EPOXY INTEREST GROUP

EVALUATION OF CORROSION-RESISTANT REINFORCING STEEL

Research Summary

In 2014, a Ph.D. thesis was presented by Sim (2014) from Purdue University. This thesis contains data on corrosion tests conducted on several types of reinforcing steel. The work considered structural design relating to bond development and four different corrosion scenarios. This selected summary will focus on the corrosion results from cracked concrete test specimens with the same bars in the top and bottom mats, as the bars in the uncracked concrete specimens did not provide sufficient data to separate the performance of the various reinforcing bar systems. The results clearly show that epoxy-coated reinforcing steel in cracked concrete will provide significant life extension compared with uncoated bars and these compared favorably with some of the stainless steels.

INTRODUCTION

The life of concrete bridge decks is frequently limited by the use of deicing salts that lead to steel corrosion. While ingress of chloride ions may be decreased by reducing the permeability of the concrete, cracks may allow direct contact between the deicing salts and the reinforcing bars. Frequently these cracks are full-depth, a result of restrained thermal and drying shrinkage. Corrosion-resistant reinforcing steel has been used to mitigate corrosion-related deterioration. The objective of the research program was to evaluate both the structural and corrosion performance of concrete bridge decks reinforced with corrosion-resistant reinforcement.

A three-phase experimental investigation was conducted using a wide range of corrosion-resistant reinforcing materials. In the first phase, structural tests were conducted on forty-five beam specimens with tension lap splices to evaluate the bond between corrosion-resistant reinforcement and concrete. Twelve slab specimens were tested in the second phase to evaluate the cracking behavior of slabs reinforced with corrosion-resistant reinforcement. Finally, 112 modified macrocells were constructed in the third phase to evaluate corrosion resistance under uncracked and cracked conditions, which are sumarized below.

BAR TYPES

The Corrosion Study included the following reinforcing bars:

— Carbon-Steel (ASTM 615)

— Epoxy-Coated Steel (ASTM A775)

— Zinc-Coated (Galvanized) Steel (ASTM A767)

— Zinc-Clad (experimental)

— Tin-plated Zinc-Clad (experimental)

— Dual-Coated Steel (ASTM A1055)

— Low-Carbon, Chromium, Steel (ASTM A1035)

— Stainless-Steel 316LN (ASTM A955)

— Stainless-Steel 2205 (ASTM A955)

— Stainless-Steel 2304 (ASTM A955)

— Stainless-Steel XM-28 (ASTM A955)

Cracked Concrete Macrocell Under Preparation For Corrosion Testing.

Table 1: Macrocell Corrosion

Bar Type	Total Corrosion (coulomb)
Tin-plated zinc-clad	5573
Galvanized (A767)	3994
Zinc-clad	1727
Carbon-steel (A615)	947
LCC (A1035)	539
Epoxy-coated (A775)	10
XM-28	9
2205	8
Dual-coated (A1055)	5
2304	2
316LN	1

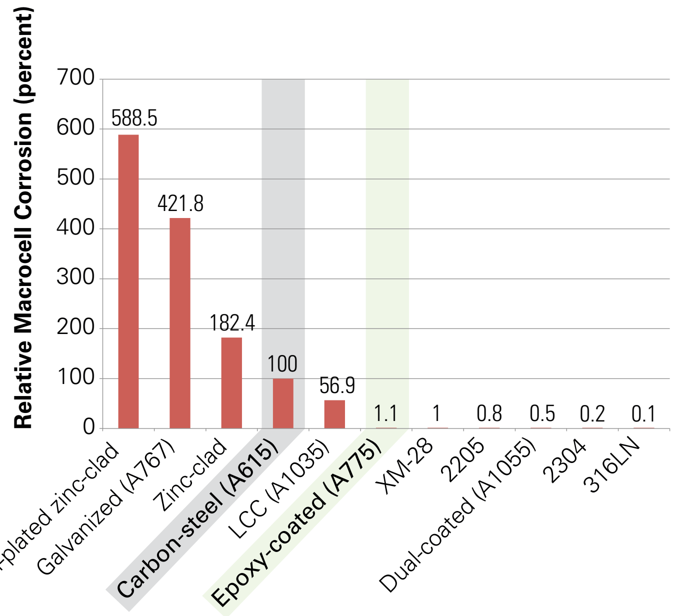


Figure 1: Relative Macrocell Corrosion.

