Technical Report Documentation Page

1. Report No. FHWA/TX-07 / 0-1774-4	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Performance of Fiber Composite Wrapped Columns and Beams in a Corrosive Environment		5. Report Date October 2006 6. Performing Organization Code
7. Author(s) H.S. Karpate, D.P. Whitney, J.O. Jirsa, D.W. Fowler, and H.G. Wheat		8. Performing Organization Report No. 0-1774-4
9. Performing Organization Name and Address Center for Transportation Research The University of Texas at Austin 3208 Red River, Suite 200 Austin, TX 78705-2650		10. Work Unit No. (TRAIS) 11. Contract or Grant No. 0-1774
12. Sponsoring Agency Name and Address Texas Department of Transportation Research and Technology Implementation Office P.O. Box 5080 Austin, TX 78763-5080		13. Type of Report and Period Covered Research Report (09/97 – 02/06) 14. Sponsoring Agency Code
15. Supplementary Notes Project performed in cooperation with the Texas Department of Transportation and the Federal Highway Administration.		
16. Abstract The objective of this project is to evaluate the long-term effectiveness of fiber reinforced (FRP) composite wraps in preventing corrosion of reinforced concrete elements in severe environments. The experimental program was established to help determine if FRP wraps provide barriers against the transportation of chlorides into the concrete, or if impermeable wraps trap chlorides and moisture beneath the wrap and thereby accelerate the corrosion process. The focus of this report is on performance of 43 specimens that were removed from exposure testing 5 – 7 years. The specimens represent typical rectangular (beam) and cylindrical (column) elements in reinforced concrete bridges. Partially wrapped versus unwrapped elements were studied. Other parameters of interest in design and construction included: cast-in chlorides to represent specimens already exposed to a corrosive environment prior to wrapping, cracked versus uncracked elements, addition of corrosion inhibitors, and materials of repair for damage to concrete due to corrosion or the construction traffic prior to wrapping. Guidelines for use of these materials are developed using the results of the test program.		
17. Key Words Corrosion, steel, concrete, FRP, polymer wrap, wrapping, fiber-reinforced plastics, fiber-reinforced polymers, repair, rehabilitation, encapsulation	18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161; www.ntis.gov.	

19. Security Classif. (of report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of pages 148	22. Price

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Performance of Fiber Composite Wrapped Columns and Beams in a Corrosive Environment

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CTR Technical Report:	0-1774-4
Report Date:	October 2006
Project:	0-1774
Project Title:	Effect of Wrapping Chloride Contaminated Structural Concrete with Multiple Layers of Glass Fiber/Composites and Resin
Sponsoring Agency:	Texas Department of Transportation
Performing Agency:	Center for Transportation Research at The University of Texas at Austin

Project performed in cooperation with the Texas Department of Transportation and the Federal Highway Administration.

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Disclaimers

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Acknowledgments

We greatly appreciate the financial support from the Texas Department of Transportation that made this project possible. The support of the Project Director, Jon Kilgore, (SAT) and Project Coordinator, W. Cox (BRG) is also very much appreciated. We would also like to thank monitoring committee members, R. Baker (LBB), David McDonnold (BRG), and Keith Ramsey (BRG) for their guidance on this project. The assistance of Paul Gugenheim and Delta Structural Technologies in providing materials and assistance in fabrication of specimens is gratefully acknowledged.

Products

Guidelines for the selection and use of wrapping materials are presented in Chapter 6.

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Chapter 1

Introduction

1.1 OVERVIEW OF PROJECT 0-1774

The project entitled, "Effect of Wrapping Chloride Contaminated Structural concrete with Multiple Layers of Glass Fiber composites and Resin," started in 1997. The preliminary phases of the project have been reported in CTR Research Report 0-1774-1, "Evaluation and Performance Monitoring of Corrosion Protection by Fiber-Reinforced Concrete Wrapping" (Verhulst 2001). In order to study the effects of using FRP wraps, a wide range of variables were considered such as cast-in chlorides, cracks, repairs, wet surfaces, wrap length, and presence of corrosion inhibitor. The specimens were placed in a tank and exposed to a 3.5% saline solution in order to accelerate the corrosive process. The characteristics of the initial series of specimens and their current status are shown in Appendix Table A-1. At the time the report was prepared, the experiment had not been active long enough to develop conclusions regarding the feasibility of using FRP wrapping.

After approximately three years of exposure to the aggressive environment of the soaking tank, all specimens in this study had signs of corrosion. Observations were reported in CTR Report 0-1774-2, "Effects of Wrapping Chloride Contaminated Concrete with Fiber Reinforced Plastics" (Berver 2001). The effects of using FRP as a corrosion mitigation solution were more apparent after being exposed for this length of time. Berver removed 10 columns and 4 beams from the corrosive environment and conducted autopsies that were included in Report 0-1774-2. Berver concluded that the FRP wrapping systems were effective in providing a physical barrier to the chlorides and the moisture. However, corrosion was not significantly reduced as moisture was able to enter the specimens from areas of exposed concrete and develop macrocells. In 2000, Berver constructed 19 additional specimens in which the primary variable was the effectiveness of 4 different corrosion inhibitors. Those specimens are listed in Appendix Table A-4. The construction details were included in Report 0-1774-2.

The results of a detailed examination of 9 column and 4 beam specimens that were removed from the exposure tank were presented in Report 0-1774-3. Half-cell potential readings were taken at small intervals over the entire surface of specimens after the FRP wrapping was removed. Extensive chloride-content sampling was carried out to supplement the half-cell potential readings. Chloride contents were compared with half-cell potential readings and with visual observations of the condition of reinforcing bars that were extracted from the concrete as the final step of the "autopsy" process.

1.2 RESEARCH OBJECTIVE

The objective of TxDOT Project 0-1774 is to determine the long-term effectiveness of FRP composite wraps in extending the life of reinforced concrete structures. The challenge is to establish a comprehensive database so that the influence of a wide range of variables included in the test program can be determined and guidelines for use of wrapping techniques to extend the service life of reinforced connector structures in a corrosive environment.

1.3 OBJECTIVE OF THE REPORT

The main focus of Project 0-1774 is the development of an understanding of the long-term effects of fiber reinforced plastic (FRP) composite wraps in preventing corrosion. The specific goal of this report is to examine the behavior of specimens that represent the support structure typical of reinforced concrete bridges. A key feature of the project is to ascertain whether FRP wraps provide effective barriers against the transportation of chlorides into the concrete and to assess the likelihood that the impermeable nature of the wraps may trap chlorides and moisture beneath the wrap and accelerate the corrosive process.

The procedures used to asses the condition were described in Report 0-1774-3. The purpose of this report is to document the performance of all remaining tests and to propose design guidelines for use of wrapping techniques to protect bridge structures in a corrosive environment.

The condition of 43 specimens remaining under exposure testing in 2005 was assessed through a detailed examination of each specimen. The data was added to that discussed in Reports 0-1774-2 and 0-1774-3. The details of all the specimens fabricated and subjected to corrosive conditions are tabulated and described as follows:

- Characteristics of all specimens (cast in 1998 and 2000).
- Chronological record of half-cell readings of all specimens
- Half-cell and chloride content readings of all specimens after removal from exposure testing and removal of wrapping material.
- A detailed description of the condition of each of the 43 tests autopsied after 5-7 years of exposure

In addition, an update of the condition of bridge support structures in the Lubbock District that were wrapped with glass composites is reported. These bridges provide a valuable source for evaluating the effectiveness of wrapping to reduce corrosion activity in the field for comparison with findings in the laboratory.

Chapter 2

Presentation of Experimental Data*

2.1 INTRODUCTION

A complete listing of the specimens cast in 1998 and their properties is presented in Table 2.1. The properties of additional specimens cast in 2000 are presented in Table 2.2. All the specimens remaining in the exposure tank after 2003 (end of the period reported in CTR Report 0-1774-3) were removed from the exposure tank for a detailed examination. Twenty-two specimens were removed and autopsied in Spring 2005 and 21 specimens in Fall 2005. These specimens have been highlighted in Table 2.1 and Table 2.2. In this supplementary report, the performance of the highlighted specimens has been evaluated and compared.

To understand how effective the FRP wrap was in preventing corrosion activity, the results are divided into two main sections: unwrapped versus wrapped. After comparing the behavior of the wrapped and unwrapped specimens, the other parameters were analyzed.

For each of the specimens reported in this supplement, a detailed description is included in Appendix A. Information gathered during the visual inspection of each specimen, including inspection of the exterior of specimens as well as the condition of reinforcing bars extracted from each specimen is presented. Half-cell readings across the surface of the concrete cylinders and beams are presented graphical to identify locations of corrosion activity. Contours of the potential across the entire surface in two-dimensions are generated to create a more effective picture of where corrosion is most likely to have occurred. Figure 2.1 shows the eight lines along which half-cell readings were taken for columns.

* This chapter supplements chapter 4 of Report 0-1774-3

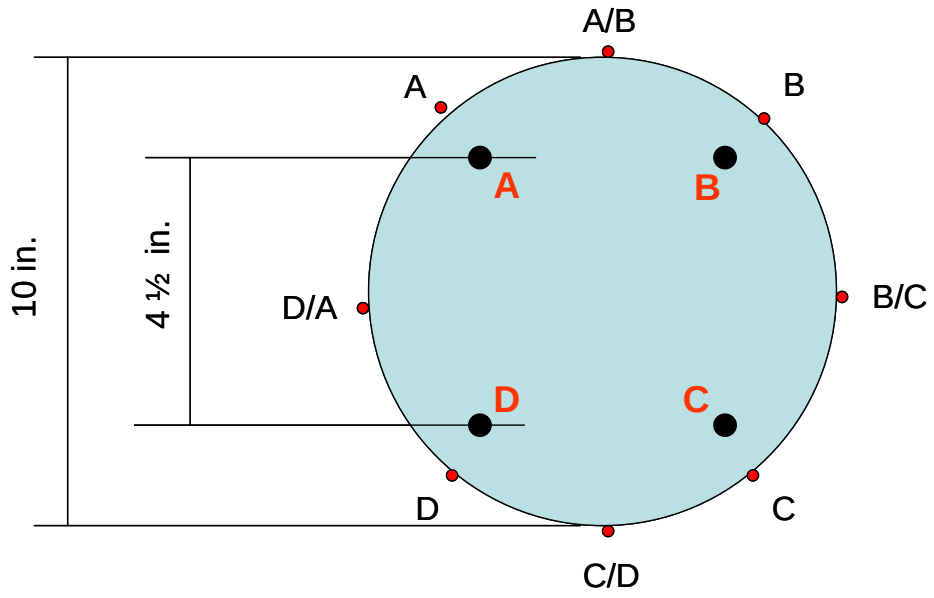


Figure 2.1 Location of half cell readings

Chloride content measurements were conducted at the same locations as the half-cell readings were taken. The chloride content was determined at various depths and the chloride content profiles were graphed. A photograph of the reinforcing bars is presented for each specimen and areas of corrosion are highlighted. The results are tabulated in this chapter and details of each specimen are provided in Appendix A.

In Table 2.3, the chronological record of half-cell readings of all the specimens cast in 1998 is given. The chronological record of half-cell readings of specimens cast in 2000 is shown in Table 2.4. . Average chloride concentrations and half-cell potential readings are determined in the wrapped and unwrapped portions of each specimen in table 2.5. The values in Table 2.5 provide an overview of effect of FRP wrapping. The specimens examined and discussed in this report are highlighted.

Table 2.1 Characteristics of specimens cast in 1998

Specimen	Built in chlorides	Wrap	Resin	Surface at Wrapping	Crack Condition	Repair Material	Corrosion Inhibitor
CC1	yes	delta-24"	Tyfo S	dry	cracked	none	ferrogard
CC2	yes	gen/del-30"	Tyfo S	wet	uncracked	LMC	none
CC3	yes	delta-24"	Tyfo S	dry	uncracked	EG	none
CC4	yes	delta-24"	Tyfo S	dry	uncracked	LMC	none
CC5	yes	generic-36"	862	dry	cracked	patch	none
CC6	yes	generic-36"	vinyl ester	dry	cracked	patch	ferrogard
CC7	yes	delta-24"	Tyfo S	dry	cracked	none	none
CC8	yes	delta-36"	Tyfo S	dry	cracked	LMC	none
CC9	yes	delta-24"	Tyfo S	dry	uncracked	none	none
CC10	yes	none	none	dry	uncracked	none	ferrogard
CC11	yes	none	none	dry	uncracked	none	none
CC12	yes	generic-30"	862	wet	cracked	none	none
CC13	no	generic-24"	862	dry	cracked	none	none
CC14	yes	generic-24"	862	dry	uncracked	LMC	ferrogard
CC15	yes	generic-24"	862	dry	cracked	none	ferrogard
CC16	yes	none	none	dry	uncracked	EG	none
CC17	no	none	none	dry	uncracked	LMC	none
CC18	yes	none	none	dry	cracked	none	none
CC18	yes	none	none	dry	cracked	none	none
CC19	yes	generic-24"	vinyl ester	dry	uncracked	LMC	none
CC20	yes	generic-24"	vinyl ester	dry	uncracked	none	ferrogard
CC21	yes	none	none	dry	cracked	none	ferrogard
CNC1	no	generic-27"	862	wet	cracked	patch	none
CNC2	no	generic-36"	862	dry	cracked	none	none
CNC3	no	generic-24"	862	dry	uncracked	none	ferrogard
CNC4	no	delta-24"	Tyfo S	dry	uncracked	none	none
CNC5		delta-36"	Tyfo S	dry	cracked	none	none
CNC6	no	generic-24"	vinyl ester	wet	cracked	patch	none
CNC7	no	none	none	dry	uncracked	none	ferrogard
CNC8	no	none	none	dry	cracked	none	ferrogard
CNC9	no	generic-24"	vinyl ester	dry	uncracked	LMC, patch	none
CNC10	no	delta-24"	Tyfo S	dry	cracked	none	none
CNC11	no	none	none	dry	uncracked	LMC, Patch	none
CNC12		none	none	dry	uncracked	EG, patch	none
CNC13	no	generic-24"	862	dry	cracked	none	ferrogard
CNC14	no	generic-36"	862	dry	cracked	none	ferrogard
CNC15	no	none	none	dry	cracked	none	none
CNC16	no	delta-24"	Tyfo S	dry	uncracked	LMC	none

Specimen	Built in chlorides	Wrap	Resin	Surface at Wrapping	Crack Condition	Repair Material	Corrosion Inhibitor
CNC17	no	delta-24"	Tyfo S	dry	uncracked	EG	none
CNC19	no	generic-24"	862	dry	uncracked	none	none
CNC20	no	none	none	dry	uncracked	none	none
RC1	yes	generic-27"	862	dry	uncracked	LMC	ferrogard
RC2		generic-31"	vinyl ester	dry	cracked	none	none
RC3	yes	delta-24"		dry	cracked	None	none
RC4	yes	none	none	dry	cracked	none	none
RC5	yes	delta-27"		dry	uncracked	LMC	none
RC6	yes	gen/del-33"	862	dry	uncracked	LMC	none
RC7	yes	generic-30"	862	dry	cracked	none	none
RC8	yes	none	none	dry	uncracked	LMC	none
RC9	yes	gen/delta-24"	862	dry	cracked	none	ferrogard
RNC1	no	delta-24"		dry	uncracked	none	none
RNC2	no	none	none	dry	uncracked	none	none
RNC3		generic-27"	862	dry	uncracked	none	ferrogard
RNC4	no	generic-36"	vinyl ester	dry	uncracked	LMC	none
RNC5	no	delta-30"	delta system	dry	cracked	none	none
RNC6	no	gen/delta-30"	862	dry	cracked	LMC	none
RNC7	no	none	none	dry	cracked	none	none
RNC8	no	generic-24"	862	dry	cracked	none	none

Notes

- The highlighted specimens are those that have been autopsied and reported in this report.
- First letter of specimen name corresponds to cylinders (C) or beams (R). If second letter is “N” there are no built in chlorides.

Table 2.2 Characteristics of specimens cast in 2000

Specimen	Wrap	Resin	Surface at Wrapping	Crack. Condition	Corrosion Inhibitor
1	delta-24"	Tyfo S	dry	Cracked	Surtreat
2	delta-36"	Tyfo S	dry	Cracked	Surtreat
3	delta-24"	Tyfo S	dry	Uncracked	Surtreat
4	delta-36"	Tyfo S	dry	Uncracked	Surtreat
5	delta-24"	Tyfo S	dry	Cracked	Cortec
6	delta-36"	Tyfo S	dry	Cracked	Cortec
7	delta-24"	Tyfo S	dry	Uncracked	Cortec
8	delta-36"	Tyfo S	dry	Uncracked	Cortec
9	delta-24"	Tyfo S	dry	Cracked	Sika
10	delta-36"	Tyfo S	dry	Cracked	Sika
11	delta-24"	Tyfo S	dry	Uncracked	Sika
12	delta-36"	Tyfo S	dry	Uncracked	Sika
13	delta-24"	Tyfo S	dry	Cracked	None
14	delta-36"	Tyfo S	dry	Cracked	None
15	delta-24"	Tyfo S	dry	Uncracked	None
16	delta-36"	Tyfo S	dry	Uncracked	None
19	none	Tyfo S	dry	Cracked	None

Notes

- The highlighted specimens are those that have been autopsied and reported in this report.

Table 2.3 Chronological record of half-cell readings in the exposure tank, of specimens cast in 1998

Specimen	10/15/00	2/5/01	2/15/02	3/5/02	1/10/03	2/10/03	12/4/03	12/16/03	4/27/03	4/19/05	10/25/05
CC1	-298		-304	-250	-322	-319	-360	-313	-355	-265	
CC2	-211		-276	-247	-280	-271	-300	-41	-373	-240	-322
CC3	-183	-225									
CC4	-238		-271	-165	-206	-194	-265	-353	-317	-247	
CC5	-438	-460									
CC6	-437	-460									
CC7		-610									
CC8	-324		-323	-304	-472	-481	-285	-301	-391	-251	-240
CC9	-270		-301	-221	-314	-284	-300	-1	-334	-210	-329
CC10	-398		-485	-398	-485	-412					
CC11	-432		-536	-252	-549	-485					
CC12	-269		-335	-237	-262	-250	-350	-18	-244	-250	-210
CC13	-440		-473	-433							
CC14	-344		-307	-285	-274	-281	-390	-343	-512	-437	
CC15	-330		-393	-324	-427	-360					
CC16	-324		-526	-440	-510	-460	-550	-480	-556	-620	-411
CC17	-385		-489	-430							
CC18		-590	-536	-485	-578	-498					
CC19	-248		-289	-266	-300	-270	-550	-466	-578	-415	
CC20	-291		-357	-294	-352	-320	-370	-280	-404	-430	
CC21	-389		-536	-446	-508	-429	-530	-457	-528	-577	-412
RC1	-266		-485	-394	-304	-170	-450	-390	-431	-465	
RC2	-377		-500	-488							
RC3	-359		-343	-257	-328	-317					
RC4		-610									
RC5	-250		-208	-170	-127	-135					
RC6	-135		-123	-110	-145	-220	-265	-904	-516	-420	

Specimen	10/15/00	2/5/01	2/15/02	3/5/02	1/10/03	2/10/03	12/4/03	12/16/03	4/27/03	4/19/05	10/25/05
RC8	-377		-513	-408	-471	-260	-470	-313	-535	-366	
RC9	-297		-246	-201	-204	-151	-620	-222	-432	-253	
RNC1	-226		-165	-140	-222	-221					
RNC2	-434		-273	-350	-456	-416					
RNC3	-389		-396	-347							
RNC4	-265		-267	-235	-173	-200	-350	-360	-380	-310	-405
RNC5	-385		-328	-295	-127	-260	-710	-343	-389	-424	-435
RNC6	-242	-230									
RNC7	-472	-470									
RNC8	-250		-314	-230	-250	-314	-284	-220	-326	-222	
CNC1	-326		-360	-325	-398	-374	-460	-422	-483		-406
CNC2	-401		-407	-376	-416	-407	-460	-477	-503	-406	-440
CNC3	-274		-375	-258	-349	-309	-420	-411	-445	-305	
CNC4	-386		-345	-305	-325	-298	-420	-418	-451	-442	-392
CNC5	-403		-413	-378							
CNC6	-356		-451	-380	-485	-455					
CNC7	-487		-523	-448	-506	-483	-610	-541	-581	-200	-466
CNC8		-410									
CNC9	-327		-307	-416	-439	-417	-480	-451	-486	-419	
CNC10	-319	-350									
CNC11	-422		-541	-492	-549	-510					
CNC12	-535		-506	-465							
CNC13		-600									
CNC14		-540									
CNC15	-418		-393	-485	-575	-393	-525	-3	-524	-410	
CNC16	-267		-332	-292	-319	-314					
CNC17	-227		-297	-229	-272	-255					
CNC18	-216		-323	-263	-306	-297	-380	-404	-421	-354	
CNC19		-560									
CNC20	-409		-572	-512	-563	-487					

Table 2.4 Chronological record of half-cell readings in the exposure tank, of specimens cast in 2000

Specimen	Half-cell readings in tank (mV)								
	2/15/2002	3/5/2002	1/10/2003	2/10/2003	12/4/2003	12/16/2003	27/04/2003	4/19/2005	10/25/2005
1	-308	-217	-339	-317	-420	-413	-450	-270	-442
2	-269	-180	-272	-278	-420	-420	-461	-380	
3	-283	-212	-308	-260	-320	-266	-330	-245	-348
4	-351	-345	-332	-335	-400	-395	-443	-405	
5	-363	-284	-424	-412	-460	-434	-489	-210	-394
6	-291	-284	-333	-338	-430	-371		-420	
7	-267	-252	-346	-320	-350	-348	-403	-245	-410
8	-389	-355	-373	-365	-430	-382	-452	-399	
9	-325	-271	-335	-283	-400	-386		-305	-334
10	-261	-184	-329	-331	-460	-337	-473	-360	
11	-321	-317	-287	-262	-555	-485	-506	-273	-351
12	-345	-415	-352	-345	-430	-374	-508	-470	
13	-230	-183	-261	-242	-280	-275	-324	-209	-345
14	-270	-253	-280	-262	-320	-5	-385	-316	
15	-287	-219	-253	-247	-350	-240	-342	-318	-313
16	-324	-305	-326	-327	-365	-356	-409	-376	
19	-536	-428	-527	-442	-410	3	-510	-415	

Table 2.5 Chloride content and half-cell readings after removal of wrap

Specimen	Autopsied Specimens Results			
	Average Chlorides (%)		Average half-cell (mV)	
	Unwrapped	Wrapped	Unwrapped	Wrapped
CC1	0.26	0.188	-383	-296
CC2	0.546	0.272	-341	-378
CC3		0.085		-225
CC4	0.303	0.114	-340	-296
CC5		0.2		-460
CC6		0.15		-460
CC7		0.22		-610
CC8		0.16		-257
CC9	0.307	0.25	-419	-342
CC10	0.337		-454	
CC11	0.29		-517	
CC12	0.566	0.271	-257	-250
CC13				
CC14	0.244	0.179	-271	-364
CC15	0.214	0.103	-477	-391
CC16	0.349		-403	
CC17	0.426		-534	
CC18	0.44		-590	
CC19	0.34	0.156	-339	-433
CC20	0.368	0.194	-274	-330
CC21	0.442		-407	
RC1				
RC3	0.08	0.082	-454	-315
RC4		0.35		-610
RC5	0.282	0.047	-438	-260
RC6				
RC7		0.12		-680
RC8	0.404			
RC9	0.284	0.126		
RNC1	0.184	0.001	-505	-339
RNC2	0.125		-412	
RNC4				
RNC5	0.636	0.302		
RNC6		0.002		-230
RNC7		0.21		-470
RNC8				
CNC1	0.367	0.136	-439	-403
CNC2		0.126		-454
CNC3	0.342	0.008	-397	-271

Specimen	Autopsied Specimens Results			
	Average Chlorides (%)		Average half-cell (mV)	
	Unwrapped	Wrapped	Unwrapped	Wrapped
CNC4	0.264	0.076	-460	-375
CNC6	0.352	0.053	-561	-401
CNC7	0.367		-418	
CNC8		0.17		-410
CNC9	0.506	0.033	-342	-410
CNC10		0.003		-350
CNC11	0.318		-463	
CNC13		0.12		-600
CNC14		0.02		-540
CNC15	0.435		-434	
CNC16	0.07	0.007	-515	-189
CNC17	0.12	0.001	-536	-94
CNC18	0.362	0.046	-389	-342
CNC19		0.13		-560
CNC20	0.414		-554	
S1	0.299	0.132	-489	-364
S2		0.179		-338
S3	0.238	0.135	-393	-335
S4		0.173		-362
S5	0.332	0.162	-365	-344
S6		0.126		-354
S7	0.294	0.166	-385	-316
S8		0.16		-360
S9	0.43	0.203	-351	-315
S10		0.355		-362
S11	0.446	0.218	-366	-330
S12		0.137		-359
S13	0.353	0.261	-367	-326
S14		0.13		-296
S15	0.453	0.147	-342	-295
S16		0.135		-333
S19	0.485		-373	

Note:

- Highlighted specimens are those that have been autopsied and are reported in this report..
- Readings are averaged in appropriate wrapped and unwrapped portions of the autopsied specimens.

Chapter 3

Discussion of Results*

3.1 INTRODUCTION

In the preceding chapter, an overview of the corrosion behavior of the reinforced concrete specimens was presented. The detailed analysis of each specimen is provided in Appendix A. The overall effectiveness of the FRP wraps and the influence of other parameters included in the study on the durability of reinforced concrete specimens in a corrosive environment are discussed in this chapter.

3.2 EFFECTIVENESS OF FRP WRAP

Of prime interest is the overall effect of the FRP wraps on reducing the corrosion of the embedded reinforcing steel. It has been hypothesized that a barrier (the wrapping material) traps chlorides or other contaminants in the concrete and exacerbates the corrosive process. An alternative view is that the FRP wrap might prove to be an effective barrier and retard chloride-induced corrosion. To determine the effectiveness of the FRP wrap, half-cell potential contours, chloride content profiles, and visual observations of corrosion on the reinforcing bars of different specimens are compared. For the specimens cast in 1998, FRP wraps were effective in inhibiting the corrosion process. Slight corrosion was observed under the wraps of the specimens cast in 2000. This may be due to the poor quality of concrete used to cast the specimens. But the amount of corrosion was small compared with the unwrapped specimens.

3.2.1 Comparison of half-cell potentials

Figure 3.1 shows half-cell profiles for unwrapped column specimens and Figure 3.2 shows the half-cell profiles for some of the fully wrapped specimens. For the unwrapped columns, the potentials lie primarily between -350 mV and -500 mV, indicating a very high probability of corrosion. For the fully wrapped specimens, the potentials range from -200 mV to -500 mV, indicating that after many cycles in the corrosion tank, it becomes increasingly difficult to predict the level of corrosion based only on half-cell readings. The half-cell readings, though, are very effective in indicating whether the probability of corrosion is very high or low. The half-cell potential profiles also provide a strong indication that the addition of FRP wrap reduces the likelihood of corrosion.

* This chapter supplements chapter 5 of Report 0-1774-3

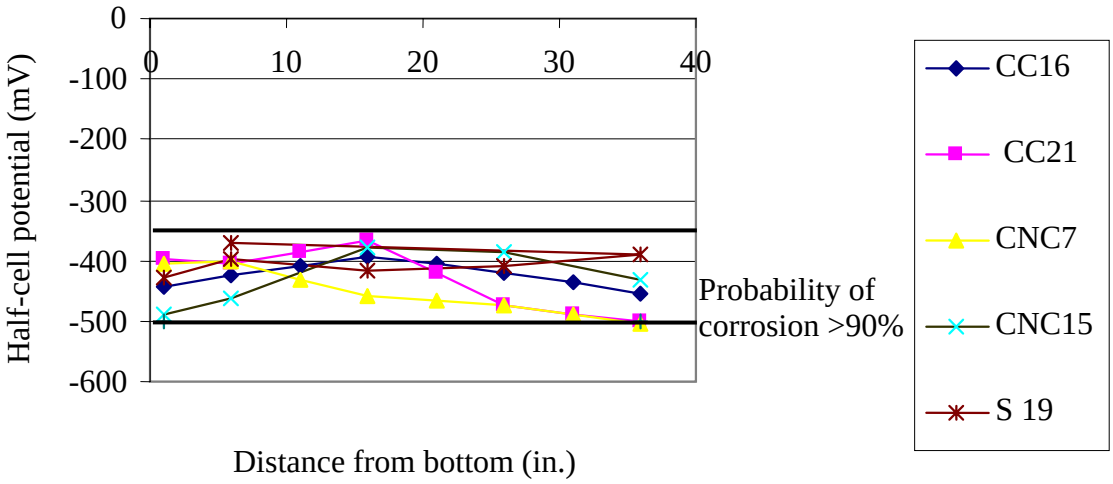


Figure 3.1 Half-cell potentials for unwrapped columns

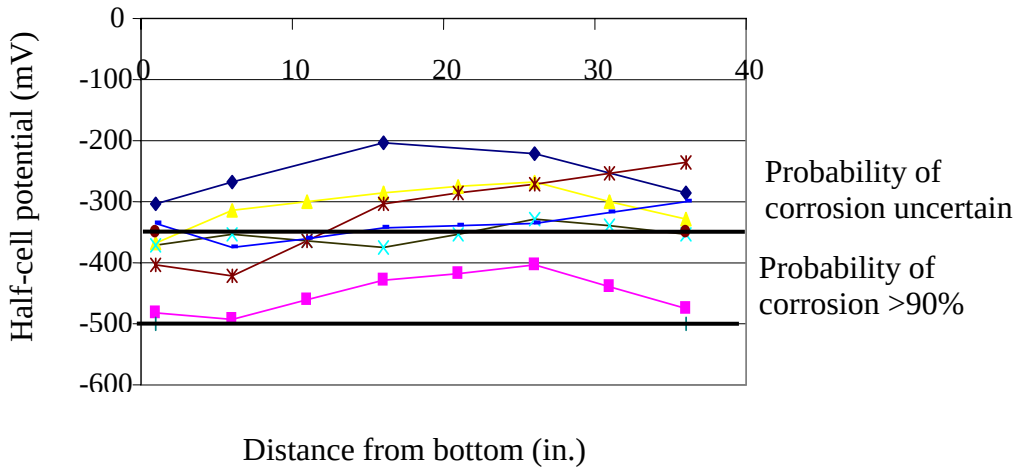


Figure 3.2 Half-cell potential profile for some of the fully wrapped specimens

Figure 3.3 shows the half-cell potential contour of a specimen CNC3, that was wrapped over the top 24 in. The half-cell readings clearly indicate that the FRP wrapping has reduced the likelihood of corrosion. Similar conclusions can also be drawn by looking at half-cell contour maps of other specimens such as CC1, CC8, CC9, CC19, CNC4, CNC18, S3, S5, S7, S11, S13 and S14. The details are given in Appendix A.

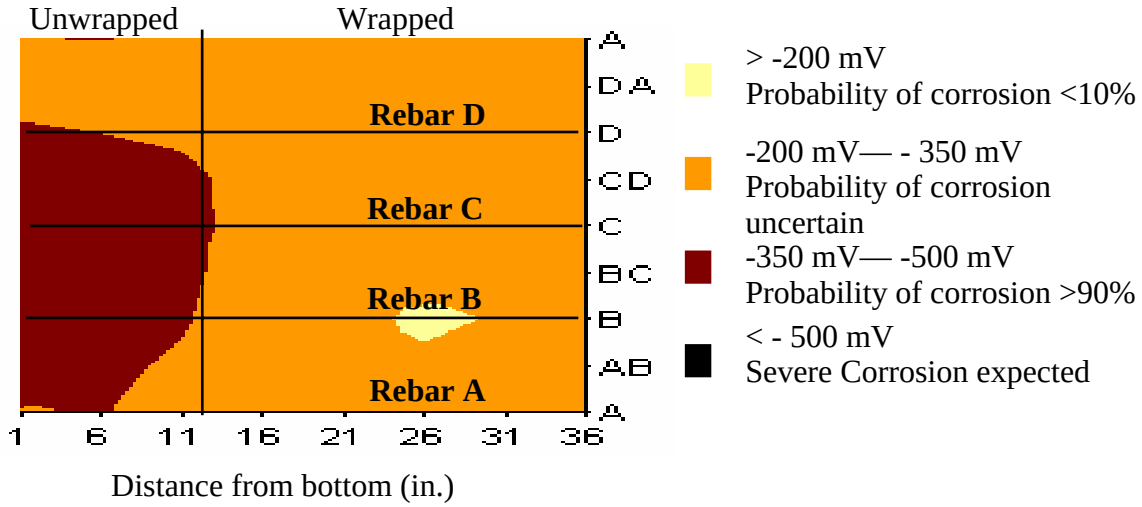


Figure 3.3 Half-cell potential contour for specimen CNC3

3.2.2 Comparison of chloride contents

The chloride contents of wrapped and unwrapped specimens clearly indicate that the FRP wrapping acts as a barrier to ingress of chlorides. Figure 3.4 shows the chloride content profiles of unwrapped specimens and Figure 3.5 shows the chloride profiles of some specimens wrapped over the top 24 in.

