EFFECT OF COMPOSITE FIBER WRAPS ON CORROSION OF REINFORCED CONCRETE COLUMNS IN A SIMULATED SPLASH ZONE

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Abstract

This research indicates that CFRP wrapping is potentially effective in reducing the effects of corrosion in specimens exposed to aggressive chloride environments. Small-scale square columns were wrapped with two layers of epoxy-coated carbon fabric and exposed to heated wet/dry cycles for up to 2.5 years. CFRP wrapped samples had decreased corrosion probabilities, reduced concrete chloride contents, and decreased reinforcement mass loss. Wrapped, uncracked samples took four to five times as long to reach a ninety percent probability of corrosion as unwrapped, uncracked samples. Wrapped, cracked samples took approximately twice as long as unwrapped, cracked samples.

Five of eight columns that were wrapped initially had mass loss values that were less than the average of all samples with the same exposure time. Unwrapped columns had an average rebar mass loss of 5.8 percent per year, for all exposure times. Columns wrapped initially had an average rebar mass loss of 4.8 percent per year, an improvement of 17 percent. Columns wrapped after one year had a rebar mass loss of 7.57 percent after 2.5 years, which was about 50 percent less than the unwrapped column of the same age, and only 18 percent more than the column that was wrapped initially. It was hypothesized that CFRP wraps affected the migration of chloride ions into the concrete and hindered the electrochemical process of corrosion by allowing the development of confining stresses in the concrete. However, there was a high degree of variability in certain measurements, especially of mass loss. Results appeared to be highly dependent on the quality of the bond between the wrap and the concrete surface.

Introduction

In coastal areas and in areas where de-icing salts are used, reinforcing and prestressing steel in concrete members is vulnerable to corrosion. This problem is worse in members with a supply of both oxygen and moisture, such as in the splash zone of bridge piers. Prevention of corrosion and related damage is being addressed in new construction through the use of epoxy coated rebar, revised construction procedures, and alternate rebar materials, including fiber-reinforced plastics. In retrofit situations in the state of Florida, cathodic protection systems and pile jacketing, a repair technique in which rigid FRP outer jackets or forms are placed around members and filled with either concrete or mortar, are often employed (1). Although numerous methods exist and are presently used to protect the reinforcement, none is without limitations.

This project investigated the use of carbon fiber reinforced polymer (CFRP) composite wraps to provide protection for, or delay the onset of corrosion in, reinforced concrete specimens exposed to aggressive chloride environments. The CFRP wrapping technique utilized is different from older jacketing techniques in that fiber sheets are directly wrapped around and bonded to underlying concrete members in a wet lay-up process. It was expected that this technique would have fewer bonding problems, improved fiber orientation and continuity, resulting in an increased ability to develop confinement. The objective of this study was to determine the effectiveness of carbon fiber wraps in decreasing the intrusion of salt water into the steel reinforced concrete and in the reduction of subsequent corrosion of the steel reinforcement. The primary focus was on wrapping newly cast scale-model concrete columns, although a few columns were exposed to a simulated seawater environment for one year prior to wrapping. Unlike other research in this area, the scale-model columns in this study had square rather than circular cross-sections.

Background and Related Research

Electrochemical corrosion of a metal is an involved process. The corrosion cell consists of an anode, cathode, an ionic current path, and an electrical current path. A passivating or protective ferric oxide film, formed on the reinforcement during the hydration process, usually protects reinforcing steel in fresh concrete. The passivating film remains intact in the highly alkaline environment of the concrete (pH approx. 13). If, however, chloride ions are introduced into the concrete, the passivating film on the steel may break down and active corrosion may develop. Corrosion begins with the reduction of the concrete pH that creates an environment conducive to the corrosion reaction. Depending on the exact reactions involved, the products of the corrosion can take up a volume as much as six times that of the original iron (2). The increase of volume creates stress on the concrete cover that subsequently results in cracking of the concrete and eventually can lead to spalling or delamination of the concrete around reinforcing steel. These cracks allow for the intrusion of greater amounts of water and chlorides and the corrosion process continues. Once corrosion starts, the cross sectional area of the steel can be significantly reduced.

