PERFORMANCE MONITORING OF REINFORCED CONCRETE WRAPPED WITH FRPs

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ABSTRACT

The major objective of this long-term investigation was to determine whether composite wrapping could be used to complement traditional repair techniques for corrosion-damaged reinforced concrete structures. Twelve bridges were selected to be rehabilitated using FRP (fibre-reinforced polymer) wraps. A companion laboratory test program was designed to simulate bridge components, specifically bridge bents (rectangular specimens) and columns (cylindrical specimens). Some other variables included length and type of wrap and resin, flexural cracks, and the presence or absence of in-built chlorides. Specimens were exposed to salt-containing environments for up to six years. Laboratory results showed that, in general, FRP wraps can restrict chloride access and the extent of corrosion. The field investigation showed similar results; the quality of the wrapping procedure was a dominant factor.

1. INTRODUCTION

Reinforced concrete bridge decks in marine environments and cold climates can suffer corrosion damage due to the ingress of chlorides from salt-laden air or deicing salts. Composite materials are currently used in the rehabilitation of structures that have suffered corrosion damage. There is some concern, however, that this might actually exacerbate the problem by trapping chlorides already present. One rehabilitation technique is to utilize traditional repair techniques followed by composite wrapping systems that will restrict the intrusion of oxygen, chlorides and other aggressive species. The rationale is to take advantage of the high strength, light weight, and low susceptibility to corrosion that these composite materials possess.

In 1997, a laboratory research program and field program were initiated to determine whether composite wrapping could be used as a means of rehabilitating corrosion-damaged structures. In the laboratory program, more than 60 cylindrical or rectangular specimens were designed to simulate bridge columns and beams [1-2]. Some of the specimens were damaged, repaired and wrapped with composite materials, and then exposed to salt-containing environments. The composite systems used included a vinyl ester resin and two epoxy resins in combination with selected fabrics containing glass fibres. Variables included type of repair material, type of composite wrapping system, length of wrap, presence or absence of cracks, and presence or absence of pre-existing chlorides. Two years into the investigation, another set of 17 cylindrical specimens was cast and added to the investigation to examine the effect of spray-on corrosion inhibitors.

In the field investigation, 12 corrosion-damaged bridges in the northern part of Texas were part of the study. These bridges had suffered severe corrosion damage as a result of applications of deicing salts for snow removal. A commercially available wrapping system was used on these bridges. Three of these structures were monitored as part of the field investigation to determine whether wrapping could arrest or minimize corrosion.

The laboratory specimens were exposed to intermittent saltwater conditions during the study. The bridges were exposed to severe environmental conditions in northern Texas. The laboratory specimens and the bridges were monitored using half-cell potential (corrosion potential), corrosion rate, and chloride measurements. Periodically, selected laboratory specimens were removed from testing and autopsied. This paper is a summary of some of the major conclusions from this investigation, especially as they relate to the field investigation [1-5].

2. EXPERIMENTS

A summary of some of the key details of the early stages of the laboratory and field investigations is presented below. Extensive details are presented elsewhere [1-2].

In the initial phase of the investigation, 18 rectangular and 42 cylindrical specimens were cast to represent elements of the bridge components; specifically bridge bents and columns. The cylindrical specimens were 91.4 cm (3 ft) long and 25.4 cm (10 in) in diameter. The rectangular prisms were 91.4 cm in length, with a 25.4 x 25.4 cm cross section. Specimens were constructed with steel cages that were formed of longitudinal and transverse reinforcement tied together with metallic tie wires. The reinforcing bars were cut into 99.1 cm lengths so that 7.6 cm of reinforcement protruded out of one end of the rectangular and cylindrical specimens. A high water: cement ratio of 0.7 was used as well as a low cover of 25 mm (1 inch). This was done to ensure enhanced chloride migration through the concrete. The specimens included ones with a number of variables, including the presence of absence of chlorides in the mix water, the presence or absence of flexural cracks, the presence or absence of a single type of spray-on inhibitor (type C), and different repair materials (patch repair or latex modified grout (LMG).

