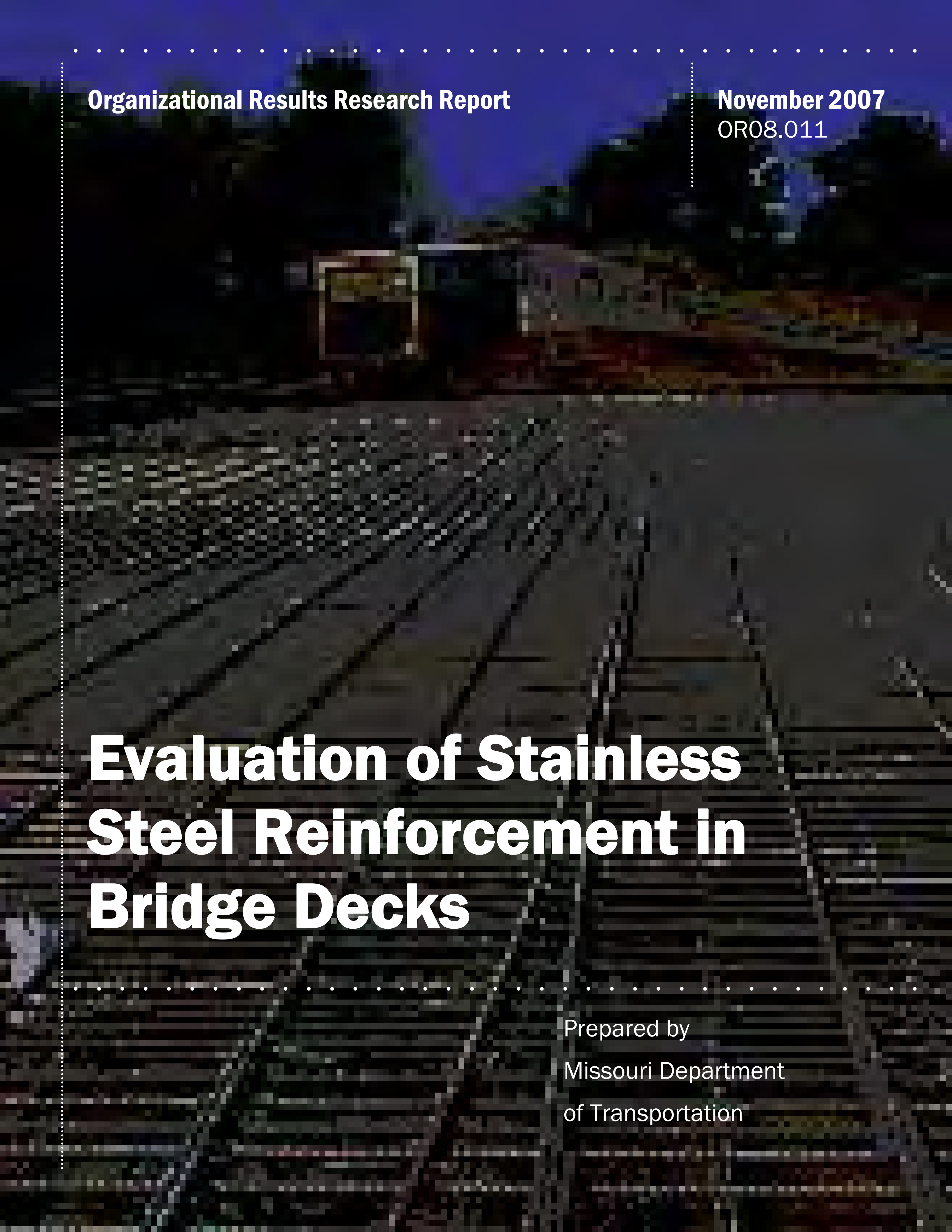

Organizational Results Research Report

November 2007
OR08.011

Evaluation of Stainless Steel Reinforcement in Bridge Decks

Prepared by
Missouri Department
of Transportation

Follow up and Final Report

RI00-027

Evaluation of Stainless Steel Reinforcement in Bridge Decks

Prepared for the
Missouri Department of Transportation
Organizational Results

By
John D. Wenzlick, P.E.
Missouri Department of Transportation

October 2007

TECHNICAL REPORT DOCUMENTATION PAGE.

