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PERFORMANCE OF COMPOSITE MATERIALS IN CORROSIVE CONDITIONS: CATHODIC DISBONDMENT OF COMPOSITE MATERIALS AND MODELING OF A COMPOSITE REPAIR PATCH FOR PIPELINES

D. Hill, A. Ertekin, N. Sridhar
Det Norske Veritas Research and Innovation – USA
5777 Frantz Rd
Dublin, OH 43017

C. Scott
CC Technologies – A DNV Company
5777 Frantz Rd
Dublin, OH 43017

ABSTRACT

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. The influence of impacts and holidays has been studied for cathodically protected substrates. The testing program provides insight concerning the effects of cathodic shielding, long term immersion, and soil corrosivity. By monitoring variables related to potential and conductivity of the electrolyte, the performance of these materials is studied. Loss of adhesion and integrity in the composite-metal system is studied to inform users about long term performance and reliability.

Keywords: composites, carbon fiber, glass fiber, disbondment, composite repair

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[1]. 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]. 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 [7]. 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 [8]. An ISO document, in particular, briefly mentions strength of materials considerations regarding patches, but provides no additional information [9]. 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.

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.

EXPERIMENTAL APPROACH

Impact and Cathodic Disbondment Testing

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[10]. 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..

TABLE 1
RESIN AND HARDENER TYPES USED IN THE TESTING PROGRAM

Generic Name	Resin	Hardener
A	Polyester styrene monomer resin	MEK peroxide in dimethyl phthalate
B	Multifunctional acrylic based monomer resin	Modified amine mixture and diphenylopropane

Impact tests were performed via ASTM G14 [11]. 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. A representative impacted specimen is shown in FIGURE 1, 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 [12]. 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 [13]. 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 2.

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.

FIGURE 1 The impact to the glass fiber reinforced polyester caused noticeable deformation around the impact site, as shown in this photograph. Scale is in inches.

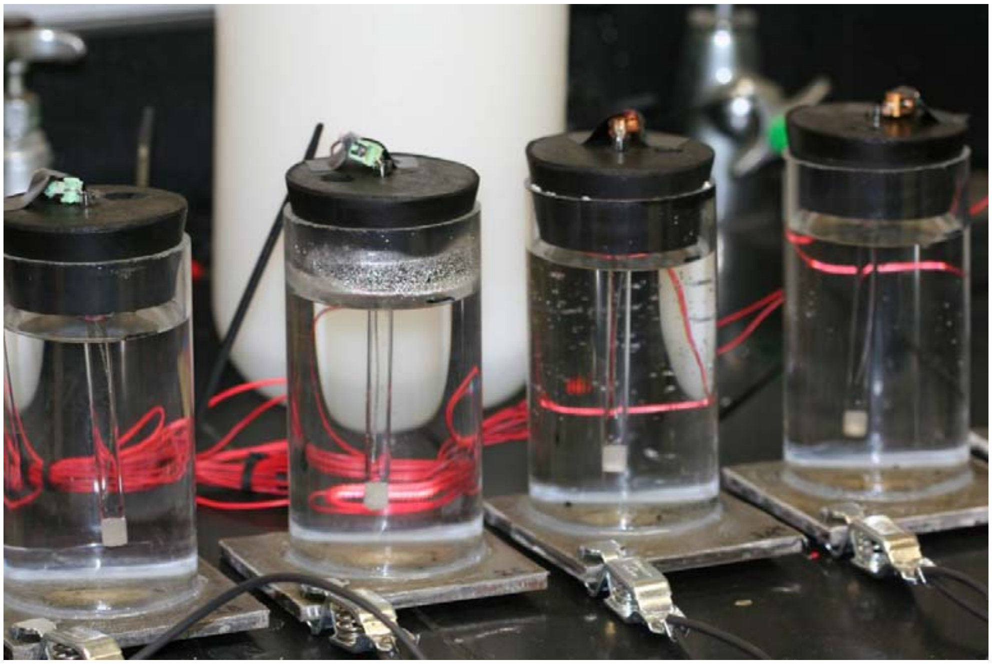

FIGURE 2 The cathodic disbondment cells are shown in the photo, attached to the composite plates via silicone adhesive.

Finite Element Models

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 [14]. The geometry of the patch and pipe FE model are shown in FIGURE 3.

