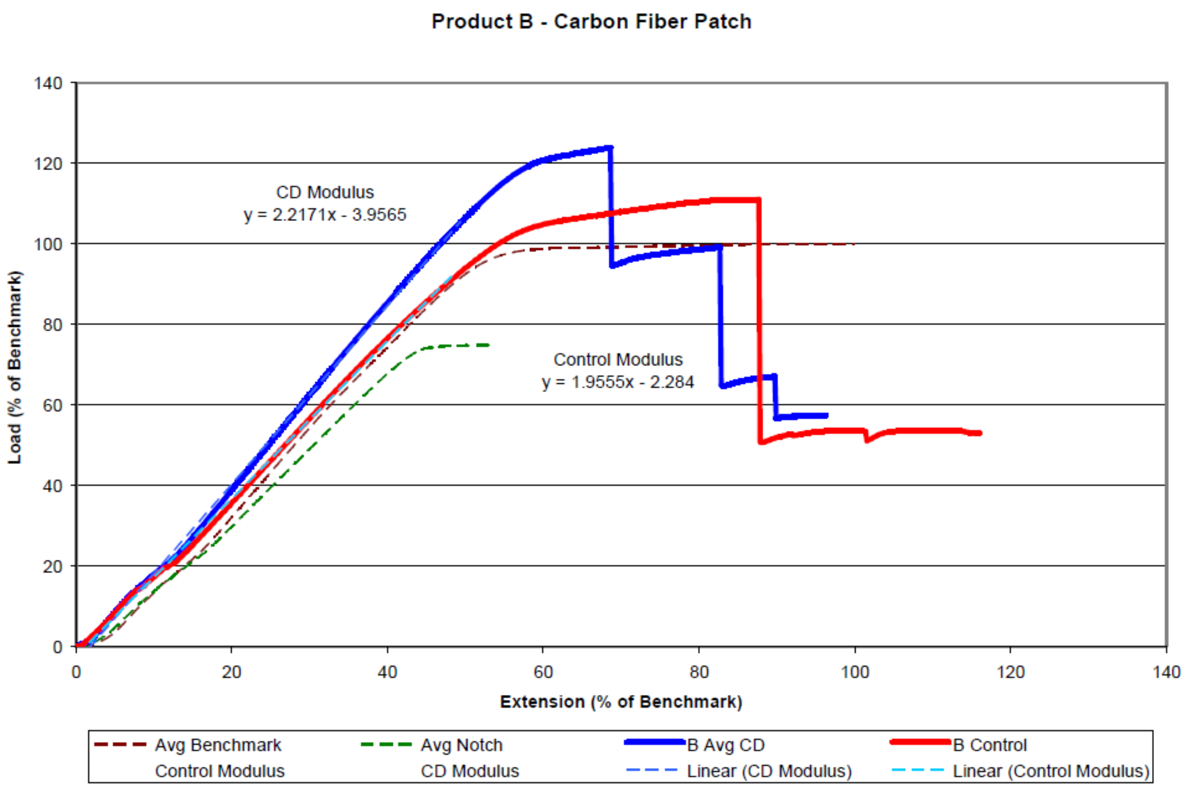


Figure 19 Product B load vs. displacement is compared against virgin steel and notched steel.

The adhesion strength of the two different patch resins is shown in Figure 20. Product B exhibited better adhesion with the pipe surface than product A, which is consistent with the four point bend data as shown above and in Figure 21.

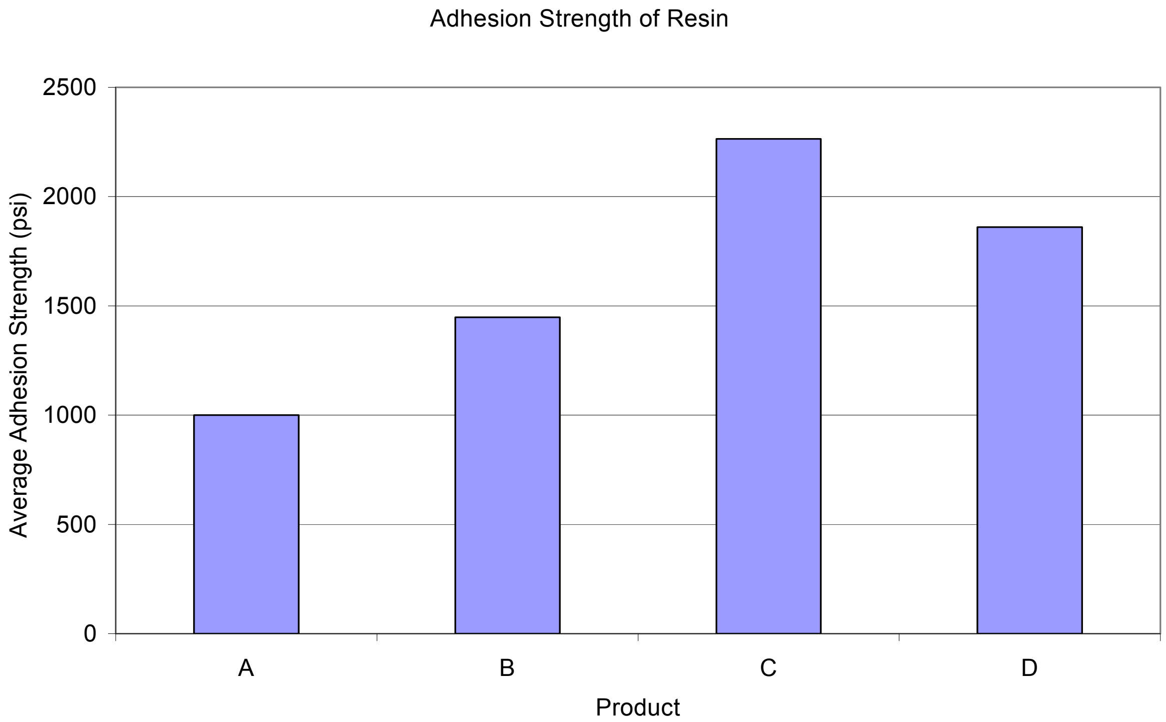


Figure 20 Adhesion strength measurements were taken of the resin only on the substrate following ASTM D4541.

In Figure 21, the relative maximum load, maximum deflection, and modulus or stiffness of each product is shown. It should be noted that products C and D are intended for full wrap applications. On the left of the figure, the benchmark or "virgin steel" specimen is the comparative standard. Assuming its load and deflection capability are 100%, all other conditions are compared against it. It can be seen that a notch in the specimen decreases the maximum load it can bear by ~25%, and that maximum load was achieved with only 50% of the deflection. The stiffness of the notched steel is also reduced to 90% of the benchmark case. Of all of the specimens, product C appeared to have the best capability of withstanding increased load, nearly doubling the load of the steel and improving stiffness by nearly 150%. After impact and disbondment, however, adhesion of product C was reduced, though it could still sustain more load than the benchmark steel, meeting the requirement that the repair restores the serviceability of a theoretical pipe in this case. Of the patch specimens A and B, only B showed better or equivalent strength and stiffness as compared to the benchmark steel. Product A improved the ability of the notched steel to bear load, but it did not meet the benchmark value. Product D exhibited a high stiffness in the control condition, similar to product C, but product D was more susceptible to disbondment than product C.

