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CATHODIC DISBONDMENT TESTING COMPARISON OF CARBON FIBER, FIBERGLASS, AND HYBRID COMPOSITE REPAIR SYSTEMS FOR PIPELINES

Matthew A. Green, Dr. Larry Deaton, PE, and Christopher J. Lazzara
Neptune Research, Inc. (NRI)
Lake Park, Florida, USA

KEYWORDS

Pipeline, Cathodic, Protection, Disbondment, Composite, Repair, Carbon Fiber, Fiberglass, Polyurethane, Water-activated, Epoxy, Coating

ABSTRACT

Composite repair systems are being successfully and heavily utilized for the repair of a wide variety of pipeline systems operating at high internal pressures worldwide. Many of these pipelines employ cathodic protection systems as a preventative measure of insuring that the pipeline does not corrode. Even with advanced cathodic protection systems, there are still times that a pipeline may become damaged or corroded and composite repair systems are a popular choice. In order to qualify a composite repair system for use on a cathodically protected pipeline, the repair system must undergo specific testing to insure that there will be no issues of disbondment of the composite due to the cathodic protection system.

This paper discusses the testing of composite repair systems with varying fiber types, resins, and installation methods. Results have been gathered for several repair system options and indicate that there is variance in the results depending on the above mentioned variables. The results of each of these systems and the impact of the fibers utilized will be discussed and conclusions made as to the effect of cathodic protection on each.

INTRODUCTION

Composite repair systems are being utilized for the repair of pipeline systems in an increasingly routine capacity. As composite repair systems gain more and more widespread usage and applications, it is imperative to know and understand the properties and function of the system being utilized. One such property is the reaction of the system when exposed to cathodic protection systems on the pipelines.

Cathodic protection systems have been successfully implemented and used as an effective corrosion protection means since the early to middle 1900's. They are typically employed in cooperation with a coating system (generally factory applied) in order to insure long term usage of the pipeline without the deterioration of corrosion. Cathodic protection is often used as a supplement to the coating, to assist in the protection of the steel pipeline in the event of pinholes, holidays, or other physical damage. With the cost of corrosion in the United States in the hundreds of billions of dollars, these corrosion protection systems can help to alleviate expensive repairs by preventing the problem in the first place.

Because even the most protected pipelines can still encounter corrosion issues or third party mechanical damage, composite repair systems are used as a means of repair and rehabilitation of such defects. Composite repair systems have been used for the repair of corroded or mechanically damaged pipeline since the mid-1990's. Since then there have been numerous codes, standards, and regulations which have outlined, developed and accepted composite repairs as a suitable and effective repair method. The ASME Post Construction Codes have highly detailed qualification, design, and installation methods for the successful implementation of composites. For the purposes of this paper, the focus will be on the requirement of verifying compatibility of the composite repairs with cathodic protection systems as outlined in Article 4.1, Section 3.4.10.6, of the ASME PCC-2 2011 standard.

In order to insure that there are no negative issues on the composite repair system from cathodic protection, it is important to characterize the effects of each. The ASTM G8 method of testing for cathodic disbondment was used with some slight alterations required due to the robust nature of the composite repair systems. This test focuses on the durability of the bond between the composite repair system and the steel substrate when the system as a whole is cathodically protected and has an introduced holiday defect. The results of various composite systems are evaluated in the following sections.

TEST SETUP

The test pipe specimens for each of the composite repair options were created using 6" nominal diameter API X42 carbon steel pipes, and each were 30" in total length. A total of ten (10) specimens were created throughout the testing program. Once the specimens were created, each were grit blasted to NACE 2 (SA 2.5) standards for near white metal blast. Each of the specimens was wrapped with a composite system to be tested. Plastic end caps were placed into the ends of the pipe specimens and press-fit sealed with silicone caulk as a means to prevent the ingress of water to the interior of the pipe specimen.