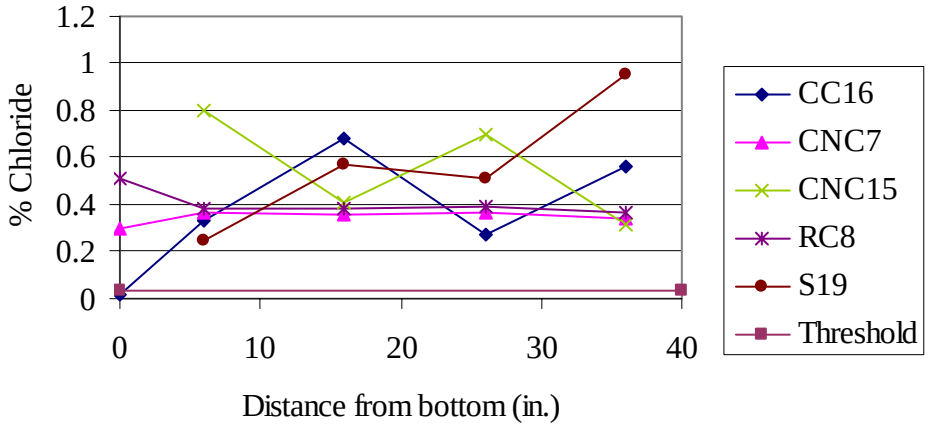


Figure 3.4 Chloride content profiles of unwrapped specimens

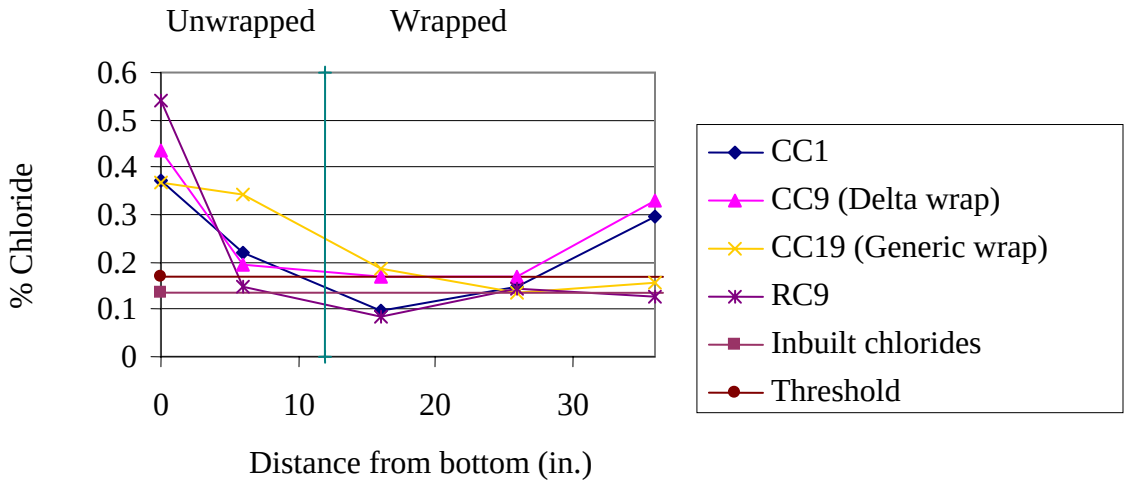


Figure 3.5 Chloride content profiles of specimens wrapped over top 24 in.

A threshold value of 0.03% chloride content as a percentage of weight of concrete is indicated in the figures. For the specimens containing inbuilt (added to the fresh concrete) chlorides (0.137% by weight of concrete), the threshold is considered as an additional 0.03% of migrating chlorides. For the unwrapped specimens, the chloride contents are much higher than the threshold value (Figure 3.4). For the partially wrapped columns, the chloride contents are high in the unwrapped portion but below the threshold in the wrapped portion (Figure 3.5). High chloride contents were found in the exposed upper end of the columns.

The observed corrosion on the extracted bars also corroborates the findings from half-cell readings and from the chloride contents that corrosion takes place in the unwrapped portion, but the FRP is effective in reducing corrosion in the wrapped portions of the partially wrapped columns. Similar results were found with specimen CC1, CC4, CC9, CC14, CC19, CC20, CNC1, CNC3, CNC4 and all the specimens cast in 2000. Refer to Appendix A for these details of the specimens.

The chloride content test is also an effective means of checking the level of corrosion in the concrete. By comparing the chloride content profiles and the photographs of the extracted rebars, the effectiveness of FRP wrapping as a protection strategy becomes clearer.

3.3 EFFECT OF OTHER VARIABLES

The effect of the various parameters such as cast-in chlorides, pre-cracking, repair material and use of corrosion inhibitors was also studied. Table 3.1 shows the percentage of half-cell readings that fall below the threshold of -350 mV (> 90% probability of corrosion), and whether corrosion was observed on rebars under the FRP wrap. The effect of different variables is then compared using these parameters.

Table 3.1 Effect of variables on half-cell potentials and corrosion

Specimen	% below -350 mV	Corrosion under wrap	Cast-in Chlorides	Wrap	Pre-cracked	Repair material	Corrosion inhibitor
CC1	42	No	Yes	Delta	Yes	None	Ferrogard
CC2	52	No	Yes	Gen/Del	No	LMC	None
CC4	27	No	Yes	Delta	No	LMC	None
CC8	2	No	Yes	Delta	Yes	LMC	None
CC9	53	No	Yes	Delta	No	None	None
CC12	0	No	Yes	Generic	Yes	None	None
CC14	50	No	Yes	Generic	No	LMC	Ferrogard
CC16	85	NA	Yes	None	No	EG	None
CC19	70	No	Yes	Generic	No	LMC	None
CC20	32	No	Yes	Generic	No	None	Ferrogard
CC21	80	NA	Yes	None	Yes	None	Ferrogard
RC1	32	No	Yes	Generic	No	LMC	Ferrogard
RC6	35	Yes	Yes	Generic	No	LMC	None
RC8	33	NA	Yes	None	No	LMC	None
RC9	15	No	Yes	Gen/Del	Yes	None	Ferrogard
RNC4	57	Yes	No	Generic	No	LMC	None
RNC5	26	No	No	Delta	Yes	None	None
RNC8	50	No	No	Generic	No	None	None
CNC1	100	No	No	Generic	Yes	Patch	None
CNC2	100	No	No	Generic	Yes	None	None
CNC3	32	No	No	Generic	No	None	Ferrogard
CNC4	62	No	No	Delta	No	None	None
CNC7	87	NA	No	None	No	None	Ferrogard
CNC9	52	No	No	Generic	No	LMC,patch	None
CNC15	100	NA	No	None	Yes	None	None
CNC18	57	No	No	Generic	No	LMC	Ferrogard
S1	75	Slight	Yes	Delta	Yes	None	Surtreat
S2	30	Slight	Yes	Delta	Yes	None	Surtreat
S3	47	Slight	Yes	Delta	No	None	Surtreat
S4	62	Yes	Yes	Delta	No	None	Surtreat
S5	67	Slight	Yes	Delta	Yes	None	Cortec
S6	45	No	Yes	Delta	Yes	None	Cortec
S7	37	No	Yes	Delta	No	None	Cortec
S8	47	Slight	Yes	Delta	No	None	Cortec
S9	30	Slight	Yes	Delta	Yes	None	Sika
S10	55	Slight	Yes	Delta	Yes	None	Sika
S11	47	Slight	Yes	Delta	No	None	Sika
S12	57	Slight	Yes	Delta	No	None	Sika
S13	40	Slight	Yes	Delta	Yes	None	None
S14	5	Slight	Yes	Delta	Yes	None	None
S15	25	No	Yes	Delta	No	None	None
S16	22	Slight	Yes	Delta	No	None	None
S19	75	NA	Yes	None	Yes	None	None

3.3.1 Cast-in chlorides

Half-cell potential readings were lower for specimens that had no chlorides cast in the concrete (Table 3.1). This indicated that the presence of cast-in chlorides may have reduced the effectiveness of the wrap. But after extracting the reinforcing bars it was observed that corrosion was not extensive. The FRP wrap was almost equally effective for concrete with and without cast-in chlorides. The FRP acts as a barrier to the ingress of chlorides, moisture and oxygen, and was effective in reducing corrosion. Figure 3.6 shows the extracted reinforcing bars from specimen CNC2 that had in-built chlorides and was wrapped com0pletely. Figure 3.7 shows the extracted rebars from specimen CC8 that had no in-built chlorides and was completely wrapped. As se0010en from the figures, FRP wrapping was effective for both specimens. Other specimens show similar results.

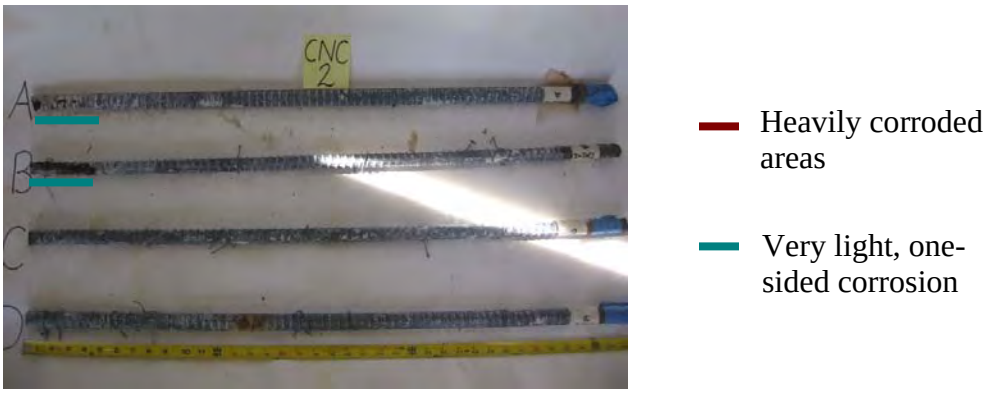


Figure 3.6 Extracted bars from CNC2

Figure 3.7 Extracted bars from CC8

3.3.2 Unwrapped specimens

For the specimens that were not wrapped, the percent of readings below -350 mV was considerably higher than the wrapped specimens. The chloride contents were also over the threshold value indicating the ingress of chlorides. For the wrapped specimens, the percentage of

migrating chlorides was lower than the threshold, indicating that the FRP wrap acted as a barrier to the ingress of chlorides. The bars were badly corroded and showed a loss of cross-section. Figure 3.8 shows the extent and level of corrosion in an unwrapped specimen.

Figure 3.8 Corrosion of bars in unwrapped specimen

3.3.3 Repair material

All the repaired specimens that were autopsied had been repaired using Latex-Modified Concrete. LMC repair material is less permeable than ordinary concrete, and it was observed that the chloride content levels below the repair material were very low. After removal of the reinforcing bars, it was observed that no corrosion had taken place below the repair material even in unwrapped regions. The LMC also acted as a barrier for the ingress of chlorides. Figure 3.9 shows the difference in the chloride contents below LMC repaired concrete and areas that were not repaired for specimen CNC9. Figure 3.10 shows the corrosion on reinforcing bars below the repair material. Similar results were observed in specimens CC2, CC4, CNC9 and CNC18.

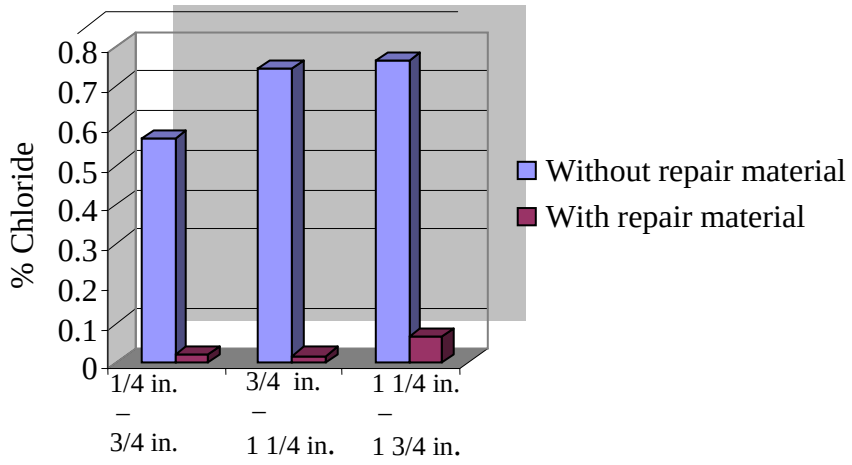


Figure 3.9 Chloride contents of concrete covered with repair material

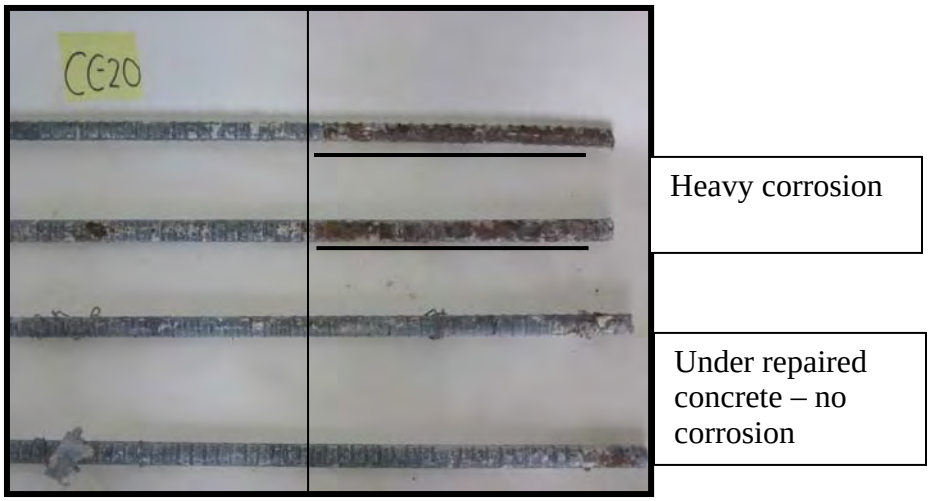


Figure 3.10 Corrosion of bar under repair material

3.3.4 Pre-cracking

The average chloride content for the pre-cracked and cracked specimens was nearly the same. The half-cell potential readings were not influenced by pre-cracking. The corrosion observed on extracted rebars indicated no difference based on pre-cracking. The FRP wrapping was equally effective on cracked or un-cracked specimen.

3.3.5 Corrosion inhibitors

Some specimens were treated using Ferrogard corrosion inhibitor. The inhibitor was generally ineffective in preventing corrosion in the unwrapped region. Specimen CC21 was not wrapped and was treated with Ferrogard. The level and amount of corrosion in CC21 was less compared with other unwrapped specimens. Ferrogard also seemed to be effective in the unwrapped regions of specimens CC1 and CC14. Figure 3.11 shows bars extracted from specimen CC15. Bars in the unwrapped portion were not corroded, possibly due to the presence of Ferrogard. However, there is insufficient data to assess the effectiveness of the Ferrogard corrosion inhibitor.

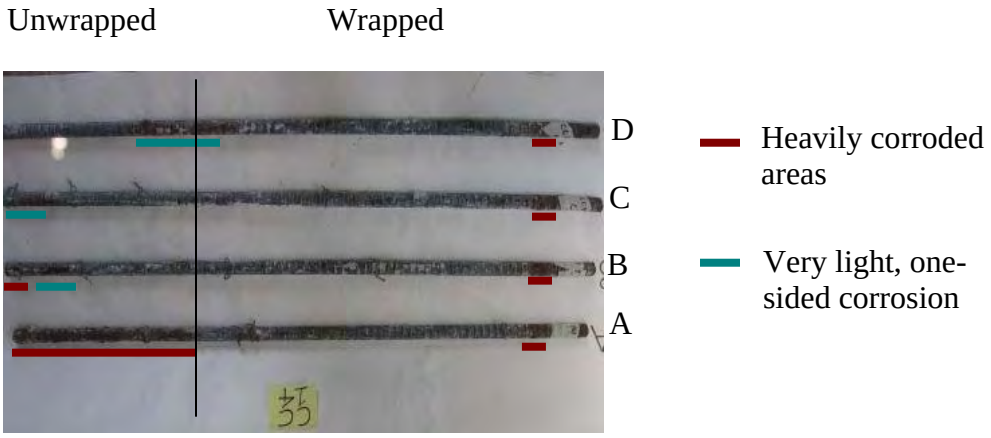


Figure 3.11 Bars extracted from specimen CC14

The specimens cast in 2001 were treated using either Surtreat, Sika or Cortec. None of these inhibitors was found to be very effective in unwrapped regions. Specimens treated with inhibitor Cortec had no corrosion under the wrap while other specimens with the other inhibitors were lightly corroded even in some areas beneath the FRP wrap. There was no marked difference between specimens that were treated with the inhibitors and those that were not

3.3.6 Type of wrap material

Two types of wrap material and resin were used, one from Delta Technologies and the other, a generic system developed in the lab. There was no marked difference in the performance of both the wrap systems. In Figure 3.5, CC9 had a Delta wrap and CC19 had a generic wrap. As can be seen, both performed similarly. The trademarked Delta material was easier to apply and had a better appearance than the generic materials. The type of resin did not appear to make a difference in the performance.

Chapter 4

Condition of FRP-Wrapped Bridges in Report of Lubbock*

4.1 INTRODUCTION

A field trip was made to the Lubbock district on 18 & 19 April, 2006 to monitor substructures of highway overpass bridges in Lubbock and Slaton, TX. Table 4.1 lists the location of the structures in the study. Wrapping of the bridges was completed in Fall 1999. Details of the wrapping process and installation of probes has been described in Reports 0-1774-1 and 0-1774-2. Additional VETEK probes were installed in bridge 13.

Table 4.1 Location of structure repaired with FRP composite

Structures	City	Interchange
1 – 2	Lubbock	State Loop 289 over Municipal Drive
3 – 8	Lubbock	US 62/82 & State Loop 289
9 – 10	Slaton	US 84 over FM 41
11 – 12	Slaton	US 84 over FM 400
13 – 16	Lubbock	US 87 over 82nd St, 98th St, 114 St, FM 1585

In Table 4.2, the locations where probes were installed to monitor corrosion activity are listed. Locations of the bridges are shown in Figure 4.1 and Figure 4.2.

Table 4.2 Concorr probe installation locations

ID#	Structure	Bent	Beam Face	Distance from End (ft.)	Steel Area (in^2)
7.1	7	7	Left	7.5	44.30
7.2	7	7	Right	4	44.30
8.1	8	4	Left	4	44.30
8.2	8	4	Right	4	44.30
8.3	8	5	Left	4	44.30
8.4	8	5	Right	4	22.15
12.1	12	1	Left	4	44.30
12.2	12	1	Right	4	44.30
12.3	12	3	Left	4	44.30
8	13	Exterior, top of bent caps			44.30
10	13	Interior, top of bent caps			44.30
11	14	Exterior, top of bent caps			44.30

* This chapter supplements the condition assessment in Report 0-1774-2 (Section 5.3)

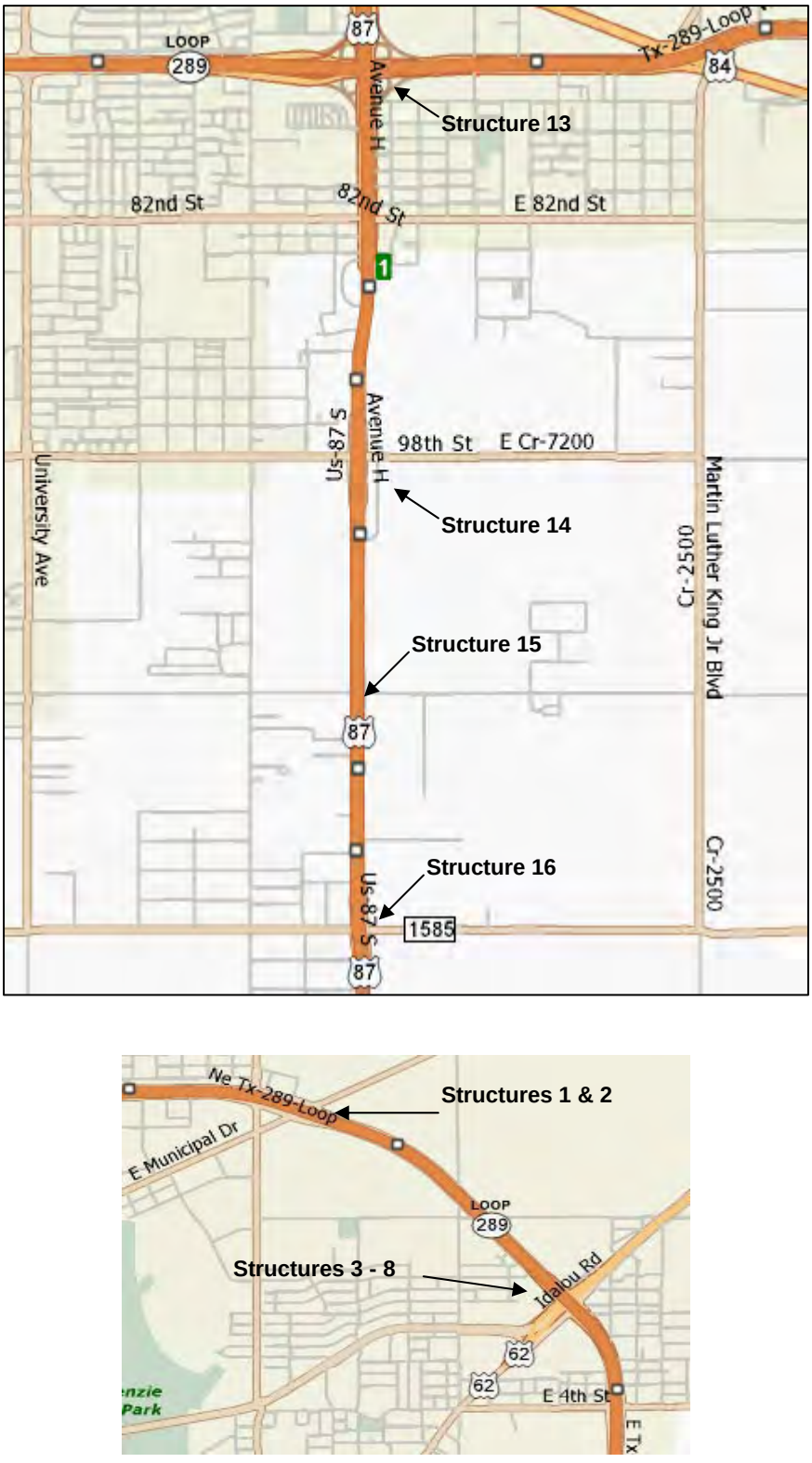


Figure 4.1 Location of bridges in Lubbock with wrapped elements

Figure 4.2 Location of bridges in Slaton with wrapped elements

4.2 FIELD INSPECTION

All the bridges were visually inspected for any signs of corrosion such as rust spots or cracking on the surface of the wrap. In addition, readings were taken from the embedded probes. In bridges that showed a high probability of corrosion based on the embedded probe readings, samples were taken to determine the concentration of chlorides. The details of each structure are as follows:

Structure 1, West bound State Loop 289 over Municipal

Figure 4.3 Rust staining on bent

Figure 4.4 Rust staining on bent, Structure 1

Rust staining was observed on the bent cap on Structure 1 (Figure 4.3 and Figure 4.4). Rusting had also been observed on this bent in an earlier report (1774-2), but it seems to have increased and spread to more areas. The rust stains were observed near the end of the bent cap, near the column joint and on the underside of the bent. No probes had been embedded in this structure. Chloride samples were extracted and the results are shown in Table 4.3

Table 4.3 Concentration of chlorides, Structure 1

	Threshold	% Chlorides
Structure # 1	0.03	0.355

Structure 2, East bound

No rust stains or cracks were observed on Structure 2.

Figure 4.5 Structure 2

Structure 5, US 62/82 and State Loop 289

A crack was observed on the under-side of the bent on Structure 5 where the FRP fabric sheets overlap (Figure 4.6). No rust staining was observed near the crack or anywhere else on the bent.

Figure 4.6 Crack on underside of bent on Structure 5

Structure 6

No cracking or rust stains were observed on Structure 6.

Structure 7, West bound

No cracking or rust stains were observed on Structure 7. The upper layer of FRP wrap has been damaged in one of the columns, but the inner layers were intact (Figure 4.7). Results from the embedded probes are shown in Table 4.4.

Figure 4.7 Damage on the upper layer of FRP wrap, Structure 7

Table 4.4 Embedded Concorr V probe readings, Structure 7

	Probe reading (mV)	ASTM Interpretation
Probe 7.1	-278	Probability of corrosion uncertain
Probe 7.2	-473	Probability of corrosion > 90%

Structure 8, East bound

No cracking or rust stains were observed on Structure 8. Results from four embedded probes are shown in Table 4.5 and indicate that the probability of corrosion was uncertain. Cracks were observed at the ends of prestressed girders along with spalling of concrete and rust stains (Figure 4.9)

Figure 4.8 Location of embedded probe in Structure 8

Figure 4.9 Cracking and Spalling of concrete at the end of girder, Structure 8

Table 4.5 Embedded Concorr V probe readings, Structure 8

	Probe reading (mV)	ASTM Interpretation
Probe 8.1	-453	Probability of corrosion > 90%
Probe 8.2	-322	Probability of corrosion uncertain
Probe 8.3	-264	Probability of corrosion uncertain
Probe 8.4	-301	Probability of corrosion uncertain

Structure 9 and 10, US 84 over FM 41 (Slaton)

Only the columns were wrapped in these structures. No rust stains or cracking were observed. No probes were embedded.

Structure 12, Over FM 400

Some of the columns in this structure were wrapped with carbon fibers instead of the glass fibers as used in all the other structures. Air bubbles were observed under these carbon wraps along with small rust stains all over the column (Figure 4.10). No rust stains or cracks were observed on other columns wrapped with the glass fibers. Readings from the embedded probes are shown in Table 4.6.

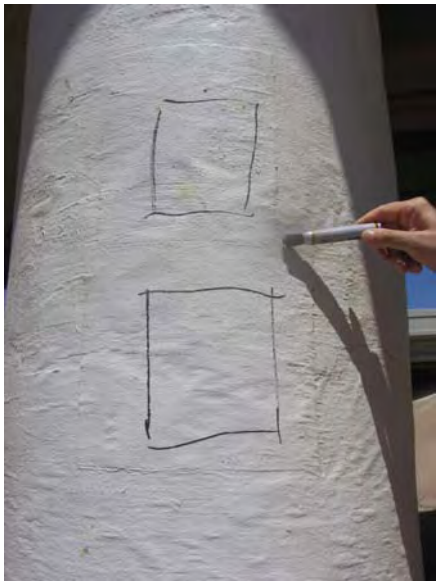


Figure 4.10 Air bubbles under the carbon fiber wrap along with rust stains, Structure 12

Table 4.6 Embedded Concorr probe readings, Structure 12

	Probe reading (mV)	ASTM Interpretation
Probe 12.1	-222	Probability of corrosion uncertain
Probe 12.2	-361	Probability of corrosion > 90%
Probe 12.3	-208	Probability of corrosion uncertain

Structure 13, US-87 over 82nd St

No rust stains or cracking were observed. Readings from the Concorr embedded probes are shown in Table 4.7. Readings from the VETEK probe are shown in Table 4.8. Chloride samples were taken from two locations on the bent cap and the concentration of chlorides is given in Table 4.9.

Figure 4.11 US 87 over 82nd St.

Table 4.7 Embedded Concorr probe readings, Structure 13

	Probe reading (mV)	ASTM Interpretation
Probe # 10 (Top end of bent cap)	-548	Severe corrosion expected
Probe # 8 (Inside, top of bent cap)	-525	Severe corrosion expected

Table 4.8 VETEK probe readings, Structure 13

Location of probe	**Gold Probe (mV)**	**Silver Probe (mV)**	**Vetek Interpretation**	**$Cu/CuSO_4$ Equivalent (mV)**	**ASTM Interpretation**
Bent (inside)	-349	336	Active corrosion	-429	> 90% probability of corrosion
Bent (outside)	-313	316	Begun / Active corrosion	-410	> 90% probability of corrosion
Column	4.3	0	No active corrosion	-94	< 10% probability of corrosion

Table 4.9 Concentration of chlorides, Structure 13

	Threshold	% Chlorides
Bent (outside)	0.03	0.04
Bent (inside)	0.03	0.19

It is interesting to note that chloride levels are sufficient to produce corrosion and the Concorr embedded probes indicate that corrosion is expected. The VETEK probes in the bent caps also indicate > 90% probability of corrosion.

Structure 14, Over 98th St

No rust stains or cracking were observed. The readings from the embedded Concorr probe are shown in Table 4.10. Readings from the VETEK probes are shown in Table 4.11.

Table 4.10 Embedded Concorr probe readings, Structure 14

	Probe reading (mV)	ASTM Interpretation
Probe # 11 (Exterior end, top of bent cap)	-348	Probability of corrosion uncertain

Table 4.11 VETEK probe readings, Structure 14

Location of probe	**Gold Probe (mV)**	**Silver Probe (mV)**	**Vetek Interpretation**	**Cu/$CuSO_4$ Equivalent (mV)**	**ASTM Interpretation**
Bent (inside)	-264	242	No action / Damage has begun	-336	probability of corrosion uncertain
Bent (outside)	-172	228	No action / Damage has begun	-322	probability of corrosion uncertain
Column	-27	0	No active corrosion	-94	< 10% probability of corrosion

For Structure 14, the Concorr and VETEK probes both indicate low or uncertain probability of corrosion.

Structure 15, Over 114th St

No rust stains or cracking was observed. No probes were embedded.

Structure 16, Over 1585

No rust stains or cracking was observed. No probes were embedded.

Observations

Visual inspection of structures may not give an indication of corrosion activity taking place. Some of the probe readings indicated a high probability of corrosion taking place which was confirmed by the chloride content tests on samples extracted from the bent caps, but there was no visible evidence of corrosion.

Monitoring of these structures should be continued because the Lubbock bridges offer the best opportunity for field assessment of FRP wrapping. In locations where the embedded probes indicate high probability of corrosion, it would be desirable to remove the wrap material and the concrete and assess the condition of the bars. It should be noted that the Concorr probes are no longer supported by the supplier so it will be difficult to continue the use of these probes to monitor corrosion. However, the VETEK probes are available and produce results consistent with the Concorr readings and consistent with visual observations.

Chapter 5

Summary and Conclusions

5.1 SUMMARY

Project 0-1774 was designed to develop a greater understanding of the long-term effects of FRP wrapping in preventing corrosion in reinforced concrete structures. Although both rectangular and cylindrical specimens were included, the focus of this report is on the specific impact of FRP wraps on partially wrapped versus unwrapped columns. However the observations made from autopsies of the beam specimens correlate closely with the column results but the number of beams is quite small and the manner in which they were exposed to the salt water in the tank was also different. For the specimens included in this supplement, a wide range of construction parameters were included. Despite the lack of comparison specimens to better assess variability of results, definite trends have emerged from the data gathered. The field assessment of wrapped elements in the Lubbock District provided an opportunity to examine the feasibility of two systems of monitoring corrosion activity. Both provided data that correlated with chloride contents, but only the VETEK system removes remains available on the market.

5.2 CONCLUSIONS

The major conclusions are as follows:

1. FRP wrapping was effective in reducing corrosion activity in the test specimens. The FRP provided a barrier to the migration of chlorides throughout the height of the column. The migrating chloride concentrations in the wrapped region were less than the threshold value. The half-cell potential readings were higher in the wrapped portions, indicating a reduced probability of corrosion. The condition of the extracted bars corroborated the results from half-cell potential readings and chloride contents.

2. FRP wrapping was effective even on partially wrapped specimens.

3. The FRP wrap was equally effective for concrete with and without cast-in chlorides.

4. Pre-cracking did not change the effectiveness of FRP wrapping.

5. Latex-modified concrete repair material appeared to play a significant role in preventing corrosion. The chloride contents under a repaired area were noticeably less than in unwrapped portions of the column.

6. Ferrogard was the only inhibitor that slightly reduced corrosion in four specimens. Other surface applied corrosion inhibitors such as Surtreat, Sika and Cortec, did not seem to be very effective in the highly corrosive exposure conditions used in the test program.

7. The half-cell potential test and the chloride content test were effective methods to assess the level of corrosion in structures. Probes embedded in the field (wrapped bridge members in Lubbock District) gave consistant results and correlated well with chloride concentrations.

While the chronological record of these measurements provides an indication of the level of corrosion, the fact only one location was sampled in the wrapped portion makes it difficult to assess overall corrosion behavior based on one value. An extensive analysis of half-cell potentials over the entire surface after the wrapping was removed was more conclusive. It would have been highly informative if some specimens had been wrapped after being exposed to the corrosive elements in the tank. This would have simulated a more realistic situation than the cast-in chlorides, since the migrating chlorides contribute most towards corrosion but their effect can not be isolated.

Chapter 6

Guidelines for the Selection and Use of Wrapping Materials

Project 0-1774 has provided data on exposure testing of specimens wrapped with layers of glass/fiber composites and resin that can be used to guide future use of these materials in regions of exposure to a corrosive environment. The purpose of these Guidelines is to translate those findings into practical application of wrapping techniques in the field.

6.1 PRIMARY FINDINGS

- FRP reduced the corrosive activity in the test specimens acting as a barrier to the ingress of chlorides and moisture. The increase in chloride concentrations in wrapped regions was lower than in unwrapped regions and reinforcement in the wrapped regions exhibited less corrosion as well. Even when chlorides were added to the concrete to accelerate the corrosion activity, wrapping lowered the migration of additional chlorides and reduced the available moisture so that corrosion in the wrapped regions was less severe.

- FRP wrapping was effective in reducing corrosion activity in partially wrapped specimens, however, the performance was better when a greater surface area of the specimen was wrapped.

- The presence of cracks in the wrapped members did not reduce the effectiveness of the wrap.

- Both trademarked and generic wrapping materials were used. There was little difference in the performance of the materials in the exposure testing. The primary difference is the ease of application. The trademarked materials were easier to install and had an improved appearance.

- Specimens that were repaired before wrapping performed well if the permeability of materials used in repair was low. Latex-modified concrete performed particularly well as a repair material.

- Chloride inhibitors did not perform well and there was no conclusive evidence that corrosion activity was changed in specimens treated with inhibitors.

- Field evaluation of bridges in the Lubbock District that were wrapped provides a means of evaluating the performance of wrapping techniques in the field. VETEK Probes installed as part of this project to monitor corrosion activity appear to be functioning well and are available on the market. Concorr probes are no longer supported by the manufacturer. While probes and chloride contents indicate a fairly high probability of corrosion in some of those bridges, it will be important to continue monitoring and to visually examine the condition of the reinforcement in those cases where severely damaged elements have been repaired and wrapped.

6.2 IMPLEMENTATION

- In highly corrosive environments, use of FRP wrapping is likely to extend the life of bridge structures. The quality of the installation is critical. The choice of materials can be left to the contractor but should be approved and installation monitored by TxDOT personnel. (Laminating resins must be UV resistant, wet out the fiberglass, and stay bonded to concrete. This suggests only lower viscosity laminating epoxies or possibly vinyl esters, but it prohibits typical less-expensive unsaturated polyester laminating resins, because they debond over time due to concrete's alkalinity attack of the double bonds.)