Concrete structures in aggressive environments, such as coastal areas, marine environments and regions where deicing salts are used, are particularly prone to premature deterioration. Marine environments present particularly aggressive conditions for reinforced concrete structures, especially in the splash zone, tidal zone, and shallow immersed zone where concrete surfaces are almost continuously wet with well-aerated seawater. At shallow depths the oxygen supply in water is normally at or close to saturation, thus affecting the rate of attack, which is influenced, and can increase dramatically, by factors such as the electrical resistivity and moisture content of the concrete, and rate at which oxygen migrates through the concrete to the steel.

Numerous studies have shown that FRP wraps provide confinement to concrete, increasing its strength and ductility (3, 4, 5); however, few have addressed the effect of confinement on corrosion. Hearn and Aiello found that one-dimensional mechanical restraint reduced the rate of corrosion in reinforced concrete (6). They theorized that this restraint promoted the consolidation and densification of corrosion products around the reinforcement. Hearn and Aiello further claimed that such consolidation hindered corrosion because the compacted layer of corrosion residual around the reinforcement limited the access of water and oxygen to the uncorroded steel.

In follow-up studies by the same research group, plus Lee, Pantazopoulou, Bonacci, and others (7), circular reinforced concrete columns were subjected to an accelerated corrosion regime, wrapped using CFRP sheets, then subjected to further post-repair accelerated corrosion, monitoring, and testing and/or tested to structural failure. Results showed that the FRP wraps greatly improved the strength of the repaired members and retarded the rate of post-repair corrosion. Moreover, subjecting the repaired column to extensive, post-repair corrosion resulted in no loss of strength or stiffness and only a slight reduction in the ductility of the repaired member. A second project looked at various techniques for wrapping column stubs with GFRP wraps, both with and without grout and moisture barriers (8). Research by Debaiky, Green, and Hope on CFRP-wrapped column stubs showed that CFRP-wrapping reduced corrosion activity, as measured by decreased corrosion current density and decreased mass loss, and reduced chloride diffusion from external sources (9, 10). However, half-cell potential readings were found to be inconsistent with other indicators of corrosion activity (10).

Despite these promising results, additional research in this area is necessary. The research projects described above either used relatively few large-scale samples, with little redundancy in the test matrices, or small-scale column stubs (150 mm x 300 mm or 6" x 12" cylinders). Further, these studies have looked exclusively at circular columns rather than columns with rectangular cross-sections.

Test Methodology and Procedures

Materials

The concrete mix design used in this study followed the Portland Cement Association guidelines for the proportioning of normal concrete mixtures for small jobs (11). All of the FRP-wrapped samples utilized the same carbon fabric and epoxy. A unidirectional carbon fabric with a tacky thread in the fill direction for stability was selected on the basis of its density and close weave. The fabric has 4 tows per centimeter width and 12,000 filaments per tow; it is 0.55 mm (0.022 in) thick and has an approximate surface density of 340 g/m^2. The fabric has a tensile strength of 3.1 GPa (450 ksi), modulus within 221-241 GPa (32-35 Msi), according to manufacturer's literature (12). The epoxy used in this research was West System 105 epoxy resin, a marine grade epoxy designed specifically for reinforcing fabrics and recommended by the manufacturer for use in this application (13). The epoxy is a two-part system that incorporates a clear, pale amber, low-viscosity (approximately 1 N·s/m^2 at 22°C) liquid epoxy resin combined with an aromatic hydrocarbon-blend curing agent. Product literature states that this epoxy offers excellent wet out and adhesion to fiberglass, carbon, and aramid fabrics. The resin is described as a Bisphenol A based epoxy resin, and the hardener is described as a modified aliphatic polyamine. It dries to a hard, clear finish. No polyester gelcoat is required; however, a clear coat of epoxy on the exterior surface is recommended.

Specimen Preparation

Fourteen scale model columns were cast over several weeks time at the beginning of the project. The columns were 15 cm x 15 cm (6 in x 6 in) square and 90 cm (3 ft) long. Figure 1 shows the column dimensions, including rebar placement and wrap placement. The dark circles show locations where chloride samples were taken. The longitudinal bars are #3 bars and the stirrups are #2 bars. Prior to casting, reinforcing bars were cleaned with a wire brush to remove all rust from the surface, weighed, and each individual length measured. To maximize the effects of the saltwater exposure in the laboratory, columns were cast with minimal cover (approximately 1 in. or 2.5 cm) over the reinforcing steel. Compressive strengths for each column are provided in Table 1. Sections of threaded PVC pipe were inserted in the ends of the columns prior to pouring the concrete to act as instrument ports, allowing access to the rebar for corrosion measurements. Pipe caps protected the rebar from exposure to air or saltwater, but were removed for testing.