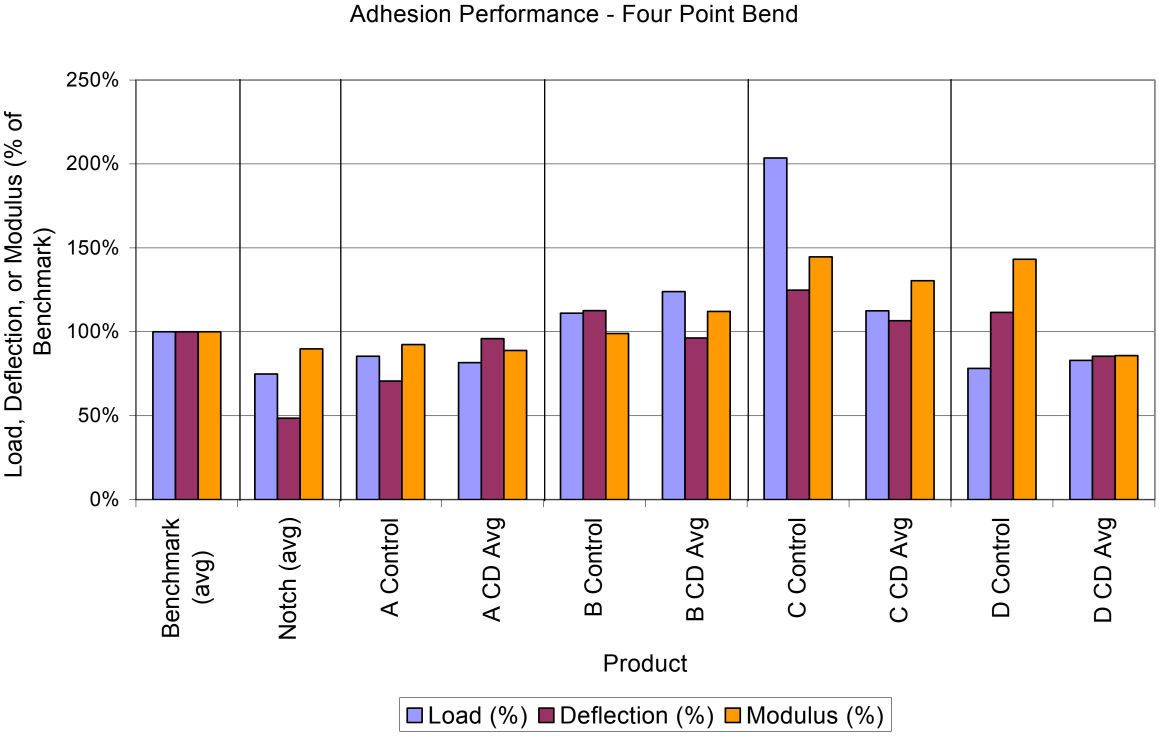


Figure 21 The peak load and peak deflection for each of the products is compared against virgin and notched steel.

There is consistency between the adhesion strength measurement and the four point bend performance. The ranking of products is evident by comparison of Figure 20 and Figure 21:

$$C > D > B > A$$

This would indicate that the much simpler method of adhesion pull-off per ASTM D4541 can be used as a "knock-down" test when evaluating two or more composite materials for a pipeline repair application. The more complicated test – four point bend per ASTM G39 - can be used to obtain more explicit data once products have been down-selected. Note that the commercially available products generally exhibit superior performance to the generic products.

4.3 Controlled Environments and Field Testing

Three test procedures were used to simulate the conditions experienced in the field, as shown in Figure 22. The triad of test procedures are described as follows:

- First, ASTM G8 was modified to incorporate two condition extremes – cathodic disbondment in a conductive and aggressive electrolyte coupled with pressure cycling at 1800 ± 200 psi. Accounting for the wall thickness of the pipe, it was calculated that the pipes would be operating at or near 70% of yield in the hoop direction of the API pipe steel vessels. They simultaneously experienced the ASTM G8 conditions while cycling.
- To compliment the cyclic loading specimens, a pipeline operator permitted the burial of test specimens in Virginia. The composite products were not applied directly to an operating pipe. Instead, they were prepared as other specimens have been prepared

and installed next to the operating pipe and connected to its existing cathodic protection system.

- Lastly, specimens were buried in an indoor soil box with a controlled cathodic protection system and controlled soil moisture. Control and impacted specimens were included in the test, and sensors were installed on control specimens.

These test environments ranged from mild to severe, as shown in Figure 22. The intention of these tests is to provide a relative scale of conditions under which these materials would be expected to perform. By gauging the intensity of the environment in this way, inferences about performance in actual conditions can be made.

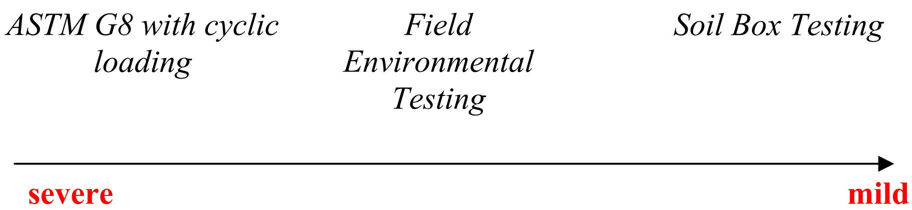


Figure 22 Three controlled environment tests were used to evaluate the cathodic disbonmdnet mechanism in these samples, ranging from severe conditions to mild conditions.

4.3.1 Cyclic Loading

The system for testing the composite specimens in cyclic loading conditions is shown in Figure 23. A solution bath was prepared for the pipes. The pipes were prepared as all other samples in the controlled environment tests were prepared: the composite was applied according to typical manufacturer specifications, it was coated with a commonly used pipeline coating, and an impact was applied to the pipe to penetration (see Figure 24). Each product was tested with one impact specimen and one control.

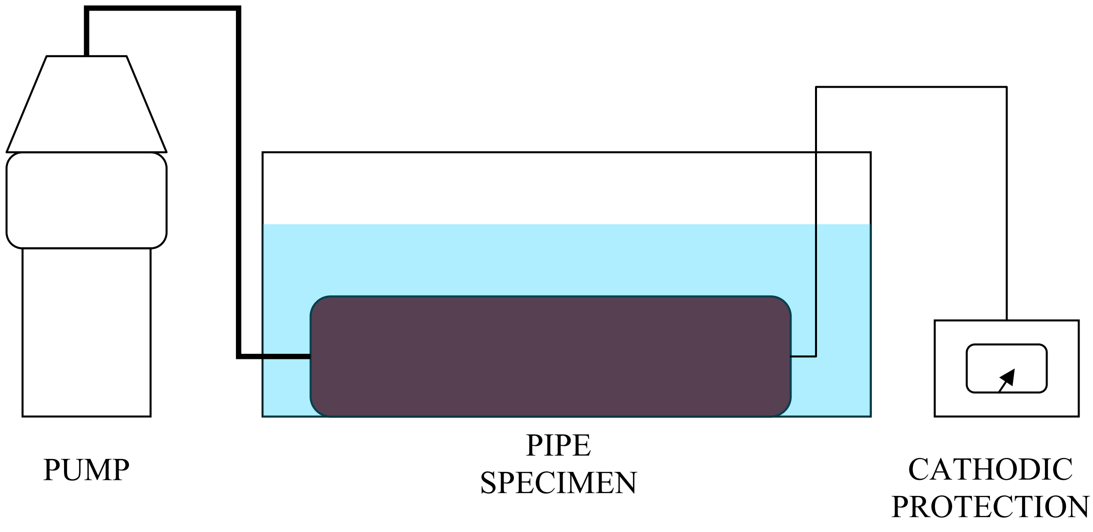


Figure 23 ASTM G8 and cyclic loading were performed simultaneously to simulate an aggressive environment.

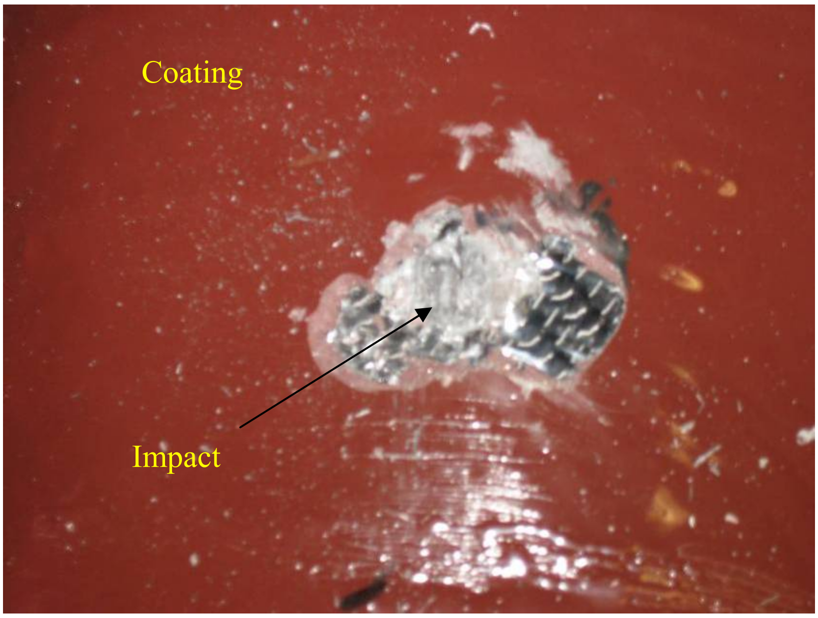


Figure 24 Before testing, product specimens were impacted and prepped for controlled environment testing using the same methods as the laboratory testing.

