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CORROSION OF EPOXY COATED REBAR IN CRACKED MARINE SUBSTRUCTURE CONCRETE

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ABSTRACT

Epoxy coated reinforcement (ECR) has been used in Florida from the 1970s to 1990s but has been discontinued due to the observation of severe corrosion in some ECR bridges after short service times. Corrosion projections have been made in earlier investigations based on corrosion initiation and propagation concepts but did not consider the presence of structural cracks. The current research in progress reexamines Florida ECR bridges after an additional decade of service, to determine if corrosion propagation took place as projected for bridges with high permeability concrete. The corrosion condition of ECR in cracked concrete locations is examined to aid in improving corrosion projection for those conditions. Field survey and laboratory examinations confirmed expectations of active corrosion in bridges with high permeability concrete. In bridges with low permeability concrete, little to no corrosion was observed with one exception. In that case, significant local corrosion was observed at near tide level locations that had relatively wide structural cracks. That corrosion was present despite large concrete cover, high quality concrete, and short service time.

Keywords: corrosion, epoxy, coating, rebar, crack

INTRODUCTION

Epoxy coated steel reinforcement (ECR) was used for corrosion control in Florida DOT (FDOT) marine reinforced concrete bridges from the late 1970's up to the early 1990's. The use of ECR for new FDOT structures was discontinued upon mounting evidence of severe corrosion in some of the existing bridges. Earlier investigations assessed the corrosion condition of 20 FDOT ECR bridges after ~5-12 years of service[1]. A model of the corrosion mechanism of ECR in marine concrete was developed[2]. Corrosion was viewed as resulting from the presence of coating production imperfections (within allowable limits at the time of construction) then aggravated by fabrication, handling, and a severe construction yard environment which promoted coating-metal disbondment[3-5]. Disbondment was found to become more extended after only a few years of service in the marine structures. Penetration of chloride ions to the rebar level resulted in severe undercoating corrosion, aggravated by extended macrocell formation with cathodes elsewhere in the rebar assembly[6-7]. Durability prognosis evaluations were formulated based on the research findings and application of an initiation-propagation deterioration model[1,4,8]. Based on measured concrete permeability properties, the model projected development of corrosion after about one more decade of service in some additional FDOT ECR bridges (a group designated as Category A here), and a lesser likelihood of early corrosion in other bridges with lower concrete permeability (Category B). Several Florida ECR bridges are now at the age of expected corrosion propagation. The present investigation examines the corrosion condition of those structures one decade after the initial projections, to validate and modify those, including introducing allowance for the possible effect of thin structural cracks on early corrosion in low permeability concrete[9].

A recent paper[9] detailed initial findings confirming expectations of corrosion development in two Category A bridges (Vaca Cut and Snake Creek) and little to no corrosion in one Category B bridge (Sunshine Skyway). Additional sites have been investigated since for a present total of three Category A bridges and three Category B bridges. Findings from the newly evaluated Florida ECR bridges are presented here with an integrated discussion of the entire body of observations. The influence of cracked concrete on corrosion development is examined in further detail.

EXPERIMENTAL PROCEDURE

Representative locations from several substructure component types (columns, footers, struts) were selected for examination, focusing on cracks on concrete sections at low elevations exposed to sea splash. Elevations are reported as distance above the high tide level (AHT). Concrete core samples (~10 cm diameter) were extracted to expose and collect ECR samples as well as for assessment of chloride penetration. Concrete clear cover was noted and checks for concrete delamination were made by hammer sounding. When cracks were observed, pairs of cores were collected along the same elevation typically ~15 cm apart on center with one core centered on crack. The in-situ condition of the exposed ECR coating was noted. Spot knife tests for coating disbondment were conducted.

Electrical continuity between coring-exposed ECR segments was tested when possible to determine possible sources of corrosion macrocell phenomena. Half-cell potentials were measured with a copper/copper-sulfate reference electrode (CSE) along the elevation of the substructure component. Concrete surface resistance was measured using a Wenner array probe with an inter-probe spacing of 5 cm, chosen as a compromise between sampling size and possible interference from embedded rebar.