The composite wrap systems included two epoxy systems (one commercially available wrap denoted as Com and one generic wrap known as Generic) and a vinyl ester wrap, also known as Generic. Wrapped specimens were fully wrapped (91.4 cm) or partially wrapped (61.0 cm). Specimens were named to denote the geometry and whether chlorides had been added to the mix water. For example, the first letter denotes shape (R for rectangular, C for cylindrical) and the following letters denote chloride additions to the mix water (C for chlorides, NC for no chlorides). There were also control specimens that were not wrapped (NW). The wrapped specimens contained a small access hole that was used for monitoring corrosion potentials. They were fitted with a removable plastic cover that was in place during exposure.

Specimens were exposed to a 3.5 % sodium chloride (NaCl) solution on a cyclical basis; a soaking period of one week followed by a dry period for two weeks. During the soaking period, the lower 30.5 cm of the cylindrical specimens were immersed in the salt solution. During the soaking period, the salt solution was allowed to drip over the rectangular specimens. Corrosion potentials were monitored using a Cu/CuSO4 (CSE) reference electrode. Corrosion potentials more negative than -350 mV vs CSE were considered to be indicative of a high probability of corrosion, while those more negative than -500 mV vs CSE were considered to be indicative of cracking [6].

When the second phase of the laboratory investigation was initiated in 2000, cylindrical specimens of the same type were used, however the only variables were type of spray-on corrosion inhibitor, (A, B, or C); the wrap length, 91.4 cm or 61.0 cm; and the presence of absence of flexural cracks. In addition, to the previous nomenclature, specimens with pre-existing flexural cracks were noted with c and the inhibitor was noted as either A, B, or C. The commercially available epoxy coated system was used for the wrapped specimens. There were also several unwrapped specimens as controls, NW.

During the approximately six years of exposure, laboratory specimens were subjected to intermitted saltwater (sodium chloride) conditions. They were monitored throughout that time using corrosion potential measurements. Selected specimens were tested using polarization resistance techniques to determine corrosion rates. Periodically, specimens were removed from testing and autopsied following a thorough post – exposure examination that included chloride analysis. Group 1 specimens were removed after approximately one year; Group 2 specimens were removed after approximately two years, Group 3 specimens were removed after approximately four years, and Group 4 specimens were removed after approximately six years.

In the case of the field investigation, 12 bridges were wrapped and corrosion rate probes were installed in strategic locations in three of the structures. Wrapping of the bridges was completed in the fall of 1999. Two probes were installed in selected bents of structure 7, four were installed in selected bents of structure 8, and two were installed in selected bents of structure 12. Corrosion potential readings and corrosion rate probe measurements were taken in May of 2000, October of 2000, and May of 2001. Corrosion potentials were measured in April of 2006.

A photograph of selected cylindrical specimens is shown in Figure 1; a photograph of one of the rectangular specimens is shown in Figure 2; and a photograph of a portion of one of the bridges is shown in Figure 3.

Figure 1: Photograph of selected cylindrical specimens showing the metal cages [1].

Figure 2: Photograph of a wrapped rectangular specimen during a drying period [3].

Figure 3: Photograph of a portion of one of the bridges in the field investigation [5].

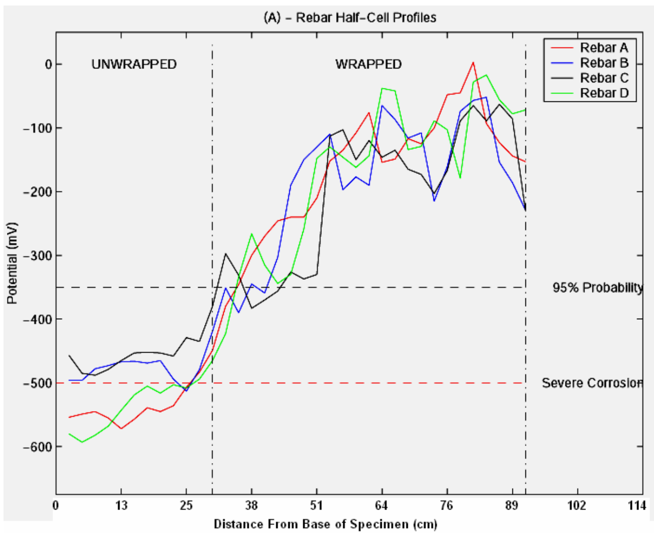
3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Post-exposure examination of laboratory specimens