Table 2: Visual Corrosion

Bar Type	Top Mat Corrosion (% of total bar area)
Carbon-steel (A615)	5.5
LCC (A1035)	5.1
Dual-coated (A1055)	0.59
Epoxy-coated (A775)	0.13
XM-28	0.07
Galvanized (A767)	0.01*
316LN	—
2304	—
2205	—
Tin-plated zinc-clad	*
Zinc-clad	*

Note that the presence of zinc corrosion was not accounted for within the analysis.

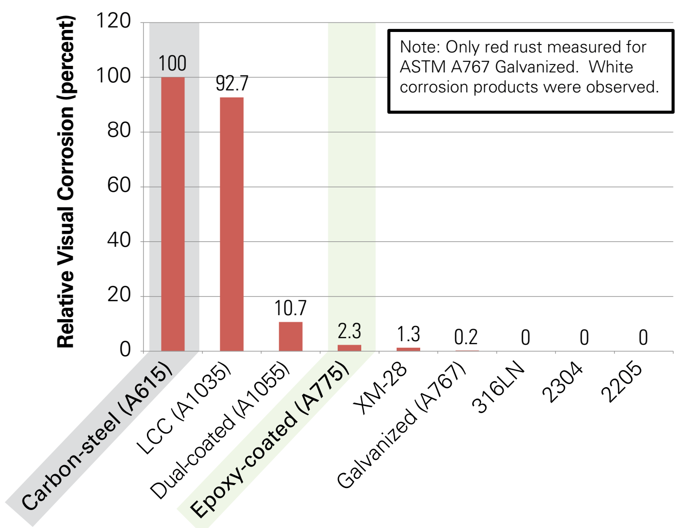
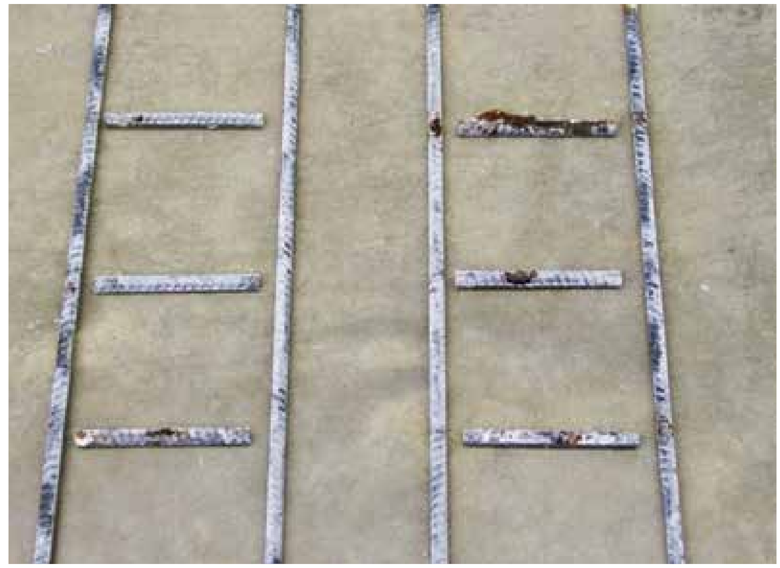


Figure 2: Relative Visual Corrosion.

BAR DAMAGE

Epoxy-coated bars may be damaged during field installation and the study utilized 1% of damage per linear foot. Damage was created in the bars by dropping a steel channel from a constant height using a load guillotine. The height that developed 1% damage on epoxy-coated rebar was determined and used to create damage on all other coated bars (galvanized, zinc-clad, tin-plated zinc-clad, dual-coated).

The amount of damage used in this study is significantly greater than that used in prior studies by researchers McDonald et al. (1998) or O'Reilly et al (2011). In addition, standard specifications used for epoxy-coated reinforcing steel require that all visible damage be repaired prior to concrete placement.



Overall corrosion on carbon-steel A615 bars (cracked specimen).

SPECIMENS

The studies used 112 concrete specimens. These specimens were from four different categories:

- Uncracked
- Cracked
- Cracked with carbon-steel bar cathode
- Cracked with different types of ties

Specimens measured 8 x 8 x 24 inches with each layer of the reinforcing consisted of two longitudinal reinforcing bars spaced at 6 in. and three transverse bars spaced at 5 in. The bar size chosen for the testing was #4 ($^1/_2$ in.) with a clear cover of 2 in.