Autopsy of the coating was conducted for evidence of coating breaks, disbondment, backside contamination[10], and corrosion under the epoxy coating. The coating thickness was measured with a magnetic coating thickness gage. In the case of one of the bridges where deep localized surface corrosion was observed, metallographic micrographs of the apparent pit cross-section were prepared. The samples were prepared by normal metallographic grinding and polishing procedures (final polish with 0.05 μm alumina suspension) and etched with a 2% nitric acid in ethanol (nital) mix.

Chloride ion penetration profiles were obtained for the field-extracted concrete cores. Powdered concrete samples obtained at various depths from the surface were analyzed for total (acid-soluble) chloride concentration; results are given in mg of Cl^- ion per gram of dry concrete. Diffusion coefficients, D, were estimated by least-error-fitting of the chloride content data to a solution to Fick's second law that assumes constant D and constant surface chloride concentration.

RESULTS

Category A Bridges

These bridges were among the Florida ECR bridges with high chloride ion diffusivity where corrosion propagation was projected to have occurred by the time of the present investigation. A summary of findings is shown in Table 1.

Vaca Cut and Snake Creek Bridges. Results from these bridges are detailed in the previous paper[9]. Evaluation showed severe ECR corrosion and coating disbondment at low elevations at the Vaca Cut Bridge, and to a lesser extent in Snake Creek. Chloride profiles are shown in Figure 1 for samples evaluated to date. Chloride concentrations greater than typically assumed conservative chloride threshold values were amply exceeded in most cases at reinforcement depth. Any evidence of preferential chloride penetration through cracks was obscured due to the high chloride bulk diffusivity prevalent at the sea splash locations examined. In general, previous model predictions[1,8] of corrosion development at ECR in these bridges by the time of the present study were confirmed by the examination.

Choctawatchee Bridge. This is a newly evaluated Category A bridge and results are presented in detail. Two of 20 footers from the ten high elevation piers had cracks wider than 40 mils (1.0 mm) (Figure 2); ten of the footers had cracks larger than 9 mils (0.2 mm). Minor concrete cracking was typical on all of the footers. Vertical and map-type cracking was observed on one of 20 columns from the high elevation piers. Rust bleedout was observed on two columns and one strut. The origin of that bleedout was not confirmed as samples of reinforcement were not obtained, but corrosion of reinforcement may be possible.

Core samples were extracted from two footers each with one wide vertical crack (>40 mils and ~25 mils (1.0 and 0.63 mm) wide respectively). Approximately 4.5 ft^2 (0.42 m^2) and 1 ft^2 (0.1 m^2), respectively, of concrete around the crack locations seemed to be delaminated as determined by hammer sounding. Extensive corrosion of the reinforcing steel (Figure 3) was observed on both footers at elevations 3.5 to 7 inch (8.9 to 17.8 cm) above high tide level, both where the crack intersected steel and in adjacent sound concrete locations

The concrete cover to vertical bar ranged from 2.8 to 4.1 inch (7.1-10.4 cm); nominal design cover was 4 inches (10.2 cm). Highly negative half-cell steel potentials were measured, -400 to -552 mV CSE. In plain steel rebar such potentials would likely be reflective of the observed ongoing corrosion, but it is cautioned that potential readings in epoxy coated rebar, especially in wet concrete, may not be always reliable indicators of corrosion condition. Concrete surface resistivity measurements on the columns ranged from 46 to 128 kΩ-cm on the columns at elevations 2 to 8 ft (0.6 to 2.4 m) AHT. Concrete resistivity on the footer ranged from 16 to 63 kΩ-cm at elevations 0 to 1.8 ft (0 to 0.55 m) AHT.

All seven ECR samples from Choctawatchee (sound and cracked concrete locations) showed significant loss of coating adhesion and severe corrosion of the steel bar.