Table 1 details the different column treatments. Half of the columns were pre-cracked by loading in a three point bending frame until the modulus of rupture was reached. This simulates the effect of damage and also accelerates the exposure to the saltwater solution. The remaining columns were left uncracked to simulate newly placed columns. Seven of the columns were wrapped initially, and three more were wrapped following one year of exposure. This set of columns simulates treatment of an existing column that has undergone repeated chlorine exposure while in the splash zone. The remainder were left unwrapped as controls.

CFRP wraps were applied to simulate expected practice in the splash zone: the fiber wraps extend beyond the high and low water levels in the immersion tank, but do not encase the entire column. The fabric wraps were applied with a hand lay-up procedure. Initially, the concrete surface was cleaned and sanded, and a light coat of epoxy was applied with a brush to the sides of the column. A layer of fabric was applied and smoothed with a roller. The process with repeated to create a two-layer thick wrap; the final coat on each sample was a clear coat of epoxy. Several inches of overlap were maintained per layer to allow confinement to develop. Specimens were allowed to cure at room temperature for approximately 24 hours prior to application of the next epoxy layer, and for 28 days prior to exposure to simulated seawater.

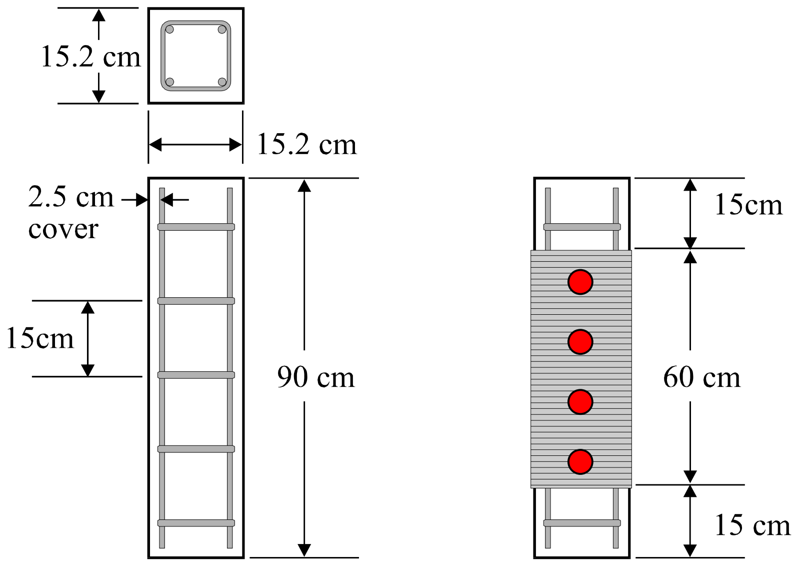

Figure 1. Schematic of column samples

Table 1. Summary of column samples in long-term exposure studies

Designation	Type	Strength (psi)	Years of Exposure	Percent Bond	Wrap Thickness (in)
1	Wrapped, Uncracked	3320	2.5	100%	0.111
14	Wrapped, Uncracked	5100	1	88%	0.067
3A	Wrapped, Uncracked	5330	2	94%	0.132
8	Wrapped, Uncracked	2900	1.5	69%	0.067
3	Wrapped, Uncracked	N/Av[1]	1	N/Av	N/Av
6A	Wrapped, Cracked	5510	2	94%	0.090
4	Wrapped, Cracked	4950	2	94%	0.100
6	Wrapped, Cracked	N/Av	1	N/Av	N/Av
9A	Unwrapped, Uncracked	4950	2	N/Ap[2]	N/Ap
12	Unwrapped, Uncracked	4240	2	N/Ap	N/Ap
9	Unwrapped, Uncracked	N/Av	1	N/Ap	N/Ap
13	Unwrapped, Cracked	3020	2.5	N/Ap	N/Ap
5A	Unwrapped, Cracked	4620	2	N/Ap	N/Ap
11	Unwrapped, Cracked	3990	1.5	N/Ap	N/Ap
5	Unwrapped, Cracked	N/Av	1	N/Ap	N/Ap
10	Wrapped after 1 year, Uncracked	3020	2.5	100%	0.058
2	Wrapped after 1 year, Cracked	3230	2.5	100%	N/Ap
7	Wrapped after 1 year, Cracked	3320	2.5	94%	0.065

[1] Not Available.
[2] Not Applicable.