The post-exposure analysis indicated that FRP wrapping was effective in reducing corrosion activity in the test specimens.

- Analysis of the specimens in Group 1 indicated that the wraps restricted chloride ingress since chloride contents after exposure were lower for the wrapped specimens and corrosion potentials were more positive for the wrapped specimens; particularly those that were initially free from cracks and chlorides. There also seemed to be some benefit from the spray-on corrosion inhibitor C. Moisture, however, was found under the wraps of some fully wrapped specimens.
- Analysis of the specimens in Group 2 continued to show that wrapping restricted chloride ingress. In some cases, cracks did serve as sites for corrosion.
- Analysis of the specimens in Groups 3 and 4 included detailed examination of each bar in each specimen. Wraps reduced corrosion activity in wrapped portions that were initially free from cracks and chlorides. Corrosion activity was especially severe near cracks. Moisture was found trapped under the wrap in some (but not all) of the fully wrapped specimens.

Figure 4a shows an example of a typical plot of corrosion potential vs distance from the base of a wrapped specimen. Figure 4b (top) shows a schematic of a bare reinforcing steel bar. Figure 4b (bottom) shows a schematic of a reinforcing steel bar removed from a partially wrapped specimen. The corroded region of the bar is highlighted.



a

b

Figure 4: a)Corrosion potential vs distance from base of specimen.
b)Schematic of bare bar and schematic of bar showing corroded region [4]

Photographs of typical wrapped and unwrapped specimens taken prior to autopsy are shown in Figure 5.

a) b)

Figure 5: a) Unwrapped specimen from Group 4 b) Fully wrapped specimen from Group 4 after removal of the wrap [4]

As mentioned, the results based on autopsies taken after one and two years of exposure seemed to suggest that corrosion activity was lower in specimens that contained inhibitor C, the only inhibitor that was used in the first phase of the investigation. Specimens such as CC1-cC, CC15-cC, and CC14-uC, which are shown in Table 1, appeared to benefit from the use of the corrosion inhibitor after five years of exposure. However, in the Phase 2-Spray-on Inhibitor investigation that focused explicitly on spray-on corrosion inhibitors, the results were not as definitive. Therefore, other factors such as repair material, may have influenced the performance of the original specimens that contained corrosion inhibitor C. Table 2 shows average corrosion potentials and average chloride contents for selected specimens.

Table 1. Autopsy Results for Selected Cylindrical Specimens; Phase [4-5] (Avg chlorides in % by weight of concrete in Wrapped and Unwrapped Portions; Avg Cor Pot vs Cu/CuSO4)

Groups 3/4							
Specimen Prefix CC	Cast-in Chlorides	FRP Wrap		AvgChlorides UW	Avg Chlorides W	Avg Cor Pot UW	Avg Cor Pot W
		Wrap	L/cm				
21- CNW	Chlorides			0.442		-407	
1-cC	Chlorides	Com	61	0.260	0.188	-383	-296
6-cC	Chlorides	Generic	91		0.150		-460
15-cC	Chlorides	Generic	61	0.214	0.103	-477	-391
10-uCNW	Chlorides			0.337		-454	
14-uC	Chloride	Generic	61	0.244	0.179	-271	-364
20-uC	Chlorides	Generic	61	0.368	0.194	-274	-330
9-u	Chlorides	Com	61	0.307	0.250	-419	-342

3.2 Post-exposure examination, field investigation

Structures were visually inspected for any signs of corrosion, such as rust spots or cracking on the surface of the wrap. The field investigation revealed a variety of conditions on the structures; particularly on the structures in which corrosion probes had been embedded.