Preferential chloride ion penetration through cracks in the Choctawatchee Bridge (similar to the other Category A bridges[9]) was overshadowed by fast bulk diffusion through the sound concrete at low elevation locations exposed to sea splash. Chloride concentrations at reinforcement depths (~4 inch (10.2 cm)) for sound and cracked concrete locations were larger than the commonly assumed 1.2 lb/yd^3 (0.7 kg/m^3) conservative chloride ion threshold value. The average chloride ion diffusivity for sound concrete from the Choctawatchee Bridge was lower than that measured in an earlier investigation[1] but it was within the range of calculated diffusivities from the same investigation. Nevertheless, a high value was still calculated (0.09 in^2/yr ($1.8x10^{-8}$ cm^2/s)).

Category B Bridges

Two additional Category B bridges (complementing earlier surveys of the Sunshine Skyway Bridge) were surveyed including the Howard Frankland Bridge and the Lillian Bridge. The concrete from the Category B bridges had very low chloride ion diffusivity. A summary of current and earlier findings for Category B bridges are shown in Table 1.

Sunshine Skyway Bridge. Results from this bridge are detailed in the previous paper[9]. Little to no corrosion was observed at any examined locations, including low elevation concrete components exposed to sea splash and higher elevations exposed to moisture from deck runoff water, despite the presence of pre-existing structural cracks with enhanced chloride penetration. At elevations exposed to sea splash, chloride ion concentration at reinforcement depth (~4 inch (10.2 cm)) for cracked concrete was above conservative threshold values (1.2 lb/yd^3 (0.7 kg/m^3)). Very low diffusivities (in the order of 10^{-9} cm^2/s) were measured in sound concrete[1,12]. Previous model predictions[1,8] had projected no early corrosion development, at least in sound concrete regions, due to the very low permeability of the concrete in this bridge.

Howard Frankland Bridge. Vertical cracks were frequently observed on the concrete footers; several large cracks were as wide as 0.040 inch (1.0 mm). The trace of the crack observed on the top of the footers of the larger cracks was several feet deep. Cracks of this type had been documented in previous inspections and are likely due to differential curing in the bulk of the concrete. Subsequent coring revealed that cracking sometimes propagated past reinforcement depth (~4 inches (10.2 cm)). Six pairs of on-crack/off-crack core samples were extracted at 3.5 to 18.5 inch (9.7 to 47 cm) AHT from 4 footers (in two footers, coring was done on two separate faces). Significant localized corrosion (morphology discussed later) was observed on 4 out of 7 on-crack bars extracted from 4 locations at 3 of the footers. In one instance where two bars were extracted from the same core, only the bar with deeper cover (11.6 cm, 1.6 cm deeper than the bar with lower cover) showed corrosion. No physical indication of corrosion was observed at any of the matching sound concrete locations. Concrete delamination was not detected at either sound or cracked locations.

Concrete clear cover to horizontal reinforcement was 10.9 to 11.7 cm, meeting nominal design requirements (4 inches (10.2 cm)). Half-cell potentials ranged from -200 to -690 mV

CSE measured at elevations from tidal zone to ~3 ft (0.9 m) AHT. The more negative values were from locations where ECR corrosion took place. As noted above, caution is in order on generalizing the significance of this observation. Concrete surface resistivity was very high (MΩ-cm range) even in the tidal zone. These high values are not likely due to concrete carbonation, since carbonated concrete depth was small (<1mm) as it is typically so in similar marine substructures[11].

