Highway IDEA Program

UNDERWATER FIBER-REINFORCED POLYMER
REPAIR OF CORRODING PILES INCORPORATING
CATHODIC PROTECTION

Final Report for Highway IDEA Project 128

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This NCHRP-IDEA investigation was completed as part of the National Cooperative Highway Research Program (NCHRP). The NCHRP-IDEA program is one of the four IDEA programs managed by the Transportation Research Board (TRB) to foster innovations in highway and intermodal surface transportation systems. The other three IDEA program areas are Transit-IDEA, which focuses on products and results for transit practice, in support of the Transit Cooperative Research Program (TCRP), Safety-IDEA, which focuses on motor carrier safety practice, in support of the Federal Motor Carrier Safety Administration and Federal Railroad Administration, and High Speed Rail-IDEA (HSR), which focuses on products and results for high speed rail practice, in support of the Federal Railroad Administration. The four IDEA program areas are integrated to promote the development and testing of nontraditional and innovative concepts, methods, and technologies for surface transportation systems.


The project that is the subject of this contractor-authored report was a part of the Innovations Deserving Exploratory Analysis (IDEA) Programs, which are managed by the Transportation Research Board (TRB) with the approval of the Governing Board of the National Research Council. The members of the oversight committee that monitored the project and reviewed the report were chosen for their special competencies and with regard for appropriate balance. The views expressed in this report are those of the contractor who conducted the investigation documented in this report and do not necessarily reflect those of the Transportation Research Board, the National Research Council, or the sponsors of the IDEA Programs. This document has not been edited by TRB.
UNDERWATER FIBER-REINFORCED POLYMER REPAIR OF CORRODING PILES
INCORPORATING CATHODIC PROTECTION

IDEA PROJECT FINAL REPORT

For the period of October 1st 2007 through June 30th 2010

Contract Number NCHRP-IDEA Project 128

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Transportation Research Board
National Research Council

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# TABLE OF CONTENTS

**EXECUTIVE SUMMARY** .......................................................................................................................... 1

**BODY** .................................................................................................................................................. 1

**IDEA PRODUCT** .................................................................................................................................... 1

**CONCEPT AND INNOVATION** ........................................................................................................ 1

**INVESTIGATION** .............................................................................................................................. 2

STAGE I – DEVELOPMENT OF PRESSURE / VACUUM BAG SYSTEMS ............................................... 2

Why Pressure Improves Bond .................................................................................................................. 2

Techniques for Improving Bond ................................................................................................................ 2

*Pressure Bagging* .................................................................................................................................. 2

  - Outer Bag ........................................................................................................................................... 2
  - Internal Bladder ................................................................................................................................. 3

*Vacuum Bagging* .................................................................................................................................. 3

  - Vacuum Bag ...................................................................................................................................... 3
  - Air Tight Seal ...................................................................................................................................... 3

Application of Pressure / Vacuum Bagging for Pile Repair ...................................................................... 4

  - *Installation of Pressure Bag* ........................................................................................................ 4
  - *Installation of Vacuum Bag* ........................................................................................................... 4

Results of Pressure / Vacuum Bagging for Pile Repair .......................................................................... 5

STAGE II – FIELD IMPLEMENTATION .................................................................................................. 7

Site ............................................................................................................................................................ 7

Chloride Analysis ..................................................................................................................................... 7

Half-Cell Potential .................................................................................................................................. 7

Anode Design ......................................................................................................................................... 7

Installation .............................................................................................................................................. 7

Junction Box .......................................................................................................................................... 9

Data Collection ..................................................................................................................................... 9

FRP Wrapping ....................................................................................................................................... 9

Water Intrusion Damage ......................................................................................................................... 10

RESULTS .................................................................................................................................................. 10

Polarization Testing ................................................................................................................................. 10

Galvanic Current .................................................................................................................................... 12

Remaining Lifetime Prediction ............................................................................................................... 15

  - Embedded Anode .......................................................................................................................... 15

LESSONS LEARNED ............................................................................................................................ 15

  - Pressure Bagging better for Wet Layup; Vacuum bagging better for pre-preg ............................. 15
Transverse layup best when pressure bagging is not used

Scaling Pressure Bag Size for Field Trials

Inner Bladder Size

Bag Material and Fabrication

Underwater Buoyancy

Special Tools for Preparation

Protection of Junction Boxes

BARRIERS TO IMPLEMENTATION

Pressure / Vacuum Bagging system

FRP-CP System

REFINEMENT OF PRODUCTS DEVELOPED IN THIS PROJECT

Alternative to Pressure Bagging

Using Disposable Bubble Wrap

Test Procedure

Cathodic Protection Use of Bulk Anodes

Remote Data Loggers

CONCLUSIONS

RECOMMENDATIONS

REFERENCES
ACKNOWLEDGEMENTS

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1. EXECUTIVE SUMMARY

This project developed a new fiber reinforced polymer (FRP) repair system incorporating a sacrificial cathodic protection (CP) system inside a FRP wrap. The FRP-CP system is versatile and can be used for repairing concrete columns or piles in seismic or non-seismic regions, on dry land or partially submerged in salt water. The system was implemented for repairing piles in estuarine waters and its effectiveness over the duration of the project proven.

The project was carried out in two separate stages. In the first stage, pressure / vacuum bagging technologies commonly used by the composite industry for bonding composite elements were refined to develop a new system suitable for infrastructure applications. This new system assured good bond between concrete and FRP, irrespective of the wetness or dryness of the concrete surface; tests showed that compared to controls, pressure bagging improved bond by over 70% and vacuum bagging by over 30%.

In the second stage, the new FRP-CP repair system was used in a demonstration project in which four corroding piles supporting the Friendship Trail Bridge, Tampa Bay were repaired. Pressure bagging was used to apply the FRP wrap following installation of the CP system. The performance of the FRP-CP system was monitored for 12 months. Results show that it is functioning as designed in protecting steel from corroding further. However, the consumption rate of the zinc anodes is higher than assumed in the design.

Additional Phase II investigations are proposed that can further simplify and improve the prototype developed in this project.