Prior to testing, samples were examined visually for debonded regions. A small number were found, especially near the corners of the square columns. It was determined that the sharp corners of the columns prevented the stiff carbon fibers from draping well over the columns' surfaces. The amount of debonding is reported in Table 1. Figure 2 shows debonded regions on a cutaway column sample; Figure 3 shows a corner region that is fully bonded. Because of concerns over concrete quality and wrap adherence in the original samples, four additional samples, one of each style, were cast one year into the project, when the first four samples were removed and tested. These samples are labeled 3A, 5A, 6A, and 9A in Table 1.

Figure 2. Debonded regions on wrap corner

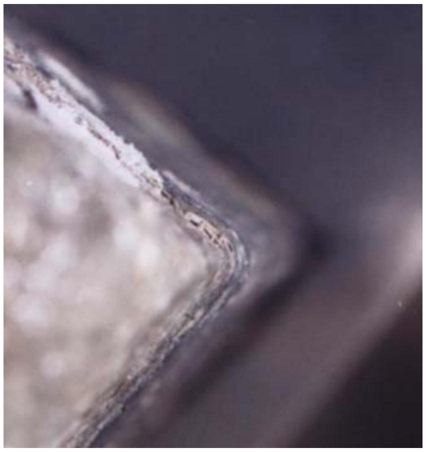

Figure 3. Fully bonded corner region

Exposure Conditions

The column samples underwent exposure tests involving alternate wetting and drying in a saltwater bath. A photograph of the tanks is included as Figure 4; this figure also shows the PVC pipes that acted as instrument ports. Heaters maintained the water temperature between 40º and 45º C. A five percent salt concentration by weight was maintained using a synthetic marine-grade salt additive; this salinity is approximately twice that of natural seawater. Water was transferred between the tanks every seven days, such that one tank maintains a high water level while the second maintains a low water level. The high water level was maintained at approximately five centimeters below the top of the wrap; the low water level was likewise maintained at approximately five centimeters above the bottom of the fabric. The one-week time span ensured thorough saturation followed by thorough drying.

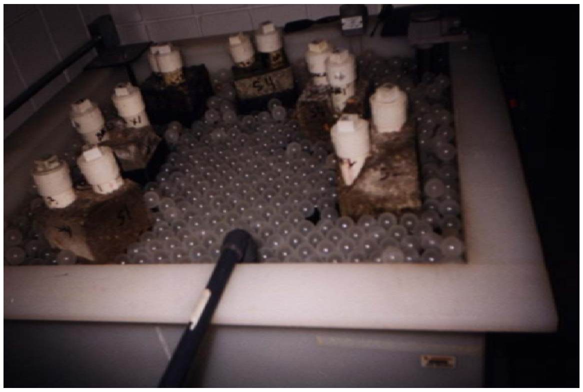

Figure 4. Photograph of immersion tank filled with water

Intermediate Monitoring and Final Testing

All columns were regularly monitored and their condition was evaluated and recorded. Corrosion potentials were measured each week, starting approximately six months into the project. Because of this, the only samples for which corrosion potentials were measured at the beginning of the exposure period are those that were cast one year into the project. There are also a few other gaps in the potential measurements, caused by equipment difficulties and/or loss of data. Corrosion potentials were taken according to procedures outlined in ASTM C 876, Standard Test Method for Half-Cell Potentials of Reinforcing Steel in Concrete, using a copper/copper sulfate reference half-cell (14).

Every six months, columns were removed from the immersion tank according to the schedule in Table 1. Chloride measurements were made on each column after its final removal from the tank; because of space limitations, these results are not discussed here. The concrete and fabric were photographed and inspected visually to evaluate their condition and degree of deterioration. Surface rust or cracking was noted when evident. Rebars were extracted using an impact hammer, marked, and placed in a 10% solution of muriatic acid for a week to remove all corrosion products and remaining concrete. The bars were then weighed to the nearest 0.01 gram, and the percent mass loss was computed for each bar.

Results and Discussion

Corrosion Potentials

Figure 5 shows individual corrosion potential graphs for all column samples, plotted against time. In this and other graphs of corrosion potential, all voltage values are negative, and larger values on the graphs are actually more negative than smaller values. The limits established in ASTM 876 are identified on this and other graphs of corrosion potential. As indicated in ASTM 876, potentials above (more negative than) 350 mV have a 90% probability of active corrosion, and those below (less negative than) 200 mV have a 90% probability of no active corrosion. These cutoffs are identified on the graphs as “Certain Corrosion” and “Possible Corrosion,” respectively.

