Responsible Design and Delivery of the Constructed Project
Edited by Abdul-Malak, M., Khoury, H., Singh, A., and Yazdani, S.

ISBN: 978-0-9960437-5-5

STRUCTURAL HEALTH MONITORING OF CORROSION POTENTIAL IN CONCRETE BRIDGE DECKS

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Structural Health Monitoring (SHM) of concrete structures during construction, as well as over its service life, has recently become more attractive to owners and consulting engineers. With the introduction of new materials and construction methods, various types of concrete structures are being instrumented with monitoring devices to determine their performance and response to various loading conditions. Among many other objectives, this includes monitoring concrete performance at the serviceability and durability limit states. This paper is an overview of an on-going program for the SHM of concrete bridge decks in the State of New Jersey focusing on field performance. Three types of corrosion sensors are instrumented to monitor the corrosion activities in concrete decks; one is the silver-silver chloride electrode and the other two are multi element probe (MEP) corrosion sensors. Other types of MEPs were also instrumented on bridge decks during reconstruction in late 1990s to monitor the corrosion potential of the bridge decks. Various types of sensors are installed in precast panels during fabrication as well as in-situ cast concrete decks during and after construction. Moreover, a laboratory-based accelerated corrosion testing program is also performed on concrete specimens using various types of rebars. This ongoing study is aimed at correlating laboratory-accelerated corrosion results with long-term performance of the steel in concrete bridge decks under field conditions.

Keywords: Accelerated corrosion testing, Silver-silver chloride electrode, Multi element probe.

1 INTRODUCTION

SHM is mainly applied to evaluate the structural long-term behavior of bridges using various types of sensors (Nassif *et al.* 2003). It can determine the extent of structural deterioration and provide its estimated remaining service life under current environmental conditions. Various factors are involved in the deterioration process of bridges such as material-related factors (i.e., permeability, chloride ingress, and corrosive reinforcement) and load-related factors (i.e., overweight and load-induced fatigue cracks). Among these factors, load induced deterioration has been studied and the phenomenon is well established (Nassif *et al.* 2016). However, corrosion of steel is not generally monitored by SHM protocol because it takes longer time than other monitoring scheme. However, it is of prime importance to monitor the corrosion potential in order to understand the long-term structural behavior as well as to estimate its service life.

Corrosion is a complex phenomenon related to material, structure type, environment, maintenance, etc., but it generally occurs when the reinforcement is exposed to chlorides. Numerous studies have been made to understand the corrosion rate and the on-set time (Arya and Ofori-Darko 2013, Gowripalan *et al.* 2000). Many studies were focusing on the electrochemical process of corrosion and its parameters to predict the corrosion rate and initiation based on results from laboratory testing. When the chloride ions start to ingress within the concrete cover, the reinforcing steel forms a thin layer of its oxide (Bazant 1979). While the thin layer resists the ingress of chloride ions to the steel reinforcement, it is passive and no corrosion will occur. As the concentration of the chloride ions increases, the layer is compromised, and the corrosion is initiated. There are additional factors that also control the corrosion process such as PH, mass transfer and diffusivity of ions and molecules such as Oxygen and ferric hydroxide, and pore water viscosity (ACI 222R-01, 2001).

The ultimate goal of this ongoing study is to find the best model to correlate laboratory-accelerated corrosion results with long-term performance of the steel reinforcement in concrete bridge decks under field conditions. The authors in this paper are presenting and discussing the corrosion monitoring results of four (4) concrete bridges in New Jersey.

2 FIELD STRUCTURAL HEALTH MONITORING (SHM) PLAN

2.1 Corrosion Monitoring Sensors

Two types of corrosion sensors were used; (1) silver-silver chloride electrode (herein Ag electrode) and (2) multi element probe (MEP).