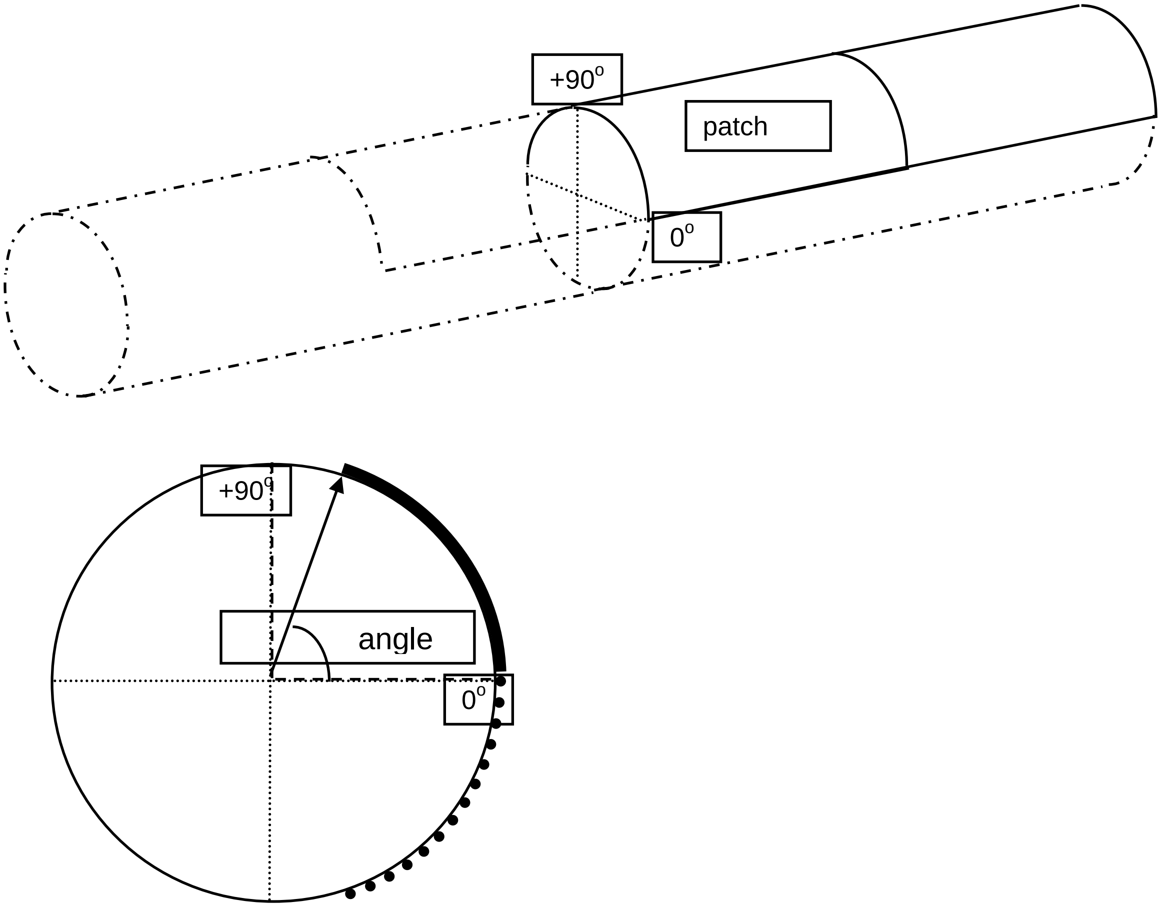

FIGURE 3 The geometry of the “quarter model” corresponds to the dimensions shown.

RESULTS AND DISCUSSIONS

Cathodic Disbondment of Composite Materials

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 4. In most cases, total disbondment was achieved.