- Where the structural members are repaired before wrapping, the materials used should have low permeability. If existing concrete is removed and replaced, such removal should extend far enough to expose reinforcement that exhibits corrosion damage. All corroded reinforcement should be cleaned. Care should be taken to prevent chlorides from penetrating through bridge deck joints and reaching the unprotected portions of top surfaces of bent caps.

- Probes to monitor corrosion activity should be installed on selected structures. When elements are wrapped, it is impossible to monitor corrosion activity visually, take half-cell readings on the surface of the concrete, or extract samples to assess chloride concentrations.

6.3 RECOMMENDATIONS

- Routine monitoring of the wrapped structures in the Lubbock District should be continued. Where wraps are used in the future, probes should be embedded in those structures and routine monitoring and inspection schedules should be established.

- Although no tests were conducted on the use of other barrier materials as alternates to FRP wrapping, the tests conducted in Project 0-1774 indicate that the FRP wraps function primarily as barriers to the ingress of chlorides and moisture. It would be of interest to examine the use of paints or other barriers that would function in a similar manner. If such materials are shown to be effective, cost and installation time should be reduced. It should also be easier to access the concrete and monitor corrosion activity because the barrier could be repaired after inspection is completed.

Appendix A

Detail Condition Assessment *

Introduction

Twenty two specimens were removed from the exposure tank and autopsied in Spring 2005 and the remaining 21 specimens were removed in Fall 2005. Descriptions of the specimens are to facilitate comparisons. The detailed analysis includes visual inspection of the surface before and after removal of the wrap, plots of half-cell potential contours, tabulation of chloride contents and plots of chloride content profiles, and visual observations of the extracted rebars.

* Appendix A is a supplement to chapter 4 of Report 0-1774-3

A1. CC1

Wrap	Delta – 24 in.
Resin	Tyfo S
Surface at	Dry
Crack Condition	Cracked
Repair Material	None
Corrosion Inhibitor	Ferrogard

Cylinder CC1 wrapped till 12 in. from bottom.

Cylinder CC1 after removal of wrap. Top 3 in. not consolidated properly.

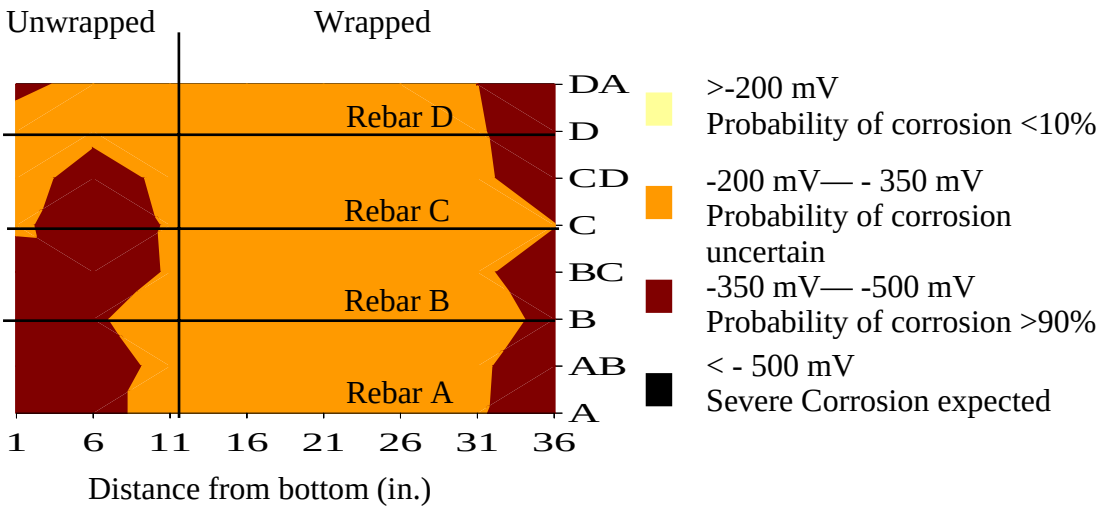
Visual Inspection:

1) The cylinder was wrapped except for 12 in. from the bottom.
2) No major cracks were visible in either wrapped or unwrapped area.
3) Heavy discoloration was observed in exposed areas.
4) After removal of wrap, it was observed that the top 3 in. in area AB were not consolidated properly.

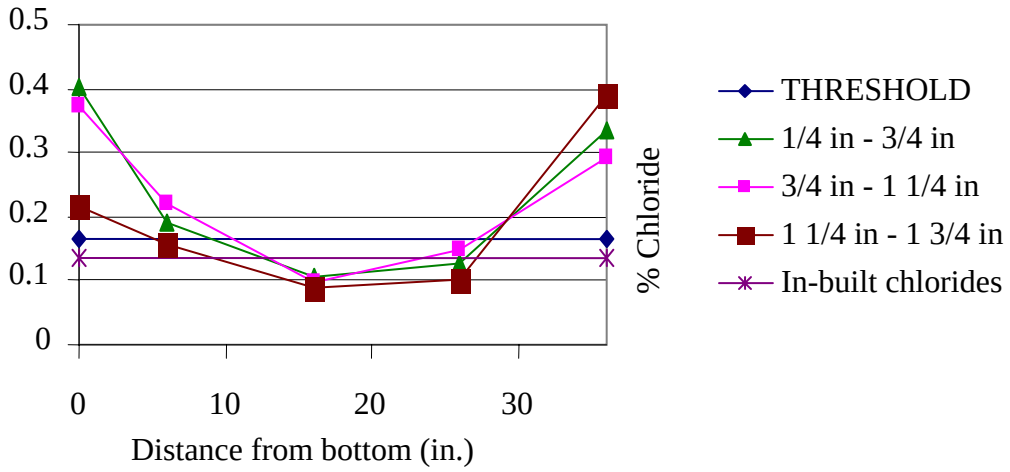
Comments:

1) No corrosion was observed except on the bottom few inches of rebars C and D.
2) Though the bottom 12 in. was not wrapped, there was hardly any corrosion in those areas. This is in contrast to other specimens where heavy rusting was observed in unwrapped areas. This could be due to the presence of corrosion inhibitor Ferrogard.

Half-Cell Potential Contour:



Chloride Content Profiles:



Corrosion of rebars:

A2. CC2

Wrap	Gen/Del – 30 in.
Resin	Tyfo S
Surface at	Wet
Crack Condition	Uncracked
Repair Material	LMC
Corrosion Inhibitor	None

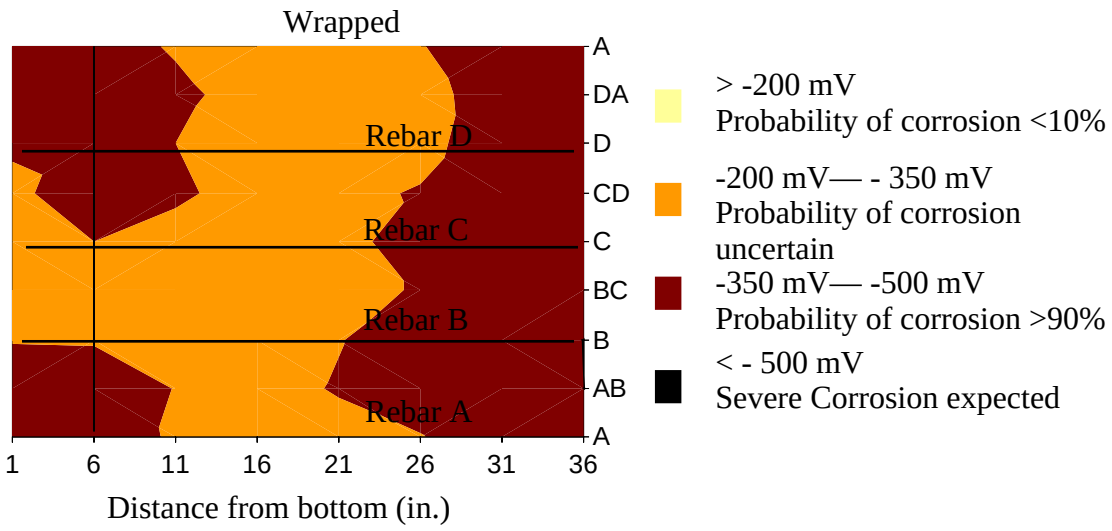
Cylinder CC 2 wrapped over 30 in.

Repair patch and rust stain over rebar B.

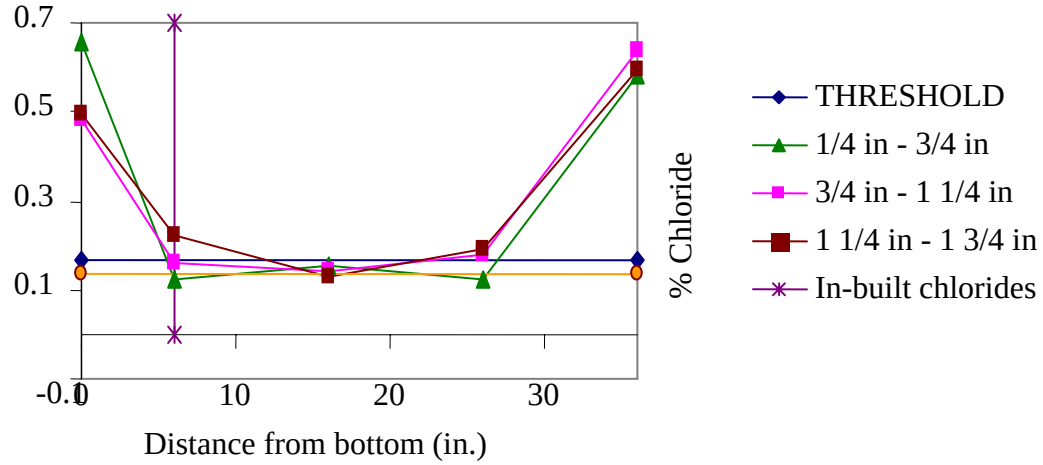
Visual Inspection:

1) The cylinder was wrapped over top 30 in.
2) The wrap was intact at all places.
3) A vertical crack of width 0.016 in. was observed over 0 in- 2 in. over rebar D.
4) A rust spot (3 in.× 2 in.) was found over rebar A.
5) A vertical crack of width 0.08 in. was observed over 0 in- 3 in. over rebar B.
6) After removal of wrap, repair patch was visible over bottom 18 in. at area DC-C-B and till 8 in. at areas BA-A-D-DC.

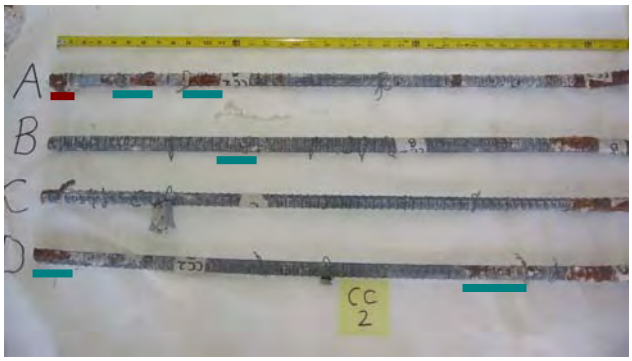
Half-Cell Potential Contour:



Chloride Content Profiles:



Corrosion of rebars:



Heavily corroded areas

Very light, one-sided corrosion

A3. CC4

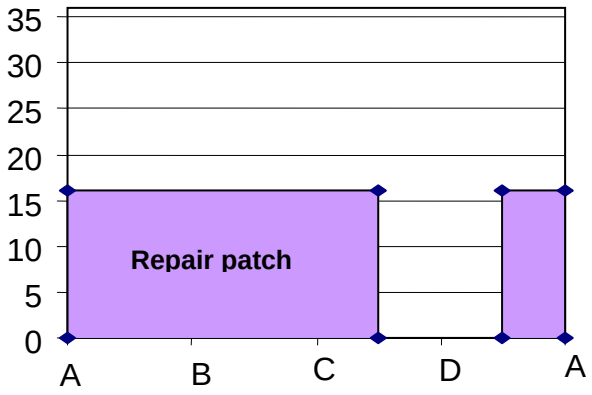
Wrap	Delta – 24 in.
Resin	Tyfo S
Crack Condition	Uncracked
Repair Material	LMC
Corrosion Inhibitor	None

Cylinder CC4 wrapped over top 24 in.

Repair patch over lower portion.

Visual Inspection:

1) The cylinder was wrapped over the top 24 in.
2) The surface of the concrete was not finished properly in the unwrapped region.
3) A 0.016-in.vertical crack was observed over rebar A extending over the lower 2.5 in.
4) The top 6 in. of concrete was not consolidated properly near rebar D and C.
5) A repair patch was visible as shown in the figure.

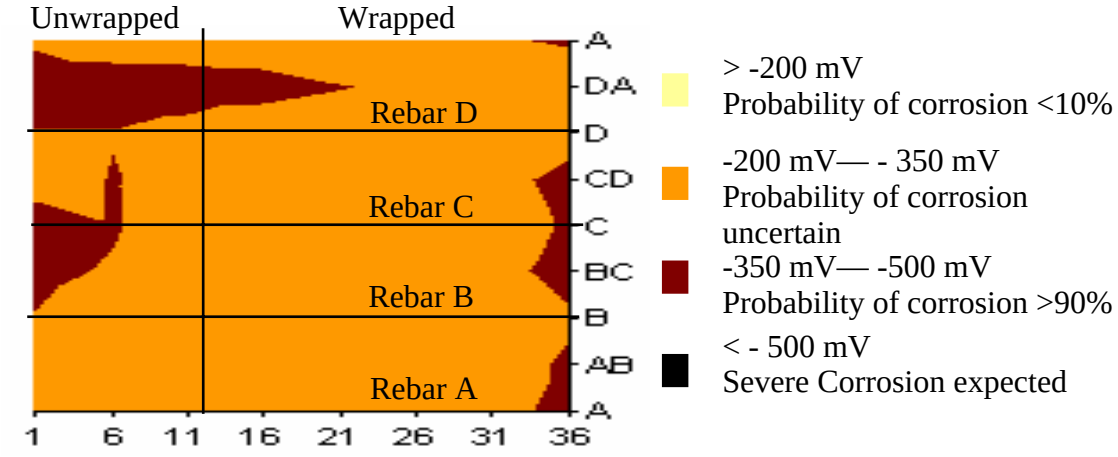


Comments:

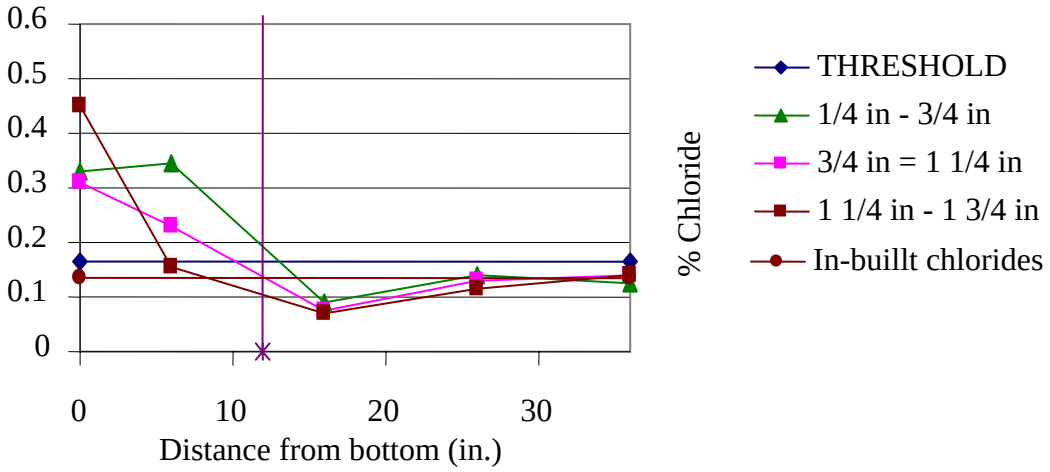
1) Heavy corrosion was not observed anywhere on the bars since the unwrapped portions of the bars were covered with repair material.

2) The half-cell potential contour and the chloride content profile corroborated with the corrosion observed on the extracted rebar.

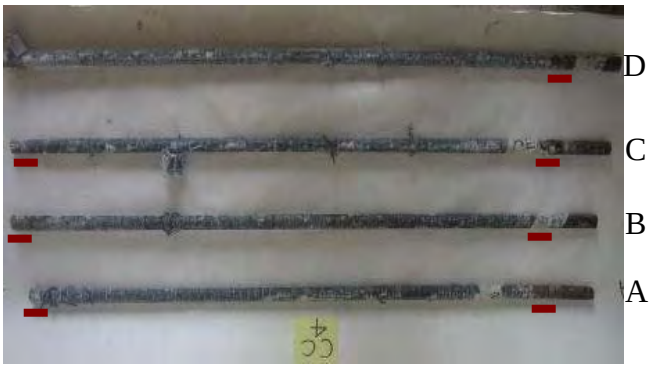
Half-Cell Potential Contour:



Chloride Content Profiles:



Corrosion of rebars:



A4. CC8

Wrap	Delta – 36 in.
Resin	Tyfo S
Surface at	Dry
Crack Condition	Cracked
Repair Material	LMC
Corrosion Inhibitor	None

Cylinder CC8 wrapped completely.

Moisture under the wrap over bottom region of rebar B.

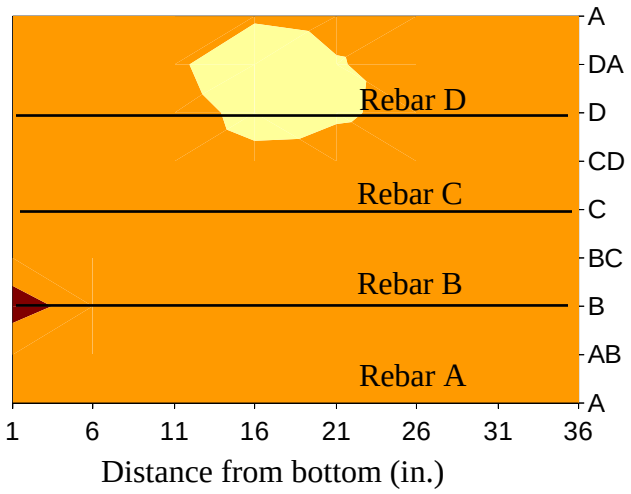
Visual Inspection:

1) The cylinder was wrapped completely.
2) The wrap was intact at all places.
3) On removal of the wrap, trapped moisture accompanied with green colored staining was observed near the bottom over rebar B.
4) Repair patch was observed over bottom 18 in. extending over areas BA-A-D-DC.
5) A horizontal crack was observed on the repair patch in area AD at 5 in. above bottom. It appeared that two layers of repair patch had been applied.

Observations:

1) Rebars in cylinder CC8 were not corroded. The chloride content is below the threshold level. The wrap has been effective in inhibiting corrosion.

Half-Cell Potential Contour:



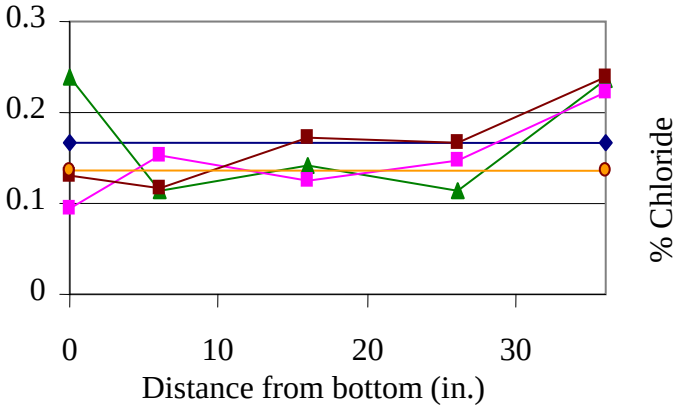
> -200 mV
Probability of corrosion <10%

-200 mV— - 350 mV
Probability of corrosion uncertain

-350 mV— -500 mV
Probability of corrosion >90%

< - 500 mV
Severe Corrosion expected

Chloride Content Profiles:



THRESHOLD
1/4 in - 3/4 in
3/4 in - 1 1/4 in
1 1/4 in - 1 3/4 in
Inbuilt Chlorides

Corrosion of rebars:

Heavily corroded areas

Very light, one-sided corrosion

A5. CC9

Wrap	Delta – 24 in.
Resin	Tyfo S
Surface at	Dry
Crack Condition	Uncracked
Repair Material	None
Corrosion Inhibitor	None

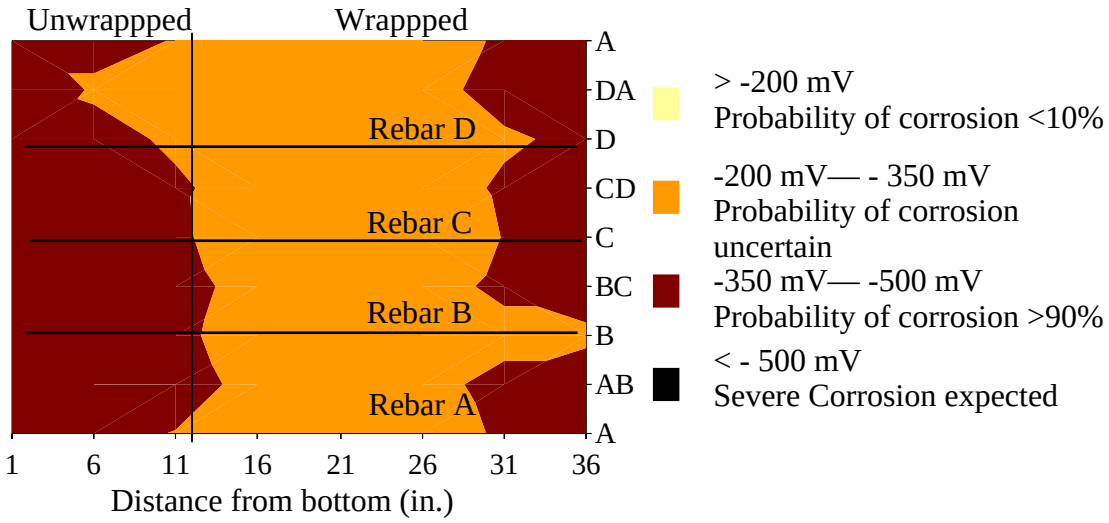
Cylinder CC9, with wrap over top 24 in.

Detail of unwrapped region over rebar A.

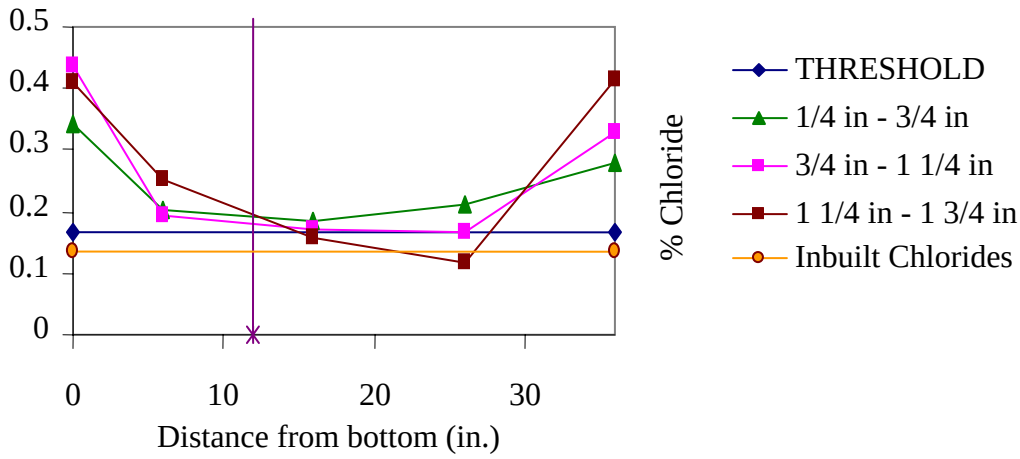
Visual Inspection:

1) The cylinder was wrapped over top 24 in.
2) The wrap was intact at all places.
3) Concrete had spalled-off in the bottom region over rebar A. Rust stains were visible underneath.
4) A horizontal crack of width 0.03 in. was observed 2 in. above bottom over area CD-B-BA.

Half-Cell Potential Contour:



Chloride Content Profile:



Corrosion of rebars:

Heavily corroded areas

Very light, one-sided corrosion

A6. CC12

Wrap	Generic -30 in.
Resin	862
Surface at	Wet
Crack Condition	Cracked
Repair Material	None
Corrosion Inhibitor	None

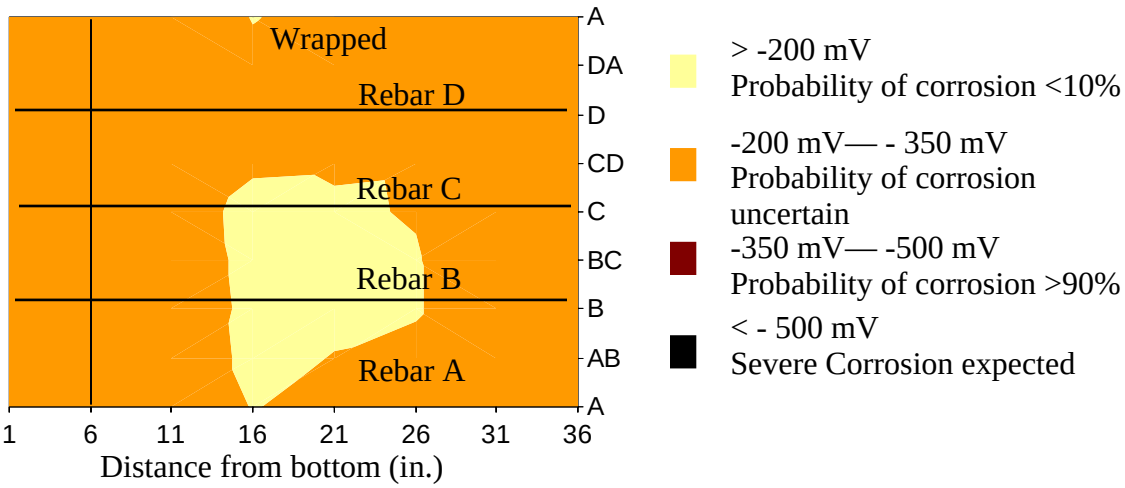
Cylinder CC12 covered with FRP wrap.

Detail of cracks and rust stains in unwrapped.

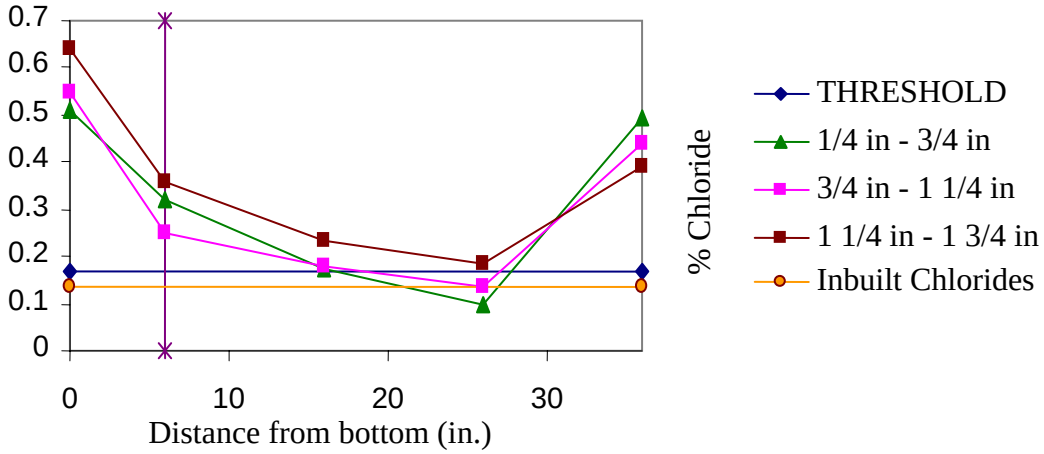
Visual Inspection:

1) The specimen was covered with wrap over top 30 in.
2) The wrap was intact at all places.
3) A horizontal crack of width 0.04 in. was observed over area D-A-B at 2 in. above bottom.
4) Concrete over bottom 2 in. over rebar A was spalled.

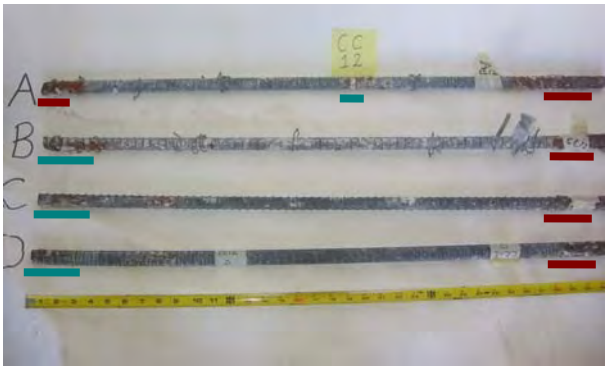
Half-Cell Potential Contour:



Chloride Content Profiles:

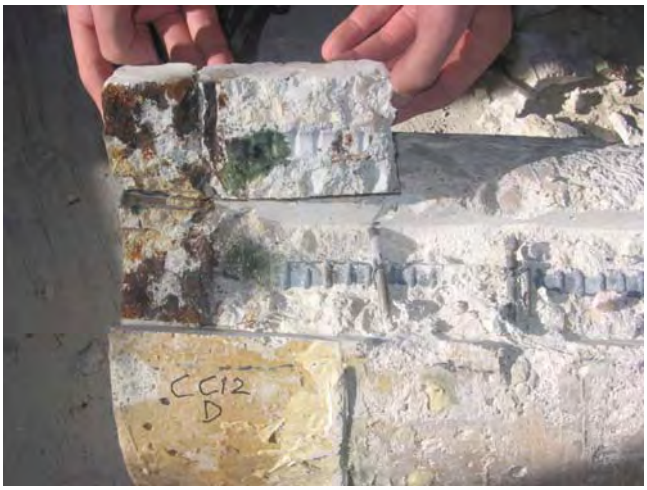


Corrosion of rebars:



Observations:

1) The rebars in unwrapped region were corroded whereas no corrosion was observed under the wrapped region.
2) Corrosion was especially heavy on rebars A and B, where the concrete had been spalled and cracks were observed.
3) Heavy corrosion was observed on one side or rebar D accompanied by a green colored residue.



Heavy corrosion near bottom of rebar D. It can be clearly seen that the rest of the bar was not corroded.

A7. CC14

Wrap	Generic -24 in.
Resin	862
Surface	Dry
Crack	Uncracked
Repair	LMC
Corrosion	Ferrogard

Cylinder CC14 wrapped over upper 24 in.

Vertical crack over rebar A with spalled-off section.

Visual Inspection:

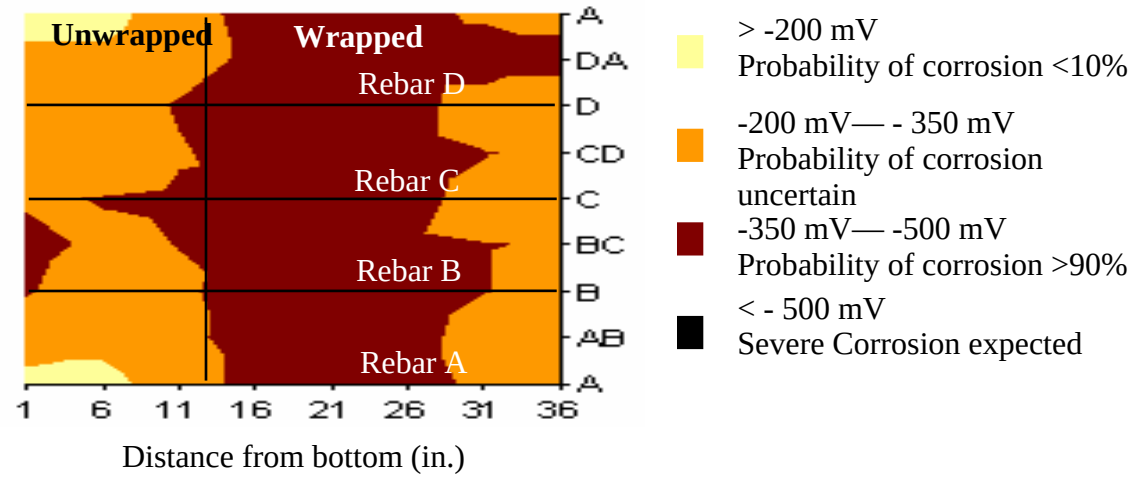
1) The cylinder was wrapped over top 24 in.
2) A section of specimen at the bottom over rebar A about 3 in. in height and 6 in. width had fallen off due to extensive corrosion. The area was filled with rust stains.
3) A 0.05-in.-wide vertical crack over rebar A extending from 24 in. from top to bottom. The crack had initiated where the wrap ended.
4) A vertical crack in area AD extended from the edge of the wrap to bottom.
5) Area AB was not consolidated properly over the bottom 4 inches.

Comments:

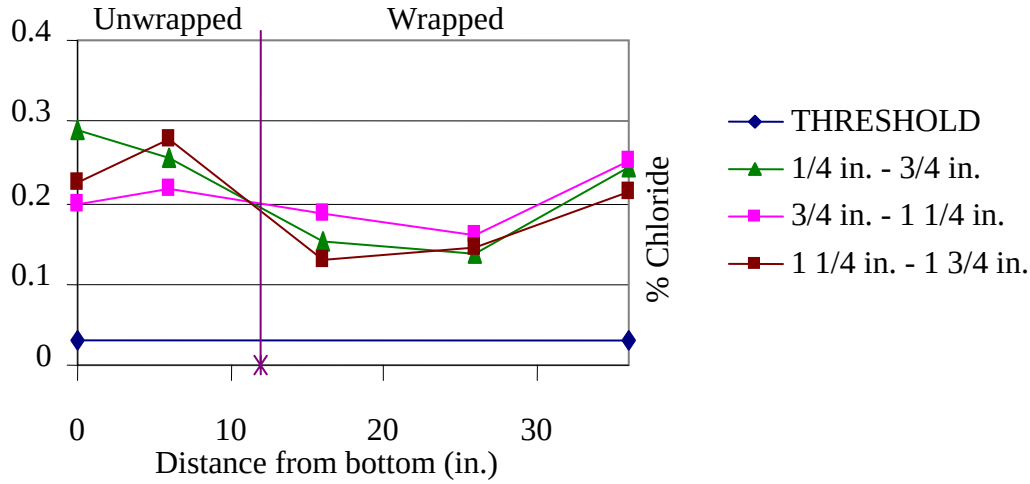
1) A high amount of corrosion was observed over the bottom 12.5 in. of rebar A, whereas rebars B, C, and D were hardly corroded.