The corrosion observed on the four ECR samples extracted from cracked locations from this bridge merits note. The crack plane was usually perpendicular to the rebar. Corrosion products were generally observed around locations with coating defects, especially near the intersection of the crack plane with the rebar. Upon removal of the coating (which was found to be fully disbonded) the underlying surface was relatively dry, with dark corrosion product regions. Exploration with a sharp knife tip at the dark region pried out some of the products, revealing pit-like features as shown in Figure 4. Sectioning of the bar with a thin diamond blade and water-free lubrication was performed at a pit-like location, with subsequent metallographic mounting of the section. The cross section (Figure 5) revealed that corrosion had affected a region much wider than the pit-like feature, having proceeded in relatively uniform fashion within the region to as much as ~1 mm deep. Except for some surface reddening, the corrosion products in that region were dense and dark-gray, suggesting a low oxidation state. As the knife tip scratched that material away with some difficulty, exploring with the tip (creating initially only a small crater) had given the appearance of clearing away corrosion products from a pit, but in reality corrosion had proceeded along a more uniform front. The corrosion product-base metal interface was examined at higher magnification revealing upon etching a ferrite-pearlite grain structure that extended, with no indication of microstructural alteration, all the way up to the corrosion penetration front where it was being consumed. Representative features are shown in Figure 6. This observation nearly rules out ascribing the observed features to causes alternative to corrosion, for example the presence of an isolated defect in the form of trapped slag or mill scale during rolling, since such condition would have been manifested by microstructural changes near the interface. Metallographic sections of the other bar samples from crack locations revealed corrosion penetration of depth and morphology similar to the one shown, always near the region of intersection of the rebar with the crack. Exposure of the metallographic sections to laboratory air resulted in slow reddening of initially dark products, as seen in Figure 5, suggesting that the corrosion product was evolving toward a higher iron oxidation state. No indications of severe corrosion were externally observed or revealed metallographically, on ECR from the peer cores on the sound concrete location next to the cracks.

Distinct preferential chloride penetration at cracks was observed in this bridge (Figure 1), similar to that noted for the Sunshine Skyway Bridge, at elevations exposed to sea splash. Chloride ion concentration at the ~4 inch (10 cm) reinforcement depth for cracked concrete was greater than commonly assumed conservative threshold values (1.2 lb/yd^3 (0.7 kg/m^3)). Much lower chloride levels were measured at bar depth in adjacent sound concrete, consistent with the low chloride bulk diffusivity (0.036 in^2/yr (~7×10^{-9} cm^2/s)) determined for this low permeability concrete.

Lillian Bridge. Very little concrete deterioration was observed[(1)]. Thin hairline cracks were observed occasionally. The main span footer had larger cracks (~10 mils (0.25 mm))

[1] Core samples were extracted only on the Florida side of the bridge.

with indication of efflorescence, some of which had been repaired earlier on by epoxy-injection. Concrete cores were extracted sampling on and off a crack location at 3.6 ft (1.1 m) AHT. Also cores were extracted from a column with no concrete deterioration at 2.8 and 3.8 feet (0.9 and 1.2 m) AHT. Concrete cover ranged from 4.1 to 5.1 inch (10.4 to 13 cm). Half-cell potentials ranged from -183 to -656 mV CSE at tidal to 5 ft AHT. Concrete resistivity of the footer and column ranged from 113 to 275 kΩ-cm at 1-7 ft (0.3-2 m) AHT.

No corrosion or only vestigial signs of surface corrosion discoloration were observed on extracted ECR. Coating defects affecting as much as 10% of the bar surface were observed on ECR from sound concrete locations. No coating defects were detected on ECR from the cracked concrete location. Full coating disbondment was observed at sound and cracked concrete locations.

Chloride diffusivity values were very low (0.015in^2/yr (~3x10^{-9} cm^2/s)) in agreement with earlier measurements[1]. Chloride penetration profile determination for cracked locations is in progress.

DISCUSSION

Severe corrosion was observed in Choctawatchee and the other Category A bridges confirming previous corrosion durability projections of early damage, based on the high chloride diffusivity values prevalent in these bridges. The high diffusivity resulted in fast chloride penetration, so concentration reached corrosion threshold values early in the life of the bridge (from a few years to one or two decades). In the Choctawatchee Bridge, the cracking observed in delaminated concrete areas resembled typical corrosion-induced cracking. That was not the case for the cracks observed at the other Category A bridges (Vaca Cut, Snake Creek). At those locations there was no concrete delamination either but it is still uncertain whether those cracks preceded the corrosion or not.