Once wrapped with the composite system, the entirety of the test specimen, including the composite, was coated with a standard epoxy coating to completely isolate the pipe from the solution except for the holidays created. The holidays were made in each pipe specimen using a 0.25" milling drill bit after wrapping and final epoxy coating. A hole was drilled through the coating and composite system and into the steel careful not to fully penetrate the wall thickness, but just to create a 0.25" diameter circle of bare steel as shown in Figure 1 below.

Figure 1 - Pipe specimen wrapped, coated, and holiday created

It should be noted that two of the test specimens were created at a later date than the first eight. These differed in initial setup in that three separate holidays were created at 120 degrees angle offsets and with a drill bit of diameter 0.375" (see Figure 2 below). The change in diameter of the drill bit used was due to the difference in composite material thickness. The ASTM G8 states that "the drill diameter shall be not less than three times the coating thickness, but it shall never be smaller than 6.35 mm (0.250 in.) in diameter." Because of this, the drill bit used in the final two test specimens had to be increased accordingly.

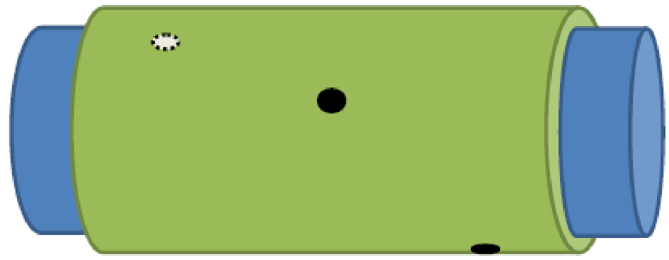

Figure 2 - Orientation of 3 holiday test specimens (top left holiday on back side of sample)

Once the pipe specimens were created and holidays drilled, each piece was placed into a plastic tub of salt water solution at room temperature (72° F / 22° C). The solution consisted of 1% mass of salts: sodium chloride, sodium sulfate and sodium carbonate, in order to create a corrosive environment in which to conduct the testing.

Figure 3 – Pipes submerged in corrosive solution

Cathodic protection cables were attached to each of the pipe specimens by exothermic welds, which were then coated with a protective covering to insure isolation of the CP to the holiday. Anodes of magnesium for each container of solution were utilized to provide the cathodic current to the specimens. Each anode was 6" x 0.5" (15.2cm x 1.3cm) and provided a 1.5 VDC vs. Cu-CuSO4 reference cell throughout the 30 day test period.

COMPOSITION OF THE REPAIR SYSTEMS

Several composite repair systems of different fiber and resin components were included in this study. Fiberglass, carbon fiber, polyurethane, and epoxy were all evaluated to determine the effects of cathodic protection systems on various combinations of these components. Annex A shows the sample matrix of composite systems with the various combination of components. In addition, some various "base" primers and wrap layers were used to evaluate the difference in cathodic disbondment. These variations were used to show the difference in results for when the carbon fiber was in direct contact with the carbon steel pipe, when only an epoxy coating was used, and when a base layer of fiberglass to guarantee isolation was used.

The epoxies used in the Primer Coat were two-part, 100% solid epoxies. When used, the base layer of fiberglass consisted of a bi-directional E-glass saturated with a resin of the same type used for saturating the carbon fiber. For Samples 1, 2 and 3, no fiberglass under layer was utilized as the composite system itself was composed of fiberglass. The resin used for saturating the fibers was either water-activated polyurethane which is pre-impregnated in the manufacturing facility, or a low viscosity epoxy system that is impregnated at time of installation.

The fiberglass used for the composite wrap was a bi-directional woven E-glass with specific architecture designed for optimum strength. The carbon/fiberglass hybrid consists of a woven polyacrylonitrile (PAN) carbon fiber in the 0° direction (hoop) and an E-glass fiber in the 90° direction (axial). The carbon fiber material was a stitched PAN carbon fiber with equal amount of fibers in the 0° direction (hoop) and the 90° direction (axial).