2. BODY

IDEA PRODUCT

The products from this research are [1] pressure / vacuum bagging systems for infrastructure applications and [2] a new FRP-CP repair strengthening system. The pressure / vacuum bagging system is simple, inexpensive, easy to use and leads to significant improvement in the FRP-concrete bond. The FRP-CP repair system stops chloride-induced corrosion of steel and can be used immediately to repair and protect corroding piles or columns.

Chloride-induced corrosion of piles in tidal waters is a world-wide problem and the cost of durable repair is significant. In Florida, the average 2008-09 cost (per linear ft) of pile repair incorporating cathodic protection was $1,442.22 (non-structural repair) and $1,727.81 (structural repair) for 16-30 in. piles (1). These costs do not include mobilization and other overhead charges. This means that a typical 6 ft repair of a corroding pile will cost from $8,653 to $10,366. The FRP-CP system developed in this project provides comparable repair at a much lower cost. Material cost of the carbon fabric supplied for the field study was $1,332 and for glass it was $453. The additional cost of adhesives and paint was $206 per pile (2).

The availability of a lower cost alternative for corrosion repair will help stretch budgets of financially strapped highway agencies in the US and elsewhere.

CONCEPT AND INNOVATION

Cathodic protection is the only proven method for controlling chloride-induced corrosion. The high strength, lightweight, corrosion resistance of FRP makes it the ideal repair material. Several independent studies have shown that FRP can slow down the corrosion rate by acting as a barrier to the ingress of deleterious materials such as moisture, chlorides and oxygen (3-5). This project develops a new FRP-CP repair system in which a sacrificial CP system stops corrosion and FRP provides strengthening while acting as a barrier and reducing the consumption rate of the anode. The state-of-practice is enhanced because of the following innovations:

FRP-Concrete Bond: Adaptation of vacuum / pressure bagging systems for bonding FRP to concrete. By providing pressure over the entire bonding surface, it ensures intimate contact is maintained while the resin cures.

Cathodic Protection: Use of embedded anodes instead of expanded mesh used in earlier attempts. This frees up the concrete surface for the FRP to bond and permit structural strengthening.
INVESTIGATION

The investigation for this project was conducted in two separate stages. In the first stage, pressure/vacuum bagging systems were developed and their effectiveness evaluated through comprehensive pullout testing. In the second stage, field repairs were carried out in which a FRP-CP system was implemented and its performance monitored for one year. A brief summary of the investigations is presented. More detailed information may be found in reports (6, 7) and published papers (8, 9).

STAGE I - DEVELOPMENT OF PRESSURE / VACUUM BAG SYSTEMS

Why Pressure Improves Bond

Concrete has a porous structure that defines the space unoccupied by the cement and its hydration products. The application of pressure forces the resin into the open pores thereby improving bond. As a result, bond failures are cohesive (in the concrete), not bond-line adhesive failures. Not surprisingly, pressure is commonly used to improve bond whether to maintain continuous contact in attaching strain gages to a concrete surface or in segmental construction where a minimum 40 psi pressure is used to join epoxied match-cast concrete segments (10).

Techniques for Improving Bond

Two alternative methods are commonly used by the composites industry for joining composite elements. These are [1] pressure bagging and [2] vacuum bagging. Their use for enhancing bond for infrastructure applications in which the substrate surface was wet had not been attempted prior to the author’s earlier study (11).

Pressure Bagging

Pressure bagging FRP repairs of vertical concrete elements such as piles or columns is relatively simple in concept and in application. The pressure bag incorporates an air-tight bladder (low tensile strength) contained within a restraining structure which can be either rigid or flexible. Flexible restraints are more desirable as they can be fitted and adapted as necessary to accommodate multiple pile sizes. The maximum restraining pressure is limited to the hoop strength of the pressure bag. Its size depends on the element that is being wrapped.

Outer Bag

The outer bag was made from rubberized nylon 4.75ft wide by 3.75ft long (Figure 1). These dimensions were used to wrap a 12 in. square pile over a 3ft length. Based on testing, refinements incorporated double stitched edges, a zipper enclosure, cinch straps for securing the bag, and a reinforced region for the flange.

FIGURE 1 Pressure bag used in laboratory study.
Internal Bladder

The internal bladder of the pressure bag was made using 0.008in thick clear PVC. It was necessary to produce a slightly oversized bladder, i.e. larger than the outer bag, to ensure full expansion when placed and inflated inside the outer bag. A 12ft x 4.5 ft PVC sheet was cut and folded over with a 6 in. overlap to form an internal bladder which was 5.75 ft x 4.5 ft. The bladder was then placed inside the outer bag and held in position using Velcro strips. The Velcro maintained the proper orientation of the bladder within the outer bag prior to inflation.

Vacuum Bagging

Vacuum bagging applies pressure by creating a vacuum (limited to a maximum of 1 atmosphere). It is particularly advantageous for large flat surfaces where hoop strength is difficult to develop or where adjacent structures are not available to provide a reaction force. No special strength considerations arise concerning tensile strength but rather a puncture resistant membrane material is sought. The maintenance of an air tight seal is critical and difficult to sustain since the concrete to be repaired is likely to be cracked.

Vacuum Bag

This system was developed for demonstration purposes only. The vacuum bags used in this study were made from the same 0.008in thick clear PVC used for making the inner bladder of the pressure bag. As with the pressure bag, its size depends on the element being repaired. For the 12 in. piles, a PVC sheet was cut to 51in. x 54in. and folded lengthwise with a 3in overlap. After gluing the overlap, a flange was installed on one surface in a similar fashion to that used for the pressure bag. The flange served as the means for connecting the bag to a vacuum pump. Since the bag was slipped over the top of the pile in the testing, its upper and lower ends were open and sealed following installation. Obviously, this would not be possible in field applications where the bag would have to be fabricated on site.

Air Tight Seal

One of the most critical aspects of the vacuum bag system is the creation of an airtight seal between the vacuum bag and the pile specimen. To provide an air-tight seal at the upper and lower ends of the bag, it was determined that a flexible material was needed which could contour to the dimensions of the pile as well as be flexible enough to contract under vacuum. After multiple trial attempts at creating a seal with putty, silicone, and tar, a suitable material was found in ½ in. thick closed-cell foam.