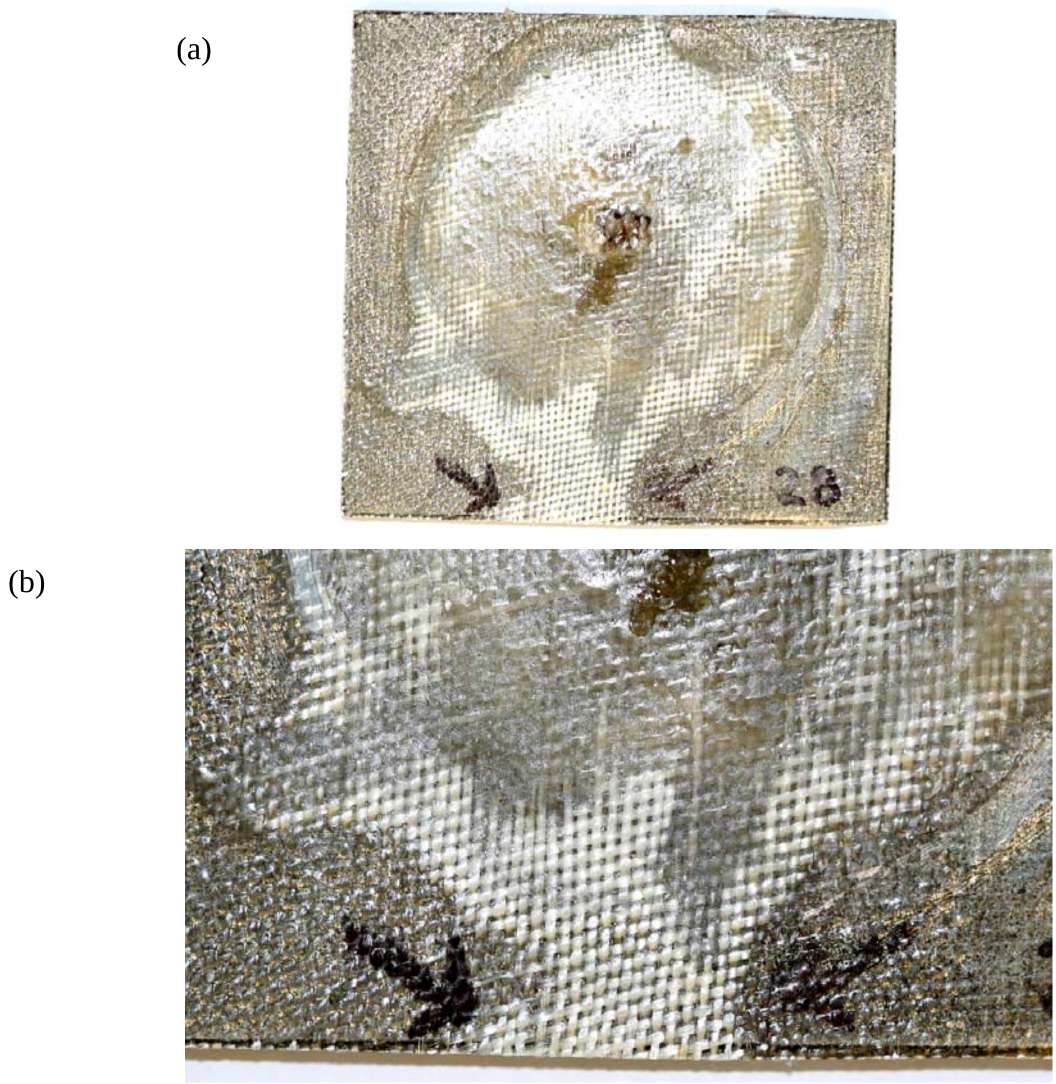

FIGURE 4 Photographic views of glass fiber reinforced polyester composites exposed to a cathodic disbondment cell show (a) the entire test area illustrating evidence of dissolution of the polyester matrix with the presence of localized dry fiber areas, and (b) a close-up of the polyester matrix dissolved 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 behavior 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 5 (taken during an active test through the acrylic cell).