The sampling of composite materials represents a variety of commercially available options. However, a small change in any of the components may have an effect on the cathodic disbondment results, and so when choosing to use a composite repair system on an operational pipeline with active cathodic protection, it is highly recommended that the individual repair system undergo the specific testing to evaluate the results. The manufacturer of the repair system should be able to provide these results if it is to be used on pipelines that employ cathodic protection.

MEASUREMENT OF THE TEST SPECIMENS

Initial measurement of the current showed 5 mA, and the final current measurement showed 0.02 μA. Daily potential measurements were made as well to insure the potential remained within the range for the duration of the test.

Typically in order to measure the disbondment, a knife is used to make radial cuts intersecting at the holiday, then remove by lifting the pieces of the disbonded coating to reveal the total disbonded area. Because of robust nature of the composite systems, this method was not practical and since the ASTM G8 method is intended for the testing of coating systems, a slight alteration was required. An alternative method of measuring the total disbonded area was devised to work for the composite systems.

Once the 30 day test was complete, the holiday area and surrounding composite edges were injected with a solution of fluorescent dye penetrant and isopropanol. The solution was allowed to soak overnight for 12 hours and sufficiently wick into the areas to help measure the disbondment. As an alternative to making the radial cuts, which would damage the underside of the composite layers and render the disbonded area immeasurable, a square area was cut with the holiday centered. The area of the cut was approximately 4-5 square inches to insure it was beyond the boundaries of the disbonded area. This method proved to be successful as it revealed distinct areas of disbondment when held under a black light. The areas were marked while under the black light, then a grid applied in order to measure the total area.

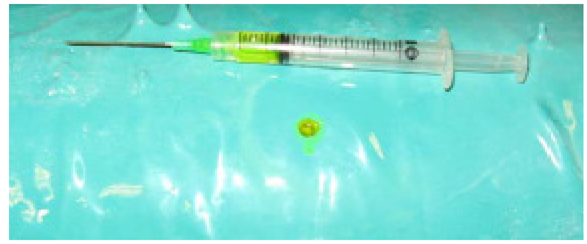

Figure 4 – Injection of fluorescent dye at holiday

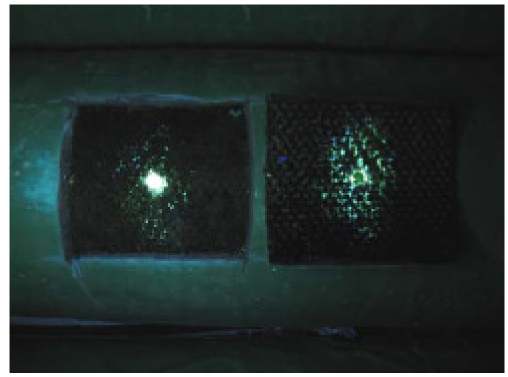

Figure 5 – Square of composite cut and under black light

RESULTS AND DISCUSSION

Results show a varied response of the individual composite repair systems to cathodic protection. Annex B provides the breakdown and individual results of each sample as well as some example pictures of the process of disbondment evaluation.

Of particular note is that most results are relatively similar and close in value with the exception of the two samples created without the base epoxy primer coat. These samples are significantly higher than all other samples which included the epoxy primer coat (by approximately 5 times). What is worth discussion is that the difference in results appear to be more controlled by the type of resin used to saturate the composite than by the fiber type being used.

It is a common discussion point that due to the conductivity of carbon fiber versus fiberglass, the carbon fiber should have results which yield more area of disbondment. While these results show a minor difference in the fiberglass and carbon fiber systems, the difference in results are far greater when comparing the resins used. For the fiberglass systems tested, they yield an approximate average area of disbondment of 0.95 in^2, whereas the composites which included carbon fiber of same resin type yield an approximate average area of disbondment of 0.76 in^2. Alternatively, the average area of disbondment for the epoxy system (full carbon fiber) is only 0.50 in^2. These numbers are independent of the fiberglass layer as there is no significant difference shown by having this in place, and also exclude the two samples which did not use the epoxy primer coat.