The foam was cut and glued into appropriate length rings using contact cement. The rings were stretched over the pile and positioned at the upper and lower extents of the vacuum bag. Photos of the flange assembly for the vacuum bag and the closed-cell foam are shown Figure 2.

After the rings were in position between the pile surface and vacuum bag, duct tape was wrapped around the outside of the vacuum bag within the region of the rings to provide confinement for initial sealing. Once vacuum was applied, the upper and lower rings became self-sealing, thereby eliminating the need for additional confinement.

FIGURE 2 Vacuum port in bag and closed cell foam about to be glued.
Application of Pressure / Vacuum Bagging for Pile Repair

The application of pressure bagging and vacuum bagging in underwater pile repair using FRP was tested in a laboratory experiment using twelve, 12in. square pre-stressed concrete piles (4 controls, 4 pressure bag, and 4 vacuum bag). Figure 3 shows (a) pressure bag and (b) vacuum bag applied to the laboratory specimens. The steps for installation of pressure and vacuum bagging are as follows:

**Installation of Pressure Bag**

Step 1: Place a protective layer over the final FRP application to separate the pressure bag from the FRP during curing. This is typically a plastic stretch-wrap.

Step 2: If necessary, place a breathable layer over the stretch-wrap. This is only for gas-generating resins.

Step 3: Wrap the un-inflated pressure bag around the pile.

Step 4: Zip the two ends of the pressure bag together and connect to the air source.

Step 5: Secure the buckles for the cinch straps and begin to inflate the bag. The cinch straps must work with the zipper enclosure and should be kept loose until minimal pressure is achieved and then tightened prior to full pressurization.

Step 6: Inflate the pressure bag to the desired pressure (safe working loads of the bag design).

**Installation of Vacuum Bag**

Step 1: Place a protective layer over the final FRP application to separate the vacuum bag from the FRP during curing. This is typically a plastic stretch-wrap.

Step 2: Place a breathable layer over the stretch-wrap to allow air to escape around the pile during vacuuming.

Step 3: Slide two closed cell foam bands, one to the top and one to the bottom of the FRP repair area.

Step 4: Slip the vacuum bag over the pile and position over the foam bands.

Step 5: Secure the plastic bag tightly over the closed cell foam and use duct tape to provide an air-tight seal.

Step 6: Connect the vacuum source to the desired pressure.

**FIGURE 3** (a) Pressure bagging; (b) Vacuum bagging.
Results of Pressure / Vacuum Bagging for Pile Repair

The effect of pressure bagging and vacuum bagging on bond was evaluated from tests conducted using twelve full-size pile specimens. Since the application evaluated was for piles in estuarine waters, the specimens were placed in a tank containing water so that half the FRP wrapped region was completely submerged while the other half was completely dry. The results from pressure / vacuum bagged specimens were compared against those for identically prepared controls where no pressure was used.

Two separate FRP systems and wrapping schemes were evaluated. A pre-impregnated fiber urethane based system (pre-preg) was evaluated as well as a field applied resin (wet layup) system. These systems were evaluated for both uni-directional (one horizontal and one longitudinal) and transverse (two bi-directional layers) wrapping schemes.

Pullout tests were conducted using an Elcometer 106 adhesion tester. A total of 422 pullout tests were conducted on 12 specimens. Figure 4 summarizes results of tests from 4 controls, 4 pressure bagged, and 4 vacuum bagged piles.

Results show an average increase in bond of 71% for pressure bagging above waterline (dry region) and 75% increase in strength below waterline (wet region). Vacuum bagging showed improvements of 56% and 33% increase in strength below waterline (wet region). Vacuum bagging showed improvements of 56% and 33% increase in strength above and below the waterline, respectively.

The results for the pre-preg and wet layup systems for the two wrapping schemes are presented in Figures 5 and 6 respectively. Inspection of Figure 5 shows that the use of pressure / vacuum bagging significantly enhanced bond strength above water for both wrapping schemes. Below the waterline, the vacuum system is more effective. The corresponding results for the wet layup system shown in Figure 6 indicate that while both pressure and vacuum bagging led to improvement in bond, pressure bagging is more effective.

A likely reason for this disparity is due to the differing reactions that take place in the urethane and epoxy resin during curing. Unlike epoxies, the urethane resin in the pre-preg system evaluated generated carbon dioxide. Vacuum bagging efficiently removes these gases whereas pressure bagging compresses and traps them within the wrap. As a result, the improvement in the FRP-concrete bond is not as good.

Figures 5 and 6 also show that the bi-directional control for both systems yielded higher values for pullout strengths, suggesting that this method should be utilized whenever an external pressure system is not used.
FIGURE 5 Average pullout test results for pre-preg system.

FIGURE 6 Average pullout test results for wet layup system.
STAGE II – FIELD IMPLEMENTATION

The goal of this stage was to implement the new FRP-CP system for repairing piles and monitor its effectiveness. Since the effectiveness of FRP in slowing down corrosion is contingent on its bond (3), the FRP wrap was applied using pressure bagging.

Site

Piles selected for the study were those supporting the Friendship Trail Bridge, Tampa Bay that had been used in earlier studies (11). The particular piles selected were on the Hillsborough side of Tampa Bay on bents 103 and 104 each with four piles designated as A-D that appeared to be in a similar state of damage. The site is recognized to be an extremely aggressive environment.

Chloride Analysis

Cores were taken out from the center of the “splash zone” (region subjected to periodic wet/dry cycles) of the piles. There was one unwrapped pile used as the control (pile 104D), two piles (104A, 104C) that were wrapped with FRP and installed with full cathodic protection, and one pile (103A) with FRP and embedded anodes only.

The chloride content was determined using the ASTM acid soluble method. The chloride content at the level of the steel varied from 1.96 lb/cy to 6.1 lb/cy. These values exceed the threshold limit for corrosion of steel in concrete of 1-2 lb/cy (12).