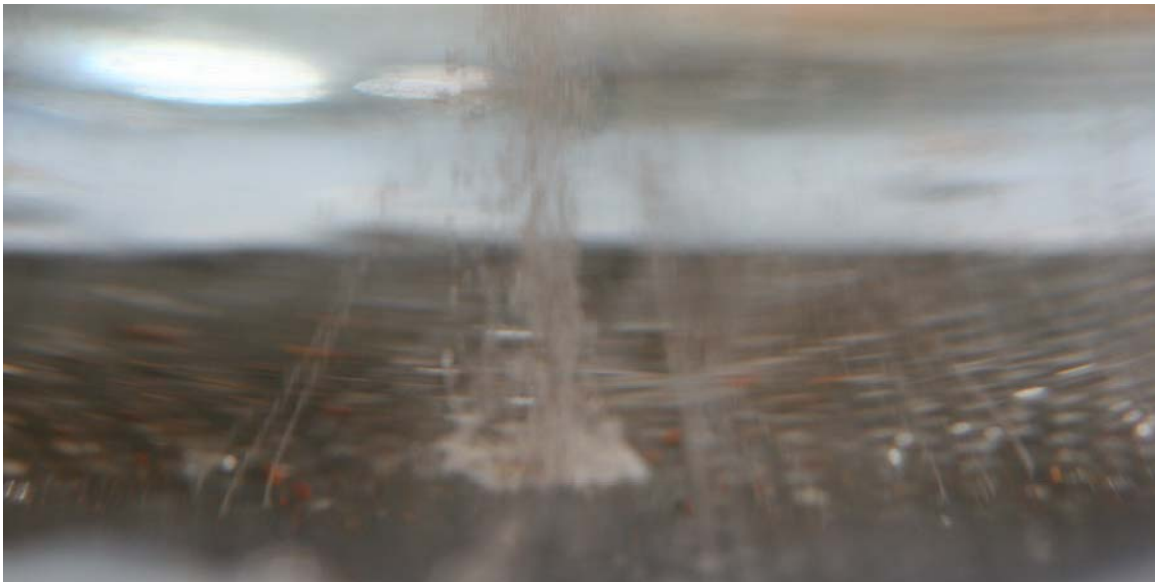

FIGURE 5 This photo was taken of a carbon fiber CD cell and shows gas evolution at the defect (center) and elsewhere on the carbon fiber surface.

In FIGURE 6, 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.

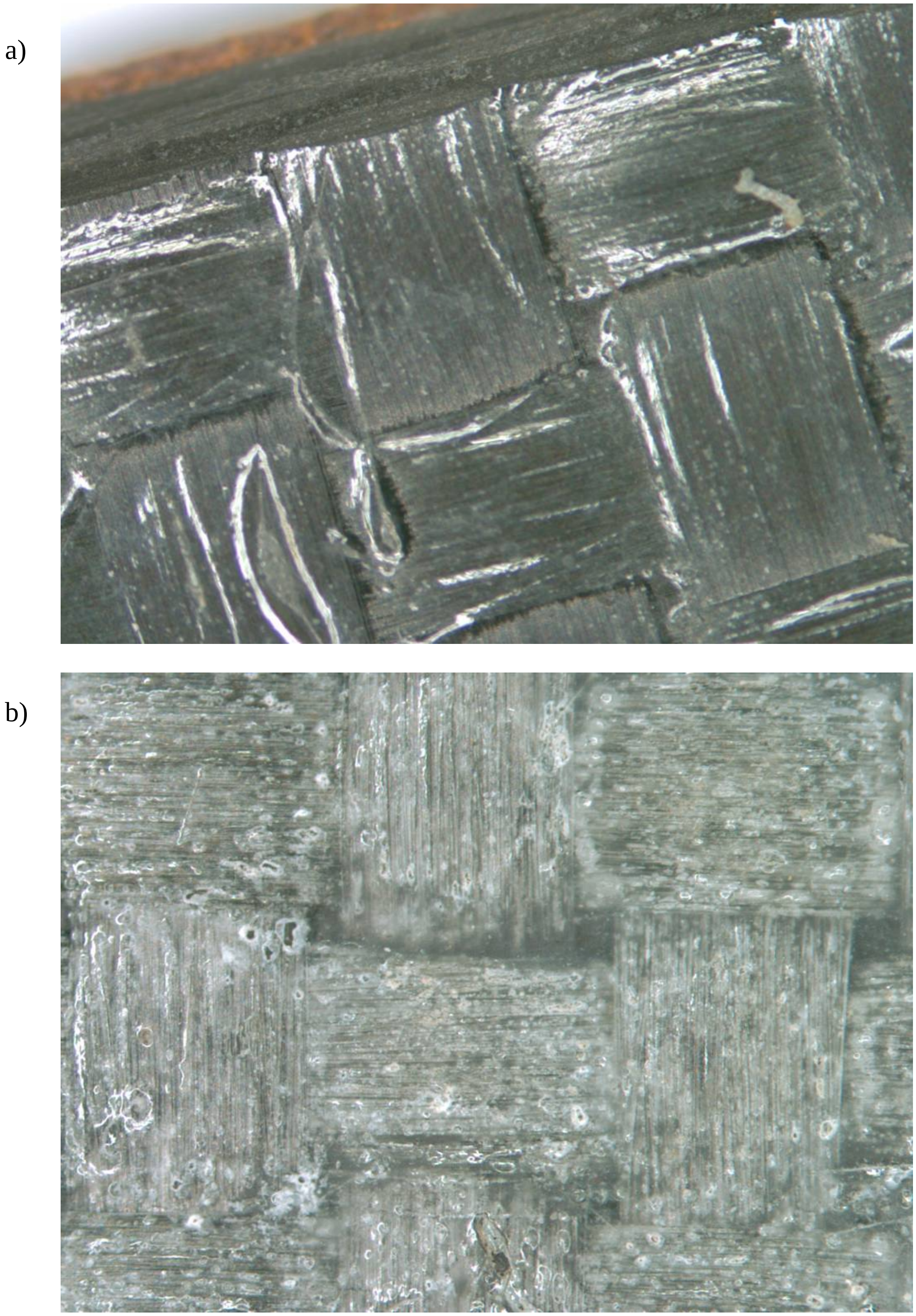

FIGURE 6 Carbon fiber with product B after nearly 30 days of cathodic disbondment shows a) no defects before, and b) pitting after.