<table>
<tr><td>1. Report No.:
OR08-011</td><td>2. Government Accession No.:</td><td colspan="2">3. Recipient's Catalog No.:</td></tr>
<tr><td colspan="2" rowspan="2">4. Title and Subtitle:
Evaluation of Stainless Steel Reinforcement In Bridge Decks Report</td><td colspan="2">5. Report Date:
November 2007</td></tr>
<tr><td colspan="2">6. Performing Organization Code:</td></tr>
<tr><td colspan="2">7. Author(s):
John D. Wenzlick</td><td colspan="2">8. Performing Organization Report No.: RI00-027</td></tr>
<tr><td colspan="2" rowspan="2">9. Performing Organization Name and Address:
Missouri Department of Transportation
Organizational Results
PO BOX 270, JEFFERSON CITY MO 65102</td><td colspan="2">10. Work Unit No.:</td></tr>
<tr><td colspan="2">11. Contract or Grant No.:</td></tr>
<tr><td colspan="2" rowspan="2">12. Sponsoring Agency Name and Address:

Missouri Department of Transportation
Organizational Results
PO BOX 270, JEFFERSON CITY MO 65102</td><td colspan="2">13. Type of Report and Period Covered:
Final Report.</td></tr>
<tr><td colspan="2">14. Sponsoring Agency Code:</td></tr>
<tr><td colspan="4">15. Supplementary Notes:
The investigation was conducted in cooperation with the U. S. Department of Transportation, Federal Highway Administration.</td></tr>
<tr><td colspan="4">16. Abstract:
This report is a follow up and final report to the report on the “ Evaluation of Stainless Steel Reinforcement, Construction Report. RDT 03 – 003”. The results of interim testing during the bridges first five years are reported for Missouri’s first cast-in-place bridge deck using solid stainless steel reinforcing bars. This deck was compared to a conventionally constructed deck using precast p/s stay-in-place panels and a top mat of epoxy coated reinforcing steel. The deck construction was completed in 2001. Fiber-optic chloride sensors were embedded in both decks but no data was obtained from them. From the physical testing done, both destructive and non-destructive, conclusions of the assessments made of the corrosion conditions of the bars and decks were made. Recommendations for maintenance of the decks and on future testing were made.</td></tr>
<tr><td colspan="2">17. Key Words:
Stainless Steel Reinforcement, Fiber Optic Chloride Sensors, corrosion, reinforced concrete bridge decks</td><td colspan="2">18. Distribution Statement:
No restrictions. This document is available to the public through National Technical Information Center, Springfield, Virginia 22161.</td></tr>
<tr><td>19. Security Classification (of this report):
Unclassified.</td><td>20. Security Classification (of this page):
Unclassified.</td><td>21. No of Pages:
14</td><td>22. Price:</td></tr>
</table>

Form DOT F 1700.7 (06/98).

Introduction

MoDOT is using innovative materials to design longer lasting reinforced concrete bridge decks. Stainless steel reinforcement has greater corrosion resistance than that of the conventional reinforcement. In this project, bridge A6059, the first in Missouri utilizing stainless steel reinforcement in the deck (see Figure 1) was completed in 2001.

Figure 1. Stainless Steel Reinforcement of Bridge A6059

Minimization of concrete cracking and spalling results in greater durability, less maintenance and repair, a longer service life, and lower life-cycle costs. The advantages of stainless steel reinforcement used in this project is documented, also, any early failure of the epoxy-coated rebar used in the companion bridge will be monitored.

Scope of Work

The control bridge A6060 was constructed using conventional epoxy coated rebar. It has identical roadway width and girder spacing with bridge A6059, but has different span lengths and skew. The bridges are on the same route with bridge A6060 approximately 600 feet (180 meters) east of A6059. This will allow a good evaluation of the durability and performance of the subject bridge deck in comparison to the conventional deck. The details of the construction of these bridges can be found in the original report published in 2003 “Evaluation of Stainless Steel Reinforcement Construction Report”. (Found as report RDT 03-003, RI 00-027 on MoDOT’s Innovations Library at http://168.166.124.22/RDT/reports/Ri00027/RDT03003.pdf).