Half-Cell Potential

The half-cell potential of all the piles was mapped with respect to a Cu/CuSO₄ electrodes. The surface potentials varied from -111 mV to -552 mV in the dry region, and from -192 mV to -629 mV in the “splash” zone. Thus there was a 90% probability of corrosion in regions where readings were more negative than -350mV.

Anode Design

A CP system was designed by Vector Corrosion (6). It was found that eight 0.47 lb anodes would be required to protect the steel to provide a 30-year design life assuming a current requirement of 0.25 mA/sq. ft. The layout of the anodes relative to the wrap and two reference electrodes is shown in Figure 7. The anodes are positioned symmetrically over the 6 ft length of the FRP wrap to ensure efficient distribution of the anodic current. A bulk anode is additionally placed 2.5 ft below the mean low water line.

Installation

In an embedded FRP-CP system, the CP system has to be installed first followed by the FRP wrap. The installation of the anodes does not require any surface preparation other than removal of obstructive marine growth from the pile surface. Additionally, connections to the reinforcing steel are made near the pile cap.

Of the eight holes that had to be drilled, the bottom two were located close to the water line. Therefore, the drilling operation was selected when low tide was expected. Holes drilled were sufficient in length to allow horizontal placement of the 14 in. long anodes. Prior to their placement, the holes were flushed with fresh water and compressed air was then used to blast out any remaining moisture or particulates from within. The holes were then pre-filled with a low resistivity grout (Figure 8) and the anode inserted. After the grout had cured, a high impedance voltmeter was connected between the reinforcing steel and the anode to verify there was no contact (indicated by a reading exceeding 1mV). If such a voltage were detected, the anode would have been deemed electrically shorted to the reinforcing steel and therefore unusable for monitoring purposes. This would have required that the anode be replaced.
Following installation, the eight embedded anodes were joined using a single continuous wire that was connected to each anode via a stainless steel bolt. A two-part epoxy putty was then placed over the bolt to prevent corrosion of the wire. The wire was then routed into grooves cut in the concrete and covered with grout for protection. Two Ag/AgCl reference electrodes were installed in the same manner in pre-drilled holes and their wires routed into grooves and covered with grout.

The final step was to install the bulk anodes. These were installed in three piles – control (104D) and wrapped piles 104 A, C. The bulk anodes were 48 lb zinc blocks that were bolted to the pile below the depth of intended wrap.
Junction Box

As mentioned earlier, the eight embedded anodes were connected using a single copper wire which created a loop between all of the anodes and the reinforcing cage (Figure 9). The bulk anodes were connected to the reinforcement cage using a separate wire.

The wire leading from the anodes was routed into a junction box where it was connected to the reinforcement cage. This was done so that a switch could be used to disconnect the anodes for testing purposes. The junction box housed the data loggers used for monitoring CP performance. The wires for the reference electrodes were also routed into the junction box so that they were protected from the environment.

Data Collection

Anodic current information was recorded using commercially available data loggers. All readings were time-stamped and therefore the exact time when anodes are connected or disconnected for the NACE tests (13) was known. To determine the role of the bulk anodes in Piles 104 C and 104 A, separate data loggers were used.

FRP Wrapping

The piles were wrapped after the CP system had been in place for over two months. This delay was to allow the system to stabilize. Preparation for the wrap began by scraping off all the marine growth within the targeted 6 ft region. Following this, the piles were ground smooth and all edges rounded to a 2 in. radius using a grinder. The surface was then cleaned with fresh water using a 3000 psi pressure washer to remove all of the debris generated by the grinding process.

Two glass fiber reinforced layers each 0.05 in. thick were applied to the prepared concrete surface. The 6 ft wrap extended 1 ft below the mean low water line (Figure 7). After the GFRP was in place, a pressure bag was placed around the pile and inflated to provide a uniform 2 psi pressure (Figure 10a). This offset the tendency of the resin-saturated FRP to slide down the pile surface and maintain intimate contact with the concrete surface while the resin cured. A photo of the piles after removal of the pressure bags is shown in Figure 10b.

FIGURE 9 Schematic of anode wiring.
FIGURE 10 (a) Pressure bag on FRP wrapped pile. (b) Completed piles in bent.

Water Intrusion Damage

The junction boxes housing the data loggers were designed for normal outdoor use. However, conditions proved to be much more severe than anticipated and salt water entered the boxes and damaged some of the data loggers. Since there was no remote monitoring system in place, this damage was not immediately detected. Following its discovery, a more robust system was designed in which all the data loggers were placed in watertight enclosures, and all interior components made of stainless steel. Probes were added to the outside of the box so that tests to evaluate the effectiveness of the CP system could be conducted without opening the junction box thereby reducing the risk of water intrusion.

RESULTS

Results from two series of tests conducted are presented. The first relates to polarization decay testing conducted to determine the total polarization of the reinforcing steel, thereby evaluating the effectiveness of the installed CP system (13). The second relates to the measurement of the anodic current that provides a measure of the level of galvanic protection afforded to the steel.

Polarization Testing

The effectiveness of a CP system can be judged by a polarization decay test in which the connection between the anodes and the reinforcement is temporarily disconnected, typically for 24 hours. Since cathodic protection essentially supplies electrons to the steel reinforcement, its potential becomes “more” negative (“polarized”) with respect to a reference electrode as long as the anode remains connected. Temporary disconnection stops the supply of electrons; as a result the steel becomes “less negative” (“de-polarized”) over this time frame.

Each polarization decay test therefore entails potential measurements on two consecutive days. On the first day, the anode is disconnected and an “instant off” potential reading taken. On the following day, potential is read once again and the anode re-connected. Although the systems may have required periods longer than 24 hrs to fully depolarize, the 24 hr mark was used for logistical reasons namely access to the site. A total of seven series of polarization decay tests were conducted to evaluate the effectiveness of the installed FRP-CP system over the 12 month monitoring period. The first reported test was conducted 26 days after the FRP wrap was in place. Results for the other five reported tests are summarized in Table 1. These were carried out after 53, 65, 183, 211 and 335 days.