2) In rebar A, the unwrapped area (0 in. to 12 in.) was heavily corroded while the wrapped area (12 in. to 36 in.) was not corroded at all.

Half-Cell Potential Contour:



Chloride Content Profiles:



Corrosion of rebars:

A8. CC16

Wrap	Unwrapped
Resin	None
Surface at	Dry
Crack Condition	Uncracked
Repair Material	EG
Corrosion Inhibitor	None

Cylinder CC16 with repair material over bottom region.

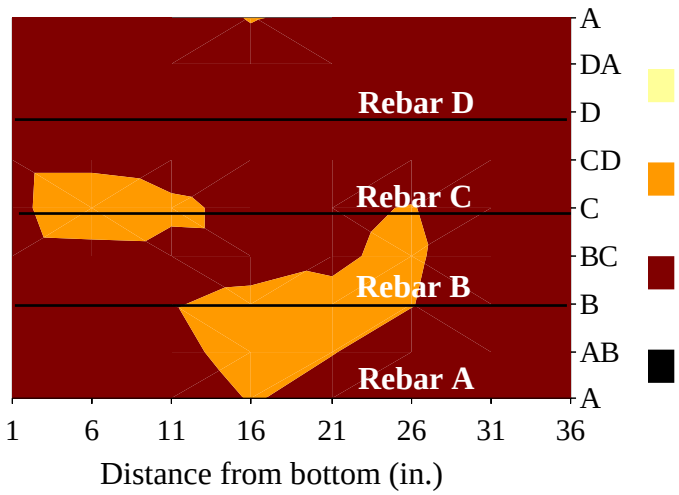
Visual Inspection:

1) The specimen was not wrapped.
2) Repair material was observed over lower 16 in. on area A-AD-D-DC-C and over bottom 6 in. on area CD-D-DA.
3) A vertical crack of width 1/8 in. was observed over rebar D extending from 20 in. to 36 in.
4) A vertical crack of width 1/8 in. was observed over rebar A extending from 6 in. to 36 in.
5) A vertical crack of width 0.06 in. was observed over rebar B extending from 6 in. to 36 in.
6) A vertical crack of width 0.07 in. was observed over rebar C extending from 16 in. to 36 in.
7) Bottom region over rebar B was not consolidated properly.

Observations:

1) Unlike in other specimens where the repair material were successful in inhibiting corrosion completely, rebars under the repair material were corroded, mostly only on one side. The amount and level of corrosion under the repair material was lesser than the areas with no repair material.
2) All the other rebars were heavily corroded since the cylinder was not wrapped.

Half-Cell Potential Contour:



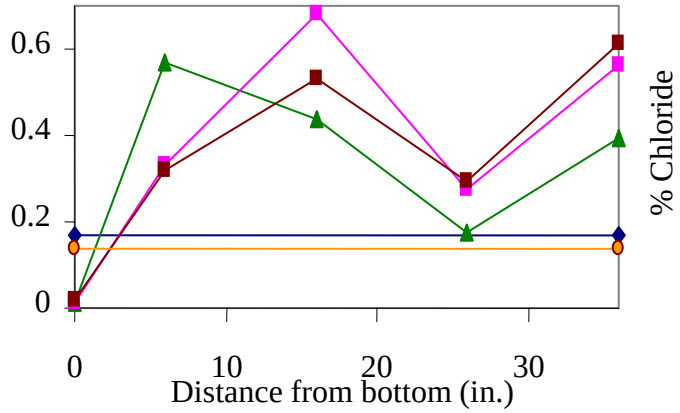
> -200 mV
Probability of corrosion <10%

-200 mV— - 350 mV
Probability of corrosion uncertain

-350 mV— -500 mV
Probability of corrosion >90%

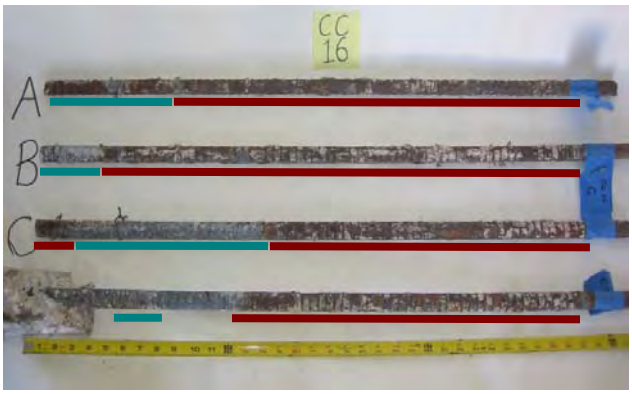
< - 500 mV
Severe Corrosion expected

Chloride Content Profiles:



THRESHOLD
1/4 in - 3/4 in
3/4 in - 1 1/4 in
1 1/4 in - 1 3/4 in
Inbuilt Chlorides

Corrosion of rebars:



Heavily corroded areas

Very light, one-sided corrosion

A9. CC19

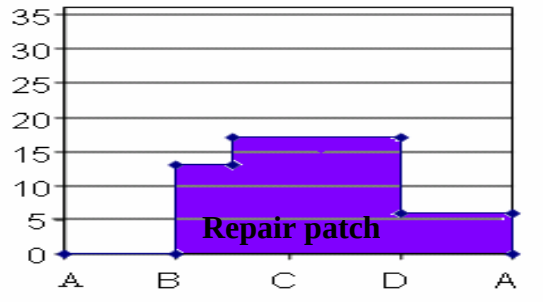
Wrap	Generic -24 in.
Resin	Vinyl ester
Surface at	Dry
Crack Condition	Uncracked
Repair Material	LMC
Corrosion Inhibitor	None

Cylinder CC19 wrap ped over top 24 in.

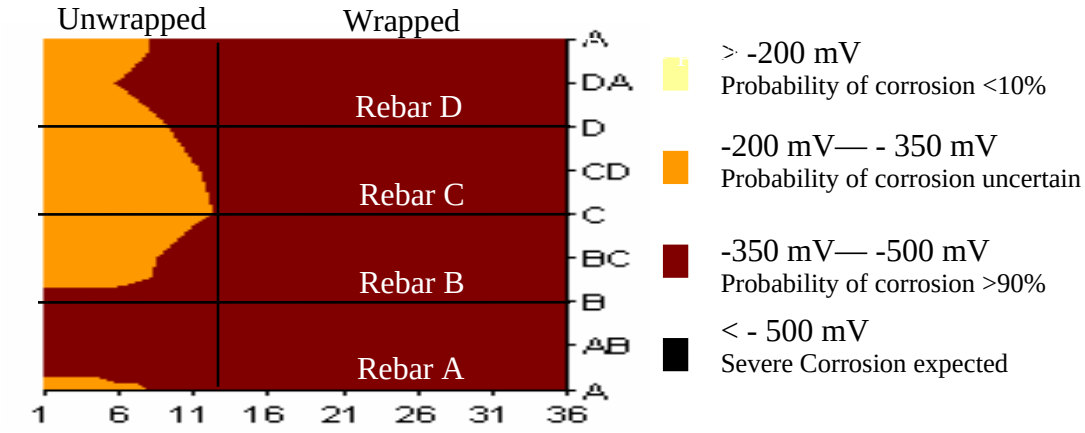
Area DA just below wrap edge was not consolidated properly. Repair patch visible at the bottom.

Visual Inspection:

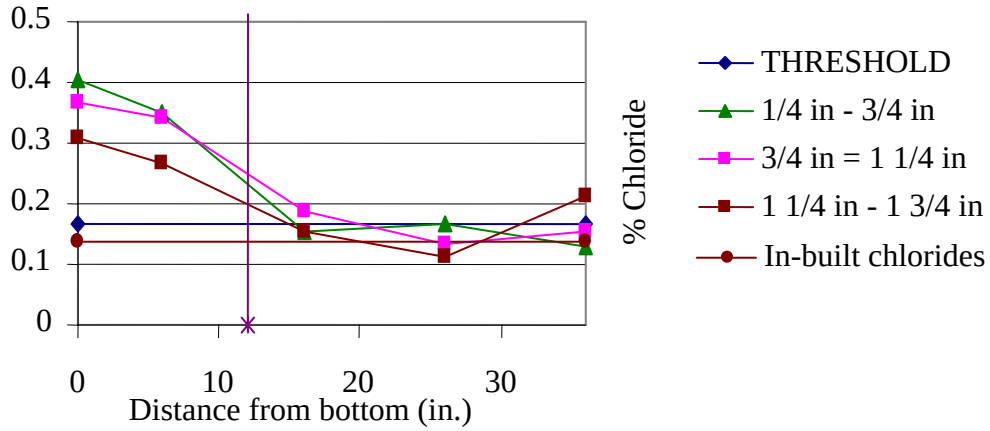
1) The column was wrapped over the top 24 inches.
2) Concrete had not been consolidated properly in area DA over a depth of about 4 in. extending from 26 in. to 30 in from top
3) A crack occurred over rebar A of width 0.013 in. extending from 26 in. till 33 in. as measured from top of the cylinder.
4) The repair patch is visible as shown in the figure below.



Half-Cell Potential Contour:



Chloride Content Profile:



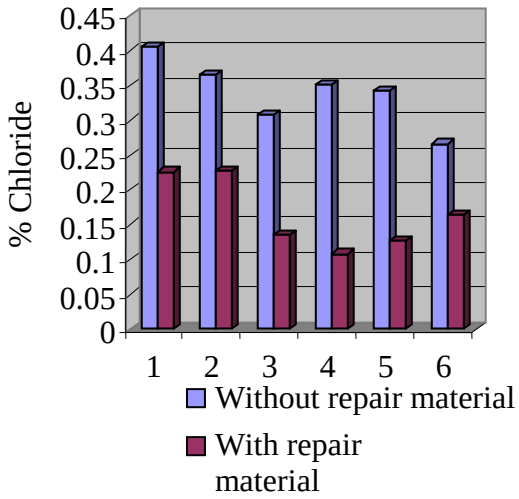
Corrosion of rebars:

Comments:

1) Heavy black corrosion residue was observed on rebar A at 13 in. from bottom and on rebar B at 34 in. from bottom.

Heavy localized rusting on rebar A.

2) It was observed that rebars B, C and D were not heavily corroded throughout. This may be due to presence of wrap over upper 24 inches and presence of repair material in unwrapped portions. Repair material was not present over area AB of the column, and it was interesting to find that lower portions of rebar AB had experienced corrosion.
3) The chloride content was calculated for areas covered with repair material and areas not covered with repair material at same heights of the cylinder. The results are shown graphically.



	Distance from bottom (in.)	Depth (in.)
1	1	¼ - ¾
2	1	¾ - 1 ¼
3	1	1 ¼ - 1 ¾
4	6	¼ - ¾
5	6	¾ - 1 ¼
6	6	1 ¼ - 1 3/4

Comparison of chloride content.

Thus it can be seen that the chloride ingression has decreased drastically where the surface was coated with repair materials.

A10. CC20

Wrap	Generic -24 in.
Resin	Vinyl ester
Surface at	Dry
Crack Condition	Uncracked
Repair Material	None
Corrosion Inhibitor	Ferrogard

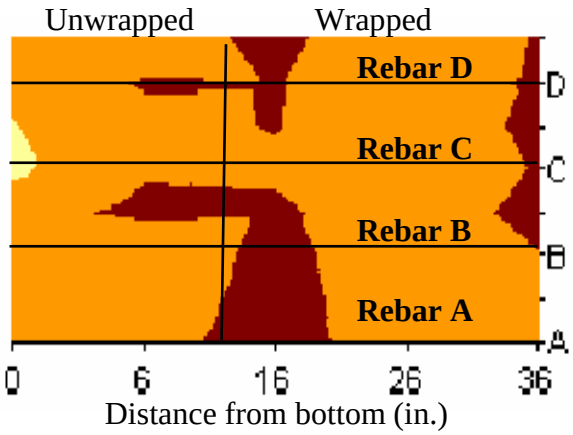
Cylinder CC20 wrapped over top 24 in.

Crack over rebar A in unwrapped region.

Visual Inspection:

1) The column was wrapped over the top 24 inches.
2) A vertical crack of width 0.03 in. occurred over rebar A extending from 25 in. to 34 in. from top.
3) A vertical crack of width 0.02 in. occurred over rebar B extending from 26 in. to 34 in. from top.

Half-Cell Potential Contour:



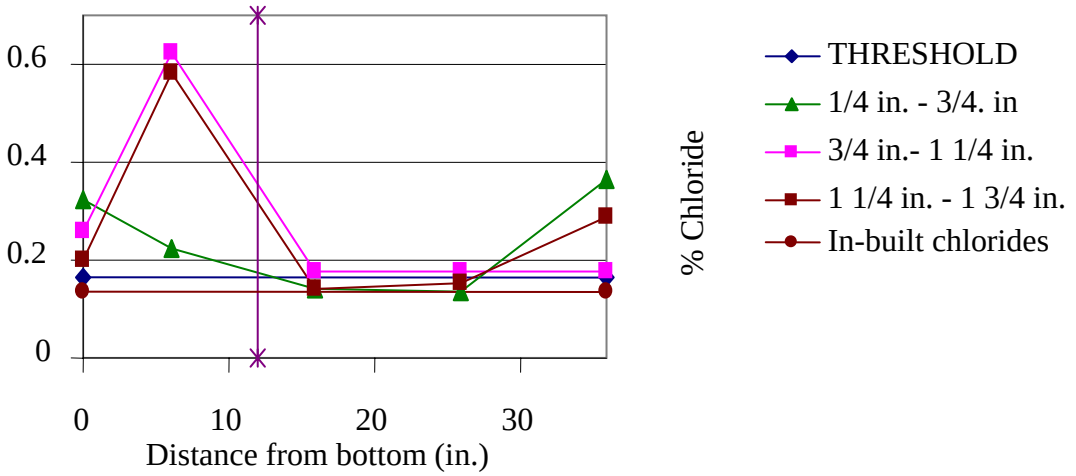
> -200 mV
Probability of corrosion <10%

-200 mV— - 350 mV
Probability of corrosion uncertain

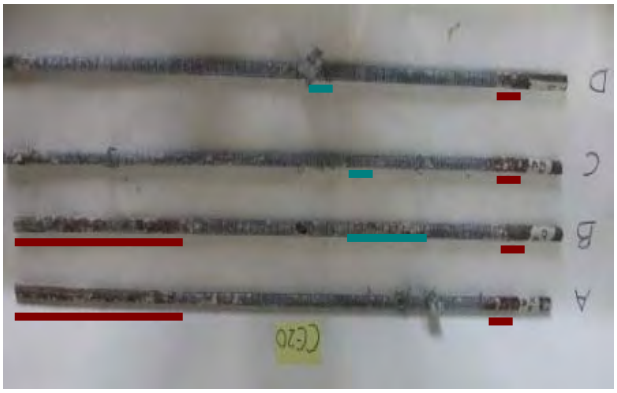
-350 mV— -500 mV
Probability of corrosion >90%

< - 500 mV
Severe Corrosion expected

Chloride Content Profile:



Corrosion of rebars:



Highly corroded areas

Areas with light one-sided corrosion

Comments:

1) Rebars A and B were corroded over bottom 11 inches. This area was not wrapped and was also cracked. The areas above 12 in., which were not wrapped, were not corroded, which may be evidence of the advantage of FRP wrapping.
2) It was interesting to note that the rebars C and D had not corroded even in unwrapped regions. It was found that the bottom 18 in. in these areas had been repaired using LMC. This implies that the repair material may have been useful in preventing corrosion due to either cutting off the air supply or moisture.
3) The wrapped areas in all the bars have not been corroded which may indicate the benefits of FRP wrapping.

Lower areas of embedment of bars A and B. Note the repair material visible in lower right corner.

Areas of embedment of bars C and D. Corrosion did not take place due to presence of repair material.

A11. CC21

Wrap	Unwrapped
Resin	None
Surface at	Dry
Crack Condition	Cracked
Repair Material	None
Corrosion Inhibitor	Ferrogard

Cylinder CC21.

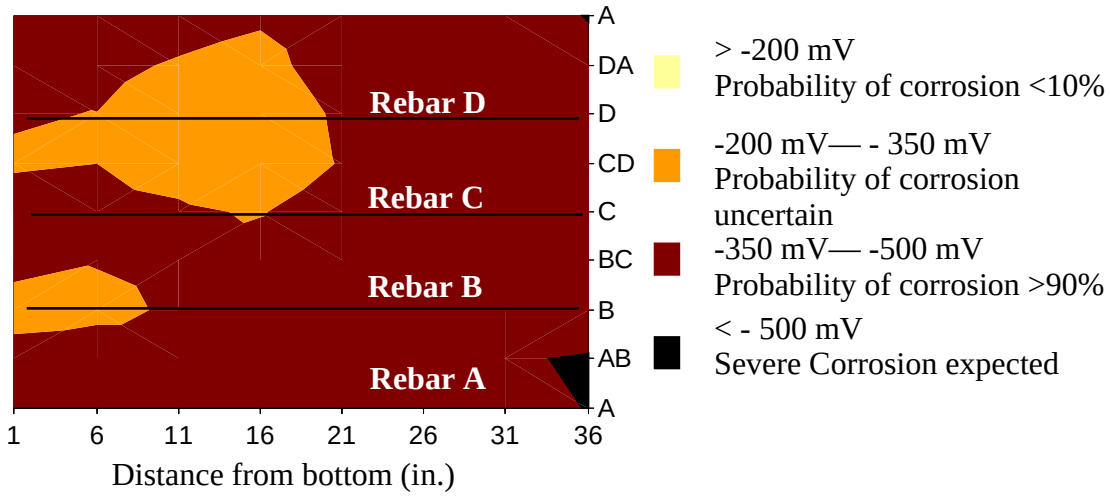
Visual Inspection:

1) The specimen was not wrapped.
2) Two vertical cracks of width 0.03 in. were observed over rebar D extending from 12 in. to 24 in. from bottom.
3) A vertical crack of width 0.04 in. was observed over rebar C extending from 0 in. to 20 in.
4) Two vertical cracks were observed over rebar B, first 0.02 in. wide extending from 25 in. to 36 in. and the second of width 0.04 in. extending from 0 in. to 20 in.
5) Rust stain (5 in. × 7 in.) was observed near bottom of rebar B.

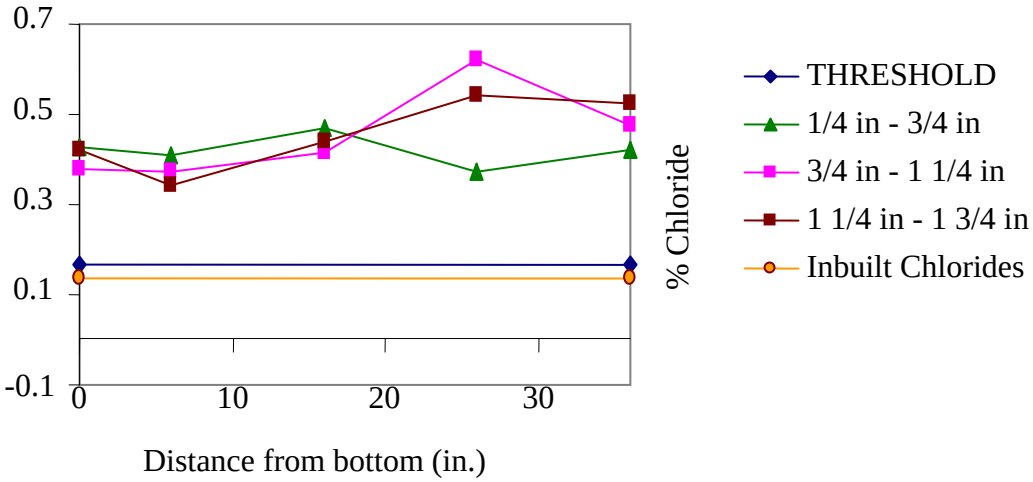
Observations:

1) Though it was not wrapped, corrosion was not as extensive as other unwrapped specimens (for example, CC16). This could be due to the presence of inhibitor Ferrogard. The inhibitor, though, is not very effective in the "splash zone" i.e. 0 in. – 12 in. from bottom.

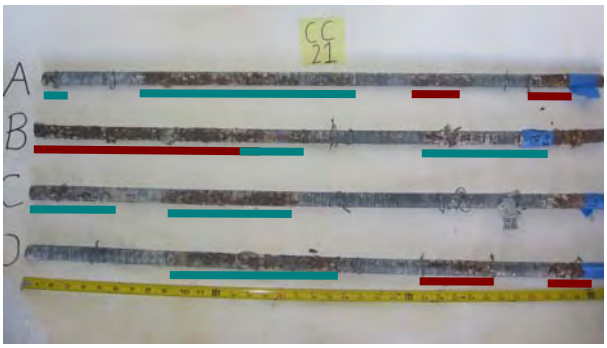
Half-Cell Potential Contour:



Chloride Content Profile:



Corrosion of rebars:



A12. CNC1

Wrap	Generic – 27 in.
Resin	862
Surface at	Wet
Crack Condition	Cracked
Repair Material	Patch
Corrosion Inhibitor	None

Cylinder CNC1 wrapped over top 27 in.

Cylinder CNC1 after removal of wrap.

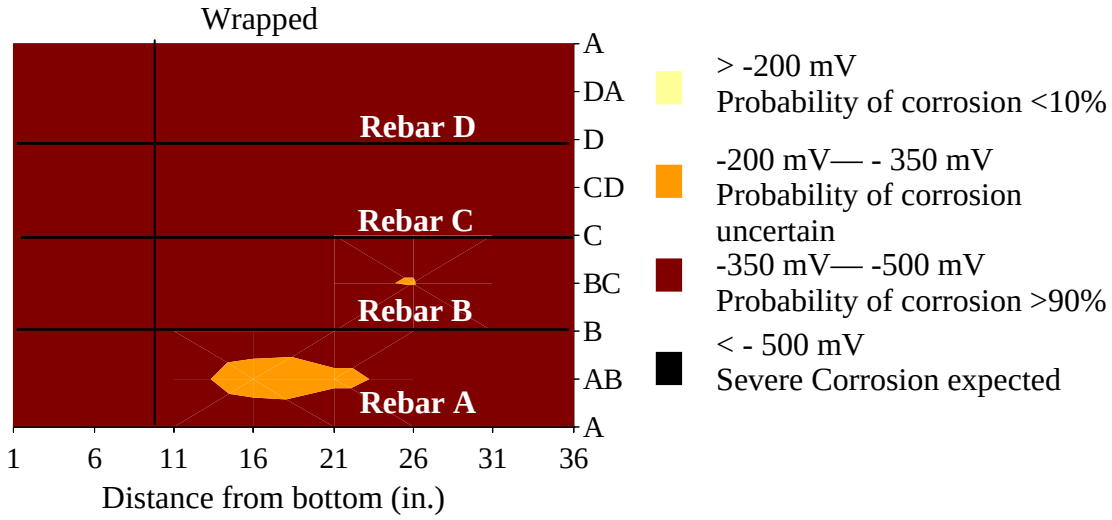
Visual Inspection:

1) The cylinder was wrapped over top 27 in.
2) The wrap was intact at all places.
3) The cylinder was covered with repair material over top 5 in.
4) The concrete was not consolidated properly.
5) Large rust stains were observed all over the surface.

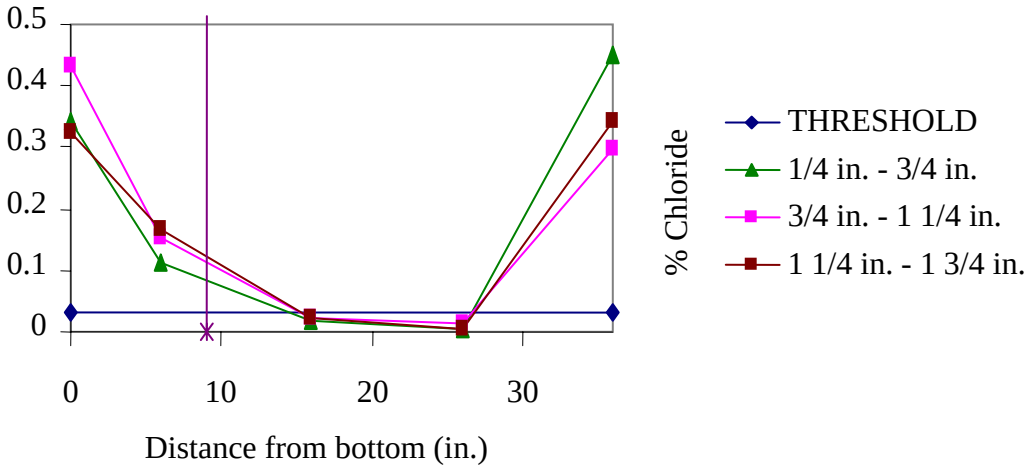
Observations:

1) Though the bottom 9 in. were not wrapped heavy corrosion was not observed on the rebars.
2) No corrosion was observed under the wrapped region.
3) Heavy corrosion was observed over bottom 8 in. of rebar B

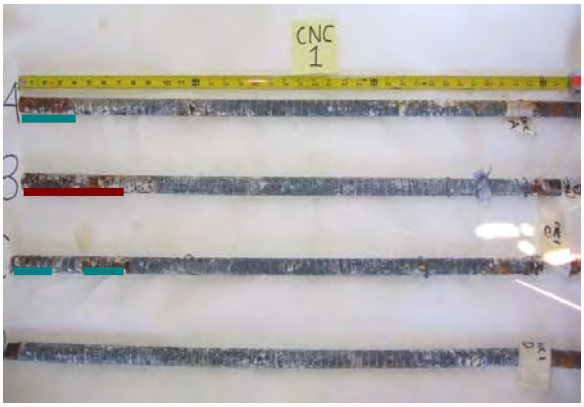
Half-Cell Potential Contour:



Chloride Content Profile:



Corrosion of rebars:



Heavily corroded areas

Very light, one-sided corrosion

A13. CNC2

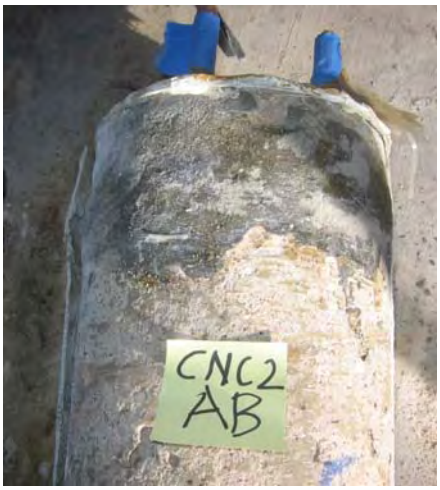
Wrap	Generic – 36 in.
Resin	862
Surface at	Dry
Crack Condition	Cracked
Repair Material	None
Corrosion Inhibitor	None

Cylinder CNC2, completely wrapped.

Cylinder CNC2, after removal of wrap with a large rust stain over rebar B.

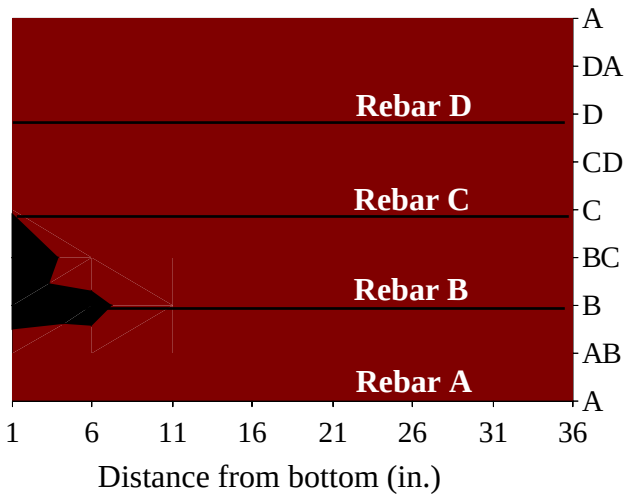
Visual Inspection:

1) The cylinder was completely wrapped.
2) On removal of wrap, trapped moisture was observed under the wrap in areas A-AB-B.
3) The top 4 in. of cylinder was covered with repair material.
4) A large stain spot was observed over rebar B (4 in.× 4 in.) accompanied with trapped moisture. The rust stain could be seen above the wrap too.



Trapped moisture under the wrap.

Half-Cell Potential Contour:



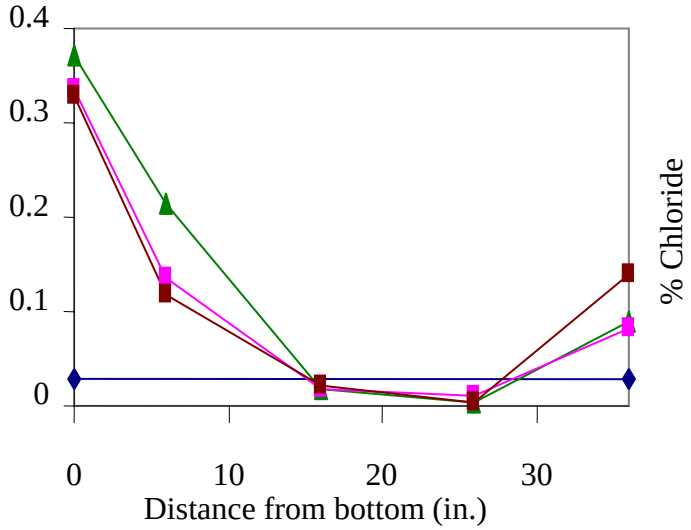
> -200 mV
Probability of corrosion <10%

-200 mV— - 350 mV
Probability of corrosion uncertain

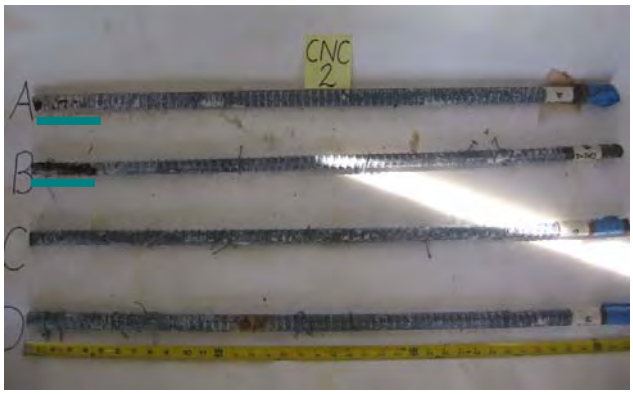
-350 mV— -500 mV
Probability of corrosion >90%

< - 500 mV
Severe Corrosion expected

Chloride Content Profile:



Corrosion of rebars:



Heavily corroded areas

Very light, one-sided corrosion

A14. CNC3

Wrap	Generic -24 in.
Resin	862
Surface at	Dry
Crack Condition	Uncracked
Repair Material	None
Corrosion Inhibitor	Ferrogard

Cylinder CNC3 wrapped over top 24 in.

Crack and rust stains over rebar A.

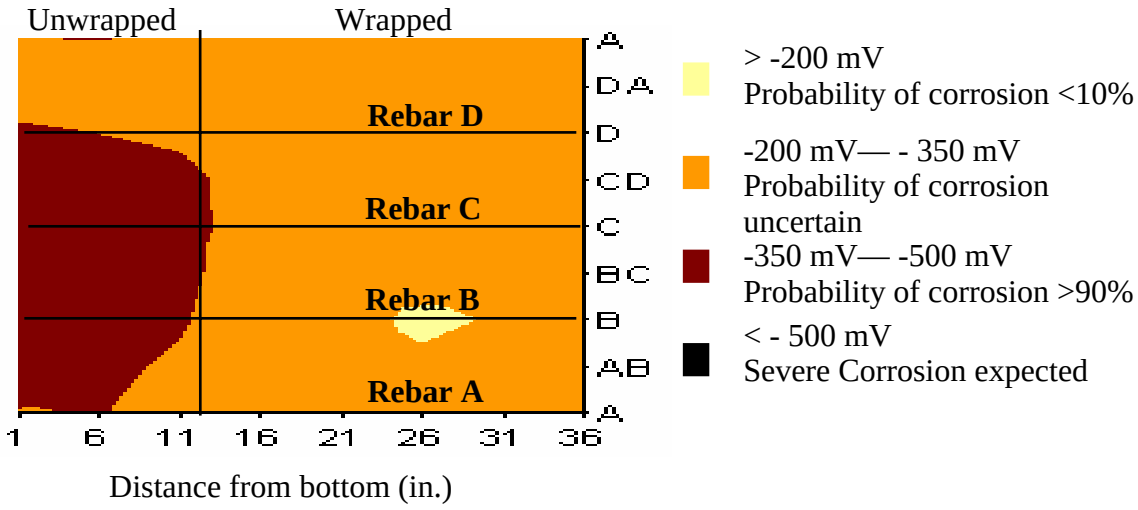
Visual Inspection:

1) The cylinder was wrapped over the top 24 in.
2) A 0.02-in. vertical crack over rebar A extended from the end of wrap to bottom.
3) Rust stains were observed on unwrapped regions in area AD and AB.

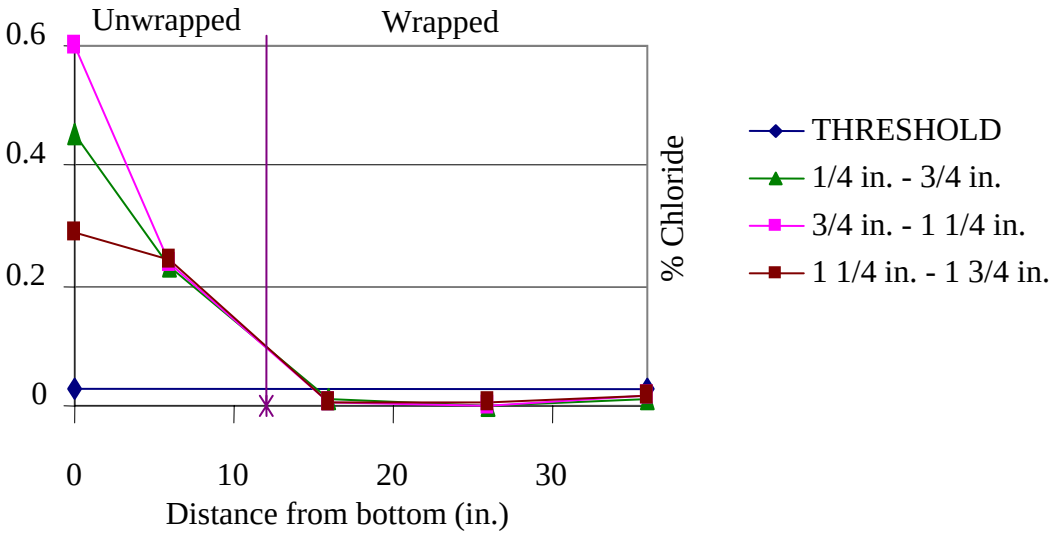
Comments:

1) Bottom 12 in. of rebars A, C and D was heavily corroded while rebar B was not corroded.
2) Wrapped areas were not corroded at all.