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 7. The pictured specimen is the same polyester specimen shown in FIGURE 4. It is evident that the inspection dye penetrated underneath the glass fiber composite and revealed a disbondment “pocket” underneath the composite layers.

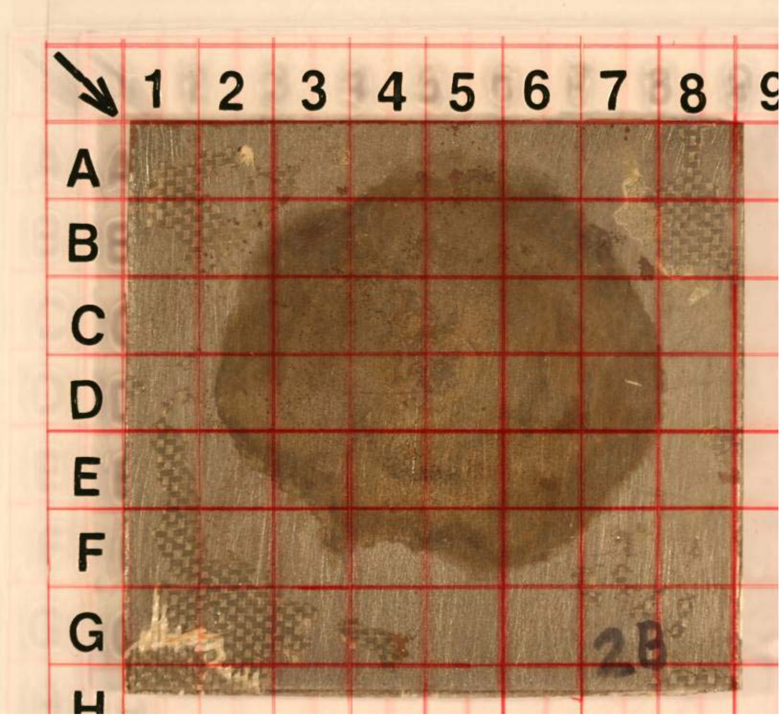

FIGURE 7 Total disbonded area for 2 layers of fiberglass with polyester matrix.

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 8.

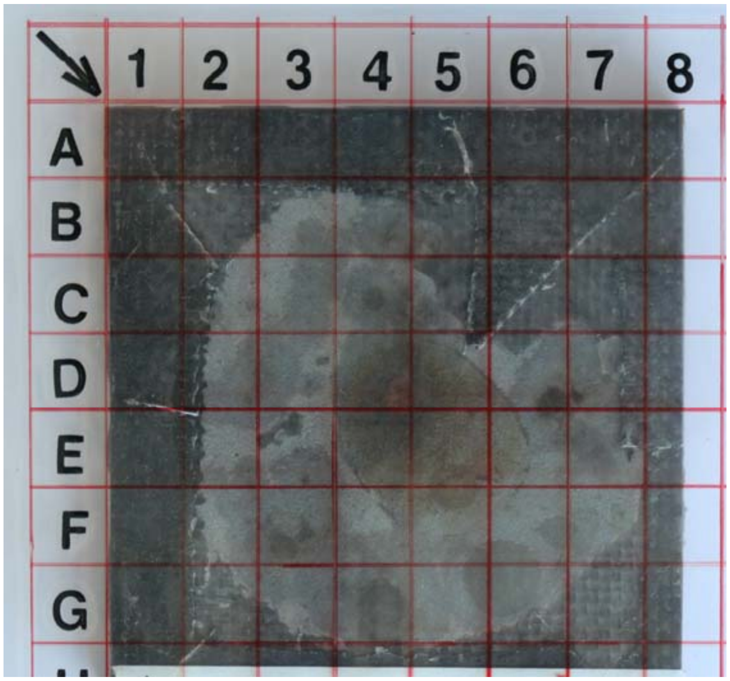

FIGURE 8 A single layer of carbon fiber in an acrylic matrix after an impact showed near total disbondment, as shown in the figure.