In Figure 5, one can see that, for the most part, the corrosion potentials of different samples of the same style are similar. However, this trend does not hold true for the wrapped, uncracked samples. As explained previously and reported in Table 1, a small number of bond defects were found in the wrapped columns, especially near the corners of the square columns. Sample #8, the one with the greatest amount of debonds, is also the wrapped, uncracked sample with the highest corrosion potential. Sample 3A, which was cast and wrapped one year into the project with particular attention to quality control, has much lower corrosion potentials than the other samples. In fact, while the remaining samples were actively corroding at 40 weeks, corrosion potentials for Sample 3A did not exceed 350 mV until after 90 weeks.

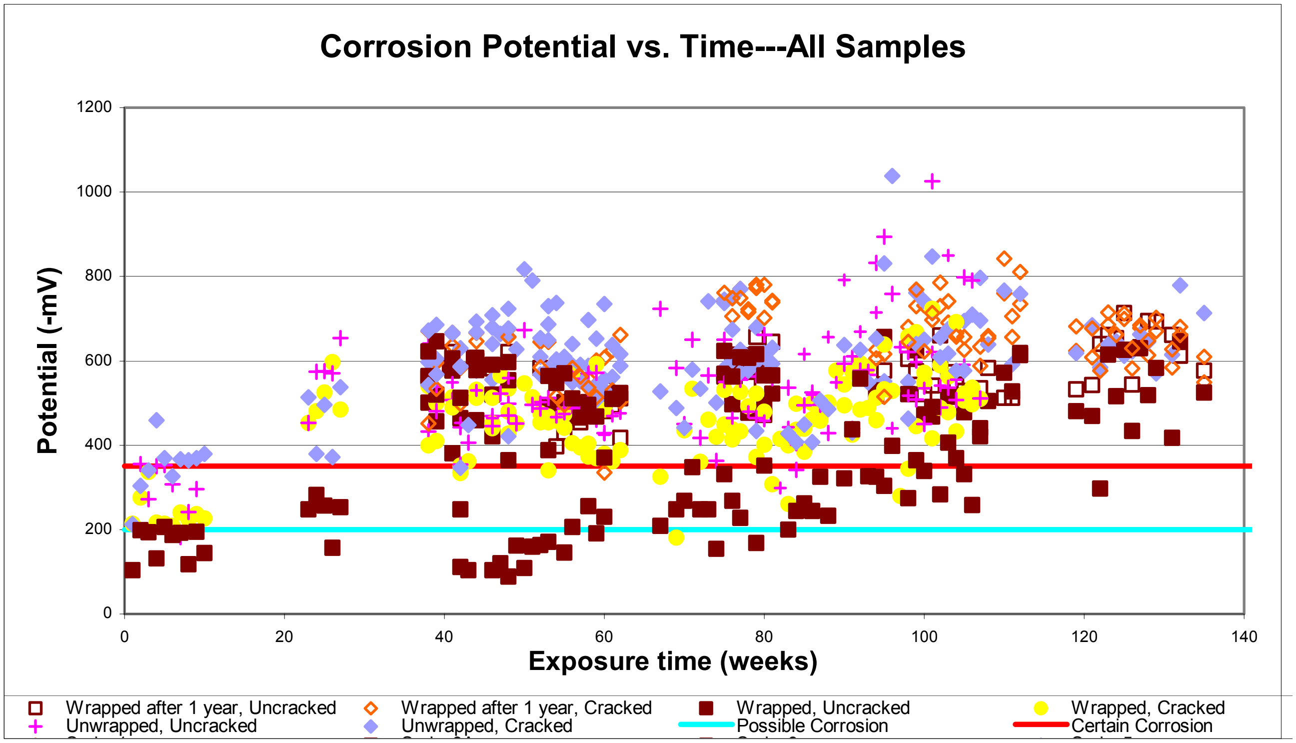

Figure 5. Corrosion potentials for all column samples

Because corrosion potentials were measured for samples 3A, 5A, 6A, and 9A from the first week of exposure, regression analysis was conducted on this data. As shown in Figure 6, which repeats the same data from Figure 5 for these four samples only, the best regression models were power series for all samples except for the wrapped, uncracked samples, where a linear curve provided the best fit with the data. The R-squared values for these regression models, although not high by traditional standards, are reasonable for the corrosion potentials. The potentials varied by 20 to 100 mV each week, depending on whether the samples had been in a wet or dry tank the prior week. According to the trendlines, an unwrapped column under similar exposure conditions would be actively corroding by 10 weeks, a wrapped, cracked sample would be actively corroding by 20 weeks, and a wrapped, uncracked sample would not be consistently corroding until after approximately 115 weeks of exposure.