Unfortunately, there does not exist a set maximum, or even a range of acceptable, disbondment area limits. Because of this lack of minimum/maximum values in the testing standards, the test itself is of little use for qualification of a composite repair system as there is nothing to meet. Drs. JM and SS Leeds discussed this fact in their article regarding coating properties and testing procedures. They state that interpreting the test results is "worrisome… and that it is worth commenting that there is no justification for the limits to disbondment set out in specifications [of companies in a given industry]. Limits are just ideas of what is thought maximum disbondment should be."

If this comment is held to be the general consensus, then what should be taken from this study is the general difference within the results of the various composite options tested. With this in mind, the findings here do show that epoxies are better than polyurethanes, fiberglass is only very slightly better than carbon fiber (in similar resin matrices), and the theory that a fiberglass layer must be applied to separate the carbon fiber from the carbon steel pipe does not appear to hold up.

CONCLUSION

Based on this testing study, there is a relatively small difference in the cathodic disbondment testing results of the various composite combinations, with the exception of those which did not contain a primer coat layer before the composite wrap. It is recommended that any composite contain this base layer of epoxy in order to more effectively isolate the composite wrap system from the host carbon steel pipe. The minor differences in the disbondment of the various system components that are noted appear to be slight, but leads to the conclusion that the overall stiffness of the composite plays a role in the amount of disbonded area. It can be seen that as the composite modulus increases (either by use of carbon fiber, or by use of a higher modulus resin) the disbonded area sees a decreasing trend. When neglecting the two large area disbondment tests which were done with no epoxy primer coat, the area of disbondment can be seen to increase as the lower modulus materials are used with the epoxy/polyurethane on the upper end and carbon fiber/epoxy on the lower end of disbondment. But when comparing these tests results, all of the range still falls within the standard results of most common industrial FBE coatings on the market.

There is a general community of thought within the pipeline industry today that when using a carbon fiber composite wrap, a layer of fiberglass should be applied to fully isolate it from the host pipe. However, this study has shown no significant difference in the results of cathodic disbonding tests for samples with or without this layer of fiberglass. But also shown is that there is no negative effect of adding this layer, and therefore either layup option should be acceptable provided that the specific composite repair system has undergone the ASTM G8 testing to prove its own specific reaction to cathodic protection.

FUTURE WORK

This paper has only studied and addressed the result of cathodic protection systems on the bonding of composite repairs. It does not purport to address the potential of a galvanic corrosion cell between carbon steel pipe and carbon fibers used in composite systems. It is the recommendation of the authors of this paper that a full study be conducted to address this separate question in full detail.

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ANNEX A

COMPOSITE MATRIX BREAKDOWN

Sample ID#	Primer Coat	Base Layer of Fiberglass	Resin Type	Fiber Type of Composite Wrap
1	Epoxy 1	No	Polyurethane	Fiberglass
2	Epoxy 1	No	Polyurethane	Fiberglass
3	Epoxy 2	No	Polyurethane	Fiberglass
4	Epoxy 1	Yes	Polyurethane	Carbon/Fiberglass Hybrid
5	Epoxy 1	Yes	Polyurethane	Carbon/Fiberglass Hybrid
6	Epoxy 1	No	Polyurethane	Carbon/Fiberglass Hybrid
7	None	No	Polyurethane	Carbon/Fiberglass Hybrid
8	None	No – Dry Carbon Fiber on Steel	Polyurethane	Carbon/Fiberglass Hybrid
9	Epoxy 1	Yes	Epoxy 3	Carbon Fiber
10	Epoxy 1	No	Epoxy 3	Carbon Fiber