Finite Element Models for Composite Repair Patches

FIGURE 9 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 3. 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.

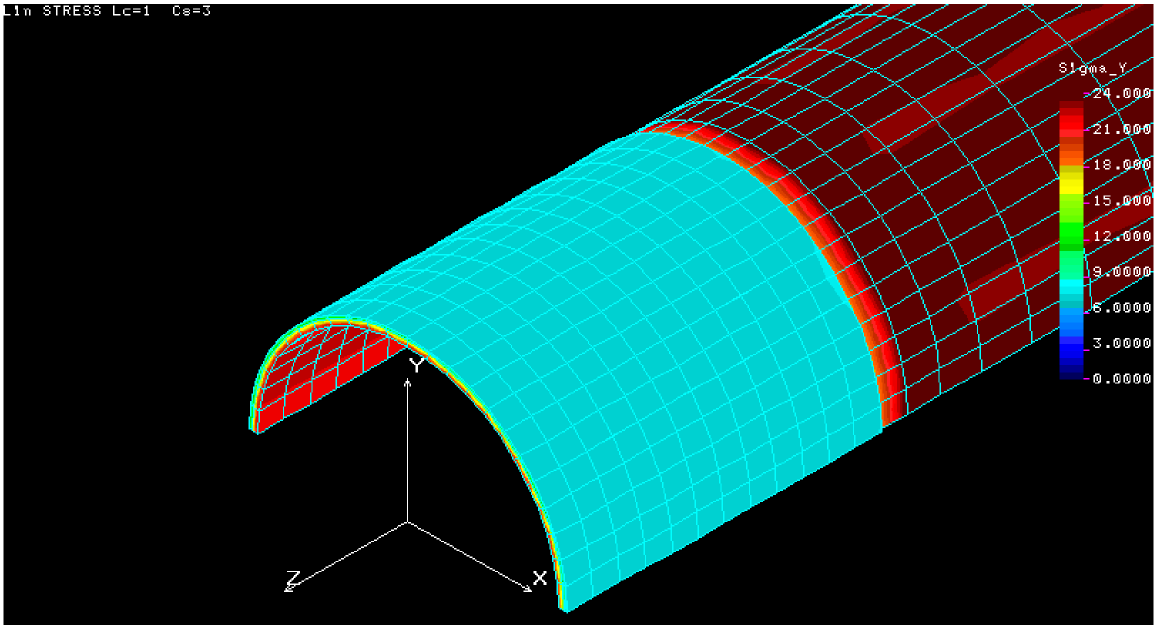

FIGURE 9 A contour plot of the hoop stress in one of the 3D steel pipe-composite repair models, with a full encirclement repair. Stress is measured in ksi.

FIGURE 10 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.