Rebar Mass Loss

After columns were removed from the immersion tank, rebars were removed and weighed to the nearest 0.01 gram, and the percent mass loss was computed for each bar. Prior to cleaning, a visual assessment was made of each bar and photographs were taken. In the unclean state, surface rust was easy to identify, as were places where the bars remained well adhered to the concrete. Figures 7 and 8 are photos of several of the rebar that underwent 2.5 years of exposure. Column #1 (wrapped, uncracked, 2.5 years exposure) had light to moderate patchy corrosion over all four bars. Column #10 (wrapped after 1 year, uncracked, 2.5 years exposure) showed moderate rusting with some section loss over most of the bars. Column #13 (unwrapped, cracked, 2.5 years exposure) showed severe corrosion, with moderate to severe section loss, including pitting corrosion, and severe rust buildup.

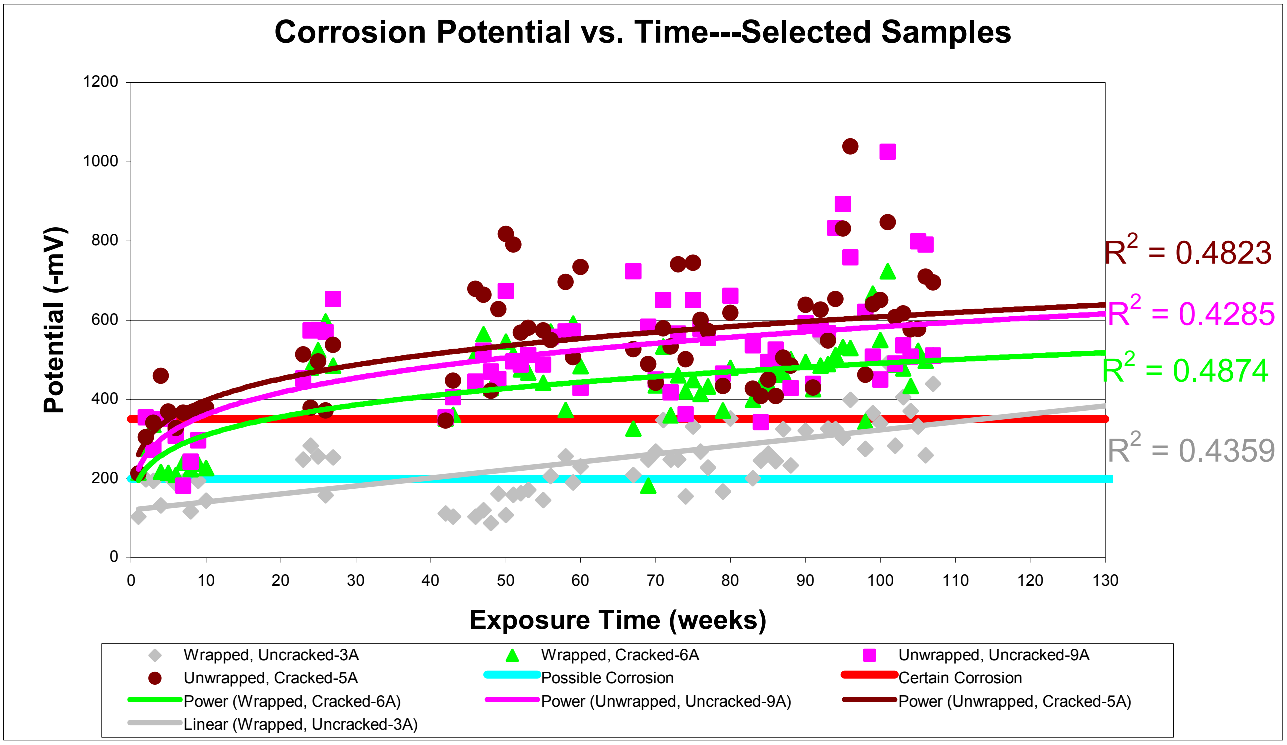

Figure 6. Data and trendlines for selected samples

Figure 7. Rebar cage after extraction from Column #1 after 2.5 years of exposure

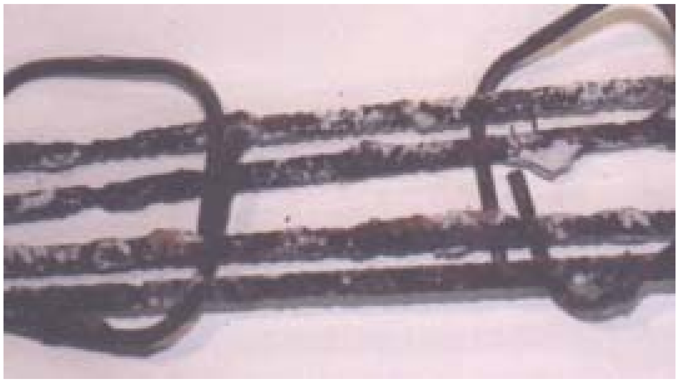

Figure 8. Rebar cage after extraction from Column #13 after 2.5 years of exposure

Figure 9 details the mass loss of each column, in comparison to the average mass loss for the relevant exposure period. As the exposure time increases, one would expect the rebar mass loss to increase also. Many, but not all, of the data points follow this pattern. The one notable exception occurs at two years of exposure, where many of the samples were the replacement columns cast and wrapped one year into the program with higher quality control standards. Presumably because of this improved quality, these columns had less mass loss on average than many other columns of equal or less exposure. In Figure 9, one can see that most wrapped columns performed better than the unwrapped samples of the same exposure length. Column #8 had a greater mass loss than average, which can be explained by the large amount of wrap that was debonded on this column, as indicated in Table 1. Table 2 lists the mass loss in each bar, sorted from smallest to largest percent mass loss. In comparing cracked versus uncracked samples, no conclusions could be drawn regarding mass loss. In many cases, there is a great deal of variability among the bars in a single column; this is evident in Column #3, which also had a higher than average mass loss.