Eight specimens were tested (one impact and one control per product). The control specimens did not have any impacts and were tested with the coating intact. The coated specimen as it was connected to the pressure piping is shown in Figure 25. The test lasted slightly longer than 30 days and endured greater than 50,000 cycles. The cycling profile is shown in Figure 26 and typically the pressure profile reached approximately 2000 psi and then dropped to 1600 psi at a frequency of about 1 cycle/min.

Figure 25 Pressure vessels for cyclic loading were monitored with pressure gauges and a common pressure solenoid, controlled by a master Labview monitoring and control system.

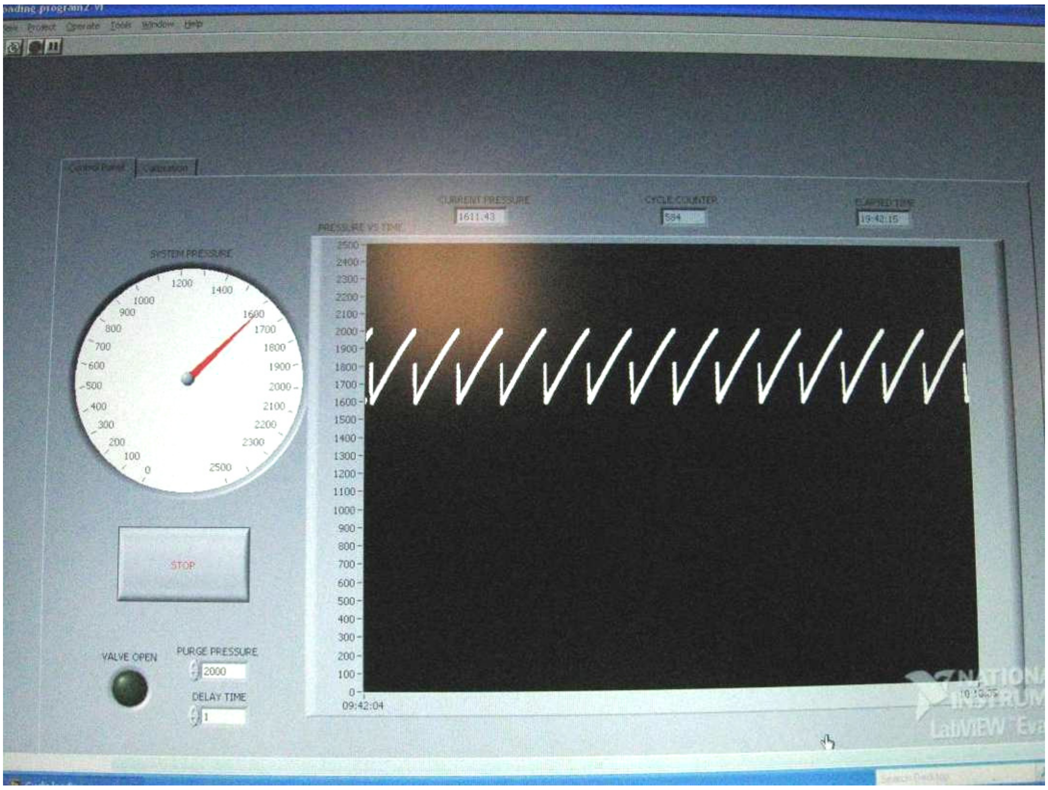


Figure 26 Cyclic loading specimens were controlled with a Labview computer and pressure solenoid.

The pressure was calculated such that the hoop stress in the pipe wall reached ~70% of yield, as would be expected for most typical operating conditions of an actual pipeline. Since the composite products were applied to the pipe in its relaxed condition, any pressure would put the composite in tension.

After testing, the specimens were inspected for disbondment. The results were consistent with the benchtop ASTM G95 tests. Product B, which had performed reasonably well with ASTM G95, performed reasonably well during the ASTM G8 + cyclcic loading test. The impact area after testing but before inspection is shown in Figure 27. After inspection and removal of coating and composite around the impact area, little disbondment was observed (see Figure 28). Note that Product B is carbon fiber and was not insulated from the pipe steel. The coating appeared to be intact but with minor disbondment from the composite around the impact area.

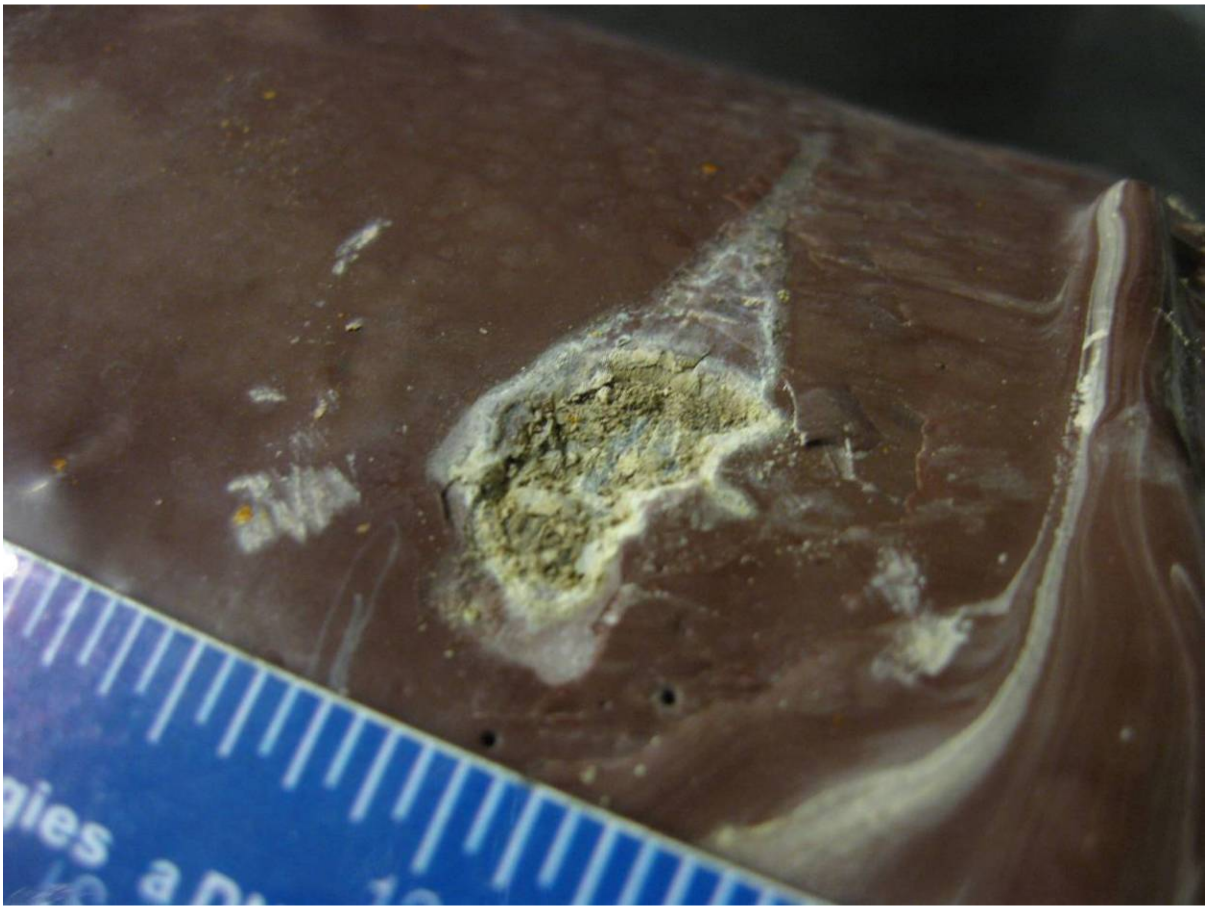


Figure 27 After testing, the impact area of Product B showed some bare steel, precipitation of NaCl due to drying of the test solution, and minor orange discoloration (scale in 1/16" increments).