Table 1 contains information for (1) the unwrapped control with both embedded and bulk anodes (104 D), (2) the FRP wrapped piles (104 A and 104 C) with the embedded and bulk anodes referred to as “FRP with full CP” and (3) the FRP wrapped pile with embedded anodes only (103 A). Since there were two reference electrodes, two sets of polarization decay tests were conducted for each pile - one with respect to the “top” reference electrode and the other with respect to the “bottom” reference electrode (Figure 7).
Three sets of measurements are presented from each test; the “I-Off” voltage reading taken immediately after the anode is disconnected and the “stabilized” voltage reading taken the following day approximately 24 hours later. The difference between these two readings is the “decay”. All readings taken with respect to the embedded Ag/AgCl electrodes were converted to equivalent Cu/CuSO₄ readings by adding 113 mV that represents the difference between both electrodes with respect to the Standard Hydrogen Electrode (SHE).

Inspection of Table 1 shows that the potential decay was generally greater at the bottom than at the top. Thus, for the control the maximum decay was 63 mV at the top (after 211 days) compared to the maximum 142 mV (after 335 days) at the bottom. For pile 104 A, with the “full CP” the corresponding values were 180 mV and 270 mV, and for pile 104 C also with “full CP”, the corresponding values were 140 mV and 164 mV. This trend was also observed by the pile with the embedded anodes only (103 A) which had decay values of 281 mV in the top and 380 in the bottom. There are two cases where the entries are marked “N/A”. These reflect inconsistent readings that were likely the result of faulty connections since similar readings were not observed later in the same piles. These anomalous readings were therefore disregarded.

According to NACE (13), a cathodic protection system is providing “full protection” if the potential decay exceeds 100 mV with respect to a reference electrode. This criterion was met instantly by the FRP wrapped pile (103 A) and by day 65, all of the FRP wrapped piles experienced this minimum level of depolarization with respect to the bottom reference electrode. Although the levels of depolarization fluctuated greatly, the control pile did not have a depolarization reading greater than 100 mV until day 335. The bottom showed a depolarization reading of 142 mV while the top showed a 20 mV depolarization 335 days after connection.

Pile 104 D contained one of the highest chloride contents (6.10 lb/cy), which suggests a very high level of corrosion. Since this pile was not wrapped, there is no barrier to limit oxygen diffusion through the concrete. When combined with the data for current density for this pile, it suggests that the galvanic system is struggling to supply enough electrons to completely stop the corrosion of the reinforcement; therefore it is incapable of generating the surplus of electrons required to polarize the steel to more than 100 mV. As the bottom of the pile is more frequently submerged

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<td>-0.665</td>
<td>76</td>
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<td>-0.651</td>
<td>97</td>
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<tr>
<td>183</td>
<td>-0.802</td>
<td>-0.664</td>
<td>138</td>
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<tr>
<td>211</td>
<td>-0.837</td>
<td>-0.743</td>
<td>94</td>
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<tr>
<td>335</td>
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<td>140</td>
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<td>FRP with Embedded Anodes (103 A)</td>
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<tr>
<td>26</td>
<td>-0.743</td>
<td>-0.629</td>
<td>114</td>
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<tr>
<td>53</td>
<td>-0.774</td>
<td>-0.622</td>
<td>152</td>
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<tr>
<td>65</td>
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<td>-0.590</td>
<td>192</td>
</tr>
<tr>
<td>183</td>
<td>-0.820</td>
<td>-0.579</td>
<td>241</td>
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<tr>
<td>335</td>
<td>-0.780</td>
<td>-0.499</td>
<td>281</td>
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</table>
than the top, there is less oxygen diffusion, and less concrete resistivity. This results in less oxygen, and greater ease with
which current can be transferred to the reinforcement, which enabled it to finally polarize to more than 100 mV.

**Galvanic Current**

The polarization decay test indicates the effectiveness of the protection provided by the CP system. However, it does not
provide a full picture of the system’s performance. A better indication is given by the current density. Current density is
defined as the quotient of the measured anodic current and the total surface area of the protected steel. For the piles, each
reinforced by eight #8 bars that were spirally wrapped by ¼ in spiral ties spaced at 9 in on center, the theoretical surface
area was calculated as 13.75 ft².

The anodic current was automatically recorded by the data loggers and the saved data was periodically
downloaded from the bridge site. The current density was then calculated by dividing the measured current by the
theoretical area of steel protected (13.75 ft²). The anodic current is not constant but varies with concrete resistivity. This
in turn is influenced by tide change. Wet concrete has a lower resistivity compared to dry concrete. The average daily
current density for each system is plotted in Figures 11-14.

Figures 11-14 plot the average daily current density (mA/ft²) with time (days) relative to the installation of the
system. The same plots also show the average daily temperature (°F). In these plots, the current density provided by the
embedded anodes is denoted by a blue line and that provided by the bulk anode, by a red line. The combined current from
the embedded and bulk anodes is shown by a green line where available. The design current density (0.25 mA/ft²) is
shown as a constant dashed line in black. Finally, the graphs are annotated by upward pointing arrows to signify days
when polarization decay tests were performed, and ranges when damage to the dataloggers prevented any data
collection.

Inspection of the current density plots indicates a number of discontinuities arising since the installation of the
bulk anodes on day 20 (seen in Figures 11-13). This is not observed in Figure 14, where no bulk anode was installed. The
polarization decay tests (shown by arrows pointing upwards) are also marked in the plots. A total of 7 tests were
performed, however this is only reflected in two of the graphs (Figures 11 and 13; the others show six) as these were the
only piles to contain data loggers which were active for all of the tests performed. The failure of the bulk anode data
logger for the FRP with full CP pile (104 A – Figure 12), the bulk anode data logger for the FRP with Embedded Anodes pile (103 A – Figure 14) can all be observed in these graphs. With the
exception of the data logger failure in Figure 11, all other data loggers failed due to unexpected saltwater intrusion into
the junction boxes. The data logger in pile 104 C is still active; however an apparent short in the system is resulting in the
data not being logged properly.

Although some data was not recorded, the system remained active as the connections from the anodes to the
reinforcement was undamaged. Because of this, the systems remained stable, as evident in the resumption of current
density trends after the boxes had been repaired.