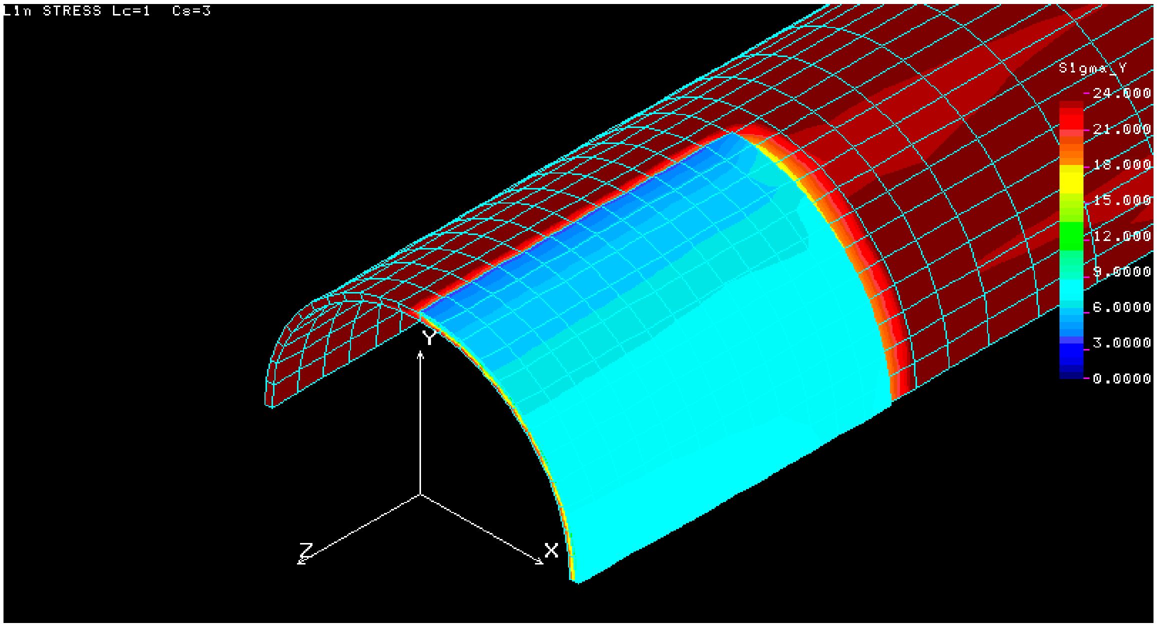

FIGURE 10 A contour plot of the hoop stress in one of the 3D steel pipe-composite repair models, with a partial (50%) encirclement repair. Stress is measured in ksi.

FIGURE 11 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.

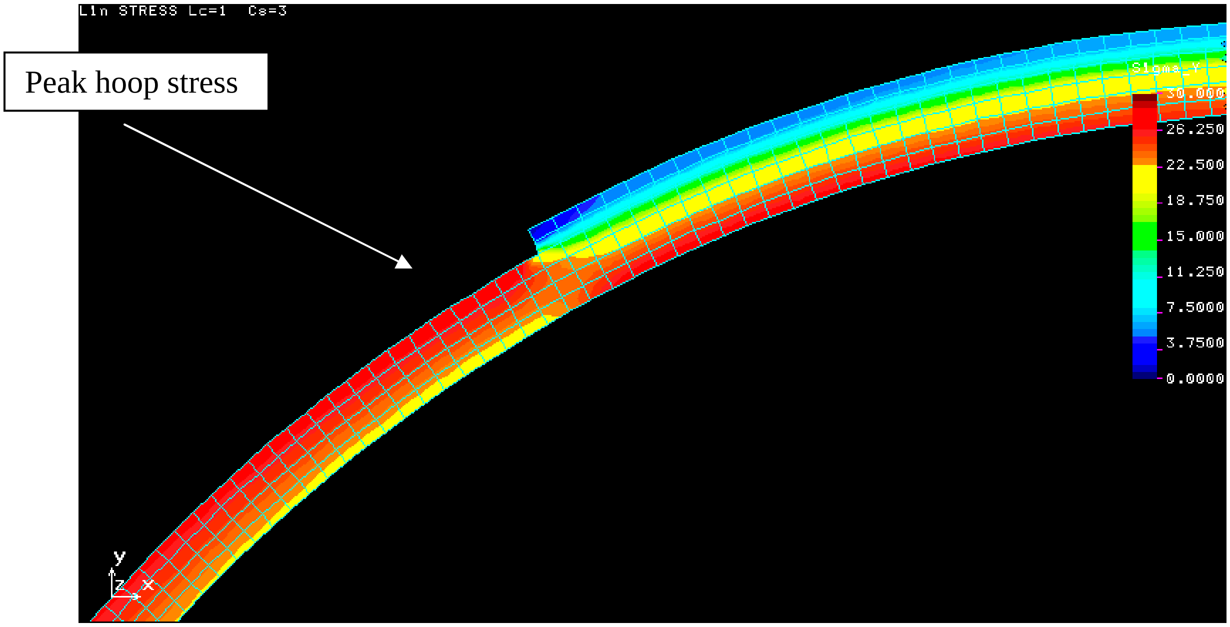

FIGURE 11 A contour plot of the hoop stress in one of the 2D transverse section steel pipe-composite repair models, with a partial (2/3) encirclement repair (magnified). Stress is measured in ksi.

FIGURE 12 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 12 corresponds to the angular coordinate geometry in FIGURE 3. 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. FIGURE 12 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.