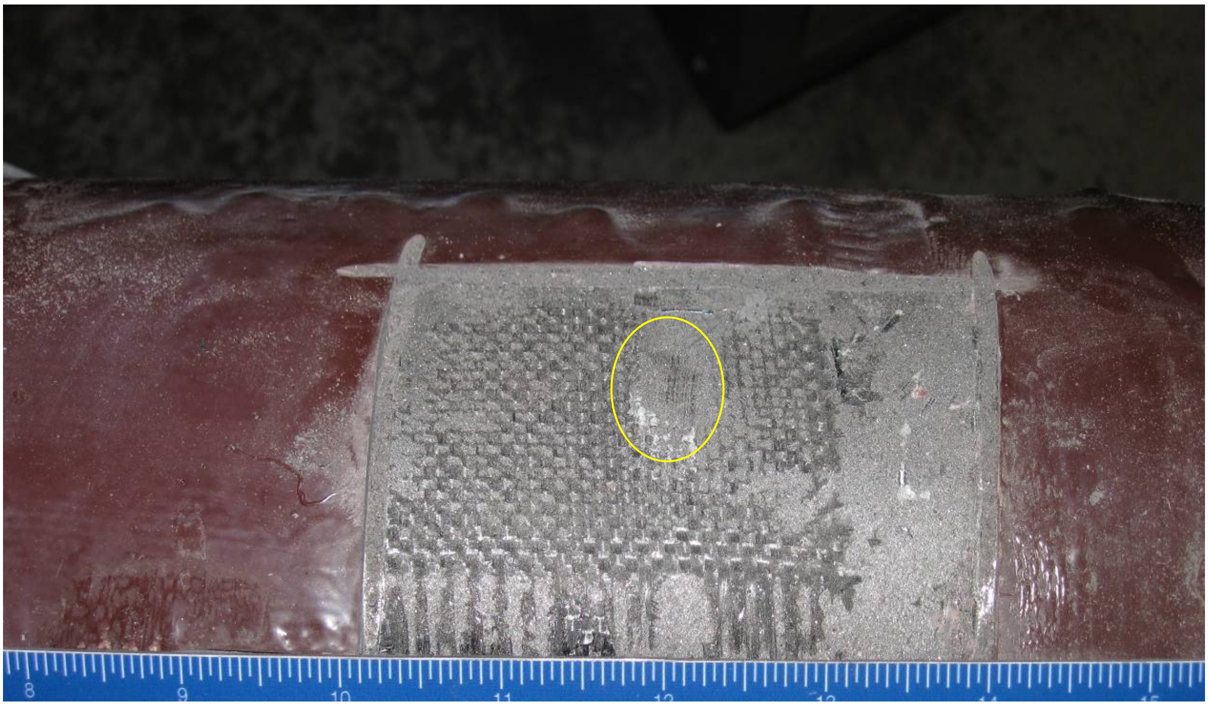


Figure 28 Product B showed minor disbondment after testing (scale is in inches with 1/16" hash marks).

There was interest in detecting disbondment, if any, near the edge of the composite repair. In only one instance was there an indication that this may occur in Product A. One should recall that Product A has exhibited poor adhesion elsewhere in this testing program and is not necessarily a fair representation of all composite repair products. However, it can be noted that the free edge of the composite product is a potential surface for water infiltration. The disbonded region is shown in Figure 29.

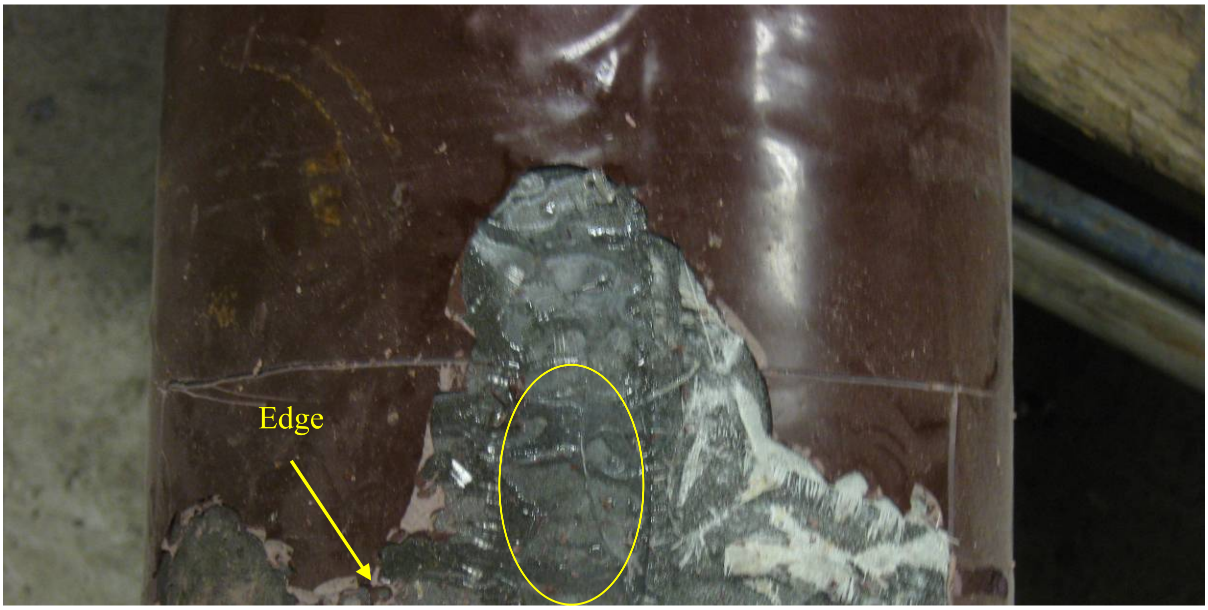


Figure 29 Product A showed minor disbondment near the edge of the composite repair after inspection.

In some instances disbondment was measured around the defect (impact) site in the cyclic loading specimens. In Figure 30 and Figure 31, examples of disbonded area are shown. In Figure 31, Product A shows the highest measured disbondment in this test when compared to the other products. Product A used an E-glass fiber with an epoxy that is commonly used in the manufacture of composite piping structures. An interesting note is that Product A, while strong and effective as a binding agent for fiber-fiber adhesive bonding, is not necessarily an effective agent for fiber-metal bonding. Though not a main finding of this report, it is an important consideration for end users when evaluating a product for use. When selecting composite repair products, it is perhaps the case that the bond to the metal is just as important as the bond between fibers.

The compiled results of the cathodic disbondment measurements are shown in the chart in Figure 32. Since average diameter of the measured disbonded area is calculated from the measured area, there is a direct correlation between these parameters. However, it can be seen that Product B exhibited good performance, and that Product C continues to outperform D, and that A remains behind.

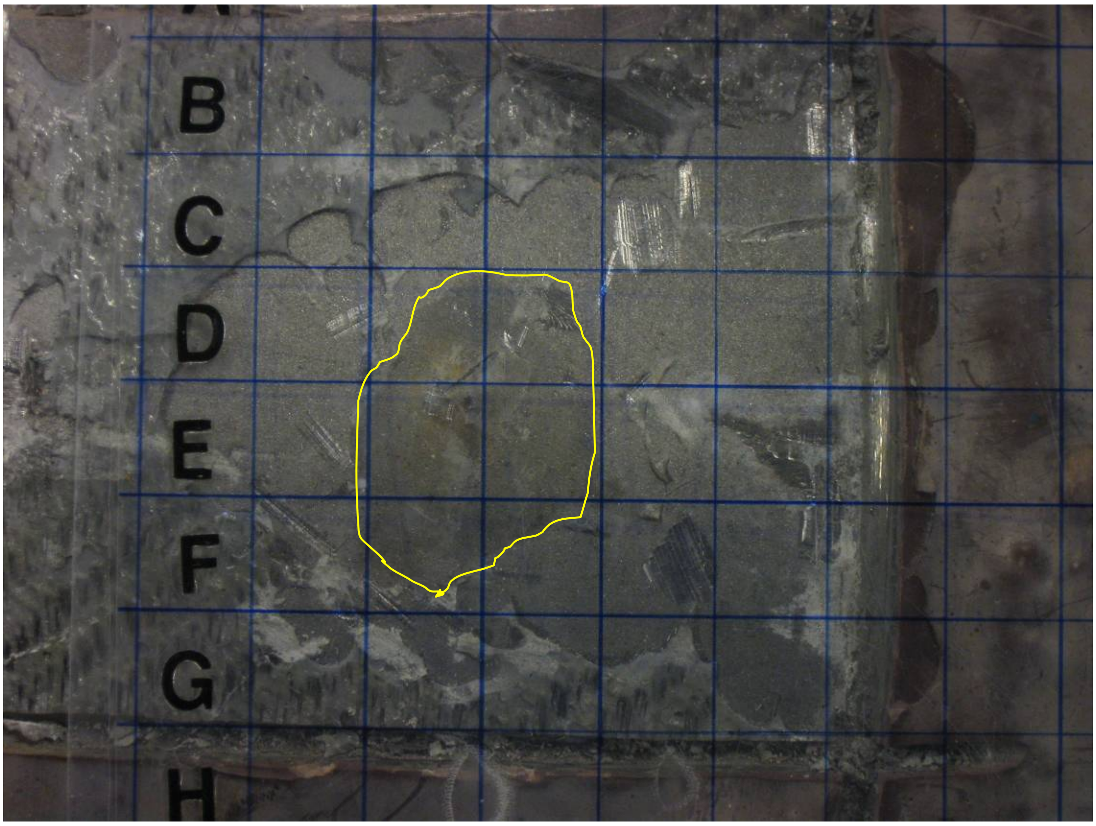


Figure 30 Disbonded area around impact site after cyclic loading test, Product C (grid scale is ½”).