Current Research Results

Costs for the rebar on this job bid in December 1999 were $ 1.40/Kg ($ 0.64/lb) for conventional black steel. $1.77/Kg ($ 0.80/lb) for epoxy coated steel (MoDOT's normal bridge deck rebar) and $5.63/Kg ($ 2.55/lb) for the solid stainless steel. This price makes the cost of solid stainless about 3 times as expensive as Missouri's regular design with epoxy coated rebar and 4 times as expensive as black rebar. This is well worth it, if it eliminates worry about corrosion problems and potholes caused by corrosion within the service life of the bridge deck, expected to be 75 years for both decks. The advantages of stainless steel reinforcement will be documented using non-destructive fiber optic chloride sensors, permeability testing, half-cell potentials readings and visual inspection.

1999 Prices of Reinforcing Steel (converted to $/pound)		
Uncoated (Black)	Epoxy Coated	Solid Stainless Steel
$ 0.64 /LB	$ 0.80 /LB	$ 2.55 /LB

Figure 2. Sensor Housings Installation

An evaluation of the constructability and performance of stainless steel reinforcement was conducted. The bridges will be researched utilizing non-destructive tests to monitor salt application and chloride penetration in correlation to presence of (or lack of) corrosion. Fiber optic chloride sensors were incorporated into both bridge decks. Ten sensors were set on each bridge at different horizons. The sensor housings were installed during the deck construction before concrete was poured. See pictures in Figure 2 for the installation of sensor housings. The picture on the left is for the stainless steel bridge deck, and the one on the right is for the epoxy coated rebar bridge. Cylinders were taken to establish the compressive strength of the concrete for each bridge. Cylinders were also taken and tested for chloride permeability of both bridges according to AASHTO T277. Chloride samples were taken from the cylinders to get a base line chloride content of the concrete. These original properties (in some cases measured at 1 year old) of the concrete are listed in Table 1. Fiber optic chloride sensors were installed into the sensor housings shortly after the bridges were open to traffic. In addition, half-cell potentials were taken and will continue to be taken to determine corrosion rates on the bridge containing stainless steel reinforcement.

Table 1: Original Properties of Deck Concrete

Bridge No.	Compressive Strength (psi)	Chloride Content (%)	Chloride Content (Lbs./cy)	Permeability (Coulombs)
A6059	8,800 (1-year)	0.005	0.2	1924 (1 year)
A6060	5,556 (28-day)	0.003	0.1	1403 (1 year)

Monitoring Performance

The original work plan intended the following to be accomplished in follow up inspections. Field observations and data collection concerning the condition and performance of each bridge deck will follow construction of the bridges. The fiber optic chloride sensors will be monitored every year for five years to verify any indications.

A construction phase report was completed and published to document the constructability with the stainless steel rebar and installation of the test systems. This interim report documenting current conditions was to be prepared at the end of the first five years. Preparation of a final report discussing and comparing over-all performance and documenting project findings was to be included in this report. Any maintenance or rehabilitation costs associated with either bridge deck should be documented throughout the service life of each structure, in an effort to determine and compare life-cycle costs.

Follow-Up Inspections

Follow-up inspections were not done on the fiber optic sensors yearly as planned because of the increased cost of the fiber optic equipment needed. It was estimated that a light source and spectrometer would cost around $2,000 but in 2002 there was no longer a low cost light source or spectrometer available except at three times the cost, $6,000 - $7,000. As an alternate a bid was obtained in 2002 from Dr. Peter Fuhr to travel back to Missouri to read the sensors. That bid was reasonable at $2,000, but it was decided to wait another couple of years when there would be a better probability of the chloride ions actually reaching the level of the sensor inlets. Because the prices have not gone down for test equipment and because Dr. Fuhr is no longer available to make the trip back, the fiber optic sensors have never been re-tested. The only data available is the initial readings done after the sensors were installed in 2001, which showed they were calibrated at the correct threshold level. In speaking with the Vermont Agency of Transportation, the same type sensors installed in three of their bridges in 1997 by Dr. Fuhr, those sensors have never had a positive reading; they were tested the first 3 years in a row after installed and again at 5 and 7 years and never tested above the threshold that they were set to detect.