An examination of Figures 11-14 shows that the average current density is lowest for the pile with only the
embedded anodes, ranging only from 1.18 mA/ft² to 3.17 mA/ft² and highest in the unwrapped control 2.3 mA/ft² to
12.69 mA/ft² (Figure 11). For the FRP wrapped piles with the full CP the corresponding ranges are 0.76 mA/ft² to 6.9
mA/ft² for pile 104 A (Figure 12) and 2.2 mA/ft² to 10.8 mA/ft² for pile 104 C (Figure 13). The peak value corresponds
to measurements recorded following the installation of the bulk anode that provided additional current. The most evident
trend which can be observed from Figures 11-14, is that the current density has reduced with time to a more stable value
for the system.

The reduced current density in the FRP wrapped piles when compared to the control pile indicates a slower
corrosion rate since less current is required to protect the same amount of steel. The lower current draw also indicates that
anodes will be consumed at a lower rate meaning that they will last longer in accordance with Faraday’s law. The slower
corrosion rate again provides field confirmation of laboratory results that indicated that FRP slowed down the corrosion
rate (3-5).
FIGURE 11 Current density plot for control pile (104 D).

FIGURE 12 Current density plot for “Full CP” pile (104 A).
FIGURE 13 Current density plot for “Full CP” pile (104 C).

FIGURE 14 Current density plot for “Embedded Anode” pile (103 A).
Remaining Life Prediction

**Embedded Anodes**

The system was designed for a 30-year life assuming a current density of 0.25 mA/ft$^2$ shown by the dotted lines in Figures 11-14. The consumption rates in all the piles greatly exceed this density. Although all four piles with embedded anodes are functioning, only three, piles 103 A, 104 A, 104 C can monitor the current from the embedded anodes alone. This makes it possible to determine the remaining anode life based on the measured consumption rate. This is summarized in Table 2. The highest remaining life (13 years) is for pile 104C, an inside pile, and the least (6 years) is for pile 104 A. The remaining life does not appear to be linked to chloride content.

<table>
<thead>
<tr>
<th>System</th>
<th>Expected Lifetime (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>103 A (Embedded Anodes)</td>
<td>12</td>
</tr>
<tr>
<td>104 A (Full CP)</td>
<td>6</td>
</tr>
<tr>
<td>104 C (Full CP)</td>
<td>13</td>
</tr>
</tbody>
</table>

While the anodes are providing current as required to fulfill the job of protecting reinforcement, embedded anodes cannot be easily replaced, and unless there is a significant reduction in the current required by the reinforcement, this systems will begin to lose effectiveness around the times stated in Table 2. An option to extending the lifespan of the system would be to insert a sufficiently sized resistor into the anode-reinforcing steel circuit that would reduce the current output of the anode system while still maintaining the polarization decay values near 100mV.

**LESSONS LEARNED**

**Pressure Bagging Better For Wet Layup: Vacuum Bagging Better For Pre-preg**

The results from Stage I laboratory tests (Figures 5 and 6) showed that pressure bagging was more effective in improving the FRP-concrete bond for the wet layup system while vacuum bagging was similarly more effective for the pre-preg system (6). Pressure exerted on the FRP by the pressure bag forced the resin into the pores of the concrete, thereby improving the FRP-concrete bond in the wet layup system. In contrast, in the pre-preg system, the chemical reactions occurring during curing of the urethane resin released carbon dioxide which was removed by vacuum bagging.

![FIGURE 15 (a) Pressure bagging (b) Vacuum bagging.](image-url)
Transverse Layup Best When Pressure Bagging Is Not Used

The results (Figures 5 and 6) show that the FRP-concrete bond in the controls where no pressure was applied was better with a transverse lay-up (Figure 16b) rather than a combination of a longitudinal first layer followed by a transverse second layer (Figure 16a) (6). This is because the transverse wrap is easier to handle; this allows greater force to be applied when the FRP is installed. Thus, bi-directional material is most suitable. When the FRP is used for longitudinal strengthening the transverse layers need to be overlapped to ensure load transfer in the longitudinal direction.

Scaling Pressure Bag Size for Field Trials

Inner Bladder Size

The size of the internal bladder needs to be large enough so that the outer bag can be fully inflated. In essence, the dimensions need to be scaled, i.e. if the pile is 50% larger, the clearances should commensurately be 50% greater. Figure 17 (a) shows the effect of not scaling the dimensions of the inner bag.

Fiber Orientation

First Layer

Second Layer

Fiber Orientation

12 in FRP Strips

(a) (b)

FIGURE 16 (a) Uni-directional wrap (b) Transverse wrap.

(a) (b)

FIGURE 17 (a) Under Inflated Pressure Bag (b) Fully Inflated Pressure Bag.
Bag Material and Fabrication

Hoop stresses are proportional to the radius. Thus, hoop stresses generated in the piles used in the field trials (20 in.) were approximately 60% greater than the laboratory piles (12 in.). This needs to be factored into the design of the pressure bag. In the demonstration project, three different failure modes occurred in which (1) the fabric failed (2) stitching of the zipper failed and (3) buckle snapped as shown in Figure 18.

Fabric failure can be remedied by using higher tensile strength material. Failure in the stitching can be remedied by using a stronger thread / multiple rows for attaching the zipper while buckle failure can be prevented by spacing the buckles more closely. In the demonstration project, emergency measures were used, e.g. using rope to secure the bag.

![Fabric failure, stitching failure, buckle failure](image)

**FIGURE 18** (a) Fabric failure (b) Stitching failure (c) Buckle failure.

Underwater Buoyancy

Since air is lighter than water, inflated bags tend to float. To prevent this, the bags have to be secured underwater using straps before the inner bag is inflated (Figure 19)

![Bag being restrained](image)

**FIGURE 19** Bag being restrained to counter underwater buoyancy.
Special Tools for Preparation

The installation of the anodes and the wiring was controlled by tides and the weather because electrically operated equipment was used (Figure 20a). This can be prevented by using hydraulically powered drills and grinders (Figure 20b) which can be used under water. Equipment operated by electrical power is best avoided.