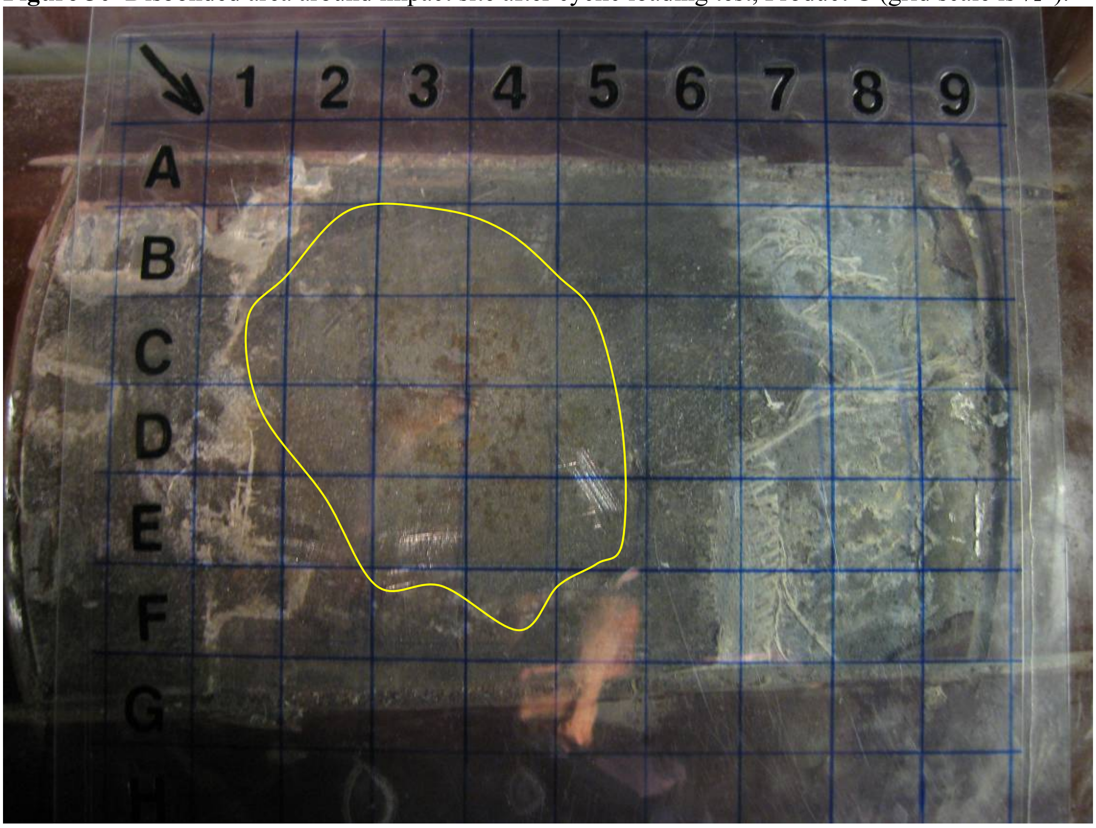


Figure 31 Approximate disbonded area under impact for Product A after cyclic loading (grid scale is ½”).

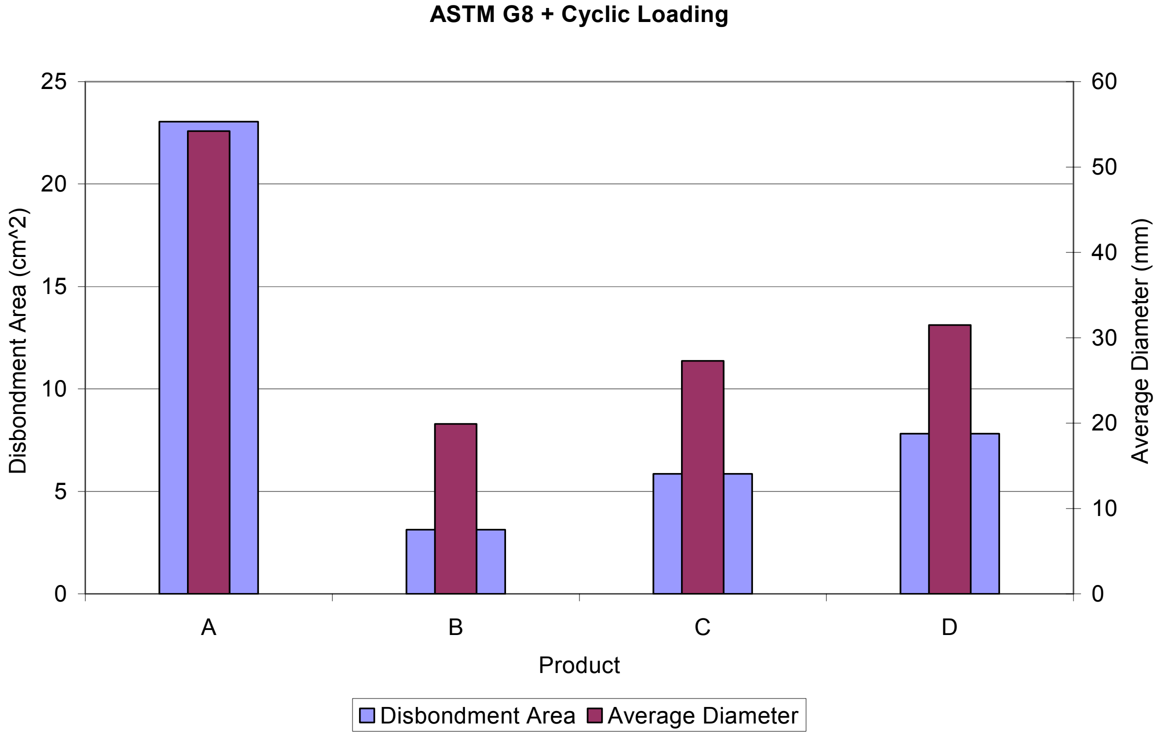


Figure 32 Disbondment area (cm^2) and average diameter (mm) of product specimens after ASTM G8 and cyclic loading.

When judged only by cathodic disbondment performance, the products appear to be ranked as follows:

B > C > D > A

This is in some disagreement with the previous ranking because Product B has moved upward in the ranks, but the order of C and D remains the same. Product A continues to be ranked last.

4.3.2 Field Testing

In November of 2008, pipe sections were installed next to an operating pipline in Virginia, with assistance from a pipeline operator. The test pipes were connected to the existing cathodic protection system. Like the cyclic loading tests, two specimens from each product were used: one impact and one control. In the photo, the additional specimens are from another project. See in Figure 33 that the pipes were installed in the same soil and CP conditions of the operating pipe.

Figure 33 Installation of the pipes at the field site in Virginia in November 2008.

In November of 2009, the pipes were retrieved from the field, and their extraction began with a backhoe as shown in Figure 34 and Figure 35. Efforts were taken to protect the specimens from the backhoe during excavation. Due to the difficult nature of locating buried objects, the specimens did incur minor damage during excavation from the backhoe and probes. These defect areas were immediately noted in order to distinguish them from the test results. Even in cautious testing conditions, 3rd party damage is still difficult to manage.

Figure 34 One year after their burial, field specimens were retrieved from Virginia.

Figure 35 Field specimens were collected in early November of 2009, and careful measures were taken to ensure soil consistency and differentiation of defects induced by extraction.