Table A.1 – Breakdown of composite system sample types

ANNEX B

RESULTS OF CATHODIC DISBONDMENT TESTING

Sample ID#	Total Disbonded Area (in^2)	Holiday Area (in^2)	True Disbondment Area of Composite (in^2)
1	1.00	0.0491	0.95
2	1.00	0.0491	0.95
3	1.00	0.0491	0.95
4	0.67	0.0491	0.62
5	1.00	0.0491	0.95
6	0.75	0.0491	0.70
7	2.50	0.0491	2.45
8	2.67	0.0491	2.62
9a*	0.660	0.11	0.55
9b	0.5	0.11	0.39
9c	0.685	0.11	0.575
10a*	0.665	0.11	0.555
10b	0.51	0.11	0.40
10c	0.66	0.11	0.55

Table B.1 – Results of cathodic disbondment testing

**Samples 9 and 10 were the two samples which included three separate holidays on the same pipe spool, so results from each of the holidays are shown here.*

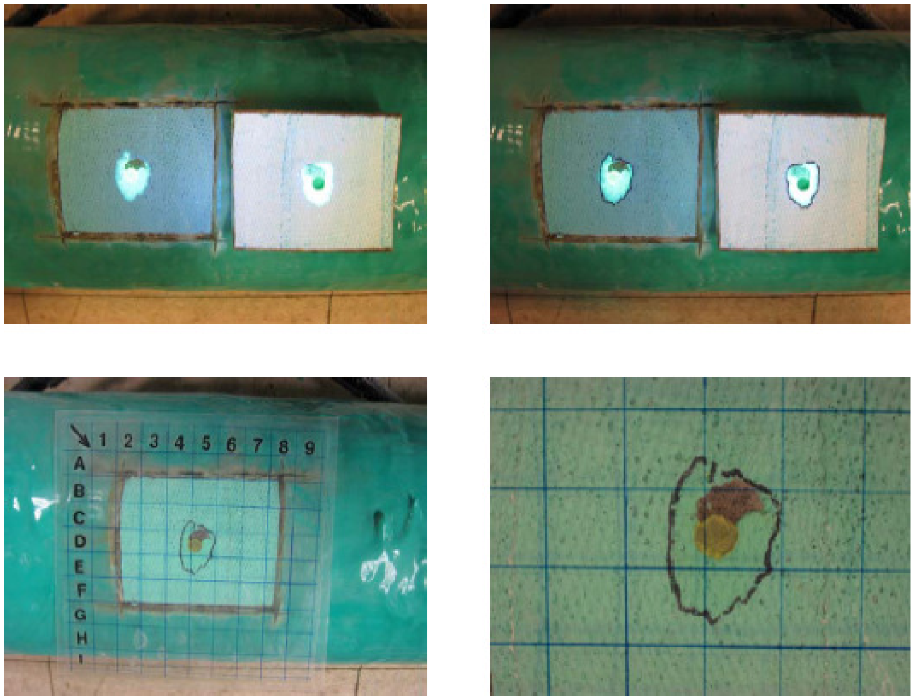

Figure B.1 – Fiberglass Sample 2: Disbonded area under black light (top left); Marking of disbonded area (top right); Disbonded area with grid layout (bottom left); Close-up of disbonded area with grid (bottom right)