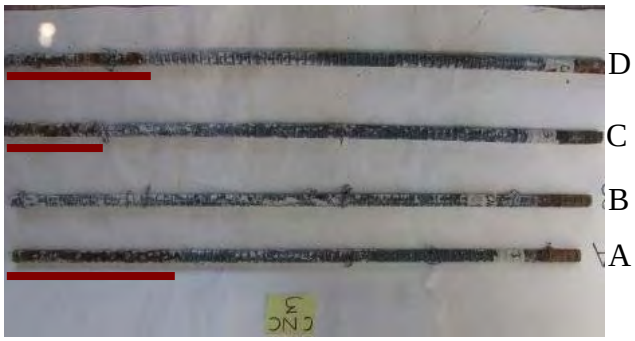
Half-Cell Potential Contour:



Chloride Content Profile:



Corrosion of rebars:



A15. CNC4

Wrap	Delta – 24 in.
Resin	Tyfo S
Surface at	Dry
Crack Condition	Uncracked
Repair Material	None
Corrosion Inhibitor	None

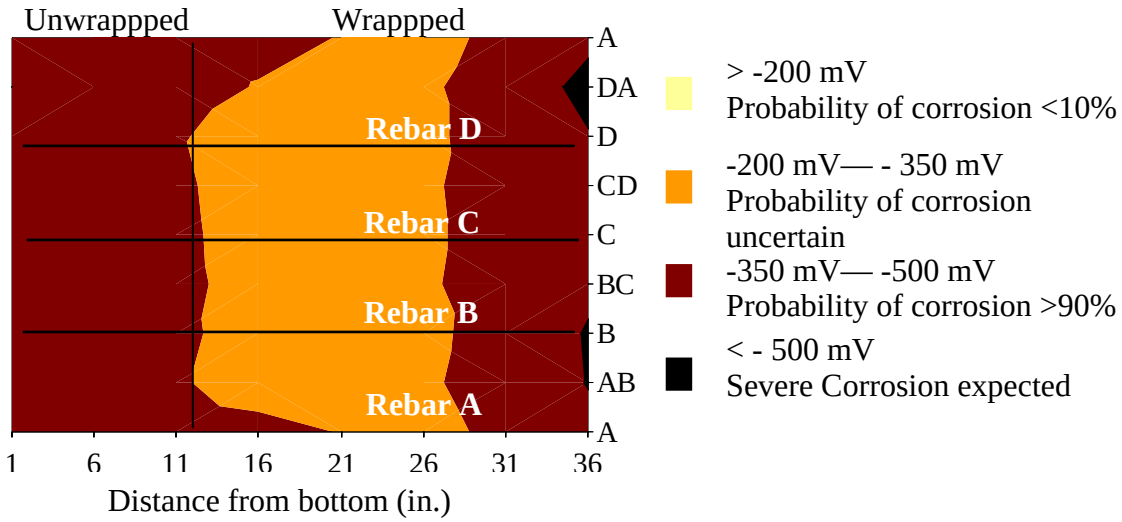
Cylinder CNC4, wrapped over top 24 in.

Cylinder CNC4, after removal of wrap.

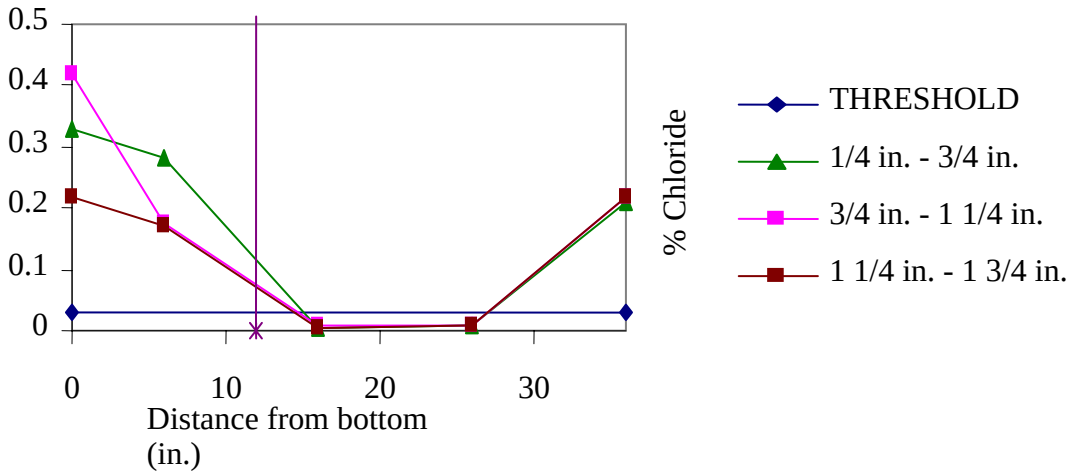
Visual Inspection:

1) The cylinder is wrapped over top 24 in.
2) The wrap is intact at all places.
3) Rust stains were observed over the bottom unwrapped region.
4) When the wrap was removed, chunks of concrete came off with it, exposing rust stains lying underneath the surface.

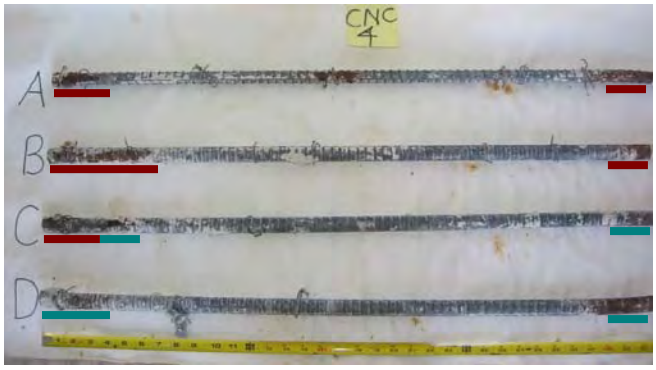
Half-Cell Potential Contour:



Chloride Content Profile:



Corrosion of rebars:



A16. CNC7

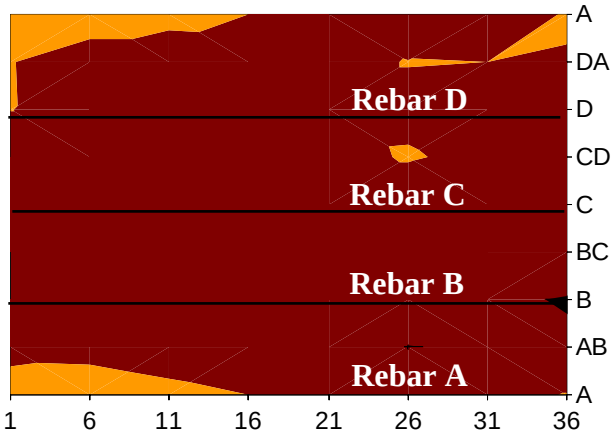
Wrap	Unwrapped
Resin	None
Surface at	Dry
Crack Condition	Uncracked
Repair Material	None
Corrosion Inhibitor	Ferrogard

Cylinder CNC7 with large rust stain over rebar C.

Visual Inspection:

1) The specimen was not wrapped.
2) A vertical crack of width 0.04 in. was observed over rebar A extending the complete height of the cylinder.
3) A vertical crack of width 0.02 in. was observed over rebar B extending the complete height of the cylinder.
4) A vertical crack of width 0.03 in. was observed over rebar C extending from 16 in. to 31 in.
5) A vertical crack of width 0.016 in. was observed over rebar D extending from 7 in. to 36 in.
6) Large rust stains were observed all over the specimen.

Half Cell Potential Contour:



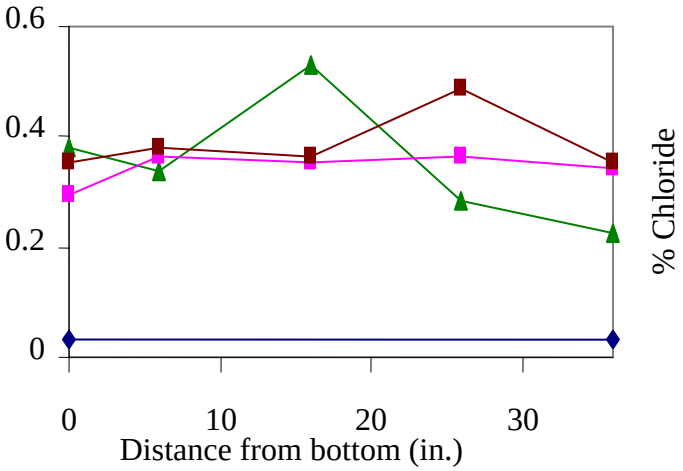
> -200 mV
Probability of corrosion <10%

-200 mV— - 350 mV
Probability of corrosion uncertain

-350 mV— -500 mV
Probability of corrosion >90%

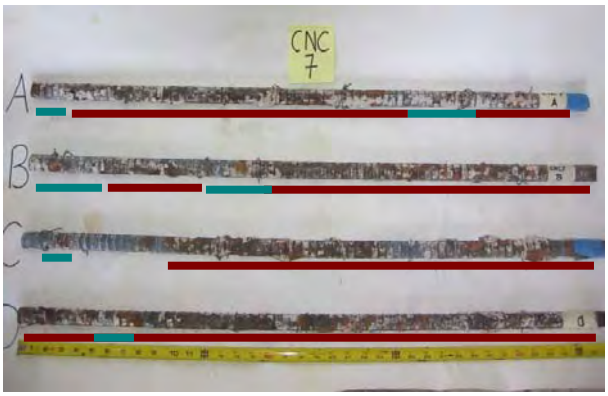
< - 500 mV
Severe Corrosion expected

Chloride Content Profiles:



THRESHOLD
1/4 in. - 3/4 in.
3/4 in. - 1 1/4 in.
1 1/4 in. - 1 3/4 in.

Corrosion of rebars:



Heavily corroded areas

Very light, one-sided corrosion

A17. CNC9

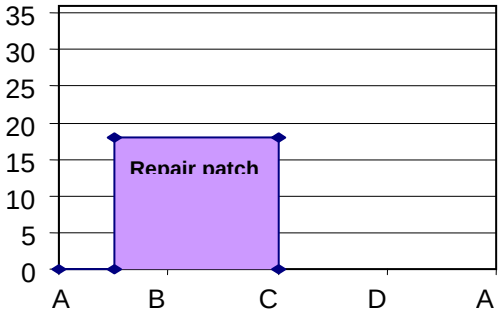
Wrap	Generic – 24 in.
Resin	Vinyl ester
Crack Condition	Uncracked
Repair Material	LMC, patch
Corrosion Inhibitor	None

Cylinder CNC9 wrapped over top 24 in.

Rust stains and unconsolidated parts over rebar D.

Visual inspection:

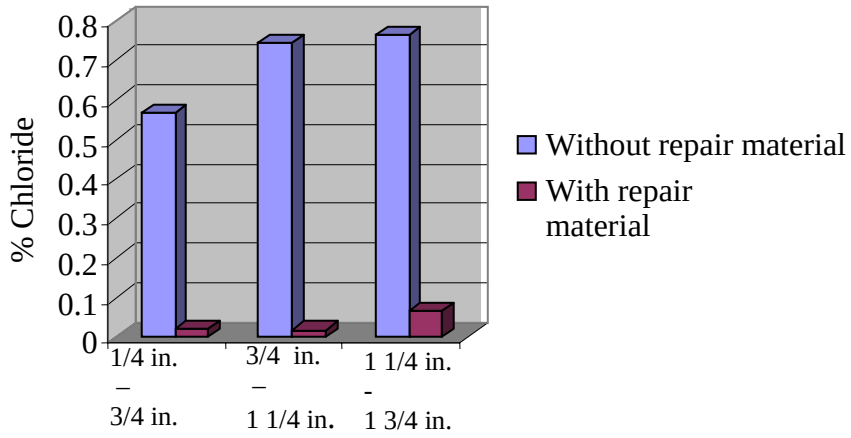
1) The cylinder was wrapped over the top 24 in.
2) Concrete was not consolidated properly just below the wrap edge in areas AD and DC and over the bottom 2 in. in area AD.
3) Unconsolidated portions extending from 14 in. to 16 in. from top over rebars D and A were filled with repair material.
4) A dark stain of width 7 in. was observed over rebar D extending from 21 in. to 24 in. from the top and of width 4 in. over rebar B extending from 14 in. to 16 in. from top.
5) Staining was observed over the unwrapped region due to wash-out/ rust.
6) Repair patch as shown in the figure below.



Repair patch.

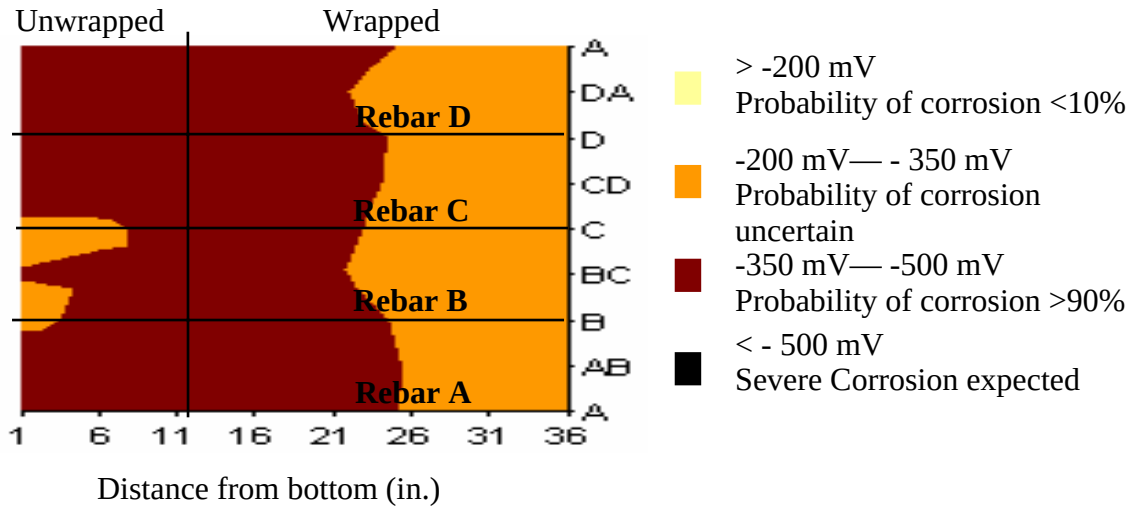
Comments:

1) Rebars A and D were corroded in the bottom unwrapped area only with no corrosion under the wrapped region.
2) Rebars B and C were not corroded even in the unwrapped portions due to the presence of LMC repair patch.
3) The chloride test results correlated well with the amount of corrosion observed on the rebars.
4) The chloride content was calculated for areas covered with repair material and areas not covered with repair material at 6 in from bottom. The results are shown graphically.

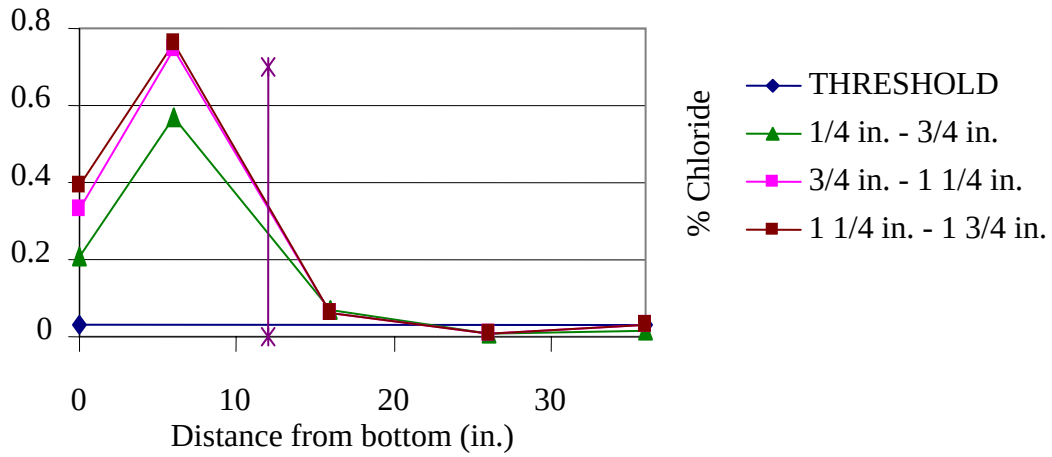


Comparison of chloride content.

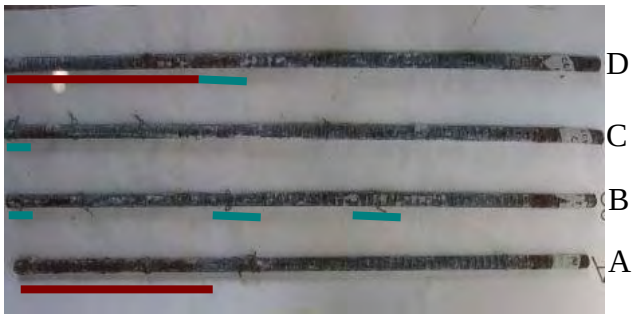
Half Cell Potential Contour:



Chloride Content Profiles:



Corrosion of rebars:



A18. CNC15

Wrap	None
Resin	None
Surface at	Dry
Crack Condition	Cracked
Repair Material	None
Corrosion Inhibitor	None

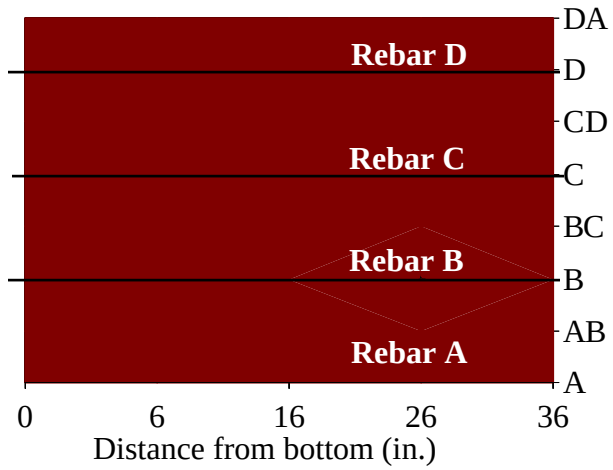
CNC15 full view with rebar A in front.

CNC15 Area DC.

Visual Inspection:

1) A vertical crack of width 0.06 in. occurred over rebar A, extending from top to 7.5 in. from bottom.
2) A vertical hairline crack occurred over rebar B, extending from 6.5 in. to 14 in. from top.
3) A vertical crack of width 0.04 in. occurred over rebar B, extending from 14 in. to 26 in from top.
4) A few vertical hairline cracks occurred in area AB, extending from 12 in. to 20 in. from top.
5) A vertical crack of width 0.04 in. occurred over rebar C, extending from top to 33 in. from top.
6) A vertical crack of width 0.06 in. occurred over rebar D, extending from top to 32 in. from top.
7) A Stain spot (2 in. in diameter) was located in area CD, at 9 in. above bottom.
8) A Stain spot (0.5 in. × 2 in.) was located over rebar C, at 9 in. above bottom.
9) A Stain spot (1 in. × 1 in.)was located in area AB, at 17 in. above bottom.

Half-Cell Potential Contour:



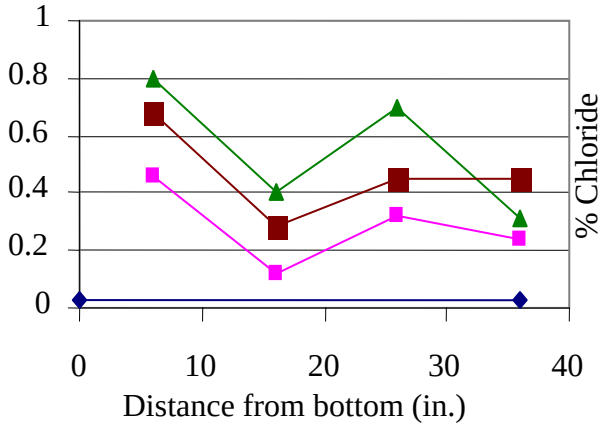
> -200 mV
Probability of corrosion <10%

200 mV— - 350 mV
Probability of corrosion uncertain

-350 mV— -500 mV
Probability of corrosion >90%

< - 500 mV
Severe Corrosion expected

Chloride Content Profiles:



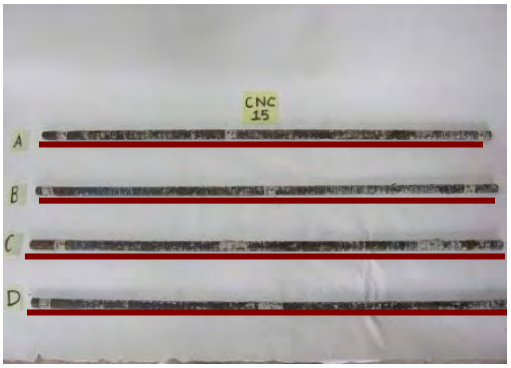
Threshold

1/4 in. - 3/4 in

3/4 in. - 1 1/4 in

1 1/4 in. - 1 3/4 in

Corrosion of rebars:



Heavily corroded areas.

A19. CNC18

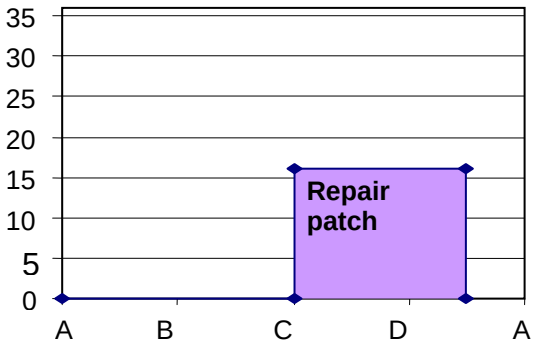
Wrap	Generic – 24 in.
Resin	862
Crack Condition	Uncracked
Repair Material	LMC
Corrosion Inhibitor	Ferrogard

Cylinder CNC18 wrapped over top 24 in. Rust stains visible in unwrapped region.

Repair patch and rust stains over rebar D.

Visual Inspection:

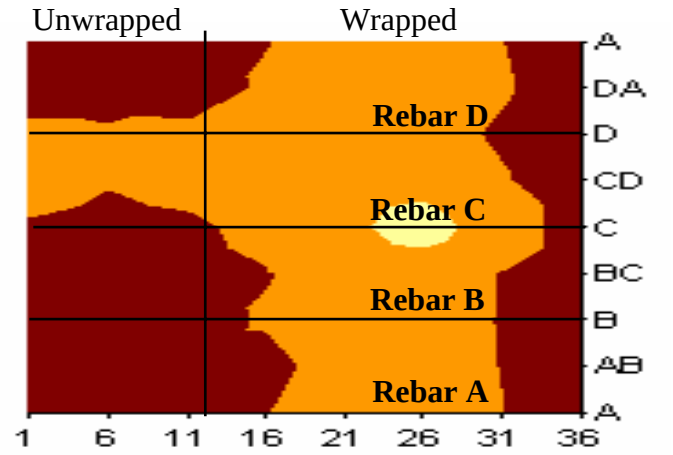
1) The cylinder was wrapped over the top 24 in.
2) A 0.016-in. vertical crack was located over rebar A, extending from 27 in. to 34 in. from the top.
3) A 0.013-in.vertical crack was observed over rebar B, extending from 27 in. to 31 in. from top.
4) Rust stains occurred in area BC in the unwrapped region.
5) The repair patch is as shown in the figure.



Comments:

1) Unwrapped portions of rebar A and B were corroded while those of rebars C and D were not. This was likely due to the presence of repair material over rebars C and D.
2) No corrosion was observed in the wrapped regions.

Half-Cell Potential Contour:



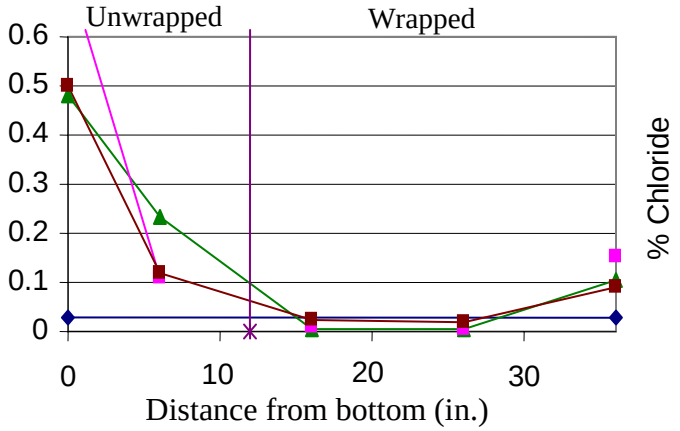
> -200 mV
Probability of corrosion <10%

-200 mV— - 350 mV
Probability of corrosion uncertain

-350 mV— -500 mV
Probability of corrosion >90%

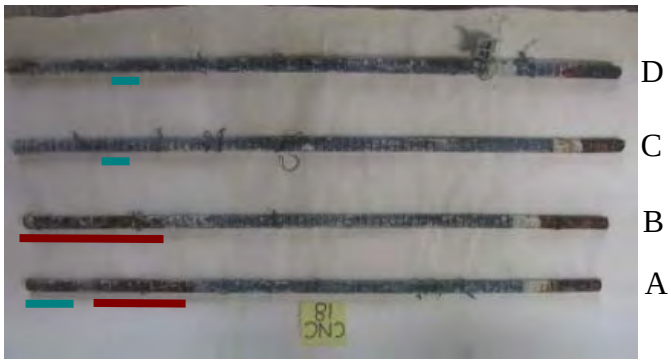
< - 500 mV
Severe Corrosion expected

Chloride Content Profiles:



THRESHOLD
1/4 in. - 3/4 in.
3/4 in. - 1 1/4 in.
1 1/4 in. - 1 3/4 in.

Corrosion of rebars:

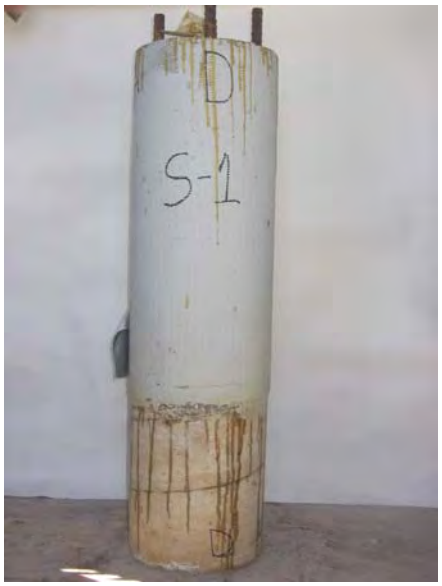


Heavily corroded areas

Very light, one-sided corrosion

A20. S1

Wrap	Delta - 24 in.
Crack Condition	Cracked
Repair Material	None
Corrosion Inhibitor	Surtreat



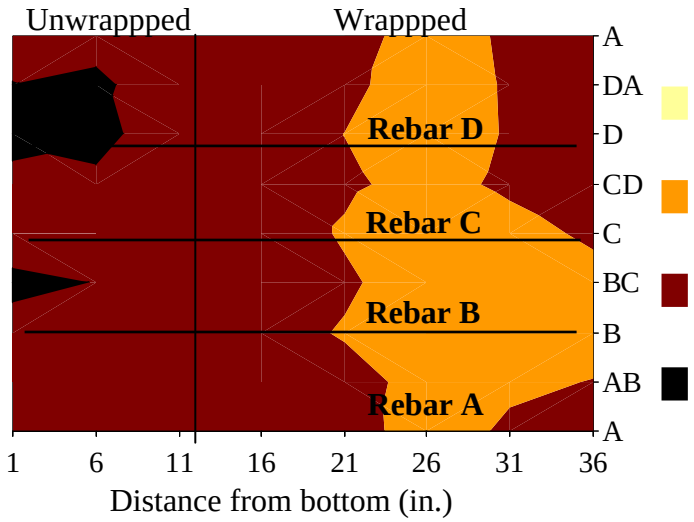
Cylinder S1 wrapped over top 24 in.

Cylinder S1 after removal of wrap.

Visual Inspection:

1) The cylinder was covered with wrap over the top 24 in.
2) The wrap was intact at all places.
3) A vertical crack of width 0.03 in. was observed over rebar A, extending from 0 in. to 12 in., accompanied with rust stains.
4) A vertical crack of width 0.016 in. was observed over rebar B, extending from 0 in. to 10 in., accompanied with rust stains.
5) A vertical crack of width 0.02 in. was observed over rebar C, extending from 4 in. to 12 in.

Half-Cell Potential Contour:



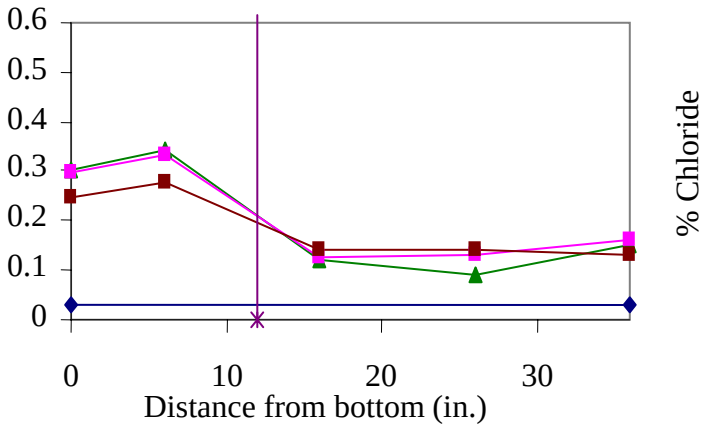
> -200 mV
Probability of corrosion <10%

-200 mV— - 350 mV
Probability of corrosion uncertain

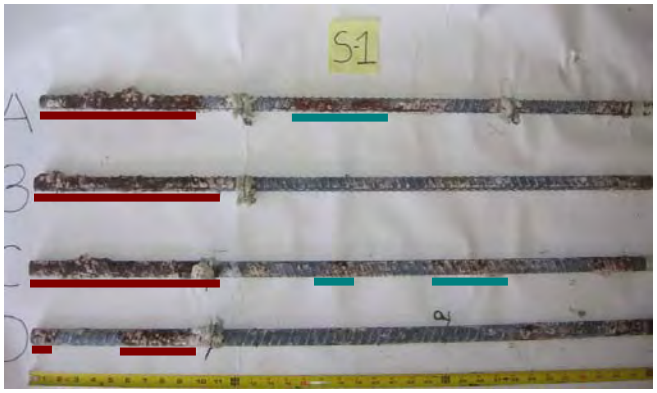
-350 mV— -500 mV
Probability of corrosion >90%

< - 500 mV
Severe Corrosion expected

Chloride Content Profile:



Corrosion of rebars:



Heavily corroded areas

Very light, one-sided corrosion

A21. S2

Wrap	Delta – 36 in.
Crack Condition	Cracked
Repair Material	None
Corrosion Inhibitor	Surtreat

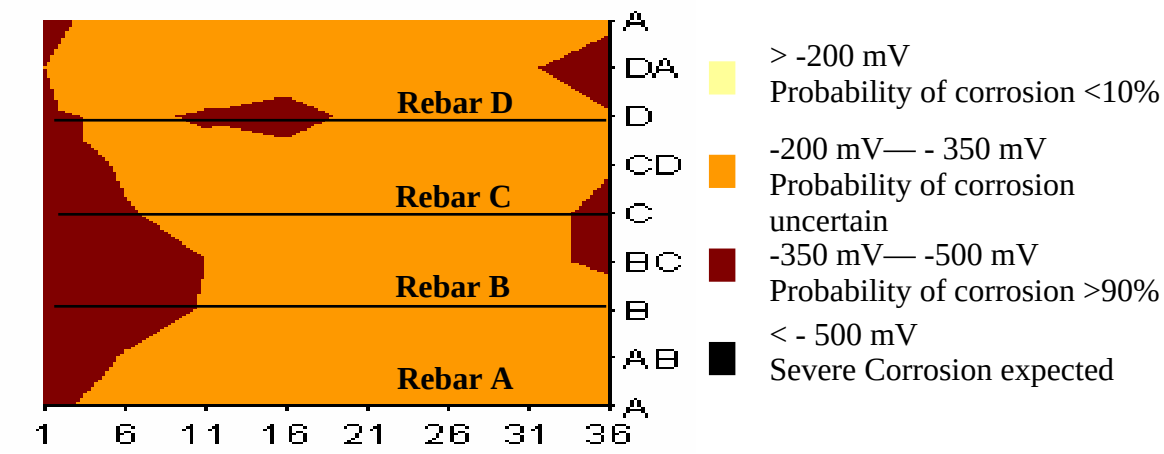
Column S2 Completely wrapped.

Column S2 after removal of wrap.