Vermont has not been able to test the sensors lately because the fiber optics used were state of the art in 1997 but now are not manufactured and only one company has the equipment necessary to test them, and rental costs for the equipment is in the vicinity of $35,000. MoDOT’s system has fiber optic material that does not need this special equipment, however, the cost is significant enough that it was decided not to purchase the needed equipment now. It may be beneficial to try and test the fiber optic sensors on our bridges at 8-10 years to see if some meaningful data can be obtained.

Bridge Deck Testing

A physical bridge deck condition survey was done on the two bridges in July 2006. The decks were sounded for delaminations and also the cracks were plotted on the surface profile maps, chloride samples were taken from the bridge to compare it to data from when the decks were new in 2001. Half-cell data was taken on the stainless steel reinforced deck, Bridge A-6060, to check for any active corrosion. Bridge A6059 is reinforced with epoxy coated steel so it was originally set up with a test grid to try and do impedance testing to detect any breaks, or "holidays" as they are called, in the epoxy coating allowing corrosion of the steel underneath. MoDOT's testing using the impedance method showed it wouldn't work in this application so no impedance testing was ever attempted.

Results of the 2006 bridge deck condition survey are as follows:

1. There was no delamination or spalling found on the surface of either bridge deck.

2. On Bridge A6059, the stainless steel reinforced concrete deck, there was 57 linear feet of cracking at five years old. The bridge is built with a 30° skew and most of the cracking was found at the skewed ends of the bridge deck, there were a couple of cracks also found over the interior bents. The rate of cracking for A6060 was 10.34 LF/ 1,000 SF (0.038M/M^2).
   Bridge A6050, the epoxy coated reinforced steel concrete deck, which doesn't have a skew, had no cracking found at five years old.

3. Concrete samples taken from the deck for chloride content are shown in Table 2 and the locations samples were taken at in the deck surface profiles in Figure 3.

Table 2: Chloride Content of Concrete Deck in 2006

Bridge A6059 (homogeneous Cl^- in 2001 – 0.2 lbs/cy)

Sample	#/cy @ ½"	#/cy @ 1"	#/cy @ 1 ½"	#/cy @ 2"
# 1	6.2	3.9	2.3	0.8
# 2	5.5	0.8	0.4	0.2
# 3	3.5	0.04	0	0.1
# 4	1.6	0.2	0.4	0.1

Bridge A6060 (homogeneous Cl^- in 2001 – 0.1 lbs/cy)

Sample	#/cy @ ½"	#/cy @ 1"	#/cy @ 1 ½"
# 1	4.3	2.0	0.04
# 2	1.2	0.08	0.1
# 3	0.4	0.4	0.08
# 4	0.4	0.1	0.1