Little to no corrosion was observed in sound concrete at the Category B bridges (Lillian, Howard Frankland, and Sunshine Skyway Bridge), even at low elevations where chloride exposure was greatest. This finding was as expected from previous modeling projections[1,8] that were based on the very low chloride permeability of the sound concrete in these bridges. However, there was widespread disbondment of the epoxy coating in all these structures even in sound concrete locations. This disbondment together with the observed frequent coating breaks are expected to facilitate corrosion initiation as chloride levels at the rebar depth increase with time.

Of greater interest in the Category B bridges are the cracked locations. There the present findings confirm substantially enhanced chloride penetration and document, for the first time, severe ECR corrosion at cracks in otherwise highly impermeable concrete in a Florida marine substructure (Howard Frankland Bridge). The findings to date do not support explaining the features observed as due to factors other than corrosion such as, for example, local rolling imperfections. Moreover, corrosion was documented at multiple coring locations. That corrosion is of concern because, in the short ~15 years service, it had progressed beyond superficial damage to clear loss of load bearing section. Such corrosion could lead in time to potentially important structural consequences if left unmitigated and enough vulnerable locations exist. Topical corrosion control action is in order.

It is worth noting that comparable preferential chloride penetration was observed for both Howard Frankland and Sunshine Skyway Bridge, but no significant corrosion has been uncovered to date in the latter. The comparatively better quality concrete in the Sunshine Skyway Bridge (bulk chloride diffusivity ~ 2-4 times smaller than at Howard Frankland) may be mitigating corrosion development there. A similar situation may exist at the Lillian Bridge which also has very low chloride diffusivity concrete. However, as only a limited number of core samplings exist, corrosion may be in progress at cracks elsewhere in those bridges as well. Frequent inspection of crack locations in these structures is therefore strongly advisable so remedial measures can be implemented on time if needed.

The results underscore an important adverse consequence of crack formation in bulk concrete components exposed to sea splash such as the footers, and provide a strong argument for improved structural design to avoid formation of those cracks during construction and service. The specification of alternative corrosion resistant rebar for new construction or repairs merits consideration as well.

Research continues to resolve other characterization issues. Unusually high surface concrete resistivity (in the MΩ-cm range) measured in the field at the Howard Frankland Bridge was confirmed with measurements of as-received extracted cores in the laboratory. As noted before the high resistivities are not likely to be caused by carbonation of the concrete pore solution, especially since high resistivity was measured in the bulk cores as well. The high quality of the concrete and self-desiccation may be contributing factors. Resistivity measurements as function of time of concrete cores exposed to high humidity are in progress to elucidate those issues.

CONCLUSIONS

- Severe corrosion was observed in Category A bridges, confirming previous corrosion durability projections of early damage based on the high chloride diffusivity values prevalent in these bridges.

- Little to no corrosion was observed in sound concrete at the Category B bridges, even at low elevations where chloride exposure was the greatest. This confirmed previous modeling projections based on the very low chloride permeability of the sound concrete in these bridges.

- Enhanced chloride penetration was confirmed at crack locations in Category B bridges, and severe ECR corrosion was observed at multiple crack locations in one of those bridges. Those instances are of concern because in the short ~15 years service corrosion had progressed beyond superficial damage to clear loss of load bearing section.

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REFERENCES

1. Sagüés, A.A. et al. "Corrosion of Epoxy Coated Rebar in Florida Bridges." Final Report to Florida D.O.T. WPI 0510603. May 1994. Available online, www.dot.state.fl.us