Cracks were obtained in the concrete specimens by applying tensile loads to the longitudinal bars. These cracks penetrated the thickness of the slabs. Target crack widths were 0.020 in., designed to represent field conditions with full-depth cracks. The obtained widths of cracks from all specimens ranged from 0.005 in. to 0.079 in. and 86% of the crack widths fell within the range of 0.015 in. to 0.035 in.

After cracks were introduced, the specimens were ponded using a 3% sodium chloride by weight salt solution. This solution was added following the ASTM G109 test procedure with a two week wet-cycle followed by a two week dry-cycle.

MEASUREMENTS

The top reinforcing bars were electrically connected with a 14 gauge copper wire wrapped tightly around the bars. These copper wires were sealed with electrical tape and additionally attached to the reinforcing steel with plastic ties. The two bottom reinforcing bars were connected in an identical fashion. The corrosion circuit was completed by connecting a 100-ohm resistor across the two mats. The voltage drop across the resistor of each macrocell specimen was collected through an 18 gauge copper wire connected between the specimens and multiplexers. The voltage data of all specimens were automatically recorded every six hours.

CORROSION CURRENT RESULTS

The data showed very little corrosion occurred in the uncracked specimens during the test period. This result may have been expected due to the use of 2 in. of concrete cover and the high quality concrete. For this reason, only data from the cracked specimens with similar top and bottom bars are discussed within this review.

The total measured current flow in coulomb is indicative of the total amount of metal loss due to corrosion that has occurred in the steel specimens. For the carbon-steel bars in cracked concrete, the total current was 947 coulomb **(Table 1)**. The three zinc or galvanized products exhibited significantly greater values than the carbon-steel bars and the LLC (A1035) bars exhibited a corrosion of 56% that of the carbon-steel bars **(Figure 1)**. The epoxy-coated, dual-coated and stainless bars exhibited total corrosion amounts 95 times less than that of the carbon-steel bars.

The epoxy-coated, dual-coated and stainless bars exhibited total corrosion currents 95 times less than that of the carbon-steel bars.

AUTOPSY

At the end of the 503 days, a single replicate for each bar type and specimen configuration was carefully autopsied and the bars extracted.

Uncracked Specimens, Same Cathode

For the uncracked specimens, light corrosion was observed on the top longitudinal bars for the carbon-steel and LCC (A1035). None of the stainless steel reinforcement showed visual corrosion; however, discoloration was observed on XM-28

Close-up of corrosion on LLC A1035 bar (cracked specimen).

Close-up of corrosion on epoxy-coated A775 bar (cracked specimen).

stainless steel. Epoxy-coated reinforcement had a small spot showing corrosion of base metal, located where the coating was damaged prior to the testing.

The galvanized (A767), zinc-clad, and tin-plated zinc-clad reinforcing steel did not have any evidence of white corrosion rust (from zinc oxides) or underlying base metal corrosion (from iron oxides), but the outer layer of the shiny pure zinc had been consumed. This zinc consumption was assumed to be mainly from the reaction of the zinc coating with the concrete during hydration rather than entirely from zinc reacting as a sacrificial anode because electrical currents demonstrated less corrosion activities. The dual-coated (A1055) bars showed no visual corrosion.

Cracked Specimens, Same Cathode

Both the carbon-steel and LCC (A1035) specimens had corrosion products in both the top and bottom mats. However, more corrosion products from iron oxides were located on the top mats, which is consistent with the electrical measurements that indicated negative currents.

Autopsy results of galvanized (A767), zinc-clad, and tin-plated zinc-clad steel reinforcement exhibited white corrosion products from zinc oxide. A greater amount of the white product was noted at the location of the cracks and especially on the transverse steel that was located parallel to the cracks.

The performance of the epoxy-coated (ASTM A775) reinforcing steel compared favorably with some of the stainless steels.

The 316LN and 2304 stainless steel did not display any evidence of corrosion. However, the 2205 stainless steel was discolored. The XM-28 stainless steel exhibited more discolored locations and a reddish corrosion spot was observed on the transverse steel.

Corrosion was limited to a local area on the epoxy-coated (A775) reinforcing; however, corrosion of the underlying base metal was observed at the ends of the transverse steel (where they had been patched and repaired prior to casting) and where the coating peeled. In addition, due to corrosion of the base metal underneath the epoxy coating, a spot where the coating was bulging was observed.