![FIGURE 20 (a) Grinding with electrical equipment (b) Using hydraulic grinder.](image)

Protection of Junction Boxes

The boxes housing the connections and the data loggers need to be adequately protected from the elements to prevent moisture intrusion leading to corrosion damage. These boxes were originally secured only at the corners and the internal circuits connected using steel screws. Water intrusion resulted in corrosion of all the wiring inside the boxes as well as damage to unprotected data loggers (Figure 21a) that had to be replaced.

This was remedied by using a larger environmental enclosure, one that was additionally secured at the middle, and had a larger rubber seal between the cover and the box. Only stainless steel screws were used inside the box and all connections made waterproof using silicone. The data loggers were placed in moisture proof boxes that were also coated with silicone. The new boxes reduced, but did not eliminate water intrusion. Several of the boxes were found to contain water when opened; however the system remained intact due to the added protection provided by the silicone.

This problem can be solved by relocating the boxes so that they are well above the maximum possible height of the waves in the Tampa Bay.

![FIGURE 21 (a) Corroded junction box (b) Modified junction box.](image)
BARRIERS TO IMPLEMENTATION

Pressure / Vacuum Bagging System

In the course of this project the USF research team was invited to assist with the FRP repair of piles supporting a private bridge in the Miami area. Despite the willingness of the USF team to implement pressure bagging at no cost to the owner, this offer was rejected. The reasons for such a rejection can only be surmised as follows:

1. Suppliers of FRP systems are reluctant to acknowledge that their installation systems are less than perfect. They deem their existing manual systems to be perfectly adequate based on their experience. The introduction of pressure bagging could be interpreted as an implicit admission of faulty installation.

2. The new system would add unnecessary costs given the belief that the existing system was satisfactory. This would be in terms of training needs, labor (since the pressure has to be sustained until the resin had cured) and logistic costs, e.g. need for electrical power to maintain the pressure or vacuum. The need to customize bags for different piles and problems related to pressure bagging multiple piles would have to be addressed.

FRP-CP System

1. The installation of embedded anodes required eight fourteen inch holes to be drilled in the piles. This process is extremely cumbersome and labor intensive. Special equipment and expertise is needed. There is no simple method for installing new anodes to replace those consumed to cathodically protect the piles.

2. A greater level of confidence would be provided by monitoring the CP-system for longer than one year. The consumption rate for the anodes is higher than designed (Table 2) indicating the need for earlier replacement of the anodes. This also highlights the difficulty in designing the “correct” anode size and layout.

3. Lack of a remote monitoring system resulted in damage to the system that could only be detected during periodic visits to download data.

REFINEMENT OF PRODUCTS DEVELOPED IN THIS PROJECT

Despite the real barriers for implementing the system, it be may be possible to allay these concerns. These are briefly described below:

Alternative to Pressure Bagging

The goal of pressure bagging is to ensure there is intimate contact between the resin-saturated FRP and the concrete substrate while the resin cures. This can be achieved by alternative means as follows:

Using Disposable Bubble Wrap

The FRP bond with concrete is always excellent at the rounded corners but poorer on flat surfaces. Pressure bagging overcomes this problem by artificially making the section more “circular” thereby exerting reasonably uniform pressure over the entire wrapped region. The drawbacks of the system are (1) the need to engineer the outer / inner bag for each different pile size so that they do not fail (Figure 18), (2) need for access to electrical power (in the tests and in the demonstration project, air compressors / vacuum pumps were run continuously in case there were leaks.

Disposable bubble wrap with horizontal cells provides a simpler alternative that can achieve the same objective, namely improving FRP-concrete bond. This type of bubble wrap widely used in packaging is inexpensive and can be tailored for the new application. This eliminates the need to design inner / outer bags for different pile sizes and their associated costs. More importantly, it can be easily integrated in current practice for installing FRP in vertical elements such as columns and piles.
A preliminary trial was conducted at USF to establish “proof of concept”. The bubble wrap used was retrieved from packages received in which there were horizontal cells over the width as shown in Figure 22.

![Bubble wrap with horizontal cell used in trial](image)

**FIGURE 22. Bubble wrap with horizontal cell used in trial.**

The bubble wrap from Novus Inflatable Plastic Packing was approximately 13 ½ in. wide and contained two inflated cells each 6 in. long and 2 in. wide with a ½ in. separation that was not inflated. The ends of the cells were tapered and the inflated depth was approximately one inch.

**Test Procedure**

The 12 in. piles used in Stage I laboratory testing were used in the trial. Two piles were tested, a “control” without the bubble wrap and a test specimen with the bubble wrap. In the testing, pressure sensitive paper was used. This paper records pressure by a change in color; the higher pressure, the darker the color. Thus, it can provide a qualitative basis for comparing pressure exerted on a wrap.

Since the test was used for comparison, no FRP wrapping was carried out. Instead, for the control, the pressure paper was directly placed on the pile surface and the blue shrink wrap applied normally in the transverse direction. For the test specimen, the bubble wrap was placed on the pressure sensitive paper with the cells in the transverse direction and wrapped over by the shrink wrap as shown in Figure 23 (a) and (b) in the same manner.

![Shrinkwrap on pile (a) Shrinkwrap with bubble wrap (b)](image)

**FIGURE 23 (a) Shrinkwrap on pile (b) Shrinkwrap with bubble wrap**

Figure 24 (a) is a scan of the results from the pile wrapped without the bubble wrap (Figure 23 a). The edges of the pile are clearly defined by dark color while the middle is distinguishable by its lighter shade of grey. This indicates that the distribution of the pressure resulting from the shrink wrap is uneven; it is higher at the edges than at the middle.
The corresponding scan for the pile with the bubble wrap insert is shown in Figure 24 (b). As before, the edges are clearly defined, however the region in the middle is darker in color compared to the pile without the bubble wrap. It may be seen that the scan plots the variation in pressure across the pile width and displays the profile of the bubble wrap containing two cells per row along the face of the pile. Clearly, there is a qualitative improvement.

The preliminary results are promising. By testing bubble wraps with a larger continuous bubbles that are large enough to encompass the entire pile width, it may be possible to develop a product that can provide the pressure needed to ensure good FRP-concrete bond both below and above the water line. Such a system can be readily implemented in the field.