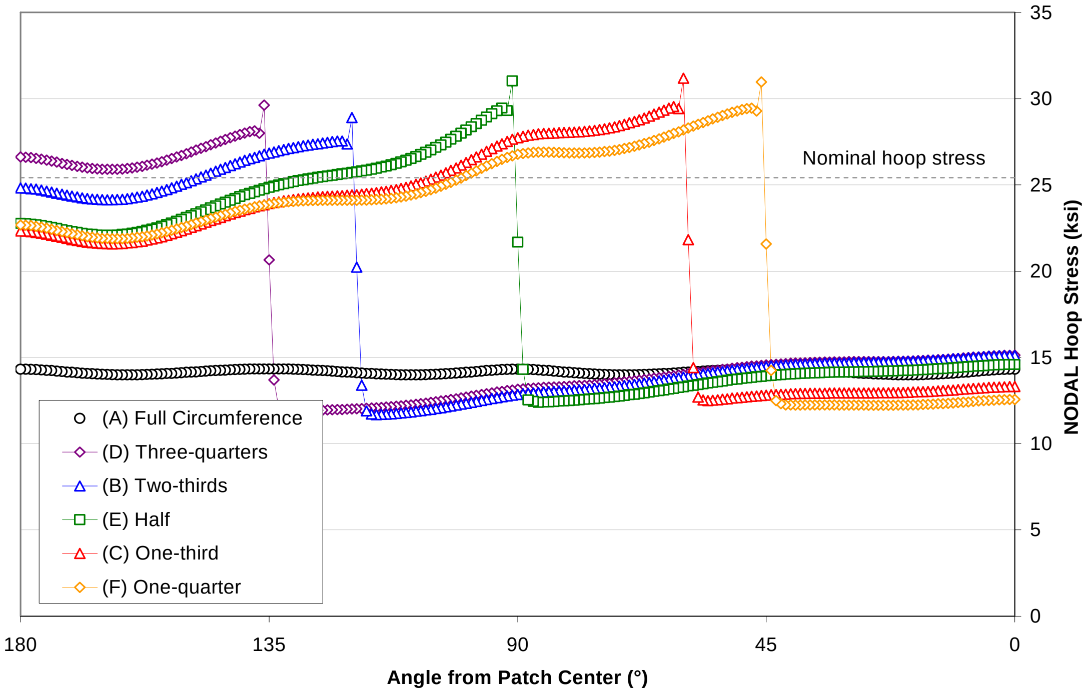

FIGURE 12 A plot of the nodal hoop stresses calculated along the external surface of the pipe model for six different models, as a function of location along the circumference of the pipe.

General Discussion

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 $^1/_8$". 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.

CONCLUSIONS

- 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 entire surface of the area exposed to the electrolyte in these test conditions.

- 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.

- 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.

ACKNOWLEDGEMENTS

Rob Denzine and Gary Snyder provided much of the data collection and fabrication for this work. Intern Kyle Wilson patiently sorted data and performed analysis. This work was funded in part by the Pipeline and Hazardous Materials Safety Administration (PHMSA).

REFERENCES

1. *Control of External Corrosion on Underground or Submerged Metallic Piping Systems. National Association of Corrosion Engineers*. Recommended practice. NACE RP0169-2002

2. *Application of a General Reactive Transport Model to Predict Environment Under Disbonded Coatings*. N. Sridhar, D.S. Dunn, M. Seth. Corrosion, July 2001

3. *Principles and Prevention of Corrosion*. Denny A. Jones. 2nd Ed. 1996

4. *Role of Hydrogen and Hydroxyl Ion in Cathodic Disbondment*. N. Kamalanand, et al. Anti-Corrosoin Methods and Materials. Volume 45, No. 4 1998 p 243-247

5. *Summary and Validation of Clock Spring for Permanent Repair of Pipeline Corrosion Defects.* Gas Research Institue. Ocotober, 1998. GRI-98/0227

6. Pipeline and Hazardous Materials Safety Administration. *PHMSA Significant Incidents Files*, August 25, 2008

7. *On the Long term Properties of Steel-Composite Interfaces for Marine Applications*. Dag McGeorge, Det Norske Veritas, Hovik, Norway.

8. *Post Construction Repair Standards*. 'Non-metallic Composite Repair Systems for Pipelines and Pipework, ASME. Draft Version 17 April 2003

9. ISO TC 67/SC 6 N Draft. *Petroleum, Petrochemical, and Natural gas Industries – Composite Repairs for Pipework – Qualification and Design, Installation, Testing, and Inspection.* Eventually to become ISO/TS 24817:2006.

10. *Near White Metal Blast Cleaning*. NACE No. 2/SSPC-SP10, NACE International (Houston, TX)

11. ASTM G14 - 04 Standard Test Method for Impact Resistance of Pipeline Coatings (Falling Weight Test)

12. ASTM G62 - 07 Standard Test Methods for Holiday Detection in Pipeline Coatings

13. ASTM G95 - 07 Standard Test Method for Cathodic Disbondment Test of Pipeline Coatings (Attached Cell Method)

14. “Stress modeling of pipelines strengthened with advanced composites materials”, Houssam Toutanji and Sean Dempsey, Thin-Walled Structures 39 (2001) Pages 153-165 Elsevier Science