- Corrosion potential readings during the first year of exposure indicated that the readings did not change significantly during that time.
- Most of the readings taken approximately five years later were similar to those that had been taken previously.
- In many cases, the effectiveness of the FRP wrap was dependent on the quality of the wrapping. Areas that were difficult to wrap often produced gaps and easy access for chloride penetration.

Table 3 shows results from certain locations on selected structures. It was clear that visual inspection may not give an indication of the overall corrosion activity taking place. Some of the probe readings indicated a relatively high probability of corrosion taking place. This was confirmed by chloride contents taken from the bent caps. The chloride contents were relatively high and much higher than the threshold value of 0.03% by weight of concrete. In many cases, when these areas were examined, there was no visible evidence of corrosion. Monitoring of these locations should be continued.

Other comments on the structures are included. Rust staining was observed on one of the bents in structure 1. Rust stains were observed near the end of the bent cap, near a column joint and on the underside of the bent. No probes were embedded in this part of the structure, but extracted chloride samples revealed average chloride values of 0.355 % by weight of concrete.

No rust stains were observed on structures 2, 6, or 7 but a crack was observed on the underside of one of the bents on structure 5, where the FRP fabric sheets overlapped.

No cracking or rust stains were observed on structure 8, however cracks were observed at the ends of prestressed girders along with spalling of concrete and rust stains. Structures 2, 4, 5, 6, 9, 10, and 11 did not contain embedded probes.

Table 2. Field Investigation Results [3,5]

Average Corrosion Potentials/Average Corrosion Rates (mm/y) from Selected Locations							
Structure	Probe ID	Bent		5/2000	10/2000	5/2001	4/2006
7	7.1	7	Left	-244/0.006	-251/0.006	-253/ 0.004	-278
7	7.2	7	Right	-477/0.019	-426/0.013	-528/0.021	-473
8	8.1	4	Left	-329/0.005	-306/0.003	-344/0.005	-453
8	8.2	4	Right	-362/0.016	-352/0.011	-384/0.017	-322
8	8.3	5	Left	-377/0.006	-392/0.004	-395/0.014	-264
8	8.4	5	Right	-351/0.011	-461/0.009	-359 /0.015	-301
12	12.1	1	Left	-305/0.039	-316/0.007	-392/0.025	-222
12	12.2	1	Right	-384/0.031	-303/0.024	-436/0.028	-361

5. CONCLUSIONS

This project was designed to develop a greater understanding of the long-term effects of FRP wrapping in preventing and minimizing corrosion in reinforced concrete structures. Rectangular and cylindrical specimens were included in the project, but the focus was mainly on the partially and fully wrapped cylindrical specimens. Several construction parameters were also included. The field assessment of wrapped elements provided an opportunity to examine the feasibility of the wrapping system.

The major conclusions are summarized below:

- FRP wrapping was effective in reducing corrosion activity in the test specimens. The FRP provided a barrier to the migration of chlorides. Chloride concentrations were lower and corrosion potential values were more positive. The condition of the extracted bars corroborated the results from corrosion potentials and chloride contents.
- FRP wrapping was effective even on partially wrapped specimens.
- The FRP wrap was equally effective for concrete with and without cast-in chlorides.
- In long-term exposure, pre-cracking did not change the effectiveness of FRP wrapping
- The repair materials played a significant role in preventing corrosion.
- One of the spray-on corrosion inhibitors seemed to reduce corrosion early in the investigation. Long-term results with different spray-on corrosion inhibitors were not as definitive.
- Corrosion potentials and chloride analysis can be effective methods to assess the level of corrosion in structures in the field. Probes embedded in wrapped elements in the field gave consistent results that correlated with chloride concentrations.
- The effectiveness of FRP wrapping in the field was very dependent on the quality of wrapping.

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