2. Sagüés, A.A., R. Powers, and R. Kessler, Corrosion/2001. Paper No.06142. NACE International. Houston, TX. 2001.

3. Sagüés, A.A and R. Powers, Corrosion/1990, Paper No. 311. Nace International, Houston, TX. 1990.

4. Sagüés, A.A. Corrosion/1994, Paper No.299, NACE International, Houston TX,1994.

5. Sagüés, A.A. and R. Powers, Corrosion/1996, Paper No.325, NACE International, Houston, TX, 1996.

6. Sagüés, A.A., H. Perez-Duran, and R. Powers, Corrosion, Vol.47, p.884, 1991.

7. Nguyen, T. and J.W. Martin, JCT Research, Vol.1, no.2, pp.81-92, 2004.

8. Sagüés, A.A. Corrosion, Vol.59, p.854, 2003.

9. Lau, K, A.A. Sagüés, and R.G. Powers, Corrosion/2007, Paper No.07306, NACE International, Houston, TX, 2007.

10. Kenneth C. Clear, Inc., "Effectiveness of Epoxy-Coated Reinforcing Steel", Final Report, March 1992, submitted to the Canadian Strategic Highway Research Program, 1992.

11. Sagüés, A.A. E.I Moreno, W. Morris, and C. Andrade, "Carbonation in Concrete and Effect on Steel Corrosion," Final Report to Florida D.O.T. WPI 051685, June 1997, Available online, www.dot.state.fl.us.

12. Sagüés, A.A. et al, "Corrosion Forecasting for 75-Year Durability Design of Reinforced Concrete," Final Report to Florida D.O.T. WPI 0510805. Dec. 2001, Available online, www.dot.state.fl.us.

Table 1. Summary of Bridge Findings

Category	Bridge	Year Built	Average D † (cm^2/s)	ρ (kΩ-cm)	Widest Crack Width (mm)	Corrosion sound/crack location
A	Choctawatchee	1979	$1.8X10^{-8}$	16-128	>1.0	Sound/Crack
	Vaca Cut	1982	$2.6X10^{-7}$	4-50	0.28	Sound/Crack
	Snake Creek	1981	$9.0X10^{-8}$	4-40	0.08	Crack
B	Lillian	1981	$3.1X10^{-9}$	113-275	0.25	None
	Howard Frankland	1991	$7.3X10^{-9}$	high MΩ-cm	>1.0	Crack
	Sunshine Skyway	1986	$1.1X10^{-9}$	~150	0.64	None

† Average diffusivity values to be updated upon additional analysis of concrete core samples.