The carbon fiber specimen (product B) is shown after 1 year of exposure in the field environment in Figure 36. In some cases the coating disbonded slightly from the composite repair surface. In general, the soil environment was not aggressive enough to incur any significant disbondment on the coating or composite.

Figure 36 After testing, specimens were inspected for disbondment at the impact site as well as in areas far from the impact site. Product B is shown here.

Specimens from the field were inspected as other specimens have been inspected. As shown in Figure 37, there is not a significantly visible disbondment zone. Indications of adhesion were consistent with specimens tested in the lab. The relatively mild environment of the soil and the short exposure time (1 year) appear to have had little effect on most of the specimens. Though the area in which the pipes were buried is fairly wet, the depth of the burial and the slope on which the pipes where buried may have contributed to good water flow away from the burial site. By maintaining a relatively dry area, the environment did not appear particularly corrosive.

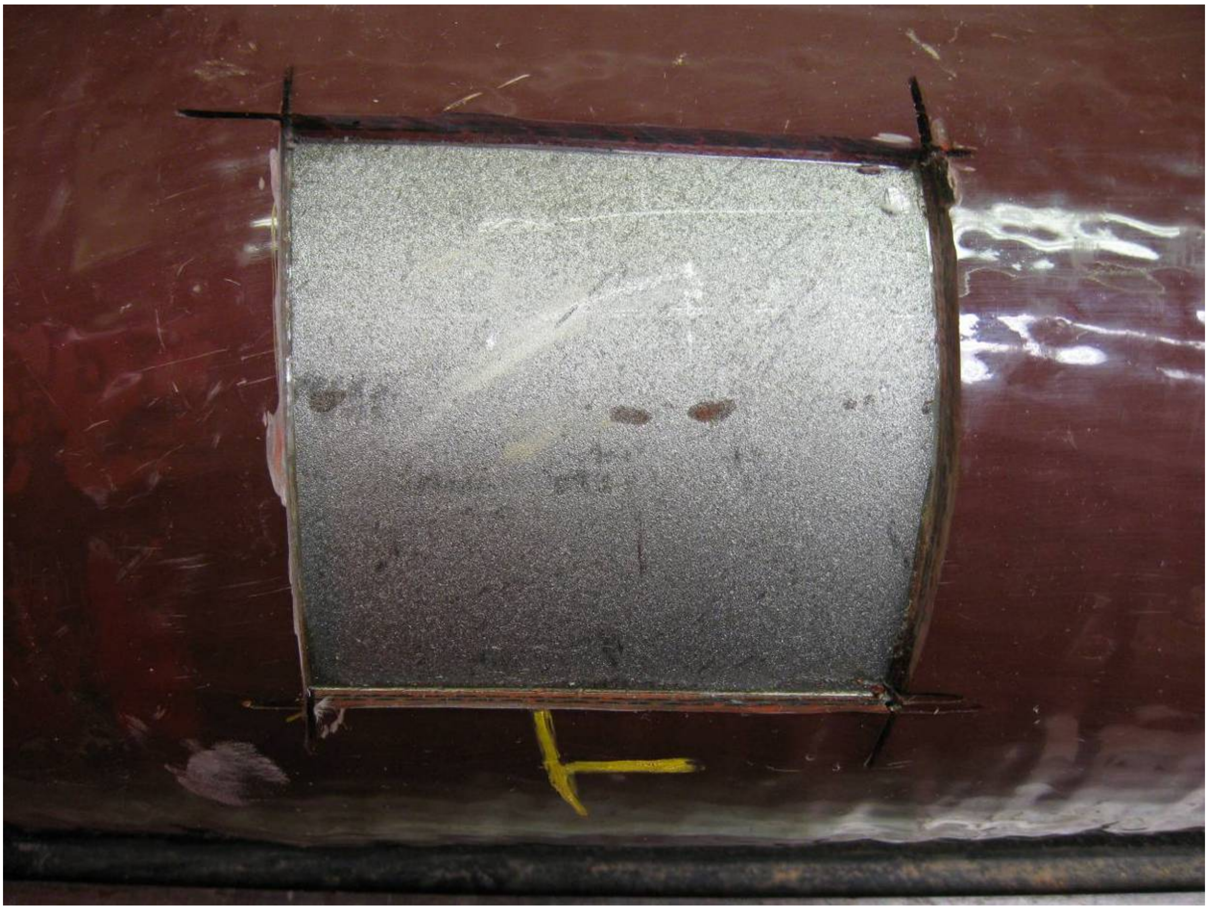


Figure 37 Specimens from the field study showed very little evidence of disbondment near the impact area.

4.3.3 Soil Box Testing

Soil boxes and field tests were used together to compare against the laboratory test results. In these tests, the pipes have been buried with one control specimen and a second specimen with pre-installed, through-wall sensing electrodes. These electrodes will monitor potential along the surface to detect whether the administered impact in the coating/composite/pipe system is affecting the potential from cathodic protection along the pipe. The sensing electrodes for the pipes are silver wires installed through the pipe wall, mounted flush with the pipe surface. Silver is used because it has an insignificant corrosion rate and therefore accurately monitors the potential of its immediate vicinity. The sensor electrode is shown in Figure 38.

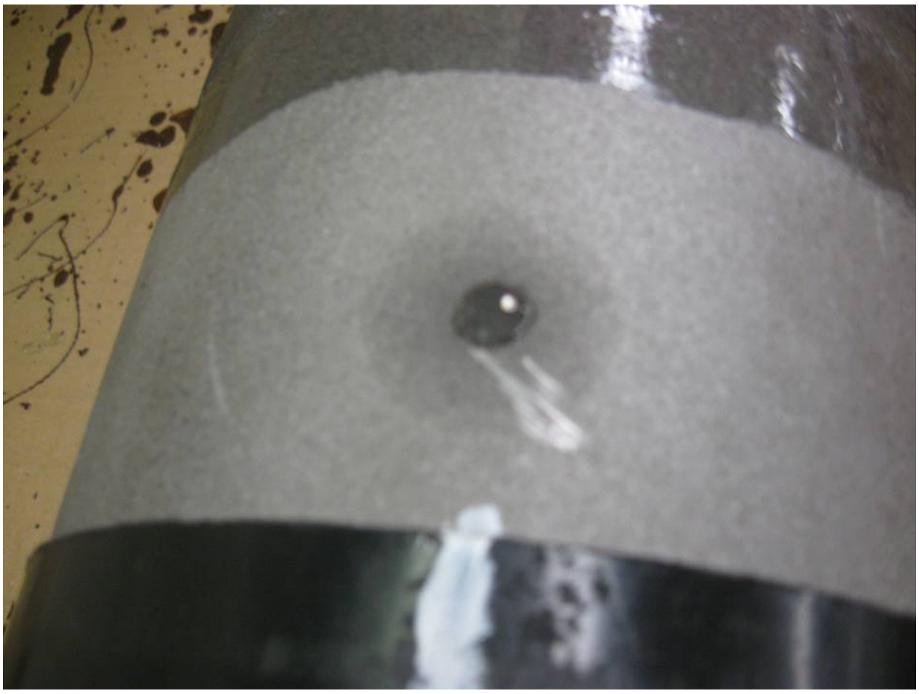


Figure 38 Electrodes were installed flush with the pipe surface to measure potential underneath the composite repair.

The soil box tests have not been terminated, and it is the preference of the project team to let the soil box tests continue for several more months. This does not interfere with the project, but DNV would like to independently evaluate the specimens and include this data in 2010 publications. One of the coated pipes prior to installation is shown in Figure 39. The soil box is shown in Figure 40.

Figure 39 The coated pipe for the soil box is shown before installation.

Figure 40 The soil boxes continue to serve the function of testing the pipes.

5 DISCUSSION

Since this work essentially translates knowledge from coatings to composites, there are some assumptions, caveats, and clarifications required.

5.1 Impacts vs. Drilled Holidays

This work has identified that when the ASTM standards for coating disbondment are used, the coating test specifies that a simulated holiday be introduced into the coating by using a drill bit. For coatings, this is acceptable because a coating holiday is a total penetration and is often small. The puncture of a coating will generally have defined edges.