Bridge A6059

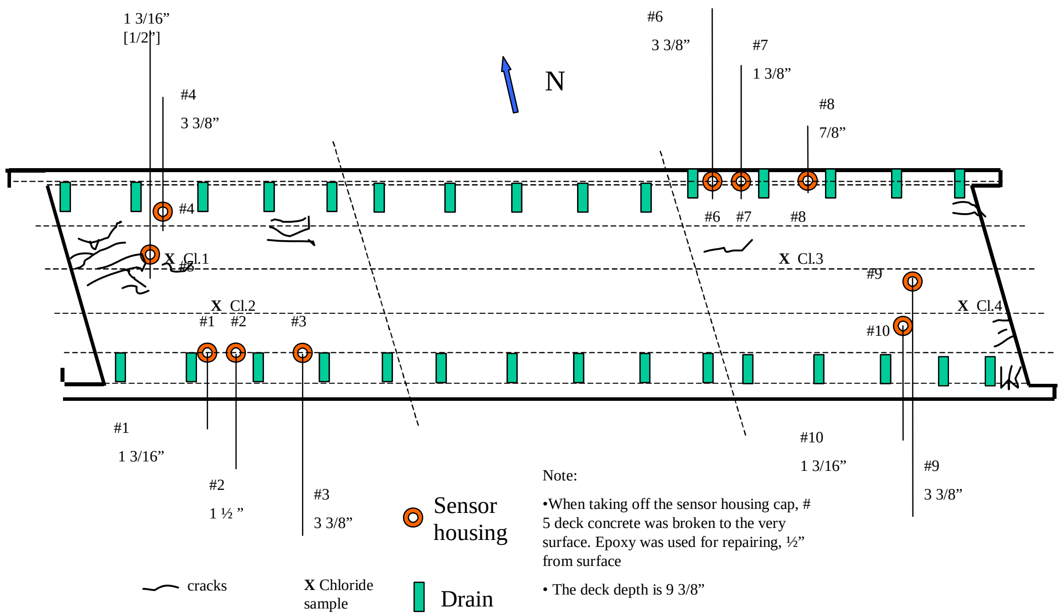

Figure 3: Surface Profile of Bridge A6059 in year 2006

Bridge A6060

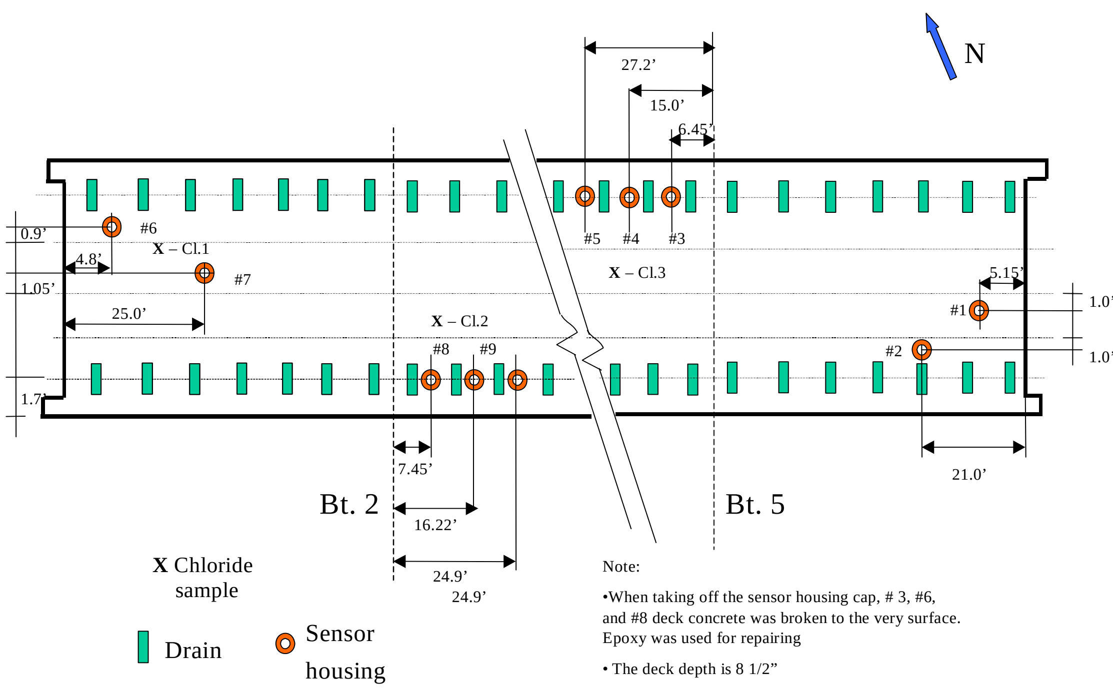

Figure 3 (continued): Surface Profile of Bridge A6060 in year 2006

4. Half-cell test were taken in 2001 and 2006 on bridge A6059 the stainless steel reinforced deck. The reference electrode used was again a CSE, Copper Sulfate Electrode and according to the test method ASTM C 876. The test is based on the difference in electrical potential of the CSE and regular milled steel reinforcing. Test results can be seen in Table 3 below (individual test are recorded in the Appendix). The 9.1% tests more negative than –200mv, those that may be corroding, were not expected in 2001 when the deck was first tested. They may be because of the stainless alloy, AISI Type 316LN, and the CSE cell being of a higher potential difference than of regular steel that ASTM C 876 is based. The stainless alloy does have a higher potential difference with the CSE but as of now there is no correction factor for this alloy. (See the Galvanic Series of Metals chart and alloy Type 316LN composition in the Appendix.) The half-cell tests do offer some comparison with the 2006 values, however, as you can see in 2006, 26.6% now test more negative than –200 mv. This is a marked increase in percentage possibly corroding, signaling that conditions have become more conducive to corrosion, but not necessarily that the stainless steel is actually actively corroding. Higher chloride levels in the concrete and some minor cracking allowing moisture in, especially on the skewed ends of the bridge, account for this.