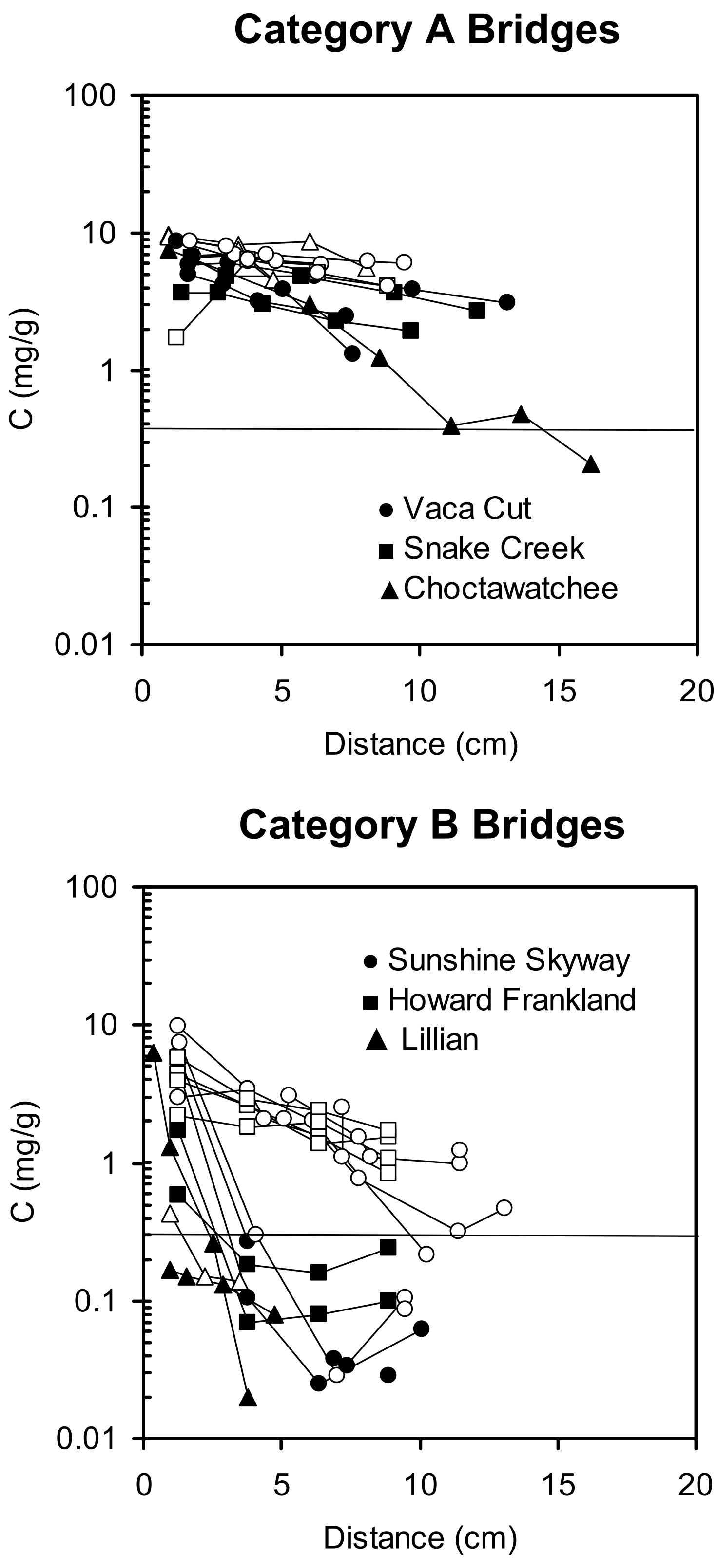

Figure 1. Chloride Ion Penetration Profiles for Category A and B Bridges. Open symbol: Cracked concrete, Closed symbol: Sound concrete. Horizontal line: Conservative chloride corrosion threshold value (0.3 mg/g, equivalent to 1.2 lbs/yd^3)

Figure 2. Large crack, >40 mils (1 mm) (Bridge over East Pass-Choctawatchee Bay).

Figure 3. Extensive reinforcement corrosion. (Bridge over East Pass-Choctawatchee Bay Pier 29, North footer).

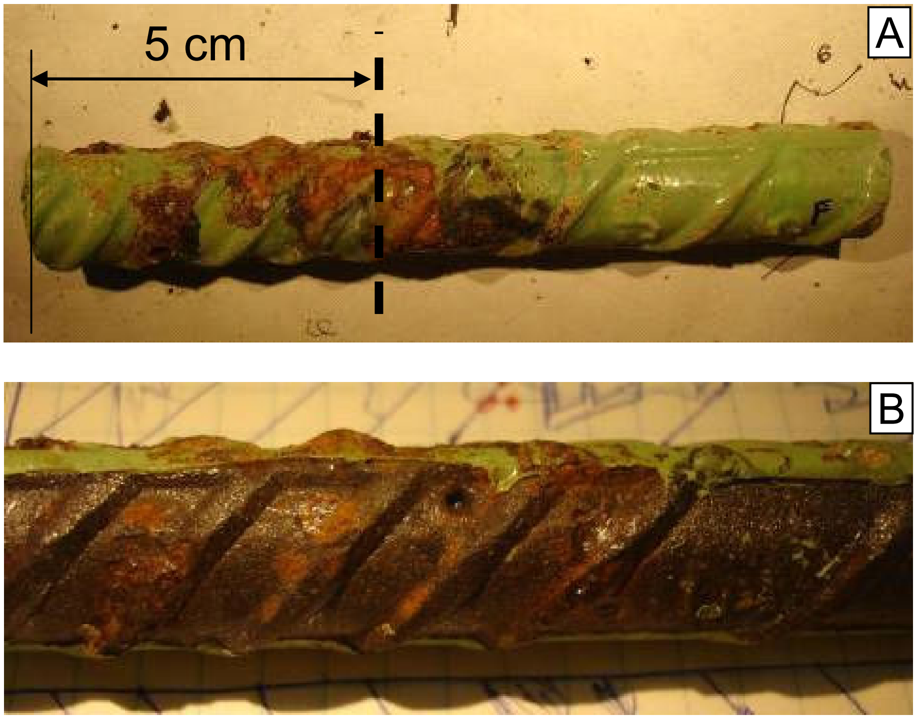

Figure 4. ECR corrosion at crack location (Howard Frankland Bridge) A. Corrosion products on bar surface. The line represents the location of the crack intersection. B. Appearance after partially removing the coating and exploring into the corrosion products.