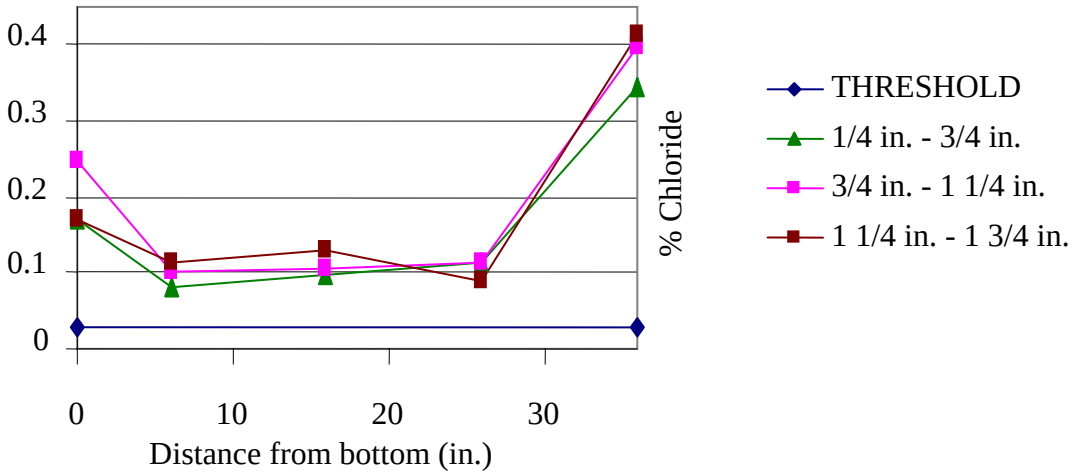
Visual observations:

1) The column was completely wrapped. The wrap was intact at all places.
2) No cracks or rust stains were observed after the wrap was removed.

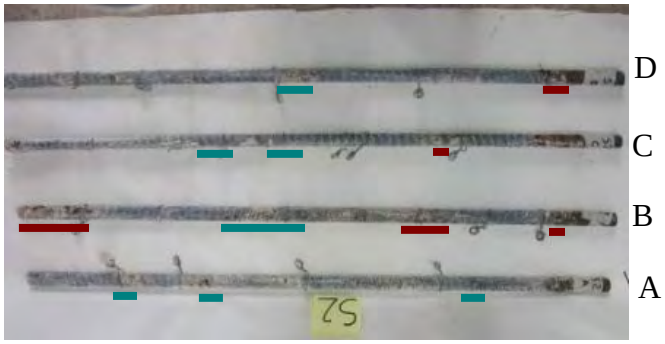
Half-Cell Potential Contour:



Chloride Content Profile:



Corrosion of rebars:



A22. S3

Wrap	Delta - 24 in.
Crack Condition	Uncracked
Repair Material	None
Corrosion Inhibitor	Surtreat

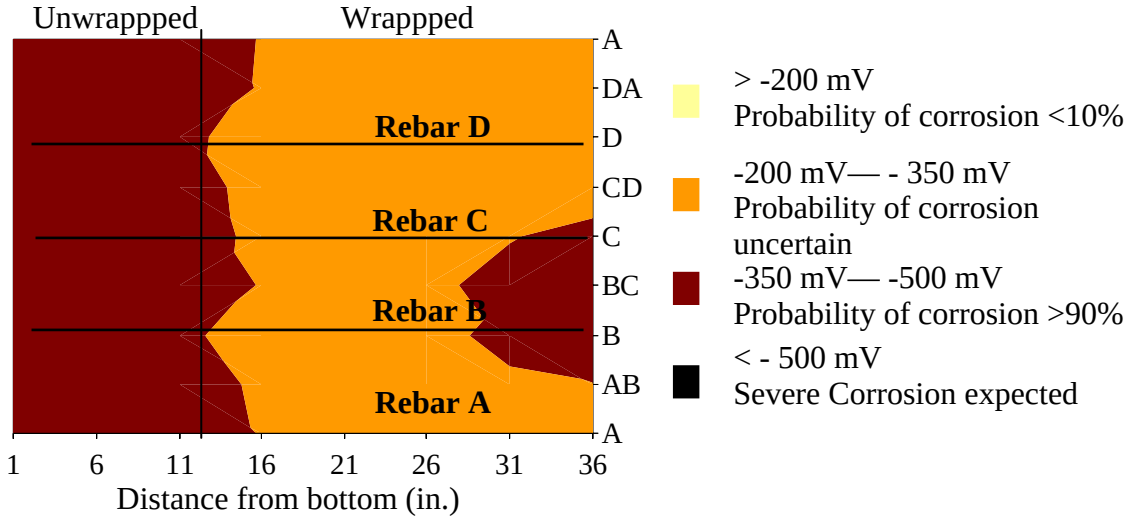
Cylinder S3 wrapped over top 24 in.

Cylinder S3 after removal of wrap.

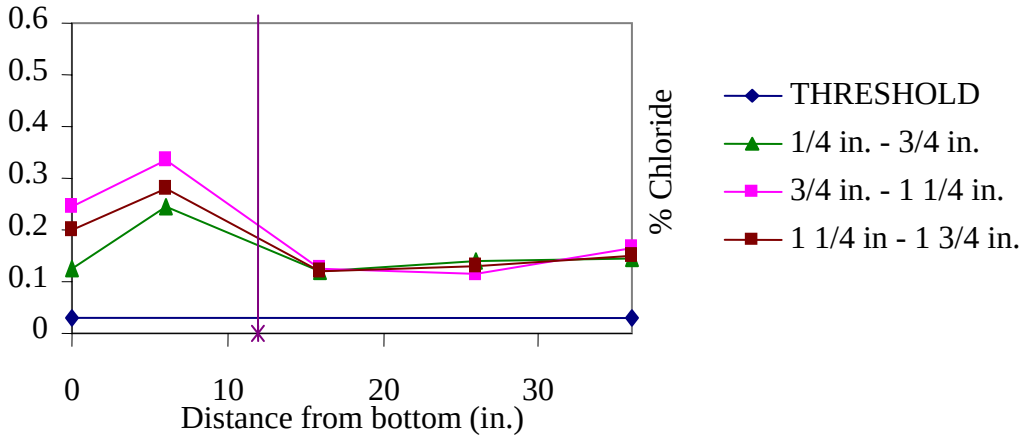
Visual Inspection:

1) The cylinder was wrapped over the top 24 in.
2) The wrap was intact at all places.
3) A vertical crack of width 0.013 in. was observed over rebar A, extending from 0 in. to 12 in., accompanied with rust stains.
4) A vertical crack of width 0.03 in. was observed over rebar B, extending from 3 in. to 12 in., accompanied with rust stains.
5) A vertical hairline crack of width 0.01 in. was observed over rebar C, extending from 2 in. to 12 in., accompanied with rust stains.

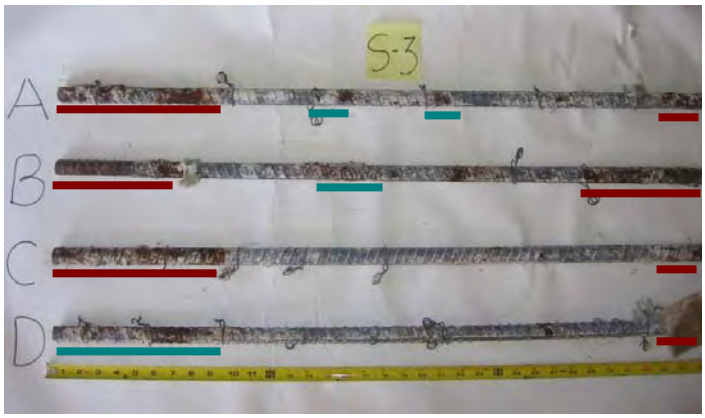
Half-Cell Potential Contour:



Chloride Content Profile:



Corrosion of rebars:



A23. S4

Wrap	Delta – 36 in.
Crack Condition	Uncracked
Repair Material	None
Corrosion Inhibitor	Surtreat

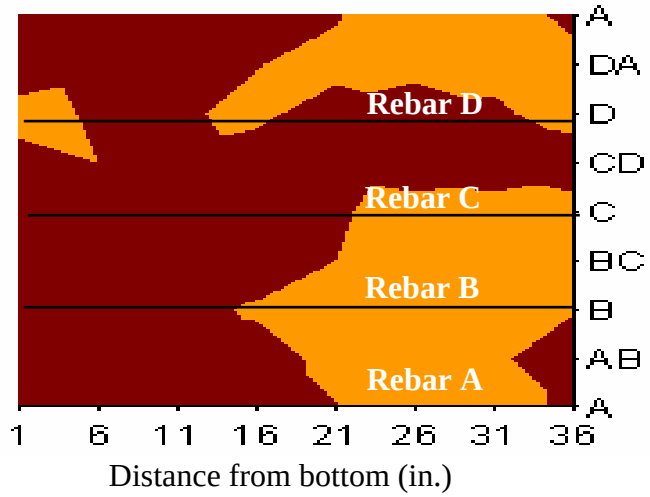
Column S4 Completely wrapped.

Column S4 after removal of wrap.

Visual observations:

1) The column was completely wrapped. The wrap was intact at all places.
2) No cracks or rust stains were observed after the wrap was removed.

Half-Cell Potential Contour:



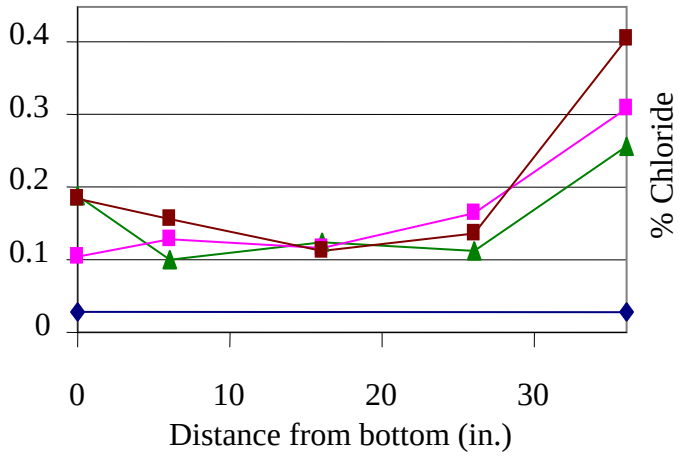
> -200 mV
Probability of corrosion <10%

-200 mV— - 350 mV
Probability of corrosion uncertain

-350 mV— -500 mV
Probability of corrosion >90%

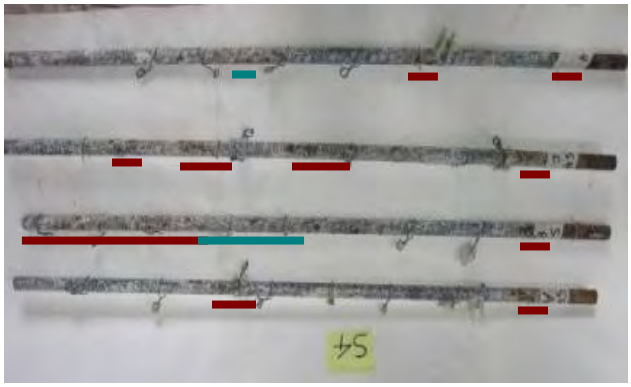
< - 500 mV
Severe Corrosion expected

Chloride Content Profiles:



THRESHOLD
1/4 in. - 3/4 in.
3/4 in. - 1 1/4 in.
1 1/4 in. - 1 3/4 in.

Corrosion of Rebars:



Heavily corroded areas

Very light, one-sided corrosion

A24. S5

Wrap	Delta - 24 in.
Crack Condition	Cracked
Repair Material	None
Corrosion Inhibitor	Cortec

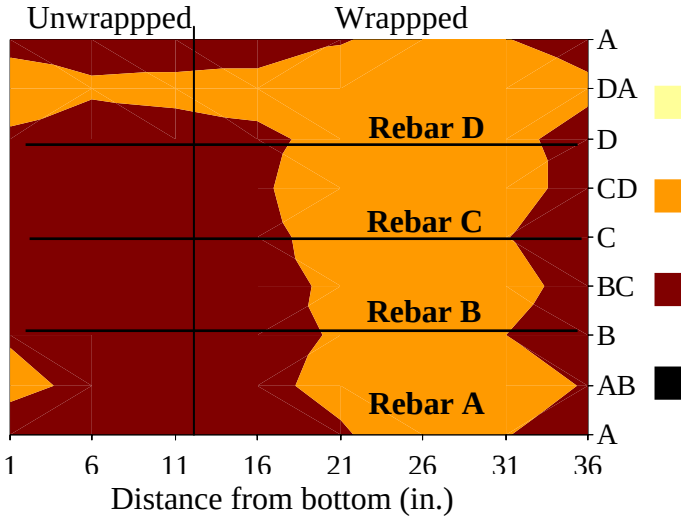
Cylinder S5 wrapped over top 24 in.

Cylinder S5 after removal of wrap.

Visual Inspection:

1) The cylinder was wrapped over the top 24 in.
2) The wrap was intact at all places.
3) A vertical crack of width 0.016 in. was observed over rebar A, extending from 5 in. to 9 in.
4) A vertical crack of width 0.016 in. was observed over rebar B, extending from 0 in. to 12 in.
5) Rust stains were observed in the unwrapped region.

Half Cell Potential Contour:



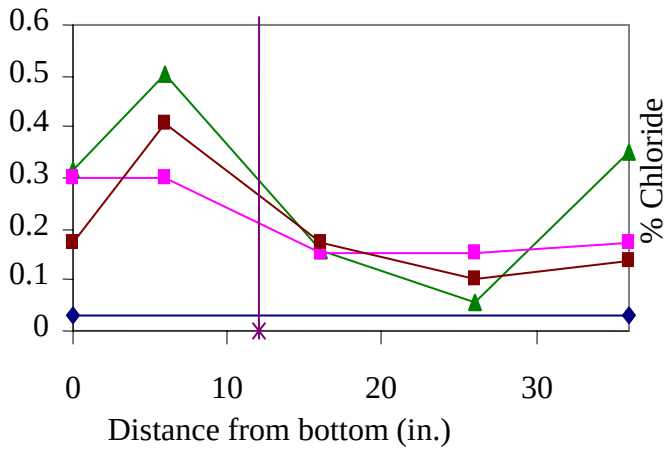
> -200 mV
Probability of corrosion <10%

-200 mV— - 350 mV
Probability of corrosion uncertain

-350 mV— -500 mV
Probability of corrosion >90%

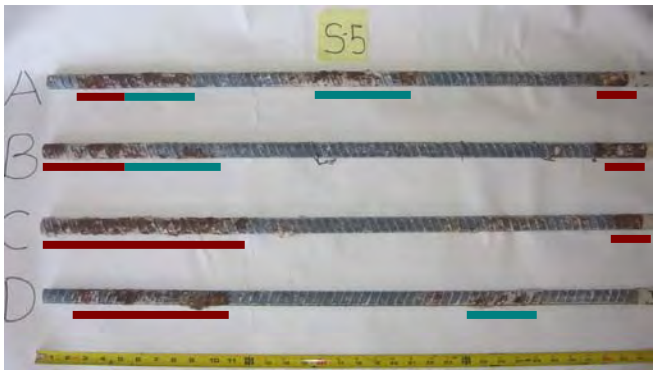
< - 500 mV
Severe Corrosion expected

Chloride Content Profiles:



THRESHOLD
1/4 in. - 3/4 in.
3/4 in. - 1 1/4 in.
1 1/4 in. - 1 3/4 in.

Corrosion of rebars:



Heavily corroded areas

Very light, one-sided corrosion

A25. S6

Wrap	Delta – 36 in.
Crack Condition	Cracked
Repair Material	None
Corrosion Inhibitor	Cortec

Column S6 completely wrapped.

After removal of wrap.

Visual Observation:

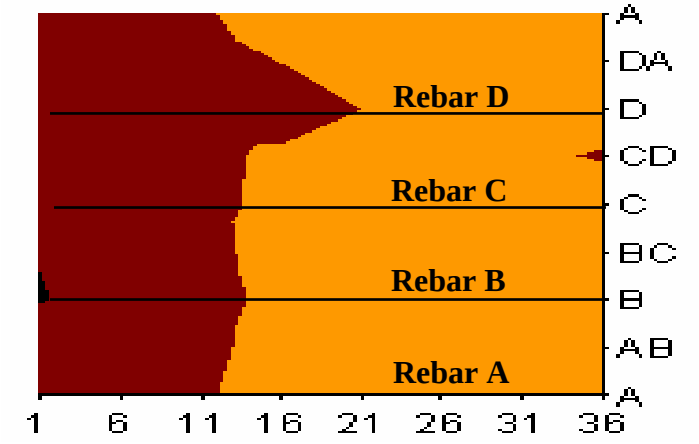
1) The column was completely wrapped. The wrap was intact at all places.
2) Rust stains were observed at 6 in. above bottom over area DA and area AB, 1.5 in. above bottom over area BC and 26 in. above bottom over rebar C.

Comments:

1) Local concentrated corrosion was observed as marked.
2) The column was completely wrapped but still there was heavy corrosion in certain areas. In most of the other specimens (cast before these new specimens), it was observed that the wrap had proved beneficial in preventing corrosion.

Heavy corrosion at 4 in. above bottom on rebar C

Half-Cell Potential Contour:



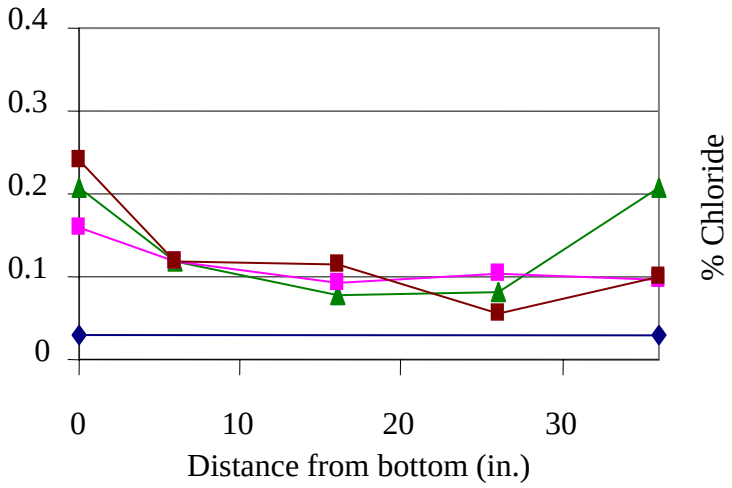
> -200 mV
Probability of corrosion <10%

-200 mV— - 350 mV
Probability of corrosion uncertain

-350 mV— -500 mV
Probability of corrosion >90%

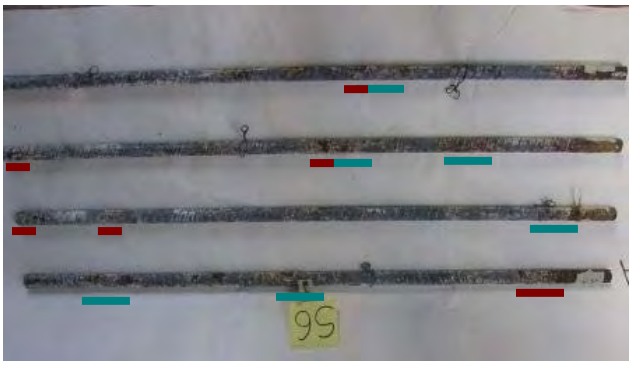
< - 500 mV
Severe Corrosion expected

Chloride Content Profiles:



Threshold
1/4 in. - 3/4 in.
3/4 in. - 1 1/4 in.
1 1/4 in. - 1 3/4 in.

Corrosion of rebars:



Heavily corroded areas

Very light, one-sided corrosion

A26. S7

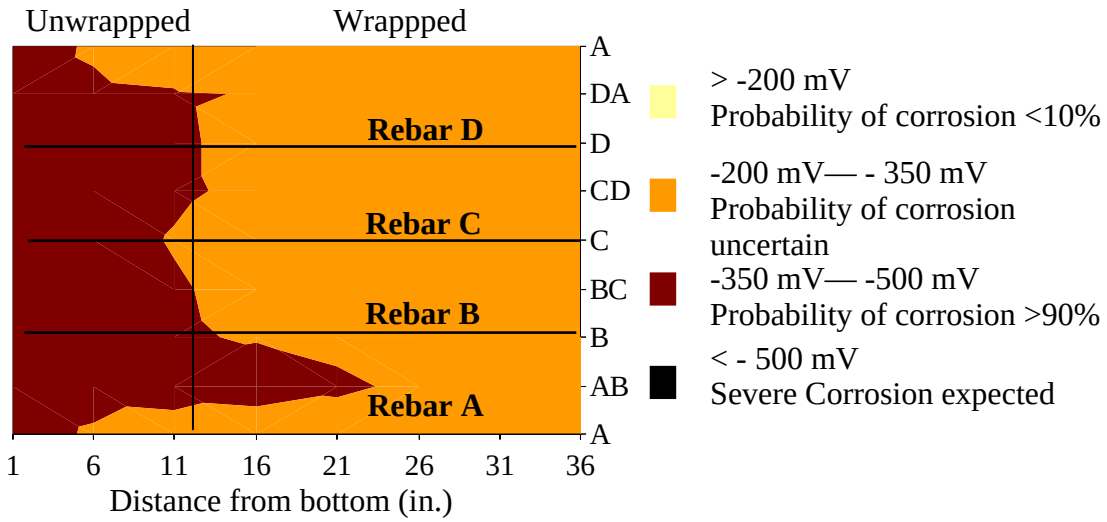
Wrap	Delta - 24 in.
Crack Condition	Uncracked
Repair Material	None
Corrosion Inhibitor	Cortec

Cylinder S7 wrapped over top 24 in.

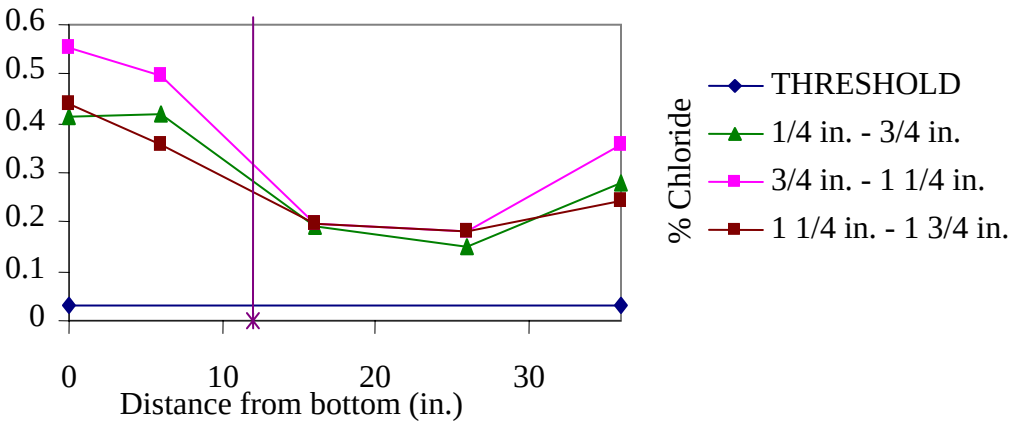
Visual Inspection:

1) The cylinder was wrapped over the top 24 in.
2) The wrap was intact at all places.
3) A vertical crack of width 0.013 in. was observed over rebar B, extending from 0 in. to 6 in.
4) A vertical crack of width 0.02 in. was observed over rebar C, extending from 0 in. to 10 in.
5) A few rust stains were observed in the unwrapped region.

Half-Cell Potential Contour:



Chloride Content Profile:



Corrosion of rebars:

A27. S8

Wrap	Delta – 36 in.
Crack Condition	Uncracked
Repair Material	None
Corrosion Inhibitor	Cortec

Column S8 completely wrapped.

No cracks or rust stains after removal of wrap.

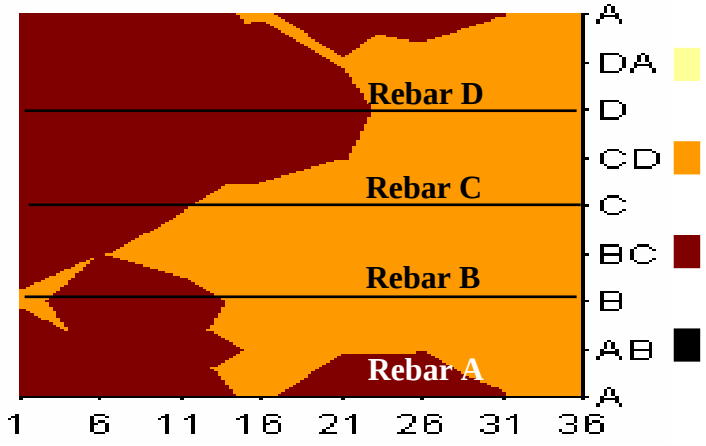
Visual Inspection:

1) The cylinder was completely wrapped. The wrap was intact at all places.
2) No rust stains or cracks were visible after removal of wrap.
3) The surface of concrete was finished properly.

Comments:

1) Though the column was fully wrapped, heavy corrosion was observed in certain areas and light corrosion in some, as marked.
2) The inhibitor used, Cortec, does not seem to be beneficial in preventing corrosion.

Half-Cell Potential Contour:



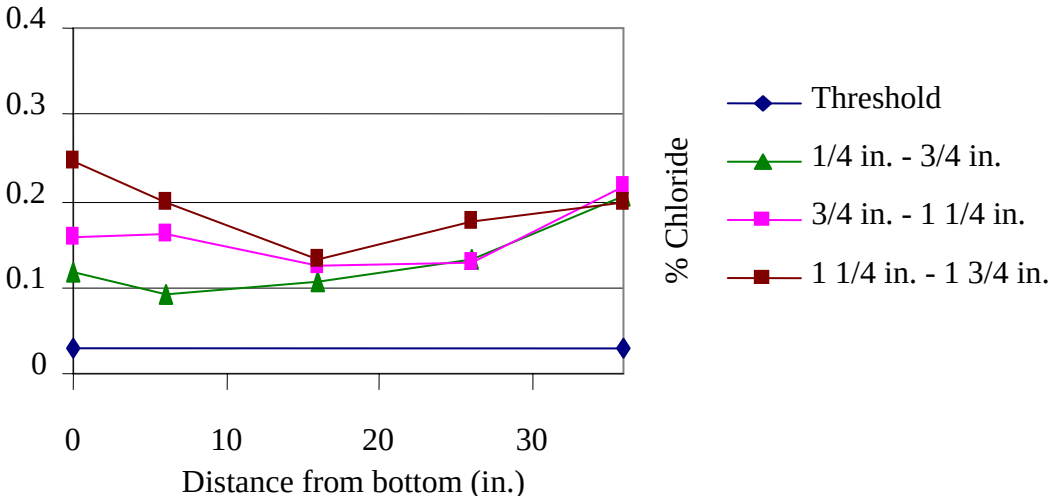
> -200 mV
Probability of corrosion <10%

-200 mV— - 350 mV
Probability of corrosion uncertain

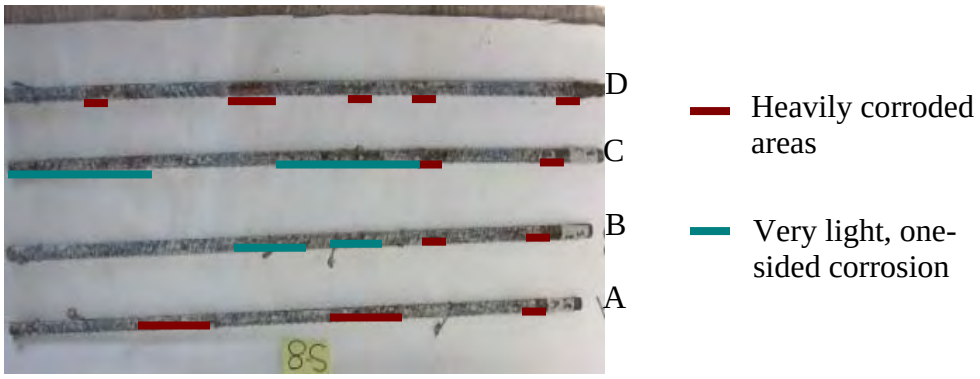
-350 mV— -500 mV
Probability of corrosion >90%

< - 500 mV
Severe Corrosion expected

Chloride Content Profiles:



Corrosion of rebars:



A28. S9

Wrap	Delta - 24 in.
Crack Condition	Cracked
Repair Material	None
Corrosion Inhibitor	Sika

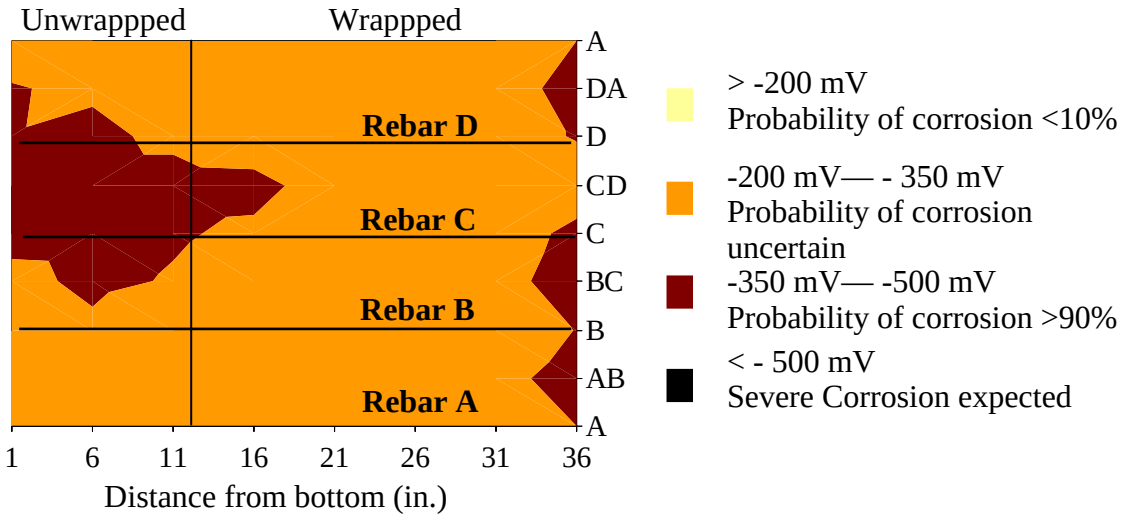
Cylinder S9 wrapped over top 24 in.

Crack over rebar C, starting where the wrap ends.

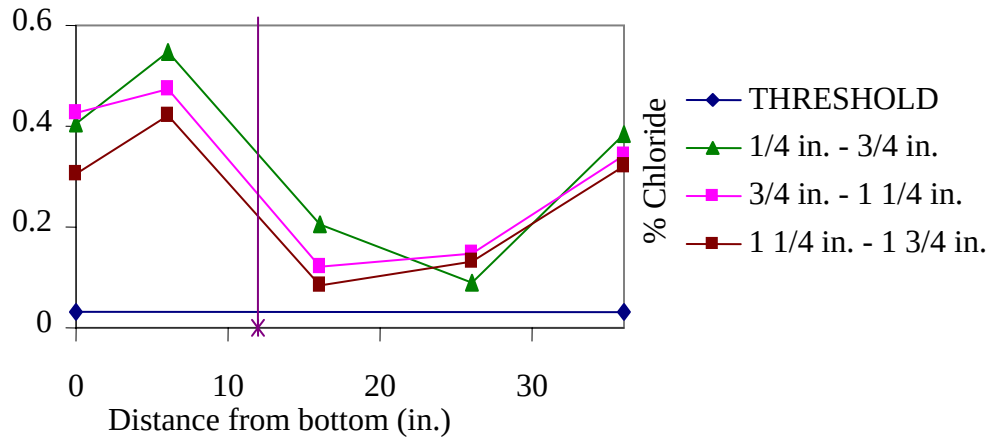
Visual Inspection:

1) The cylinder was wrapped over the top 24 in.
2) The wrap was intact at all places.
3) A vertical crack of width 0.02 in. was observed over rebar B, extending from 9 in. to 12 in.
4) A vertical crack of width 0.02 in. was observed over rebar C, extending from bottom to 12 in.

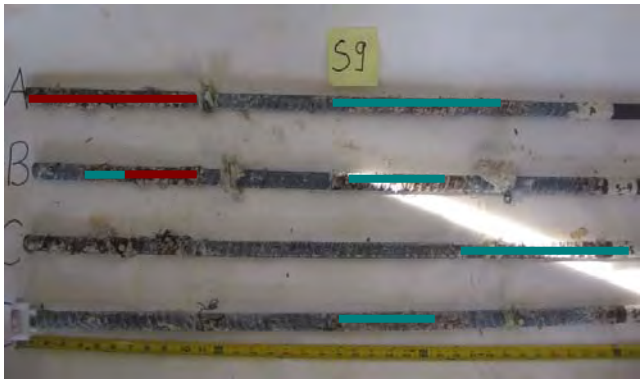
Half-Cell Potential Contour:



Chloride Content Profile:



Corrosion of rebars:



A29. S10

Wrap	Delta – 36 in.
Crack Condition	Cracked
Repair Material	None
Corrosion Inhibitor	sika

Cylinder S10 completely wrapped.

Cylinder S10 after removal of wrap.

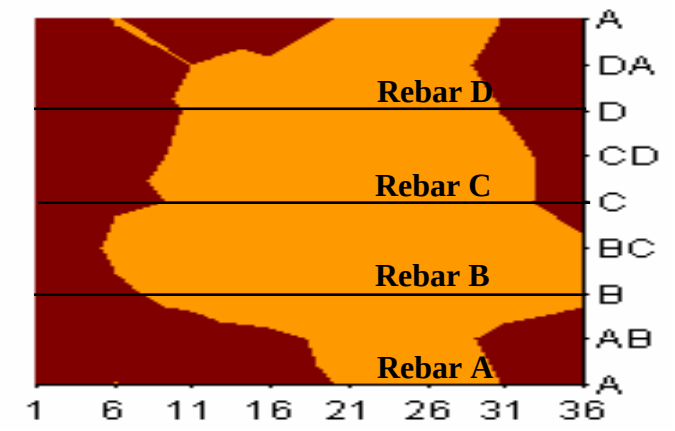
Visual observations:

1) The column was wrapped till bottom. The wrap was intact at all places.
2) No cracks or rust stains were observed after removal of wrap.

Comments:

1) The level and amount of corrosion is lesser when compared to specimens S6 and S8.