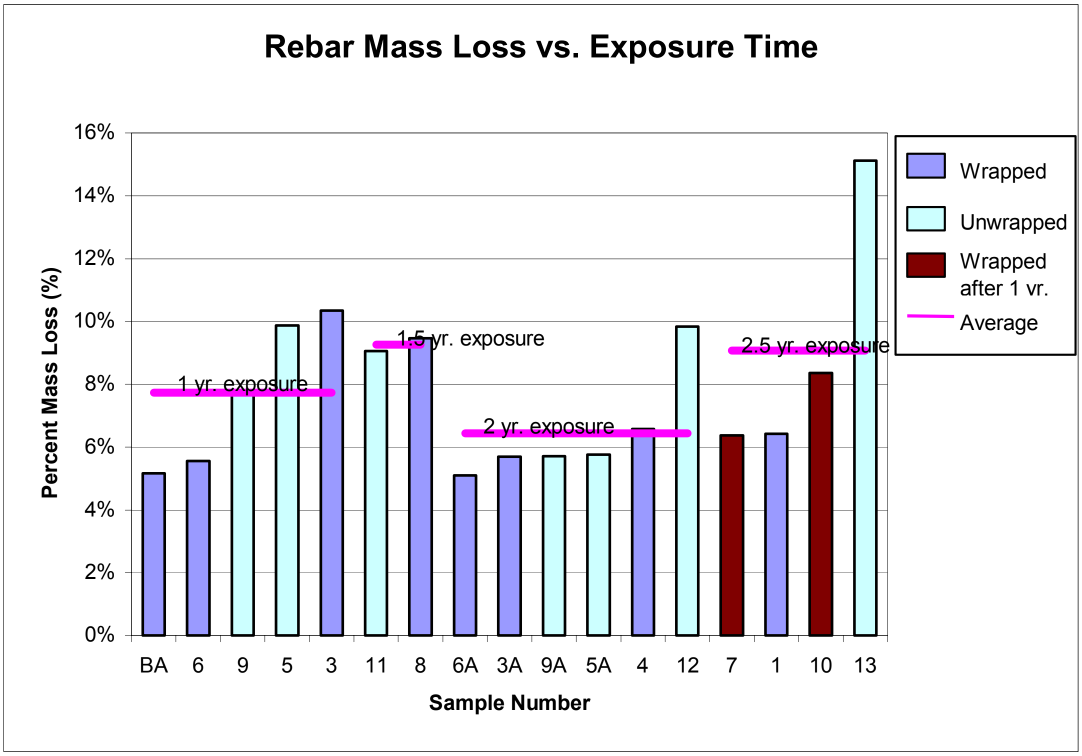

Figure 9. Rebar mass loss for all columns plotted against years of exposure

Conclusions and Future Research

Results from this study indicate that wrapping steel reinforced concrete columns with carbon fiber reinforced polymers offers significant potential for increasing the steel's resistance to corrosion. CFRP wrapped samples showed evidence of decreased corrosion potential through lower half-cells, reduced concrete chloride contents, and decreased reinforcement mass loss. In this experiment, it took wrapped, uncracked samples four to five times as long to reach a ninety percent probability of corrosion, when compared to unwrapped samples. It took wrapped, cracked samples approximately twice as long to reach a ninety percent probability of corrosion, when compared to unwrapped samples. Five of eight columns that were wrapped initially had mass loss values that were less than the average of all samples with the same exposure time. Unwrapped columns had an average rebar mass loss of 5.8 percent per year, for all exposure times. Columns wrapped initially had an average rebar mass loss of 4.8 percent per year, an improvement of 17 percent. Columns wrapped after one year had a rebar mass loss of 7.57 percent after 2.5 years, which was about 50 percent less than the unwrapped column of the same age, and only 18 percent more than the column that was wrapped initially.

Table 2. Percent mass loss for all rebar

Designation	Exposure Time	Type	Percent Mass Loss				
			Bar 1	Bar 2	Bar 3	Bar 4	Average
14	1	Wrapped, Uncracked	3.0%	4.6%	5.8%	7.2%	5.2%
6	1	Wrapped, Cracked	3.7%	3.9%	6.3%	8.3%	5.6%
9	1	Unwrapped, Uncracked	7.3%	7.5%	8.1%	8.1%	7.8%
5	1	Unwrapped, Cracked	6.9%	9.2%	10.3%	13.1%	9.9%
3	1	Wrapped, Uncracked	8.1%	8.6%	9.6%	15.0%	10.3%
11	1.5	Unwrapped, Cracked	6.7%	9.7%	9.7%	10.1%	9.1%
8	1.5	Wrapped, Uncracked	6.2%	7.0%	11.8%	12.8%	9.5%
6A	2	Wrapped, Cracked	3.7%	4.5%	5.4%	6.7%	5.1%