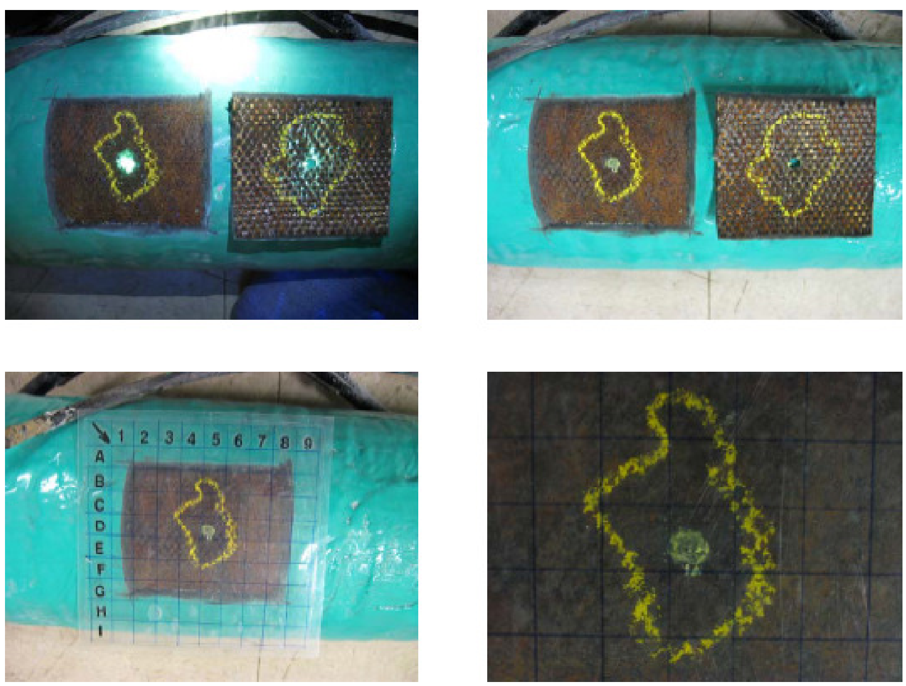

Figure B.2 – Carbon/Fiberglass Sample 8: Disbonded area under black light (top left); Marking of disbonded area (top right); Disbonded area with grid layout (bottom left); Close-up of disbonded area with grid (bottom right)

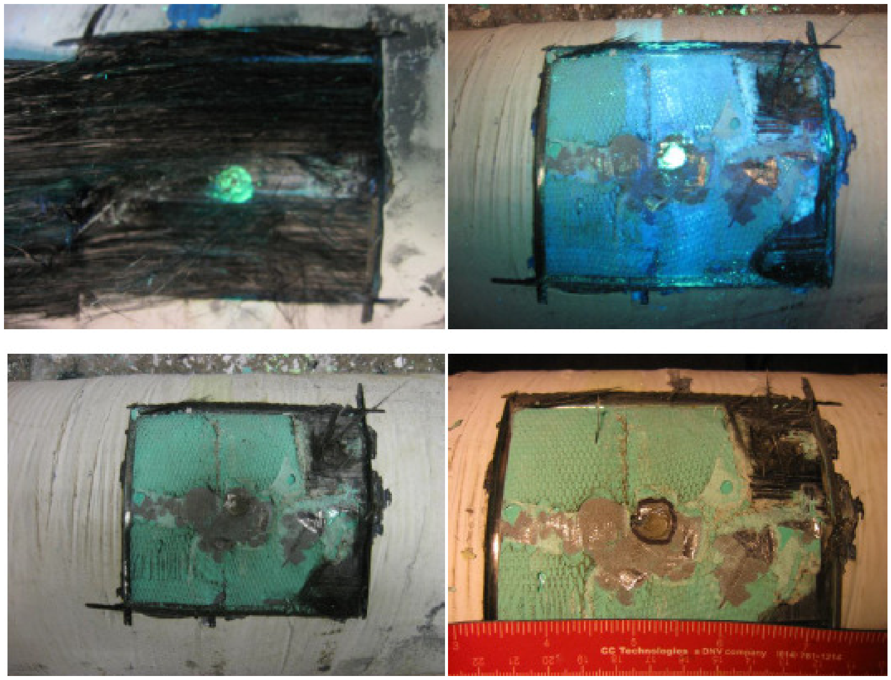

Figure B.3 – Carbon Sample 9b: Removing composite square (top left); Disbonded area under black light (top right); Disbonded area (bottom left); Close-up of disbonded area with outline (bottom right)