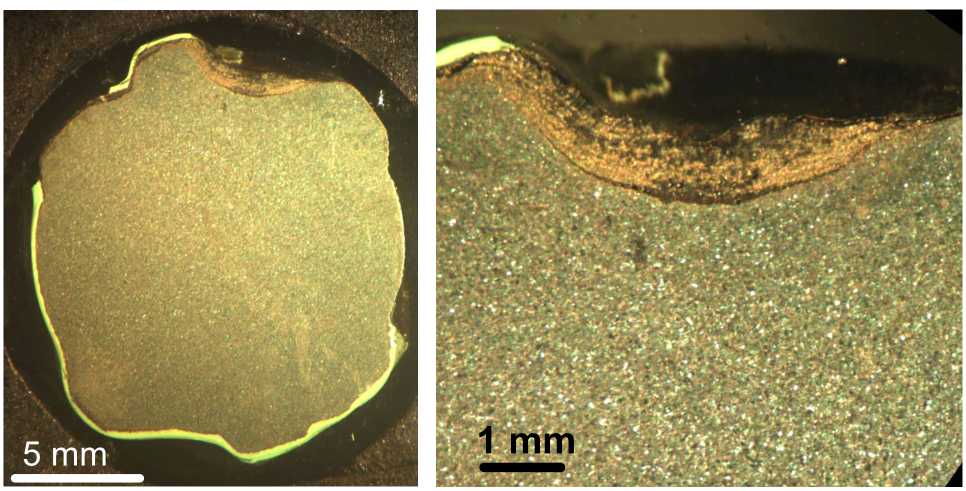

Figure 5. Cross section of ECR bar showing severe corrosion at a crack location of Howard Frankland Bridge. Left: Entire Bar cross-section. Right: Close up of corrosion penetration.

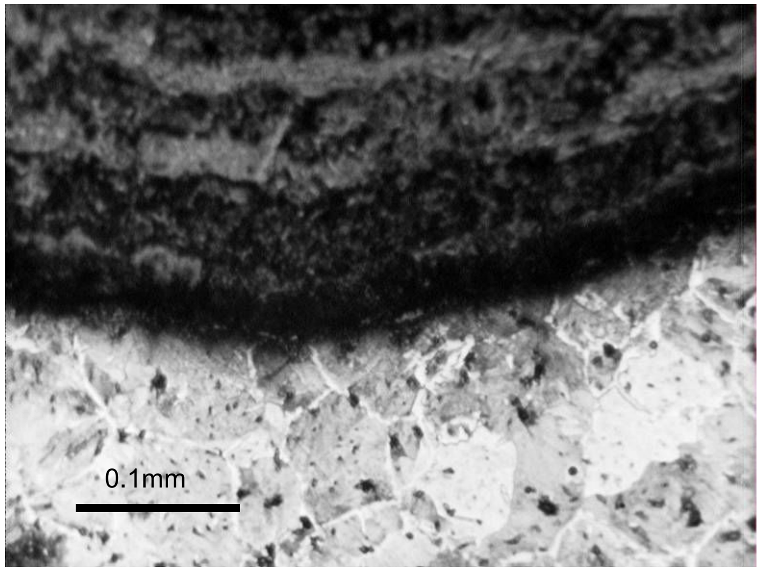

Figure 6. Corrosion product - base metal interface showing progression of corrosion into the microstructure of the rebar steel (Howard Frankland Bridge).