3A	2	Wrapped, Uncracked	4.1%	4.6%	6.9%	7.2%	5.7%
9A	2	Unwrapped, Uncracked	2.7%	5.3%	5.5%	9.4%	5.7%
5A	2	Unwrapped, Cracked	2.7%	4.7%	5.7%	9.8%	5.7%
4	2	Wrapped, Cracked	2.8%	6.2%	8.1%	9.3%	6.6%
12	2	Unwrapped, Uncracked	7.4%	8.5%	8.8%	14.5%	9.8%
7	2.5	Wrapped after one year, Cracked	5.8%	6.0%	6.7%	7.0%	6.4%
1	2.5	Wrapped, Uncracked	4.4%	6.2%	7.5%	7.6%	6.4%
10	2.5	Wrapped after one year, Uncracked	5.5%	5.9%	8.8%	13.3%	8.4%
13	2.5	Unwrapped, Cracked	9.3%	12.3%	18.8%	20.1%	15.1%

However, there was a great deal of variability in the results, and some wrapped samples performed worse than unwrapped samples. Despite the fact that a second set of samples was cast with slight filleting of the corners to improve the bond, perfect bond was difficult to achieve. Because good bond with the concrete is an important factor in confining the concrete and reducing corrosion activity, additional research into techniques for wrapping rectangular columns is needed. Further research into the residual axial and flexural strength of CFRP wrapped samples with corrosion damage is also recommended. Additional laboratory studies involving more samples are needed, and field studies should also be undertaken to determine whether the laboratory results under accelerated conditions are replicated under service conditions.

The FRP wrapping technique discussed herein improves on older jacketing techniques, resulting in an increased ability to develop confinement in the concrete. A number of automated systems are available for applying FRP wraps, as are epoxies that cure under ambient conditions and in contact with water (15, 16). These technologies extend the possibilities for applying wraps to either new piles under controlled factory conditions, or to existing piles in the field. If successful, this research will potentially lead to an improved method for preventing and reducing corrosion in reinforced concrete piles and columns for marine use.

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