Since composite repair systems are a relatively new technology, the ASTM standards used for this evaluation were adapted slightly to accommodate the different properties of the composite repair systems. ASTM G14 is designed to impact pipeline coatings, but the impact energy required to penetrate a composite is significantly higher. Therefore, more weight (accomplished with increased tup weight), greater height (likely > 1 m), and repeated impacts are often required to intentionally achieve penetration for composite repair systems. In addition, the ASTM G62 holiday detection test normally requires a wet sponge to defect pipeline coating defects which are usually small and shallow; however the thickness of the composite system can make it difficult to detect conductivity with the sponge method. In this case, a metal pick like what is used for most commercial multi-meters was instead used to gently make contact with the interior of the impact site and test for conductivity with the bare pipe steel. Once conductivity was detected, the impact site was deemed to have reached full penetration.

Impact energy is most easily measured in Joules, which are SI units of energy. An alternative measurement of energy is foot pound-force, or ft*lbf. These units may present the literal picture of applying a force to a torque arm. If the tup from the impact tests were attached to a lever, and a person were to apply a force to that lever (similar to a shop press or hydraulic lift jack) such that the force would push the tup into the surface, then there is an "energy" associated with this action that is a measure of the damage tolerance of the composite. However, materials deforming at high speed behave differently than materials deforming at low speed. The inelastic and rapid nature of the collision adds some unpredictability to the deformation of the composite system, and it should be noted that these materials absorb almost all of the energy from the impact inelastically. Therefore, while the units can be converted from Joules to ft*lbf, neither unit captures the full meaning of the impact event. Generally, it can be said that these composites are more resistant to impact than most coatings because of their ability to absorb energy during impact. However, this does not mean that the system is impervious to impact damage.

These impact tests may approximate dropped rocks or hard objects from the bucket of a backhoe during excavation or burial. Impact from the backhoe itself is another consideration but is not adequately simulated by these tests because of differences in impulse (force magnitude and force duration) and the kinetics of the collision. The aspect ratio of the rock edges and features, its weight, and its angle of impact will greatly influence its damage potential, but the tests performed here would generically simulate a 12 lb. (4.5 kg) rock with rounded corners dropping from ~10 ft (~3 m) above a coated composite repair on a pipeline. Probes used for locating buried pipe may have similar impact energy depending on the precautions taken by the field inspection crew. Under those conditions, full penetration would not likely occur with just one impact for thick and strong composite systems. Thinner composite systems may endure less impact energy.

In these tests, the impact was repeated at the same location multiple times. The chances of multiple rocks hitting the same impact site are extremely unlikely, but the purpose of the repetition is to determine the conditions required to fully penetrate the composite. Since penetration of the composite system will expose bare metal, the same concerns about exposed metal under a coating would apply to the composite system.

Impacts in composites differ from coatings in that there are different damage modes to consider, such as the severing of fibers, cracking of the resin matrix, and energy absorption during the inelastic collision. This is captured by ASTM G14 and for this reason, ASTM G14 should be the preferred preliminary test to compliment ASTM cathodic disbondment tests for composite repair systems.

5.2 On the topic of disbondment

Composite systems to be used on pipelines can be thicker (near ~ ½” or 1.25 cm for some E-glass products) than what was tested in this work, and the soil environment will be less aggressive. Some carbon fiber products, however, use only a few layers and can be as thin as 1/8” (0.3 cm). The energy of impacts is likely to be greater - such as during a digging incident - and the post-impact exposure time will be significantly longer. Under cathodic protection conditions, an impact scenario may pose a threat to the long term integrity of the composite, provided that water ingresses between the composite and the cathodically protected steel. Of particular importance is the effect of impacts near the edge of the repair. This is most critical for a patch, but may also be of importance for the edges of a full encirclement repair.

Polymer matrix materials in composites are likely to be more brittle than coatings because of the desire to optimize design for strength. Coatings are developed specifically for hydrophobic properties, while composite matrix materials are designed for optimum mechanical properties. In addition, coatings are designed for optimal adhesion to a metal substrate, while matrix materials are designed for improved adhesion between fiber layers. Water absorption and uptake of the two materials are therefore different, though the eventual degradation mode during cathodic disbondment is similar. This work indicates that polymer resin matrix materials are subject to degradation in alkaline environments induced by the electrochemical conditions supported by cathodic protection.

Cathodic disbondment tests were verified to be a mechanism of integrity failure of the fiber reinforced composites. It is evident that the polymer matrix in this case is susceptible to cathodic disbondment in a fashion similar to coatings. The environmental water quality test performed on the polyester specimen indicated the presence of styrene, which one may reasonably conclude came from dissolution of the polyester resin—a styrene monomer—in the test matrix. The environmental quality test also confirmed high concentrations of alcohols and carboxylic acids. Since polyesters are usually made through condensation of alcohols and carboxylic acids, the presence of these ingredients in the solution is attributed to the decomposition of the resin matrix. Trace amounts of chloroform likely indicates the dissolution of organics and subsequent reactions with NaCl and evolved Cl_2 (g) on the anode. It should also be noted that after the tests, the solution had a soapy consistency, though the pH was near 7. Dissolution of the polymer is considered to be the likely explanation for this observation.

Regarding the study of the composite patch repair, consideration of the geometry suggests that there may be a redistribution of stresses involved that could exceed pipe yield strength in the pipe wall if the internal pressure is near the maximum operating pressure (MAOP), typically based on 72% yield stress (YS). Unless the internal pressure requirements are low enough so as not to exceed the yield specifications in the pipe wall, there may be a change in load bearing thickness at the edge of the composite repair that could act as a stress concentrator. This would result in a required de-rating of the pipe, if the pipe is operating at its original (MAOP) specification, or would require that a patch repair only be used in situations where the internal pressure of the pipe resulted in stresses lower than the typical 72% of yield. In some cases, if the line is already de-rated because of other integrity issues, the composite patch may be a viable repair alternative.

As shown above, a composite repair patch may be considered a viable repair alternative in cases when the pipe is operating below its original MAOP, or the stress concentrations are still low enough so as not to exceed the specified hoop stress for the pipe. The strength of the repair does not appear to depend on the axial length or circumferential extent of the patch. In extreme cases where the patch is nearly fully circumferential, care must be taken to examine the overlap of hoop stress concentrations at either circumferential limit of the repair.

It should also be noted that there are stress concentrations around the edges of the patch, though there are also stress concentrations at the edges of the full encirclement wrap as well. It is likely that the edges of any composite repair, full encirclement or otherwise, are the most susceptible areas of water ingress, possible disbondment, or potential adhesion loss.

5.3 Regarding Mechanical Properties and Testing Methods

The use of four point bend to test the strength of the repairs is applicable as long as one only considers what is happening in the elastic region of the stress-strain curve, because this behavior is most similar to hoop stress. The reason why this distinction must be made is that *the hoop stress calculations per ASTM G39 are only valid for the elastic behavior of the bent specimen.* Once the specimen yields or failure occurs, the hoop stress calculations are no longer valid. The four point bend test can provide information about adhesion strength whether the product is intended as a full encirclement repair or a patch repair; some epoxies adhere better to the surface than others, and this is especially true depending on the surface preparation. It appeared that product C was applied after the surface was ground with a grinding wheel. The finish underneath product D looked very much like mill finish.

Products A and B were both bead blasted according to NACE field standards. The disbondment behavior depends greatly on the stiffness of the resin matrix and the overall stiffness of the repair. Some repair materials are more forgiving, others are more stiff. There appears to be a correlation between the bulk modulus of the repair and its disbondment behavior – more elastic and better adhered specimens disbond steadily, while stiffer specimens disbond in bursts. It should also be noted that ASTM G42 is only relevant if the composite material is expected to serve at elevated temperatures; otherwise, ASTM G42 has little relevance to normal buried service on cathodically protected pipelines in underground soil environments.

It has been shown elsewhere that tapering or other stress relieving considerations should be made at the edge of the patch.5 In addition, it is shown that adhesion of the patch to the metal substrate is fundamental to its function. For full wrap specimens, the continuous boundary condition of connected edges is intended to overcome the issue of adhesion to the pipe surface. It is also shown from the results that the function of some full-wrap resins is primarily intended for cohesive strength with less emphasis of adhesion on the surface, though adhesion with the surface prevents possible water ingress as well as seepage of moisture into the matrix itself, especially if any cracking is present. Adhesion with the surface has relevance to the ability of the cathodic protection system to protect the wetted pipe, and in environments where the pH is significantly high, the integrity of the resin itself may be an issue. 5, 6 It is suggested that if a composite repair is to be implemented in environments where coating adhesion is considered of importance, then the suggested test protocols should be applied to composite materials to also evaluate their adhesion properties.