Half-Cell Potential Contour:



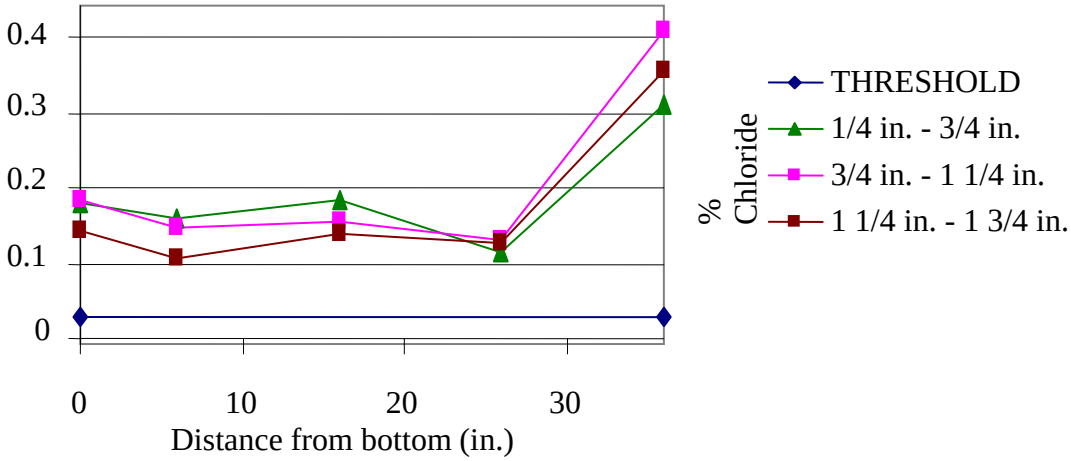
> -200 mV
Probability of corrosion <10%

-200 mV— - 350 mV
Probability of corrosion uncertain

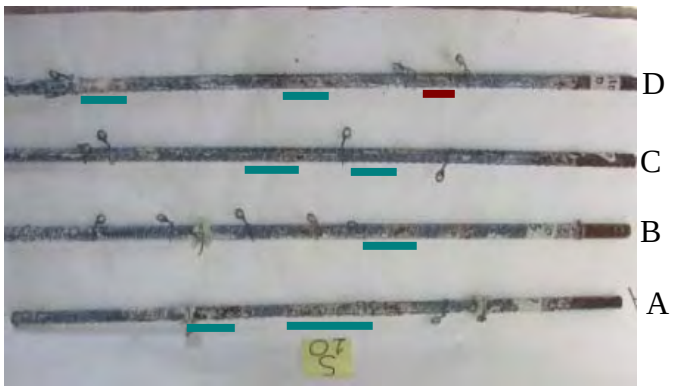
-350 mV— -500 mV
Probability of corrosion >90%

< - 500 mV
Severe Corrosion expected

Chloride Content Profile:



Corrosion of rebars:



Heavily corroded areas

Very light, one-sided corrosion

A30. S11

Wrap	Delta - 24 in.
Crack Condition	Uncracked
Repair Material	None
Corrosion Inhibitor	Sika

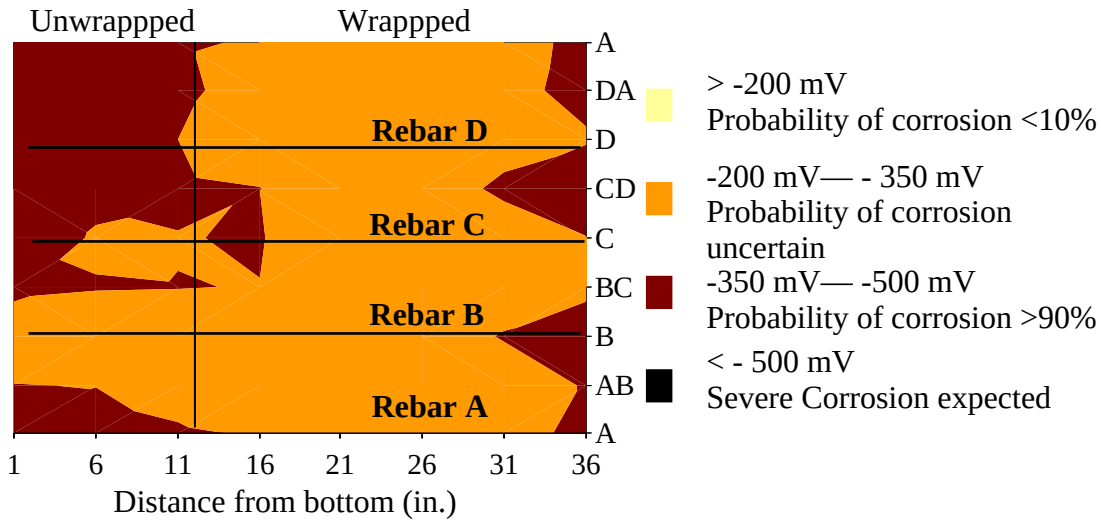
Cylinder S11 wrapped over top 24 in.

Cylinder S11 after removal of wrap.

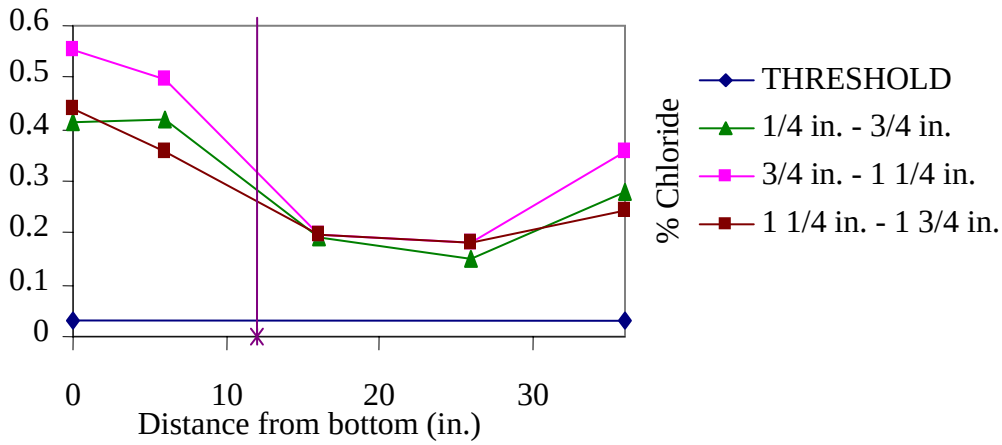
Visual Inspection:

1) The cylinder was wrapped over the top 24 in.
2) The wrap was intact at all places.
3) A vertical crack of width 0.04 in. was observed over rebar C, extending from 0 in. to 12 in.
4) A vertical crack of width 0.016 in. was observed over rebar B, extending from 2 in. to 12 in. accompanied with rust stains.
5) A vertical crack of width 0.016 in. was observed over rebar D, extending from 0 in. to 10 in.
6) Bottom (4 in. × 2.5 in.) chunk of concrete had fallen in area CD.

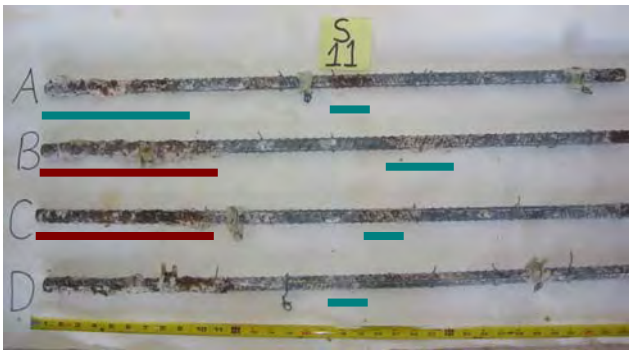
Half Cell Potential Contour:



Chloride Content Profile:



Corrosion of rebars:



Heavily corroded areas

Very light, one-sided corrosion

A31. S12

Wrap	Delta -36 in.
Crack Condition	Uncracked
Repair Material	None
Corrosion Inhibitor	Sika

Specimen S12 with wrap intact.

Specimen S12 after removal of wrap.

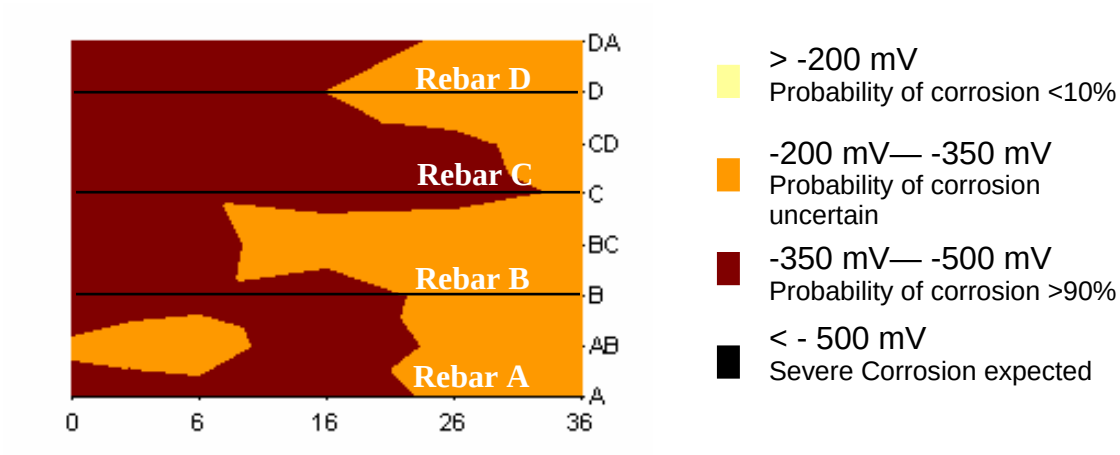
Visual Inspection:

1) The cylinder was wrapped over the full length. The wrap was intact in all places.
2) No rust stains or cracks were observed before or after removal of wrap.

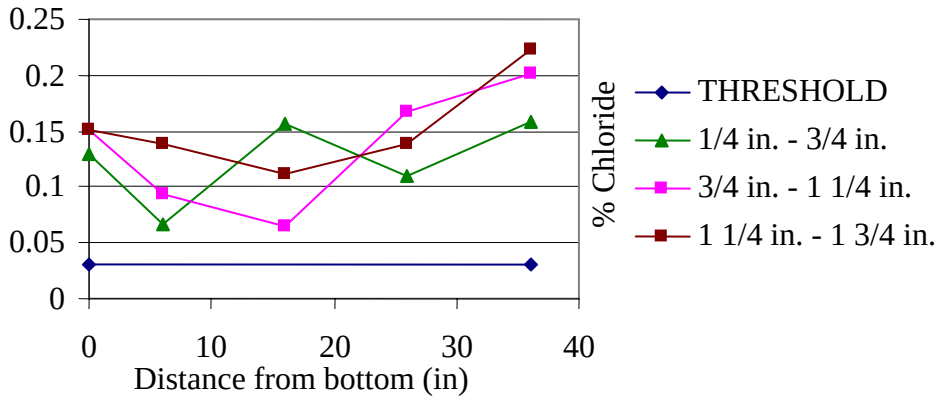
Comments:

1) The amount of corrosion was very low throughout, except on rebar C which was more corroded than the others.
2) Very little loss of cross-section was observed on the rebars.
3) Compared to cylinder S16, which had the same parameters except that it did not contain any corrosion inhibitor, corrosion was lower in cylinder S12 which contained the corrosion inhibitor Sika.

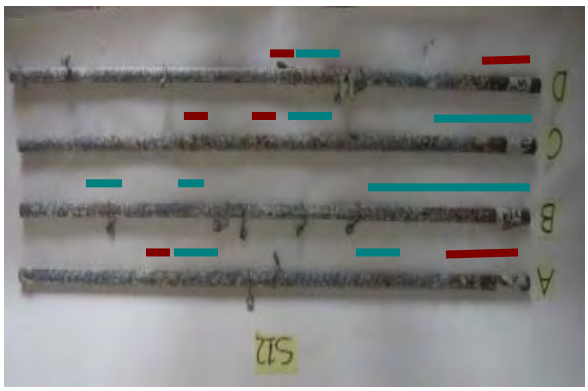
Half-Cell Potential Contour:



Chloride Content Profiles:



Corrosion of rebars:



Heavily corroded areas

Areas with light, one-sided corrosion

A32. S13

Wrap	Delta - 24 in.
Crack Condition	Cracked
Repair Material	None
Corrosion Inhibitor	None

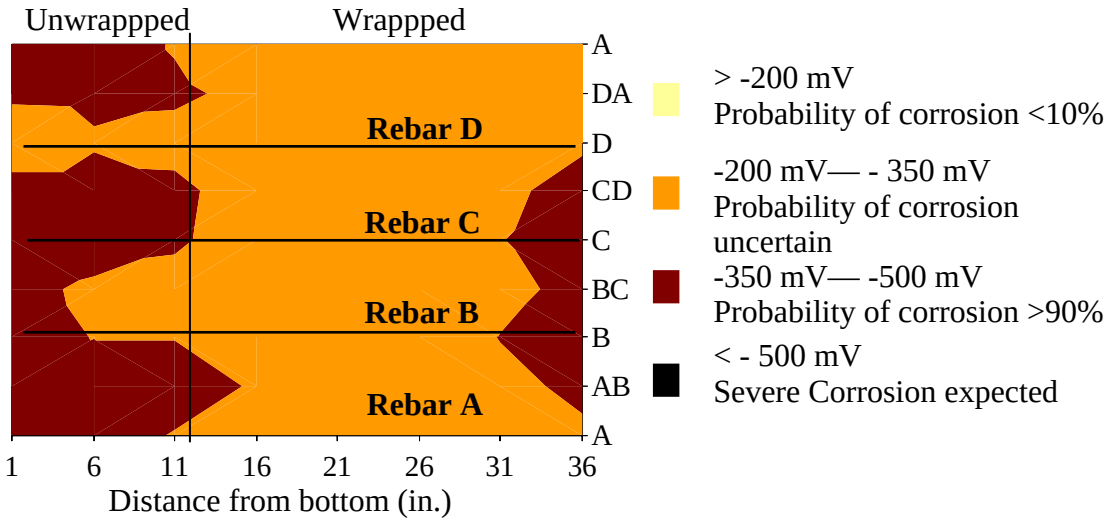
Cylinder S13 wrapped over top 24 in.

Crack and rust stains over rebar B on cylinder S13.

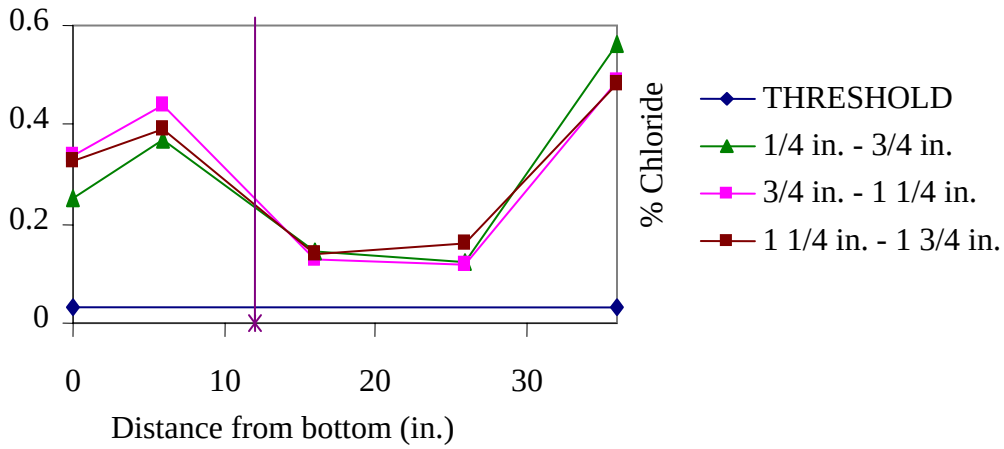
Visual Inspection:

1) The cylinder is wrapped over the top 24 in.
2) The wrap was intact in all places.
3) A vertical crack of width 0.013 in. was observed over rebar A, extending from 6 in. to 12 in.
4) A vertical crack of width 0.03 in. was observed over rebar B, extending from 0 in. to 12 in.
5) A vertical crack of width 0.03 in. was observed over rebar D, extending from 0 in. to 12 in.
6) Rust stains were observed in the unwrapped region.

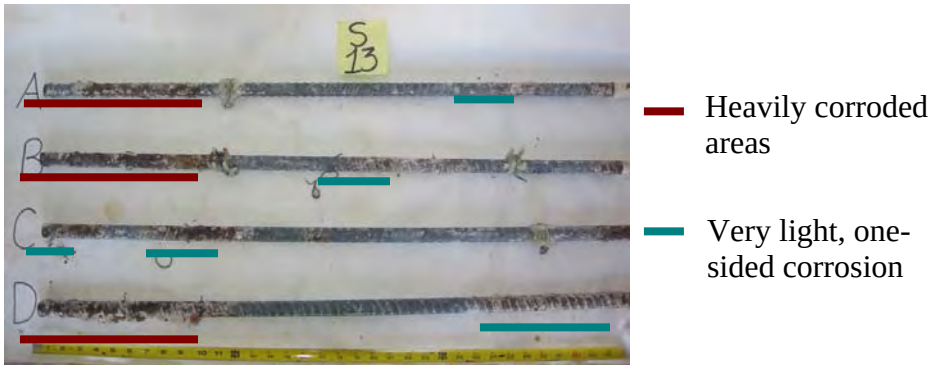
Half-Cell Potential Contour:



Chloride Content Profiles:



Corrosion of rebars:



A33. S14

Wrap	Delta- 36 in.
Crack Condition	Cracked
Repair Material	None
Corrosion Inhibitor	None

.

Specimen S14 with wrap intact.

Specimen S14 after removal of wrap.

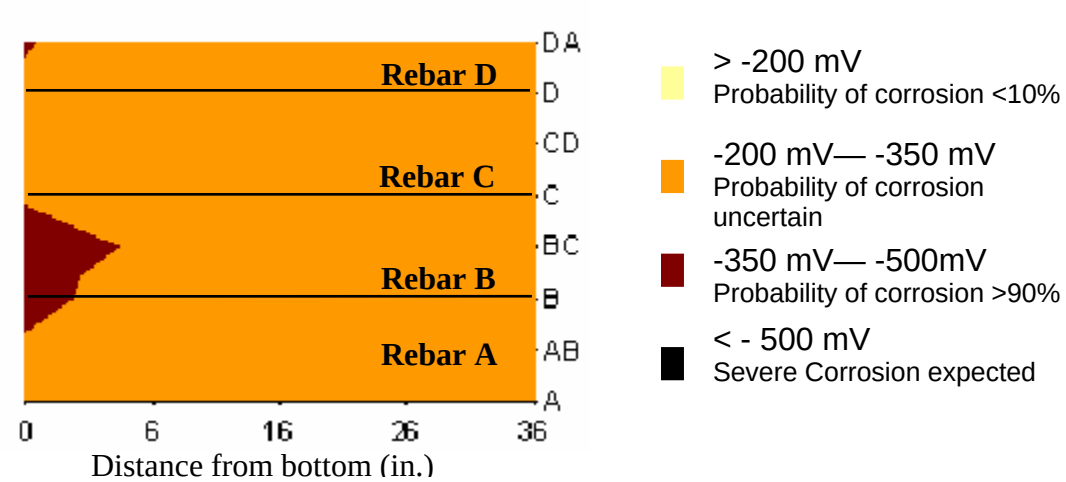
Visual Inspection:

1) The cylinder was completely wrapped. The wrap was intact in all places.
2) No rust stains or cracks were observed before or after removal of wrap.

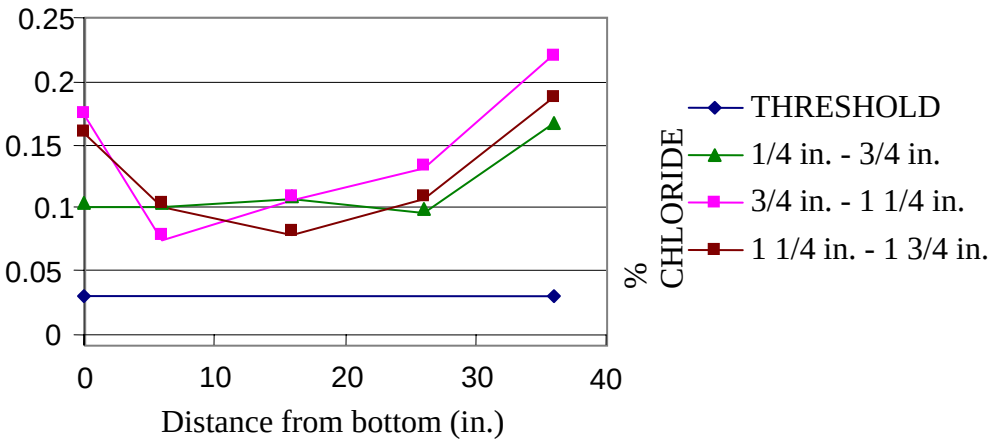
Comments:

1) The level of corrosion was higher than that of cylinder S16, possibly since cylinder S14 was cracked while S16 was uncracked. Overall the amount of corrosion was much lesser than that of unwrapped specimens.
2) Very less loss of cross-section was observed on the rebars.

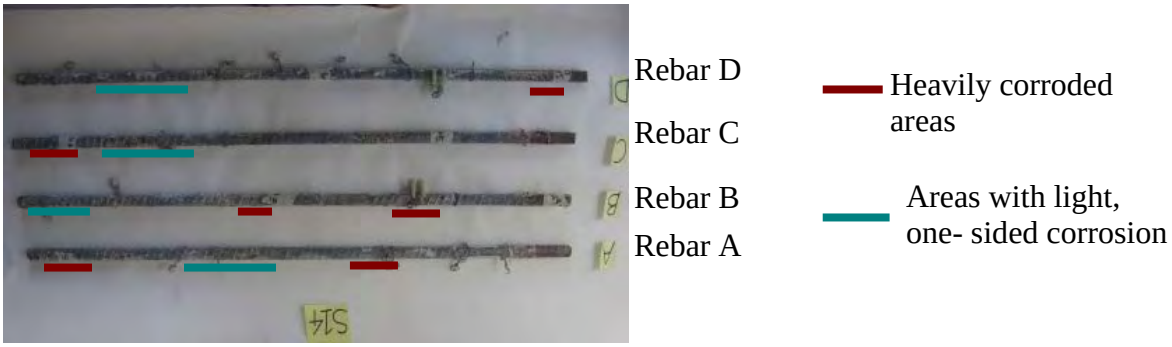
Half-Cell Potential Contour:



Chloride Content Profiles:



Corrosion of rebars:



A34. S15

Wrap	Delta - 24 in.
Crack Condition	Uncracked
Repair Material	None
Corrosion Inhibitor	None

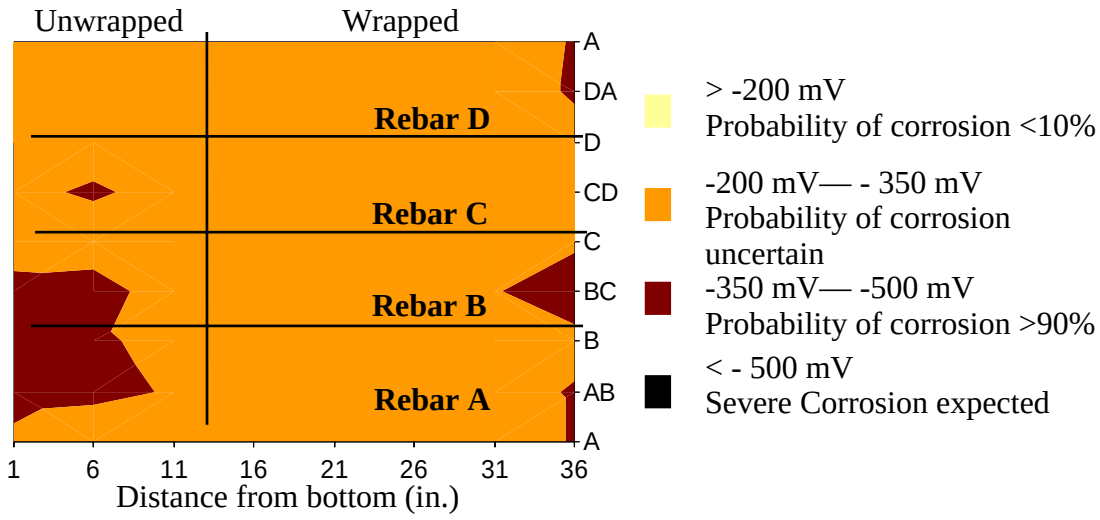
Cylinder S15 wrapped over top 24 in.

Cylinder S15 after removal of wrap.

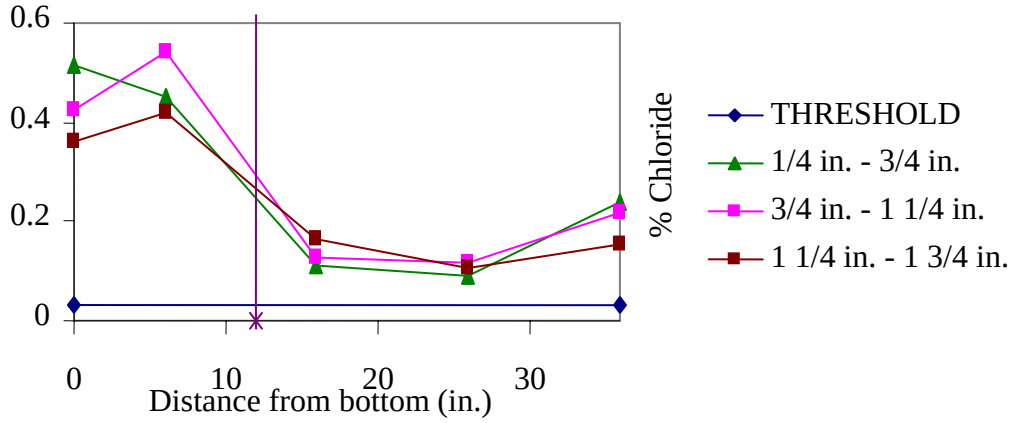
Visual Inspection:

1) The cylinder is wrapped over the top 24 in.
2) The wrap is intact in all places.
3) A vertical hairline crack (width 0.01 in.) was observed over rebar D and rebar C, extending from 0 in. to 12 in., accompanied with rust stains.
4) Small rust stains were observed all over the unwrapped region.

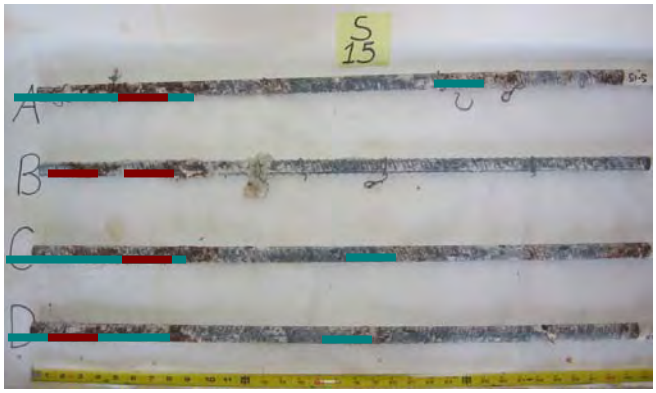
Half Cell Potential Contour:



Chloride Content Profiles:



Corrosion of rebars:



A35. S16

Wrap	Delta – 36 in.
Crack Condition	Uncracked
Repair Material	None
Corrosion Inhibitor	None

Cylinder S16 with wrap removed.

Cylinder S16 completely wrapped.

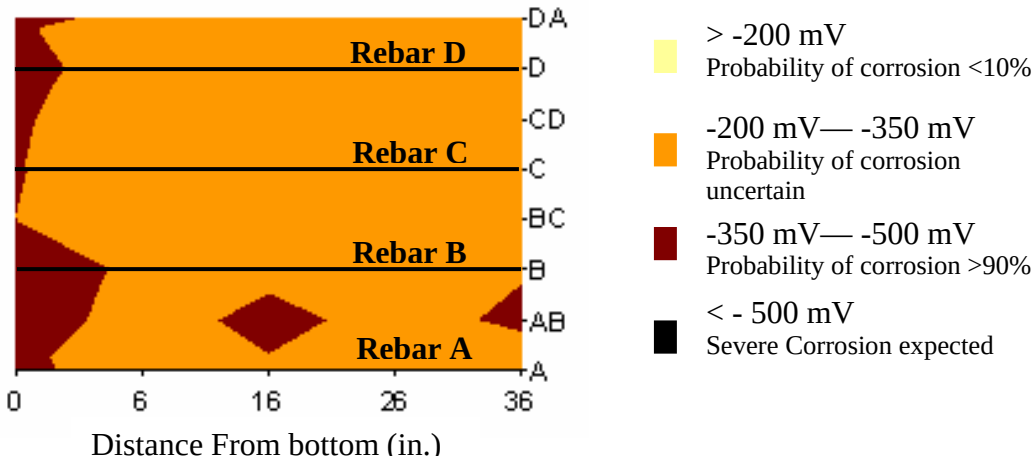
Visual Inspection:

1) The cylinder was completely wrapped. The wrap was intact in all places.
2) No rust stains or cracks were observed before or after removal of wrap.

Comments:

1) Rebar A was corroded only near the top. No major corrosion was observed anywhere else.
2) Rebar B, C, D were lightly corroded intermittently. Very less corrosion was observed on rebar D.
3) There was a marked difference in the level of corrosion of unwrapped and wrapped specimens.
4) It was observed in nearly all the specimens that the top 1 in. to 1 1/2 in. of rebar, just below the surface on the exposed upper end, was always corroded. The portions of the rebars that were extended out underwent heavy corrosion, and the corrosion extended to the covered portions as well.

Half-Cell Potential Contour:



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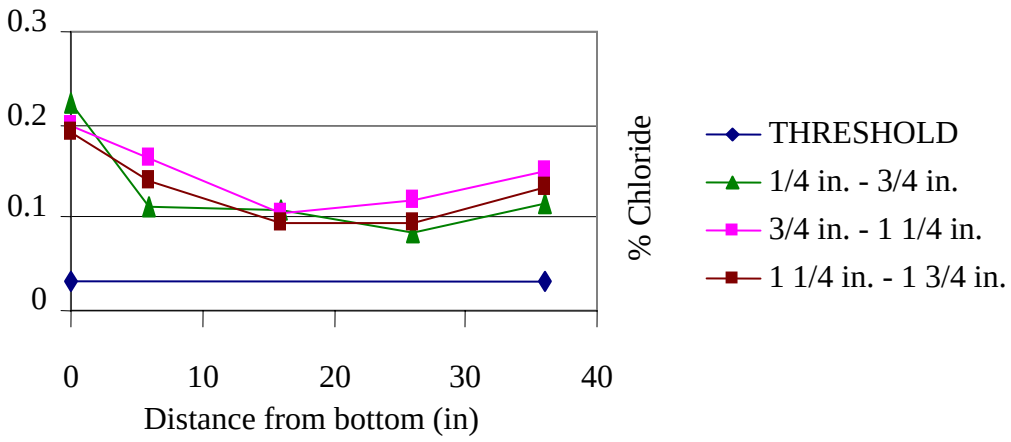
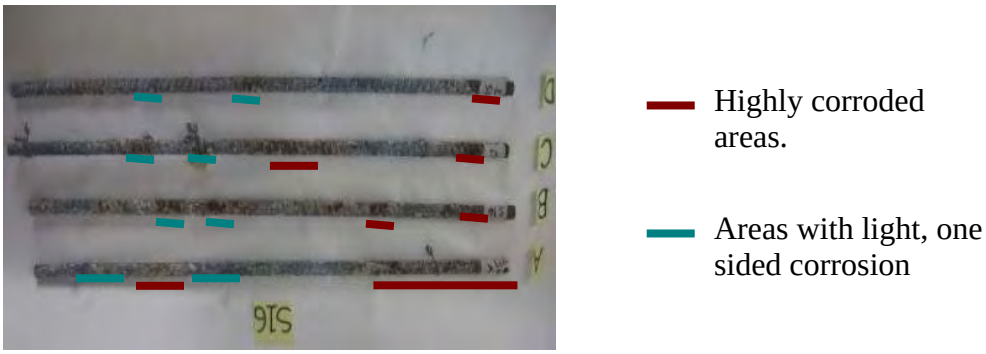


Corrosion of rebars:



A36. S19

Wrap	None
Resin	None
Crack Condition	Cracked
Repair Material	None
Corrosion Inhibitor	None

Specimen S19, Rebar A in front.

Spalling and cracking at bottom of Area AD.

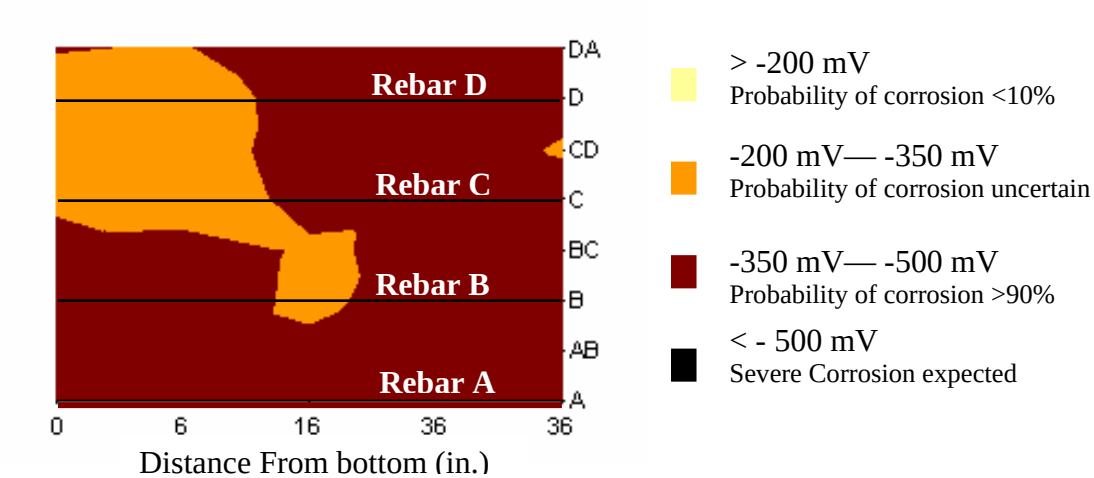
Visual Inspection:

1) A vertical crack of width 0.013 in. occurred over rebar A, extending from the top to 22 in. from top. Wider cracks of width 0.03 in. occurred near bottom.
2) A vertical crack of width 0.02 in. occurred over rebar B that turned diagonal after 20 in. from top. Approximately 3/4 in. diameter stain spots were located at top near rebar B.
3) A vertical crack of width 0.02 in. occurred from top to bottom over rebar C. Stain spots of approximately 3/4 in. diameter were located along the crack.
4) A vertical crack of width 0.016 in. occurred from top to bottom over rebar D.
5) The concrete was spalled over bottom area AD.