Table 3: Half-cell Testing of Stainless Steel Reinforced Deck on Bridge A6059

<u>Original Half-Cell Tests - 2001</u>

Range	No. Tests	Percentage
<-350 mv	1	1.3
>-350 mv, <-200 mv	6	7.8
>-200 mv	70	90.9
No Readings	3	
Total Tests	77	100.0%

<u>Half-Cell Tests at 5 years in 2006</u>

Range	No. Tests	Percentage
<-350 mv	9	5.2%
>-350 mv,<-200 mv	37	21.4%
>-200 mv	127	73.4%
No readings	16	
Total Tests	173	100.0%

5. Costs of maintaining the bridge decks and salt applied during winter de-icing have been hard to document because of maintenance operations procedures in this rural area of northern Missouri. Costs charged to the two bridges since they were opened started in 2003 and are shown in Table 4.

Table 4: Bridge Maintenance Costs

Bridge Costs by Fiscal Year				
	2003	2004	2006	Grand
	Total	Total	Total	Total
WBA6059A - BRG A6059, MO 6 X LITL MEDCN C	708.33	112.72	115.89	936.94
WBA6060A - BRG A6060, MO 6 X LITL MEDCN C	931.38			931.38

In talking to the Maintenance Superintendent in the area it was found that the large costs in 2003 were to mud jack the approach slabs and not actually money spent on the bridge decks. The smaller amounts on Bridge A6059 were for incidental work like flushing the deck or sealing surface cracks. He did inform me that the decks had been sealed in 2007 using Pavon© Indeck, which is an asphalt based crack sealers that is applied to the whole deck, similar to a flycoat applied to some AC pavement. It is used to fill in all the cracks and lasts about three years before needing re-applied. Both brides A6059 and A6060 were coated, so the cracking in the deck was at least bad enough on A6059 that it was worthwhile for both of the decks, which are so close together, to be sealed. Salt costs are charged to the roadway and salt is applied at 200 lbs/mile. It can be seen from the chloride data and half cell data that the west end of bridge A6059 is getting more salt applied to it than the rest of the bridge or bridge A6060. This is because Bridge A6059 is right at the bottom of a hill on the west end and has more salt runoff accumulating on it. There is not sufficient data to be put into any algorithm to figure a life-cycle cost analysis at his time.

Cost Comparison of Special Reinforcement in MoDOT Projects

<u>Stainless Steel Rebar (FY 2000) – project as built</u>

A6059 in Grundy County (Route 6), 3 spans (14m-14m-14m), 10.8m roadway
Let in December 1999; bridge opened June, 2001 Solid stainless steel rebar (Grade 316LN or better) in 220mm cast-in-place slab
Bid price: Reinforcing Steel (Stainless Steel) - $ 5.63/KG ($ 2.55/lb): Reinforcing Steel (Epoxy Coated) - $ 1.77/KG ($ 0.80/lb): Reinforcing Steel (Bridges) - $ 1.40/KG ($ 0.64/lb)
Advantages: Greater corrosion resistance will help to minimize concrete cracking and spalling, resulting in greater durability of deck and lower life cycle costs
Disadvantages: Higher initial material costs; limitation on bar lengths
Evaluation: Non-destructive tests on in-service bridges to monitor salt application, chloride penetration, and presence of (or lack of) corrosion; field observations over life of bridge
IBRC (Innovative Bridge Research & Construction) Funding: $185,000

Stainless Steel Clad and Fiber Reinforced Polymer Rebar (FY2001)

A6098 in Newton County (Route 86), 3 spans (14.5m-14.5m-14.5m), 12.0m roadway Stainless steel clad was not used on this bridge and has not been used on a MoDOT bridge as yet because of the lack of a stable supplier of the product in the US.