6 CONCLUSIONS

There are some conclusions from this work that lead to a recommended practice for qualifying composite repairs for use in cathodically protected pipelines and moist environments.

In Table 2, the ranking of the products according to test method is shown.

Table 2 The ranking of products according to test method.

Test Method	Product Ranking	Metric
Pull Off Adhesion	C > D > B > A	Adhesion strength
Four Point Bend	C > D > B > A	% of load borne as compared to virgin steel
ASTM G8 Cyclic Loading	B > C > D > A	Disbonded area

The following conclusions are derived from these tests.

- The composites tested showed susceptibility of the polymer resin matrix to cathodic disbondment and degradation in alkaline environments
- Carbon fiber is conductive, and carbon fiber composites, if not sufficiently insulated from the metal surface, show evidence of polymer dissolution over the outer surface of the area exposed to the electrolyte in these test conditions. Most commercial products that use carbon fiber will insulate the fibers from the steel surface.
- Impacts, if penetrating fully or nearly to the metal substrate, can aid in the cathodic disbondment behavior of the composite repair. Impacts do not necessarily have to fully penetrate the composite to aid in CD.
- A composite repair patch, rather than full encirclement, leads to peak hoop stresses in the pipe around the edges of the composite repair patch. The peak hoop stress appears

to be significant relative to the nominal stress in the undamaged pipe, and the MAOP should be recalculated to account for these stresses. Tapered edges can possibly accommodate and redistribute this stress.

- The peak stresses calculated appear to be independent of the size of the repair patch, for a given combination of composite wall thickness and modulus. This implies that a smaller patch does not necessarily have a lower load bearing capacity than a large patch, as intuition might suggest.
- The reinforcement benefits of the patch, and the shear and radial stresses at the edge of a composite repair patch, appear to be independent of the patch size. This indicates that a smaller patch could be just as effective as a large patch, though this would be influenced by the size of the damage being repaired.

6.1 Suggested Procedures for Qualifying Composite Repairs for Pipelines

The conclusion of this work is that some standards for testing of composite repair products for cathodic disbondment shall require minor revisions.

Step 1: Evaluate bond of composite with steel substrate. Perform pull-off adhesion with ASTM D4541.

Step 2: Down select product from pull-off adhesion tests. Four point bend testing per modified ASTM G39 may be used to qualify the ASTM D4541 measurements. Impact and cathodic disbondment may be applicable to these tests (see below). It is recommended that these steps be taken, but Step 1 can be used to screen products and reduce the number of four point bend tests.

Step 3: Perform cathodic disbondment per ASTM G95, G8, or G42, with the modifications described below.

By following these steps, simple tests can be used to reduce the product selection test matrix initially, perhaps reducing cost for the end user. The following test protocol to evaluate the performance of composite materials in cathodic protection conditions is suggested:

1. Decide to test the system in the coated condition or uncoated condition and proceed accordingly.
2. Perform impact testing with ASTM G14: Standard Test Method for Impact Resistance of Pipeline Coatings (Falling Weight Test).
   a. Modification: use appropriate weight and height during impact to achieve penetration to metal. If repeated impacts at same location are necessary to achieve full penetration, consider recalculation of weight and height to achieve penetration with a single impact.
   b. Note: much larger heights and weights may be required (in comparison to coating impact tests)
3. Perform ASTM G62, Standard Test Methods for Holiday Detection in Pipeline Coatings, to confirm penetration of composite layers.
   a. Modification: a conductive probe may need to be substituted for the wet sponge in this test
   b. Note: care must be taken to not artificially alter the impact damage when testing conductivity. Also note if carbon fiber is conductive with substrate.

4. Perform cathodic disbondment tests as appropriate, using ASTM G8 (Standard Test Methods for Cathodic Disbonding of Pipeline Coatings), ASTM G95 (Standard Test Method for Cathodic Disbondment Test of Pipeline Coatings – Attached Cell Method), or ASTM G42 (Standard Test Method for Cathodic Disbonding of Pipeline Coatings Subjected to Elevated Temperatures) as appropriate.
    a. Modification: electrolyte composition, voltage, and test duration can vary depending on the specific requirements for the product, but all should remain consistent with the intent of the standard. Multiple specimens can be used so that short duration tests can compliment long duration tests in order to gauge evolution of disbondment behavior (if any) over time.
    b. Note: Test duration may need to be lengthened for some products, and if electrolyte is modified, for example, 3% NaCl or equivalent may be a suitable modification. Elevated temperature tests are only required if the product is expected to serve in cathodically protected and elevated temperature conditions.
5. Inspect per ASTM CD test specifications
    a. Modification: dye penetrant may need to be injected into the defect in order to sufficiently wet the interior disbonded area (if any) and mark the absence of adhesion.
    b. Note: removal of composite will require cutting and grinding around the defect site. A square or circular cutting pattern with a ~4” radius is a good rule of thumb, but may vary depending on product type.

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8 RESULTING PUBLICATIONS TO DATE AND PILOT SERVICES

The following publications have resulted directly from this work:

“Mechanical Properties and Performance of Composite-Reinforced Steel Pipelines in Wet Environments with Cathodic Protection.” NACE Corrosion 2010. D. Hill, N. Sridhar, R. Denzine, G. Snyder. Paper #14670.

“Performance of Composite Materials in Corrosive Conditions: Cathodic Disbondment of Composite Materials and Modeling of a Composite Repair Patch for Pipelines.” NACE Corrosion 2009. D. Hill, A. Ertekin, N. Sridhar, C. Scott. Paper #09329.

“Performance of Composite Materials in Corrosive Conditions: Evaluation of Adhesion Loss via Cathodic Disbondment and a Newly Developed NDE

Technique". Ceramic Transactions, MS&T 2008. Pittsburgh, PA. D. Hill, C. Scott, A. Ertekin, N. Sridhar.

A publication has been submitted to IPC 2010 to be held in Calgary, Alberta, Canada in October of 2010. It is also likely that these project results will be summarized in a journal publication – likely *Corrosion Journal*.

On a final note, efforts to transition the services developed via this project to a DNV Business Area are underway with reasonable success. It is hoped that these services will be fully transferred from DNV R&I to the DNV Columbus staff by the end of 2010. This project is therefore in a pilot stage, as shown in Figure 41.

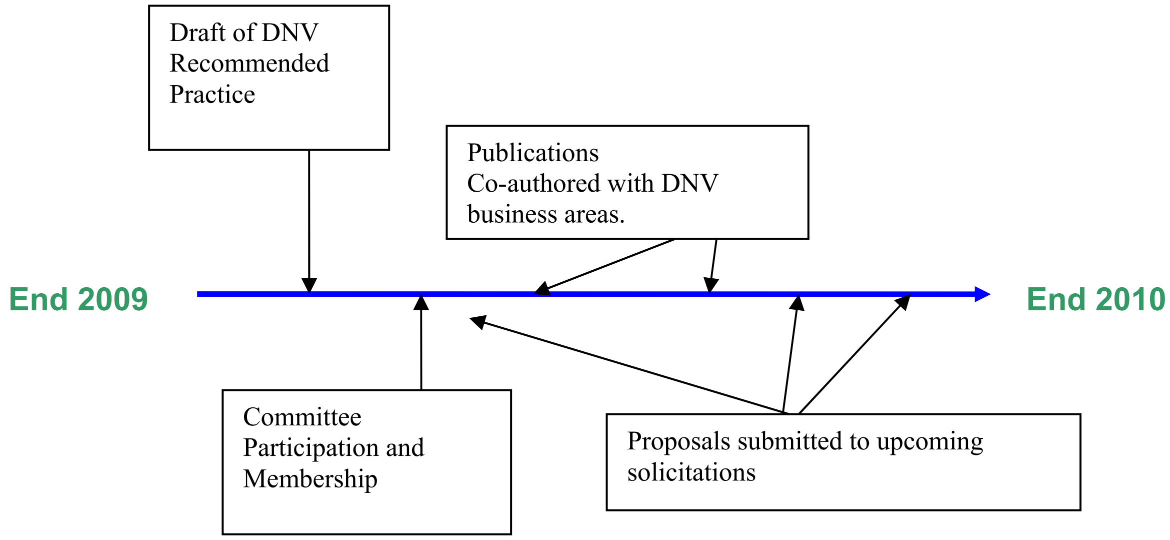

Figure 41 Transition plan to translate developed services from DNV R&I to DNV Business Area in 2010.

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