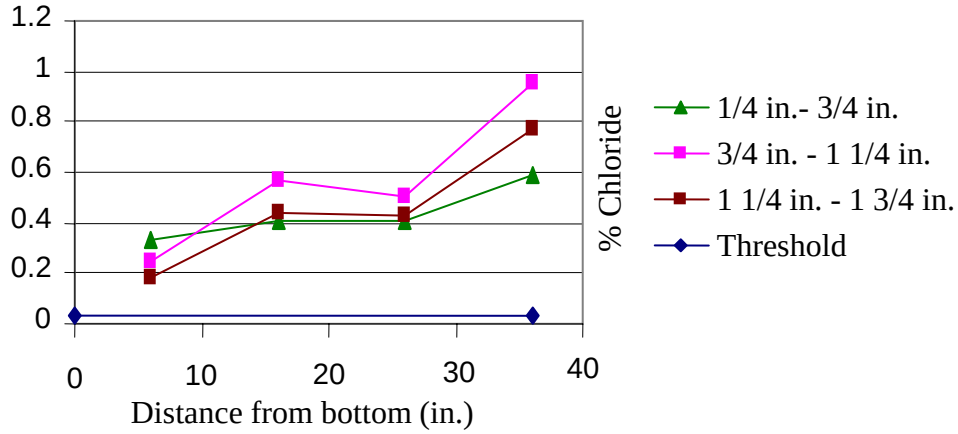
Comments:

1) Rebar A was much less corroded than rebar D, even though the half-cell readings indicate otherwise.
2) Bars were not corroded where spacers were embedded.
3) Rebar A was lesser corroded over bottom 11 in., especially on one side; and was intermittently corroded above that.
4) Rebars C and D were highly corroded, especially at the bottom. (Spalling and large cracks had been observed near the bottom.)

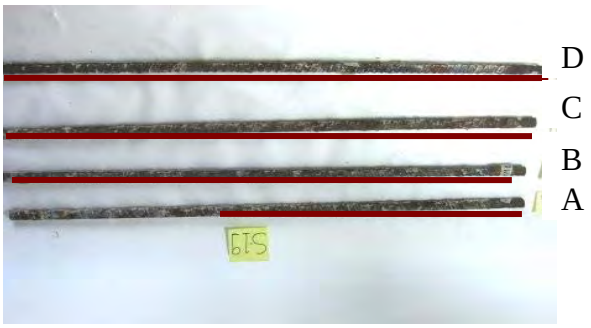
Half-Cell Potential Contour



Chloride Content Profiles:



Corrosion of rebars:



A37. RC1

Wrap	Generic-27”
Resin	862
Surface at	Dry
Crack Condition	Uncracked
Repair Material	LMC
Corrosion Inhibitor	Ferrogard

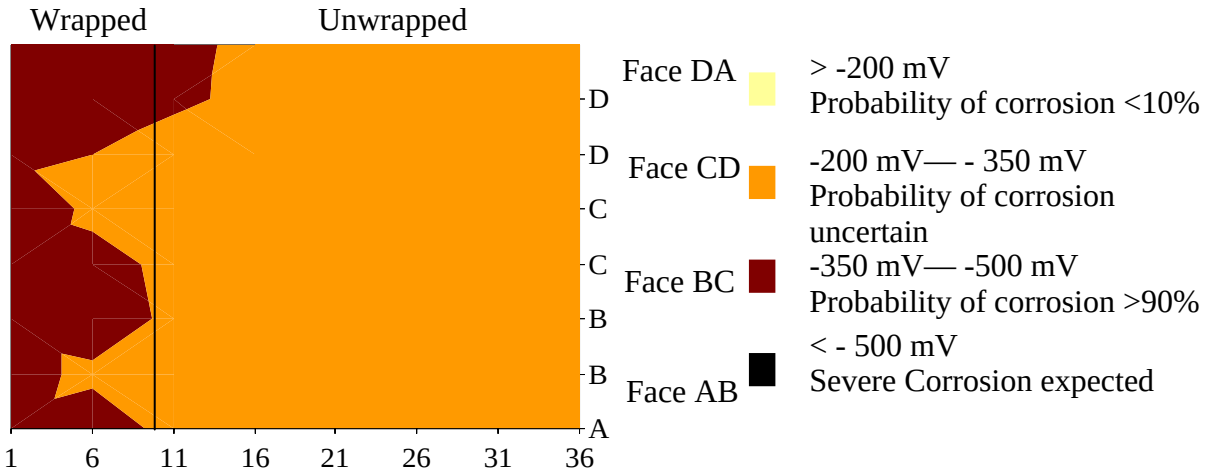
Specimen RC1 wrapped over the top 27 in.

Specimen RC1 with rust stain on rebar B.

Visual Inspection:

1) The square specimen was wrapped over the top 27in.
2) A vertical crack of width 0.05 in. was observed over rebar D extending from 0 in. to 5 in. on face DC.
3) A vertical crack of width 0.05 in. was observed over rebar C extending from 0 in. to 4 in. on face BC.
4) A vertical crack of width 0.01 in. was observed over rebar B extending from 0 in. to 2.5 in. on face BC.
5) A vertical crack of width 1/8 in. was observed over rebar B extending from 0 in. to 2 in. on face AB.
6) A vertical crack of width 0.02 in. was observed over rebar A extending from 0 in. to 2.5 in. on face AB.

Half-Cell Potential Contour:



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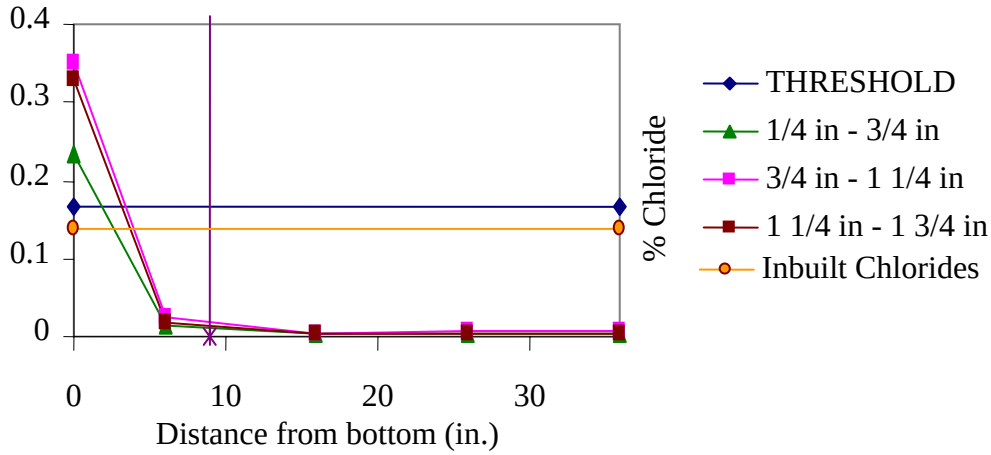
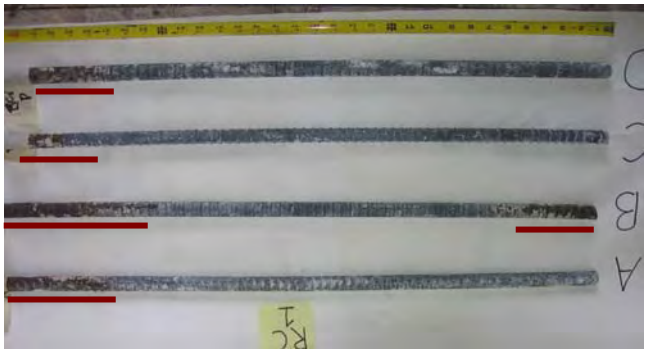


Corrosion on rebars:



Heavily corroded areas

Very light, one-sided corrosion

A38. RC6

Wrap	Gen/del-33”
Resin	862
Surface at	Dry
Crack Condition	Uncracked
Repair Material	LMC
Corrosion Inhibitor	None

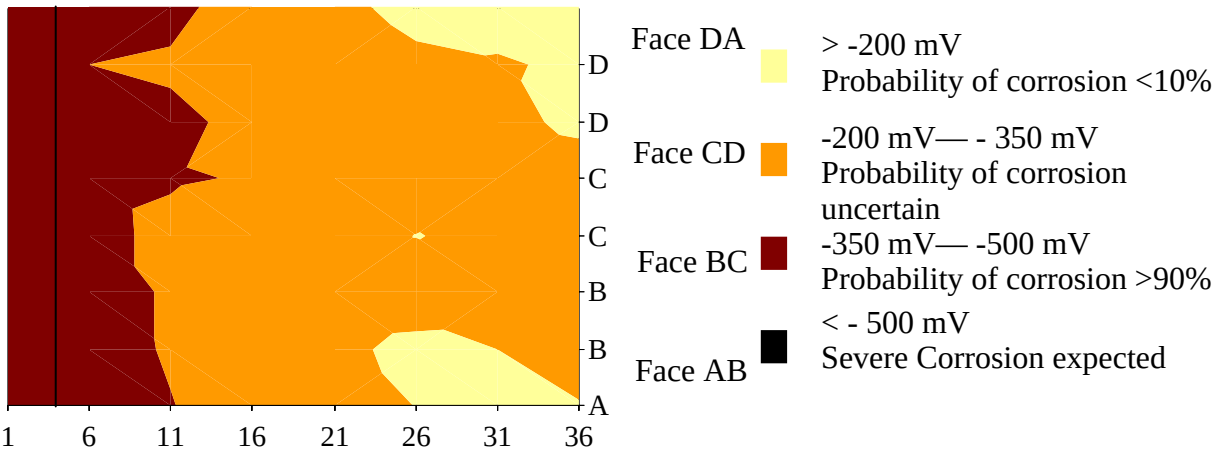
Specimen RC6 wrapped over the top 33 in.

Specimen RC6 after removal of wrap

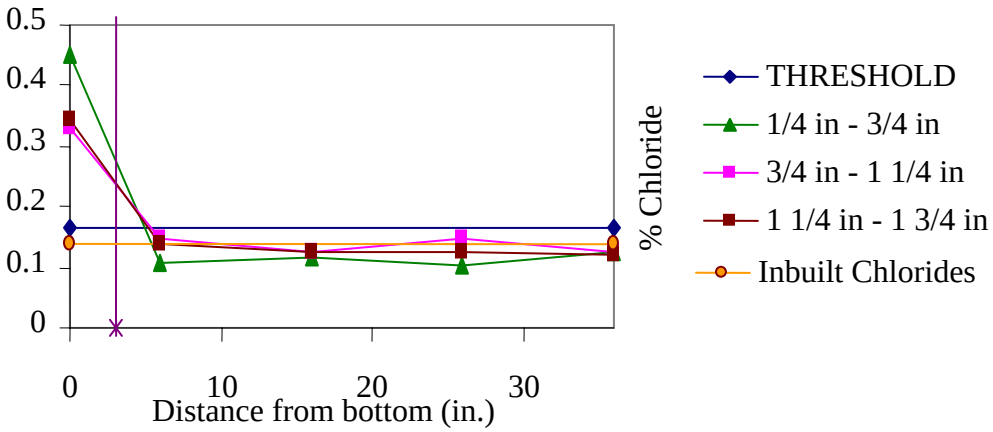
Visual Inspection:

1) The specimen was covered with repair material extending from 20 in. to 36 in. over face DA and half each of face AB and DC.
2) Vertical cracks of width 0.03 in. and 0.013 in. were observed over rebar D extending from 0 in. to 4 in. on face DA and from 0 in. to 7 in. on face CD respectively.
3) Vertical cracks of width 0.02 in. were observed over rebar A extending from 0 in. to 2.5 in. on face AB and from 0 in. to 4 in. on face AB.
4) Vertical cracks of width 0.016 in. were observed over rebar B extending from 0 in. to 5 in. on face AB and from 0 in. to 7 in. on face BC.
5) Vertical cracks of width 0.01 in. were observed over rebar C extending from 0 in. to 6 in. on face BC and face CD.

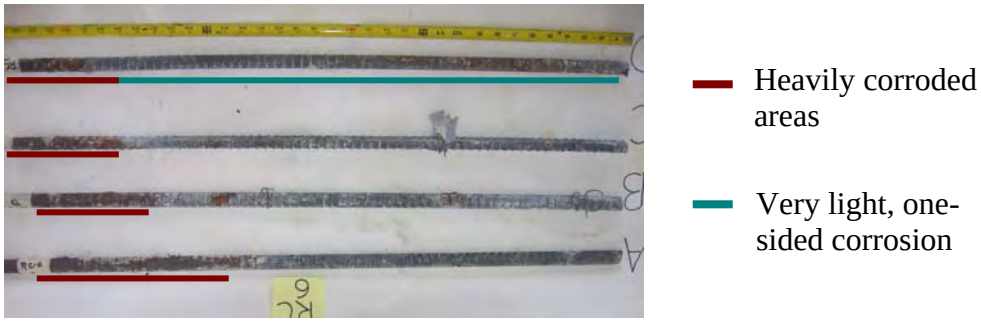
Half-Cell Potential Contour:



Chloride Content Profiles:



Corrosion on rebars:



A39. RC8

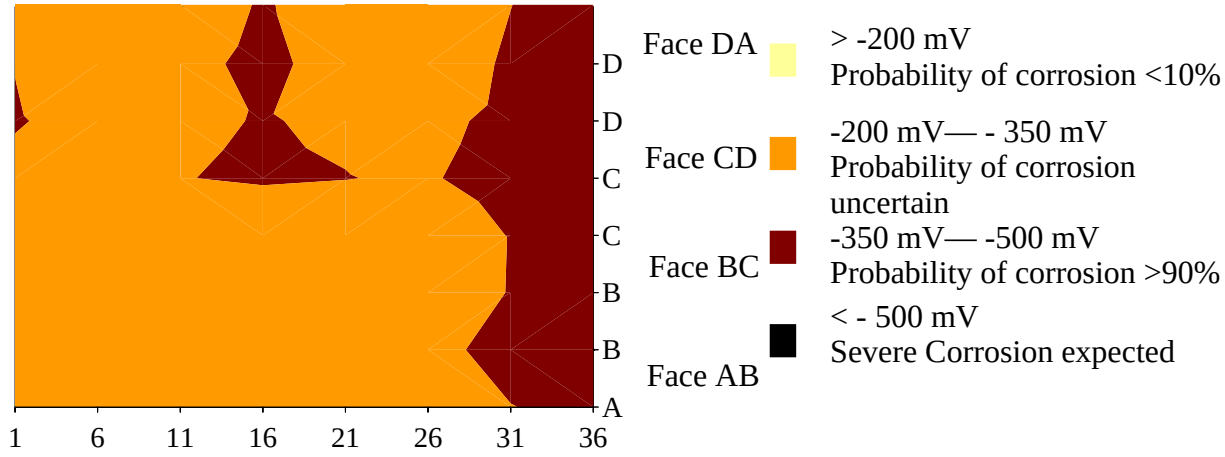
Wrap	None
Resin	None
Surface at	Dry
Crack Condition	Uncracked
Repair Material	LMC
Corrosion Inhibitor	None

Specimen RC8 with no wrap.

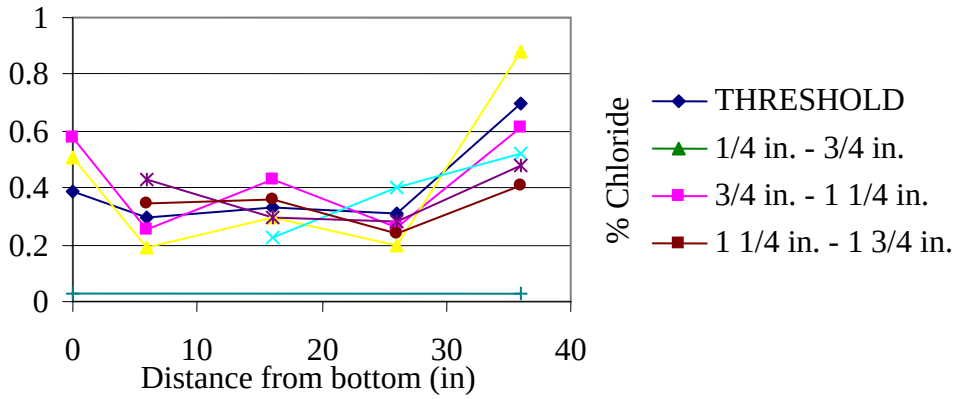
Visual Inspection:

1) Large vertical cracks of width 1/8 in. were observed on each side on each rebar extending over the full length of the specimens.
2) The cracks were accompanied with large rust stains.
3) Concrete had spalled-off over the lower end of rebar B.

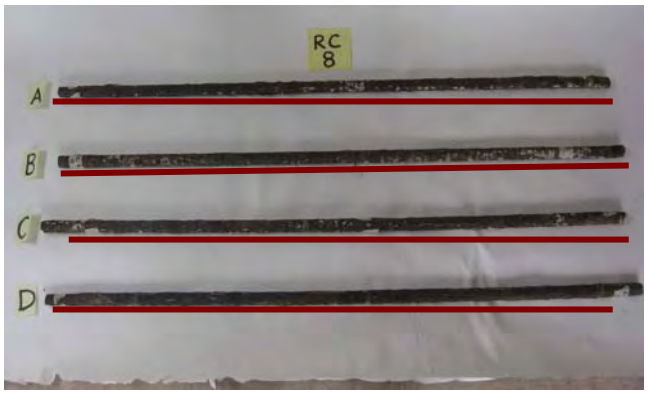
Half-Cell Potential Contour:



Chloride Content Profiles:



Corrosion on rebars:



Heavily corroded areas

Very light, one-sided corrosion

A40. RC9

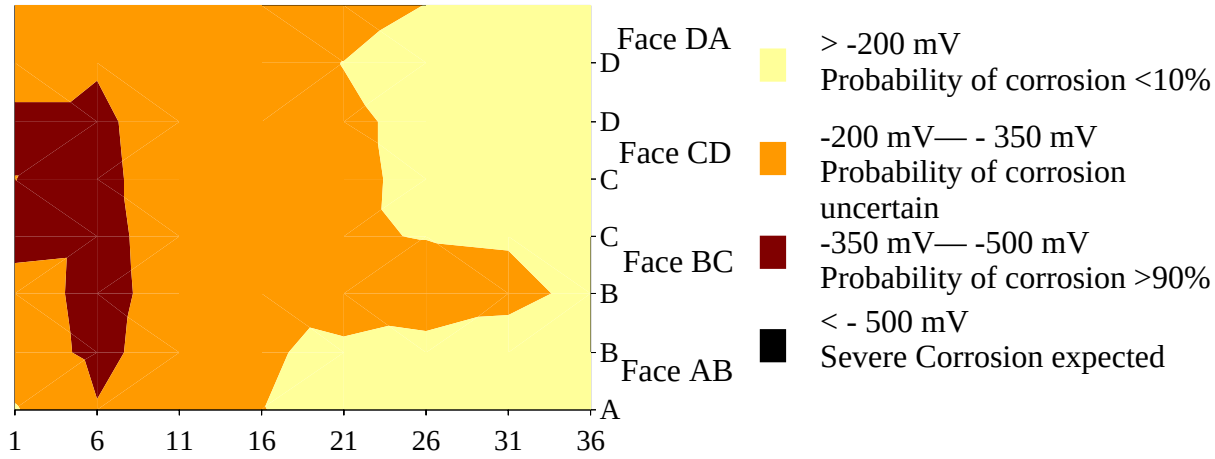
Wrap	Gen/del – 24 in.
Resin	862
Surface at	Dry
Crack Condition	Cracked
Repair Material	None
Corrosion Inhibitor	Ferrogard

Specimen RC9.

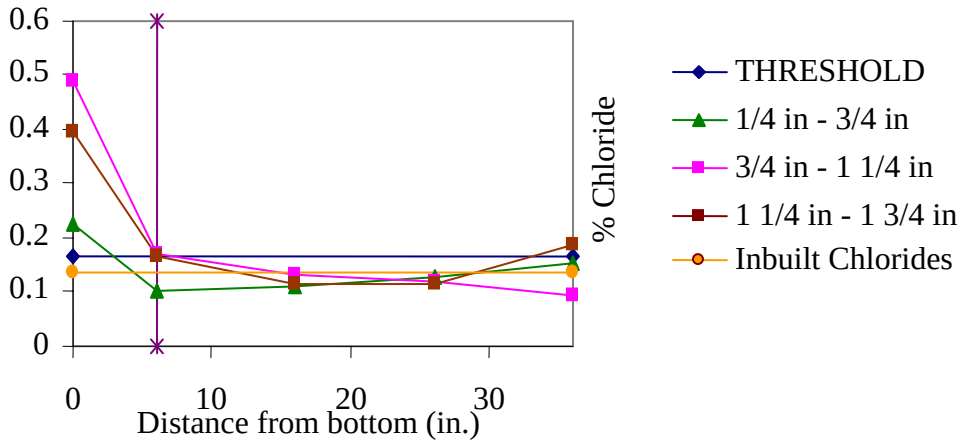
Visual Inspection:

1) A vertical crack of width 0.07 in. was observed over rebar C extending from 0 in. to 4 in. on face CD.
2) Vertical cracks of width 0.02 in. and 0.06 in. were observed over rebar D extending from 0 in. to 4 in. on face CD and face DA respectively.
3) A vertical crack of width 0.04 in. was observed over rebar A extending from 0 in. to 4 in. on face DA.

Half-Cell Potential Contour:



Chloride Content Profiles:



Corrosion on rebars:

A41. RNC4

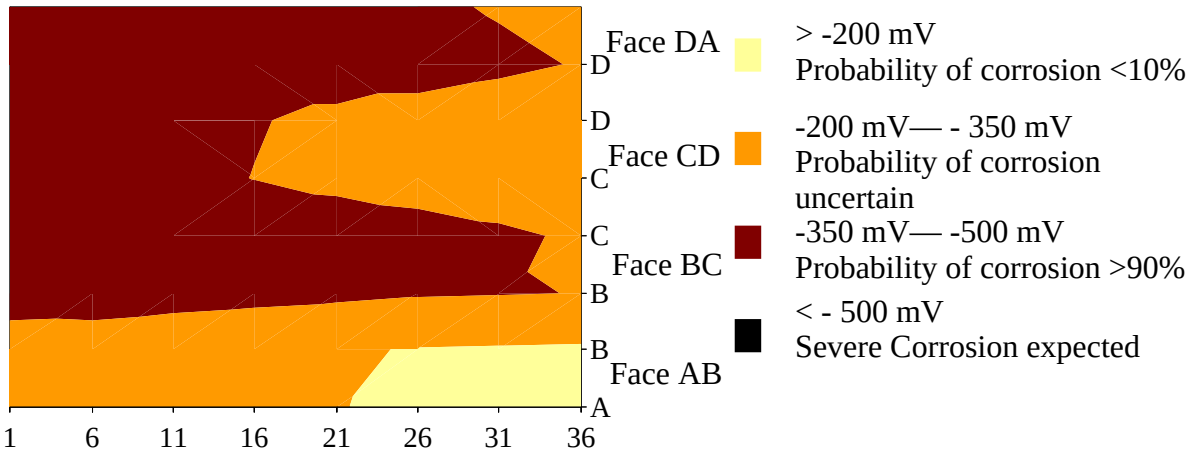
Wrap	Generic – 36 in.
Resin	Vinyl ester
Surface at	Dry
Crack Condition	Uncracked
Repair Material	LMC
Corrosion Inhibitor	None

Specimen RNC4 before and after removal of wrap.

Visual Inspection:

1) The specimen was completely wrapped and the wrap was intact in all places.
2) No cracks or stain spots were visible on the wrap.
3) The specimen was covered with repair material extending from 0 in. to 17 in. over face BC and CD.
4) A rust stain was observed on the lower end of rebar A.

Half-Cell Potential Contour:



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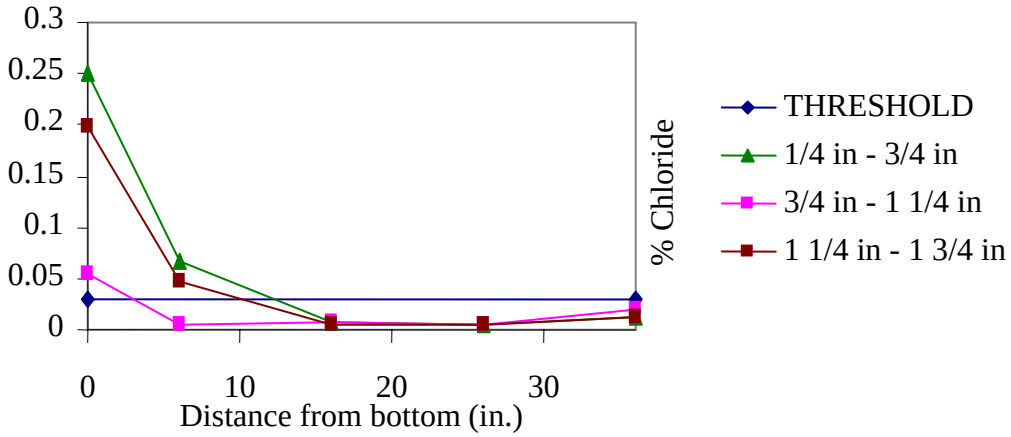


Corrosion on rebars:

Heavily corroded areas

Very light, one-sided corrosion

A42. RNC5

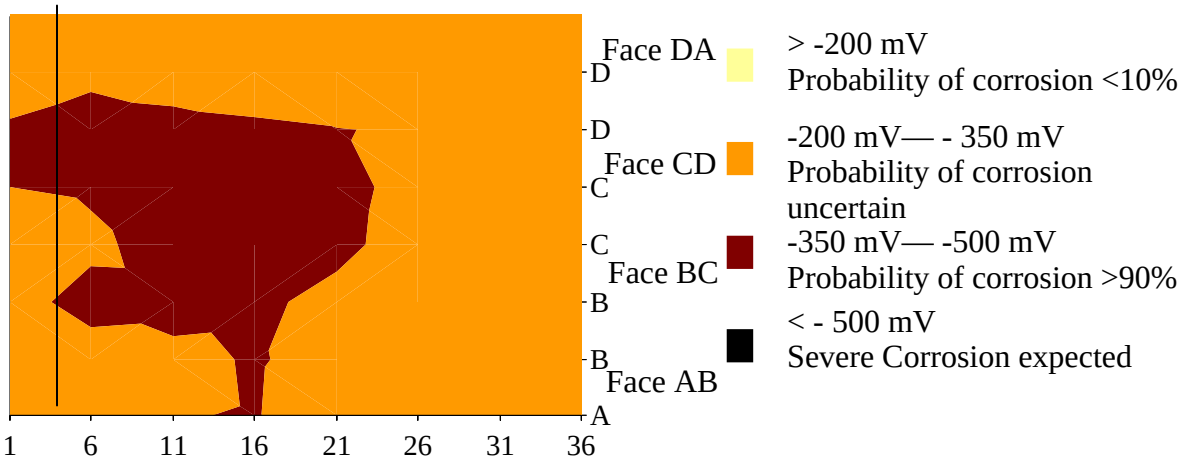
Wrap	Delta – 30 in.
Resin	Delta system
Surface at	Dry
Crack Condition	Cracked
Repair Material	None
Corrosion Inhibitor	None

Specimen RNC5 before and after removal of wrap.

Visual inspection:

1) A vertical crack of width 1/8 in. was observed over rebar A extending from 0 in. to 6 in. on face DA.
2) A vertical crack of width 1/8 in. was observed over rebar D extending from 0 in. to 6 in. on face CD.
3) A vertical crack of width 3/16 in. was observed over rebar C extending from 0 in. to 6 in. on face CD.
4) A vertical crack of width 3/16 in. was observed over rebar B extending from 0 in. to 7 in. on face BC.
5) The specimen was covered with repair material extending from 16 in -36 in. over face CD.

Half-Cell Potential Contour:



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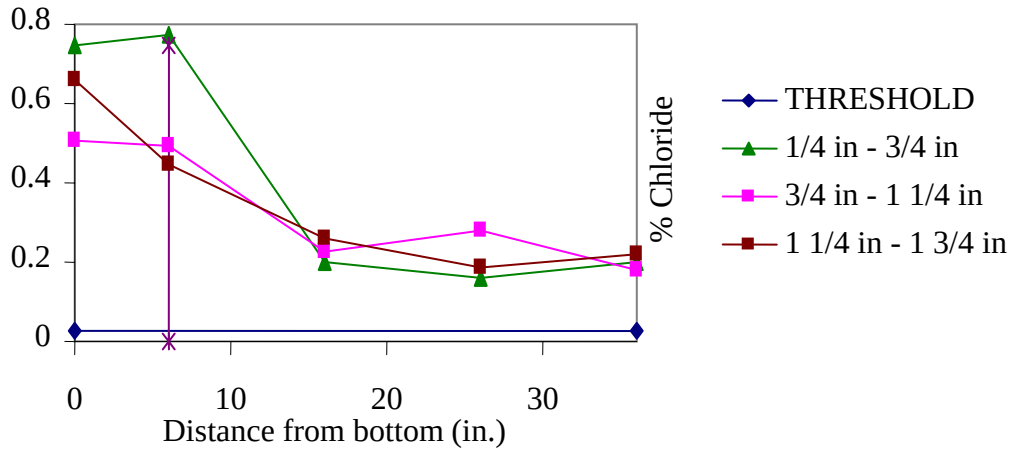


Corrosion on rebars:

A43. RNC8

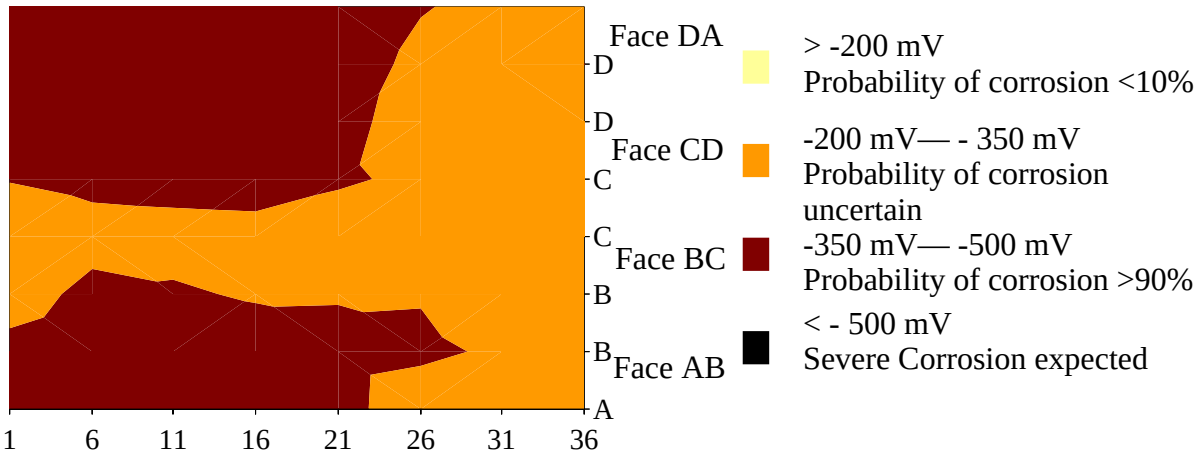
Wrap	Generic – 24 in.
Resin	862
Surface at	Dry
Crack Condition	Cracked
Repair Material	None
Corrosion Inhibitor	None

Specimen RNC8 before and after removal of wrap.

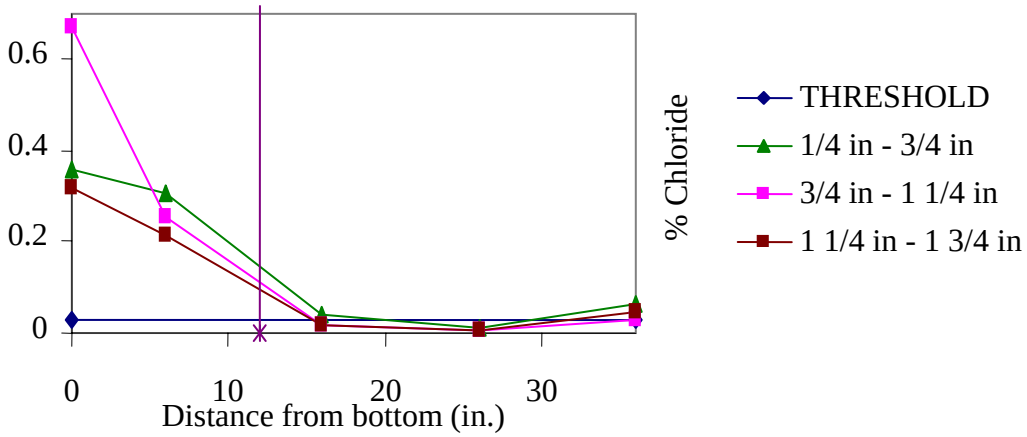
Visual Inspection:

1) A vertical crack of width 1/8 in. was observed over rebar B extending from 0 in. to 6 in. on face AB.
2) A vertical crack of width 0.08 in. was observed over rebar A extending from 0 in. to 7 in. on face AB.
3) A vertical crack of width 3/16 in. was observed over rebar C extending from 0 in. to 7 in. on face CD.
4) A vertical crack of width 0.06 in. was observed over rebar D extending from 0 in. to 7 in. on face CD.
5) A vertical crack of width 0.06 in. was observed over rebar D extending from 0 in. to 7 in. on face DA.

Half-Cell Potential Contour:



Chloride Content Profiles:



Corrosion of rebars:

Heavily corroded areas

Very light, one-sided corrosion

References

Verhulst, S.M., Fuentes, L.A., Jirsa, J.O., Fower, D.W., Wheat, H.G., and Moon, T., "Evaluation and Performance Monitoring of Corrosion Protection by Fiber-Reinforced Composite Wrapping," Center for Transportation Research Report 0-1774-1, January 2001.

Berver, E.W., Jirsa, J.O., Fowler, D.W., Wheat, H.G., and Moon, T., "Effects of Wrapping Chloride Contaminated Structural Concrete with Fiber Reinforced Plastics," Center for Transportation Research Report 0-1774-2, October 2001.

Shoemaker, C.L., Quiroga, P.N., Jirsa, J.O., Fowler, D.W., and Wheat, H.G., "Detailed Evaluation of Performance of FRP Wrapped Columns and Beams in a Corrosive Environment," Center for Transportation Research Report 0-1774-3, June 2004.