Cathodic Protection Use of Bulk Anodes

The installation of embedded anodes is cumbersome and time consuming since it entails drilling a large number of deep holes in the concrete (eight 17 in. holes in this study - 14 in. for the anodes and 3 in. for the cover). Moreover, replacing the anodes after they have been consumed may not be practical.

In contrast to embedded anodes, bulk anodes can (in theory) provide a significant amount of protection. They are simpler to install and easy to replace. Research done at Florida Atlantic University (14) and preliminary tests done at USF (15) indicate that bulk anodes alone are not capable of fully protecting substructure elements within the splash zone. The relationship between concrete resistivity and the “throwing distance”, i.e. the height and distance above the location of the bulk anode where the steel is cathodically protected, is shown in Figure 25. This plot assumes the same area of concrete and steel as the Friendship Trail Bridge.

![FIGURE 24 (a) Results for control with shrinkwrap (b) Results for bubble wrap.](image)

![FIGURE 25 Resistivity vs throwing distance for Friendship Trail Bridge](image)
Figure 25 shows that there is an inverse exponential relationship between concrete resistivity and throwing distance. Bulk anodes alone can protect steel if the concrete has low resistivity.

Since the connections of the embedded anodes and the bulk anode are separate, it is possible to disconnect the embedded anodes and determine the level of protection provided in the wrapped region for the piles repaired in this study. Additionally, investigations could also be undertaken to determine if it is possible to lower the resistivity of the concrete or shorten the distance for which the bulk anode must “throw” its current, e.g. by installing sub-surface electrodes as shown in Figure 26. This can make bulk anodes a viable and an affordable CP option.

In the proposed system shown in Figure 26, the sub-surface electrodes will serve as a means for reducing the resistivity of the system, thereby enabling the bulk anode to “throw” current over a much greater distance than otherwise possible. The new circuit will have the current flowing from the anode to the reinforcement, then to the electrodes and down to the water, as opposed to being from the reinforcement directly to the water. As these electrodes are made of a non-corrosive material such as titanium, and exposed to water below the FRP wrap, the resistance of the system is greatly reduced. The installation of the electrodes is simple and will not require the extensive drilling or grinding to route wiring. Before such a system is implemented, laboratory testing will be needed to investigate its feasibility.

Remote Data Loggers

The two main problems in the acquisition of data throughout this project were:

1. Data loggers were repeatedly damaged by water intrusion.
2. Loss of CP was not known until the boxes were opened and the data was reviewed.
As this task was performed approximately every second month, problems which arose shortly after a reading had been taken were not detected quickly. These problems can be avoided by placing the data loggers away from the tidal zone and installing an appropriate remote monitoring system.

CONCLUSIONS

This report presents findings from an 18 month study in which new concepts for corrosion repair using FRP were explored. The study was conducted in two stages. In the first stage, pressure / vacuum bagging technologies used by the composites industry for joining composite elements were modified for infrastructure use. In the second stage, a field demonstration study was carried out in which a combination of embedded and bulk anodes were used to cathodically protect steel inside a FRP wrap and its performance monitored for one year. The work reported received significant financial support from Hillsborough County and industry. Specifically, Vector Corrosion designed the CP system, donated all galvanic anodes, data loggers, reference electrodes and provided practical help in the installation of the CP system. Fyfe and Air Logistics donated all the FRP material needed for the project.

Numerous lessons were learned from this study. These are summarized below:

1. Pressure / Vacuum Bagging Systems (Figure 3)
   A. The effectiveness of these systems depends on the resin type. For epoxy-based resins, pressure bagging works better; for urethane-based resins in which chemical reactions during curing lead to release of carbon dioxide, vacuum bagging works better (Figures 5 and 6).
   B. If no external pressure is applied, layouts using bi-directional material applied transversely give better bond than when uni-directional material is applied in the longitudinal direction followed by transverse direction (Figure 16).
   C. hoop stresses are higher in larger bags. The material of the bag, the stitching and the buckles need to be able to resist this (Figure 18). The inner bladder needs to be oversized so that the outer bag is fully inflated (Figure 17).

2. FRP-CP System (Figure 7)
   A. Results of polarization decay tests indicate that the embedded anode system successfully polarized steel inside the FRP wrap (Table 1).
   B. Measured protective currents were higher in the unwrapped control compared to the FRP wrapped piles (Figures 11 to 14). This indicates lower corrosion rates and confirms findings from laboratory studies that have shown FRP tended to slow down the corrosion rate. Lower currents imply less anode consumption and therefore longer service life for the anodes in the FRP wrapped piles.
   C. A pile (103A) with embedded anodes alone provided similar corrosion protection compared to one with both the embedded and bulk anodes. This suggests that bulk anodes may not be required if the FRP wrap is extended below the mean low water line.
   D. Special measures are needed to protect all electrical connections inside the junction boxes to prevent damage by salt water intrusion (Figure 21). Hydraulically operated tools improve efficiencies (Figure 20).
   E. The results support laboratory findings that FRP reduces but does not stop corrosion of steel since the anode consumption is lower for FRP wrapped piles.

3. Barriers to Implementation
   A. Though capital costs associated with pressure bagging / vacuum bagging systems are modest, there is reluctance to implement such systems because of uncertainty regarding benefits.
   B. FRP-CP system using embedded anodes is cumbersome to install. The effectiveness of the system based on data obtained from one year of monitoring may not be enough; additional monitoring would be useful to estimate the anode service life.
RECOMMENDATIONS

Perceived barriers may be addressed by limited Phase II investigations in which (1) a simplified pressure bagging system using disposable bubble wrap is used (Figure 24) (2) cathodic protection system is provided using bulk anodes in combination with special non-corrosive elements to transmit the current over the entire pile (Figure 26).

REFERENCES

15. J. Aguilar. Feasibility of Bulk Anodes to Provide Cathodic Protection to Corroding Reinforced Concrete Piles Wrapped with Fiber Reinforced Polymer. Project for CES 6933, University of South Florida, Department of Civil and Environmental Engineering, Fall 2009, 15 pp.