Steel Free Bridge Decks

A deck with fiber reinforced polymer (FRP) rebar was not built until 2007. Two bridge deck replacements were let which incorporated bottom mat reinforcement of graphite rebar and top reinforcement of fiberglass rebar; additionally to add to the toughness of the concrete mix polypropylene fibers were mixed into the concrete. Bid costs for GFRP Reinforcing Bars (#4 – ½ IN.) averaged for the two bridges was $6.27 LF. [The equivalent in lbs. of steel would be $4.19 LB.] Cost for CFRP Reinforcing Bars (#6 – ¾ IN.) averaged $1.95 LF [Equivalent to $2.93 LB.] In comparison Reinforcing Steel (Epoxy Coated) was bid at $1.70 lb for this project and the average statewide bid for 2006 was $1.18 LB. The 2006 price for Reinforcing Steel (Bridges) was $1.08.

Cost Comparison of Bridge Deck Concrete Reinforcement used by MoDOT						
Year	Uncoated (Black)	Epoxy Coated	Solid Stainless Steel	Stainless Steel Clad	FRP Fiberglass	GFRP Graphite
1999	$ 0.64 /LB	$ 0.80 /LB	$ 2.55 /LB			
2001				Not Available		
2007	$ 1.08	$1.70			$ 2.93 /LB	$ 4.19

Conclusions

The work plan for research study of this project was very ambitious back in July 2000 when these bridges were being built. It was believed we would have a good non-destructive testing (NDT) program for both these bridges the experimental stainless steel reinforced deck and the conventional epoxy coated reinforced deck. The fiber optic sensors on MoDOT's bridges were expected to have a shorter time to show an indication of the threshold of chlorides than those tried in Vermont because the mouths of the sensors were set closer to the surface. It has turned out that the high cost testing equipment and unavailability of the inventor have caused the fiber optic chloride sensors never to be used. No NDT testing has been done on the epoxy rebar, either, because the electrical impedance testing has never been used successfully outside of the laboratory. It was necessary therefore to rely on visual inspection of the surface of the concrete deck and old non-destructive as well as destructive testing techniques to evaluate the bridge decks. This has not yielded as much data as was hoped. There was not enough data or a good algorithm found to make a life-cycle cost analysis either.

From the 2006 deck survey data it has been verified that there has been:

- Very little cracking damage on either the stainless steel or the conventional deck.
- Chloride data gained by drilling samples show only one location on the where they are well above the corrosion threshold at the level of the stainless steel bars
- Half-cell tests show are not conclusive because they aren't calibrate for 316LN steel but show a more corrosive environment than in 2001 but not rebar corrosion.

The only conclusion to be drawn is that the chloride in the deck already may have caused corrosion to black steel and it is beneficial to have the stainless steel reinforcement. There is no data available, however, for comparison between the stainless steel and the epoxy-coated steel.

RECOMMEDATIONS

A cost comparison between the various reinforcements used by MoDOT was looked at. It showed that the best price comparison to stainless steel was fiberglass FRP bars. MoDOT is planning to design a bridge deck replacement with both layers of GFRP, glass fiber reinforced polymer, rebars in the near future.

- It is recommended that maintenance forces continue to seal any cracks in the deck surface, to keep chlorides and moisture out of the concrete.

- It is recommended that MoDOT continue to look for more corrosion resistant reinforcement for bridge decks because we will continue to apply salt for the safety and convenience of the traveling public.

- Finally it is recommended that MoDOT revisit trying to read the fiber optic chloride sensors used in the two decks when they reach ten years in service. Also a physical survey should be made of both bridge decks to see what corrosion data can be obtained and the condition of the stainless and epoxy coated rebar. It would also be beneficial to take cores from both decks in order to look at and appraise the condition of the reinforcing bar at that time.

Appendix

Table 3. Half-cell Potential Test Readings (millivolts)

. Half-cell Potential Test Readings (millivolts)

Bridge A6059, Survey Direction: W				
	Offset (ft.)			
Station (ft	3	6	9	12
2	-334			
6	-255	-218	-327	-371
10	-138	-134	-232	-236
14	-151	-147	-129	-150
18	-114	-123	-147	-104
22	-116	-114	-96	-113
26	-77	-108	-89	-103
30	-84	-78	-63	-91
34	-94	-101	-79	-106
38	-71	-76	-56	-79
42	-62	-115	-82	-73
46	-113	-100	-67	-45
50	-101	-158	-100	-79
54	-76	-117	-107	-126
58	-86	-92	-106	-108
62	-119	-114	-119	-100
66	-79	-69	-60	-85
70	-45	-95	-46	-62
74	-90	-83	-77	-77
78	-105	-109	-104	-94