Cracked specimens with dual-coated (A1055) bars did not show significant corrosion, but corrosion was observed at the location where damage was introduced prior to testing. The zinc under the epoxy layer was consumed and red iron oxide products were observed.

The surface area of all longitudinal and transverse steel was 103.7 in.^{2} From the visual observations, the amount of corrosion was documented **(Table 2)**. Only reddish-brown (from red iron oxide) and blackish (from black iron oxide) corrosion were considered in this evaluation and any white corrosion products from zinc were ignored.

The amount of corrosion of the top carbon-steel bars was 5.5% of the total bar area. Using this as the baseline, the LCC (A1035) materials exhibited almost the same amount of corrosion as the carbon-steel bars **(Figure 2)**. The dual-coated (A1055) bars exhibited 10 times less corrosion than the carbon-steel bars. The epoxy-coated (A775) bars exhibited 40 times less corrosion than the carbon-steel bars.

The XM-28 bars exhibited corrosion approximately 80 times less than that of the carbon-steel (A615) bars. The other stainless steel bars did not exhibit corrosion.

SUMMARY AND RESULTS

Based on the results of this study, Sim reached the following conclusions:

- While all uncracked specimens showed relatively low currents at 503 days of exposure, cracked specimens demonstrated high corrosion activity that was electronically measured by the macrocell test and confirmed by visual examination through an autopsy of the specimen.
- Autopsy results demonstrated that most of the longitudinal steel corroded at the intersection with the transverse steel while the transverse reinforcement corroded over its entire length. The transverse steel, typically located parallel to the cracks, was under direct chloride exposure over its entire length, while the longitudinal steel had direct exposure only at the location of the cracks.
- When corrosion-resistant chromium based reinforcing steel is used in the top mat and carbon-steel bars are used in bottom mats, a galvanic couple resulted where the bottom carbon-steel corroded to protect the top corrosion-resistant reinforcement. This galvanic couple occurred because the cracks in the macrocells were formed full-depth where chlorides can easily reach the bottom carbon-steel bars from the first day of testing.
- Both the electrical current measurements and autopsy results demonstrated that mixing reinforcement where carbon-steel bars are provided in the bottom mat is detrimental to corrosion resistance.

Additional conclusions based upon review of the data from the thesis are shown below:

- The length of testing was found to be insufficient for the uncracked specimens and few conclusions about the performance of the various products in uncracked concrete may be obtained.
- The data presented for galvanized and zinc results are difficult to interpret due to the fact that the corrosion on these products are not the same as those derived from the carbon-steel bars. These products showed evidence of high macro-currents and white zinc-based corrosion products.
- The low-carbon chromium steel bars (ASTM A1035) did poorly in these tests with corrosion rates of 57% that of the carbon-steel bars. Observed corrosion that was 93% that of the carbon-steel bars.
- The dual-coated (ASTM A1055) bars exhibited significantly lower corrosion rates than the carbon-steel bars and observed corrosion was also substantially reduced.
- Two of the stainless steel bar types (2205 and XM-28) exhibited discoloration and one exhibited corrosion in the cracked beam test. (XM-28).
- The epoxy-coated (ASTM A775) reinforcing steel showed significantly lower visual corrosion in the cracked concrete specimens than that of the carbon-steel bars. The amount of corrosion was approximately 2.5% that of the amount observed in the carbon-steel bars. These bars also exhibited measured corrosion currents 95 times less than that of carbon-steel bars.
- The performance of the epoxy-coated (ASTM A775) reinforcing steel compared favorably with some of the stainless steels.

The amount of corrosion for the epoxy-coated was approximately 2.5% that of the amount observed in the carbon-steel bars.

REFERENCES

Sim, C., "Structural and Corrosion Performance of Concrete Bridge Decks Reinforced with Corrosion-Resistant Reinforcing Steel," Ph.D. Thesis, Purdue University 2014.

McDonald, D.B., D.W. Pfeifer, and M.R. Sherman, *Corrosion Evaluation of Epoxy-coated, Metallic-Clad and Solid Metallic Reinforcing Bars in Concrete.* 1998, Federal Highway Administration: McLean VA. p. 137.

O'Reilly, M., D. Darwin, J. Browning and C.E. Locke, Jr., *Evaluation of Multiple Corrosion Protection Systems for Reinforced Concrete Bridge Decks.* 2011, The University of Kansas Research Inc.: Lawrence KS.

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