Range	No. Tests	Percentage
<-350	1	1.3%
>-350,<-20	6	7.8%
>-200	70	90.9%
NO readin	3	
Total Tests	77	100.0%

Table 3. Half-cell Potential Test Readings (millivolts)

	Bridge A6059, Survey Direction: W				
	Offset (ft.)				
Station (ft.)	3	6	9	12	16
2					
6					
10				-451	-376
14		-378	-373	-235	-249
18	-288	-223	-253	-208	-205
22	-221	-196	-189	-186	-150
26	-165	-216	-185	-210	186
30	-166	-206	-179	-166	-210
34	-189	-213	-200	-215	-213
38	-177	-162	-155	-157	-160
42	-145	-132	-149	-144	-123
46	-187	-166	-112	-111	-135
50	-166	-152	-141	-146	-80
54	-152	-115	-87	-100	-84
58	-182	-175	-220	-190	-176
62	-196	-162	-156	-158	-172
66	-162	-148	-156	-176	-131
70	-138	-171	-176	-162	-162
74	-155	-164	145	-149	-167
78	-182	-155	-165	-162	-167
82	158	-130	-143	-142	-138
86	-72	-121	-141	-120	-147
90	-109	-155	-172	-152	-123
94	-130	-123	-164	-162	-163
98	-124	-149	-151	-138	-151
102	-170	-158	-100	-230	-220
106	-172	-181	-179	-177	-182
110	-190	-172	-181	-118	-119
114	-167	-158	-169	-158	-175
118	-174	-158	-154	-169	-172
122	-177	-186	-190	-182	-183
126	-169	191	-189	-202	-197
130	-176	-196	-180	-190	-202
134	-216	-269	241	-237	-202
138	-223	-241	-223	-230	-236
142	-266	-298	-252	-279	-356
146	-267	-298	-299	-363	-398
150	-297	-383	-449		

Range	No. Tests	Percentage
<-350	9	5.2%
>-350,<-20	37	21.4%
>-200	127	73.4%
NO readin	16	
Total Tests	173	100.0%

Chemical Compositions of Stainless Steels used for Rebars

Grade	UNS No.	Cr	Ni	Mo	C (max.)	N	Type
304	S30400	19	9.5		0.08		austenitic
304L	S30403	19	10		0.03		austenitic
316	S31600	17	12	2.5	0.08		austenitic
316L	S31603	17	12	2.5	0.03		austenitic
316LN	S31653	17	12	2.5	0.03	0.13	austenitic
2205	S31803	22	5	3.0	0.03	0.14	duplex
others							

Nominal compositions in weight percent, balance Fe.

Table 2-7. Galvanic Series of Some Metals and Alloys in Seawater

Noble or Cathodic End ↑

Platinum
Gold
Graphite
Titanium
Silver
Chlorimet 3 (62 Ni, 18 Cr, 18 Mo)
Hastelloy C (62 Ni, 17 Cr, 15 Mo)
18-8 Mo Stainless Steel (passive)
18-8 Stainless Steel (passive)
Chromium Stainless Steel 11-30% Cr (passive)
Inconel (80 Ni, 13 Cr, 7Fe) [passive]
Nickel (passive)
Silver Solder
Monel (70 Ni, 30 Cu)
Cupronickels (60-90 Cu, 40-10 Ni)
Bronzes (Cu-Sn)
Copper
Brasses (Cu-Zn)
Chlorimet 2 (66 Ni, 32 Mo, 1 Fe)
Hastelloy B (60 Ni, 30 Mo, 6 Fe, 1 Mn)
Inconel (active)
Tin, Lead
Lead-tin Solders
18-8 Mo Stainless Steel (active)
18-8 Stainless Steel (active)
Ni-Resist (high Ni cast iron)
Chromium Stainless Steel, 13% Cr (active)
Cast Iron
Steel or Iron
2024 Aluminum (4.5 Cu, 1.5 Mg, 0.6 Mn)
Cadmium
Commercially Pure Aluminum (1100)
Zinc
Magnesium and Magnesium Alloys

Active or Anodic End ↓

(Source: M. G. Fontana and N. D. Greene "Corrosion Engineering," McGraw-Hill, New York, 1978, p. 32, Ref. 20).

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