2.1.1 *Silver-silver chloride electrode*

The Ag electrode is a permanent passive electrode used to measure the potential difference between electrode and reinforcement. Figure 1(a) shows the Ag electrode after installation adjacent to a steel rebar. When the chloride ion ingresses in the concrete, the Ag electrode, counter lead, and the concrete works as a battery. It generates a small voltage reading, and the corrosion risk can be determined. Higher chloride ion results in higher voltage readings and therefore higher corrosion potential. Low voltage (< 300 mV) indicates passive corrosion (or not corrosion), high voltage (> 600 mV) indicates active corrosion, and 300~600 mV indicates 50% possibility of corrosion.

2.1.2 *Multi element probe (MEP)*

The MEP measures the corrosion rate as well as on-set of corrosion using different probes. Two types of MEP were used for this study; one is ECI-2 sensor by Virginia Tech., Inc. and the other is CPMP-2 produced by Corrosion Service. Figure 1(b) and (c) shows both MEPs; on the left (b) is ECI-2 and on the right (c) is CPMP-2. ECI-2 MEP integrates of black steel electrode, manganese dioxide (MnO_2) reference electrode, stainless steel base counter electrode, 4 strips of stainless steel (SS) conductive sensors, and Ag electrode. ECI-2 MEP is capable of monitoring the linear polarization resistance (LPR), open circuit potential (OCR), resistivity (R), and chloride ion concentration. The corrosion potential is determined using Table 1 depending on the readings from the MEP. For example, for an LPR over 10 kOhm-cm^2, which is considered high, while the OCP and Chloride content is low (e.g., less than 300 mV) this indicates that there is no corrosion activities. On the other hand, when LPR is less than 10 kOhm-cm^2 and the OCP and Chloride content is high (e.g., more than 600 mV) this indicates high probability of corrosion activity.

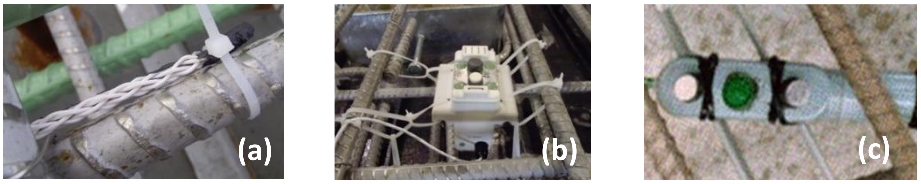


Figure 1. Installation example of Ag electrode and two MEPs (ECI-2 and CPMP-2).

Table 1. Application table to judge the corrosion rate.

LPR	OCP	Resistivity	Chloride	Corrosion possibility
Low	Low	Low	Low	High likely
Medium	Low	High	High	Likely
High	Low	Low	Low	Unlikely
High	High	High	High	Unlikely

2.2 Corrosion Monitoring Bridges

2.2.1 *Newark Bay Bridge*

The Newark Bay Bridge (NBB) is a major corridor that connects Newark and Bayonne, NJ. It was originally constructed in 1956 as a part of the New Jersey Turnpike, and the bridge was reconstructed in early 2010 using precast panels to minimize any traffic-induced cracking. This bridge has two types of spans (see Figure 2) – main truss span and floorbeam spans. Two types of rebars were used for the precast panels; the majority of the precast panels were made with epoxy-coated rebars and limited number of panels were made with duplex stainless steel (SS). Ag electrodes and one ECI-2 MEP were instrumented in selected precast panels during casting the concrete in 2012. High-performance concrete (HPC) was used for the entire bridge.

Figure 2. Newark Bay Bridge and typical sensor layout in the precast deck panels.

2.2.2 *Patcong Creek Bridge*

The Patcong Creek Bridge is located on the Garden State Parkway which underwent major widening and rehabilitation that was completed in 2012. The HPC and duplex SS were used for the entire bridge as it is located near the eastern coast ,very close to sea shore. A number of Ag electrodes were installed in multiple spans and one ECI-2 MEP was installed as shown in Figure 3 (a). The corrosion monitoring started in 2013.

2.2.3 *Bridge No. 84.1*

This bridge was reconstructed in 1998 using HPC and galvanized steel. The CPMP-2 MEPS were installed on entire span as shown in Figure 3 (b). The corrosion potential was monitored for the first 2 years by the NJTA engineers, and then by the authors followed up in 2016.

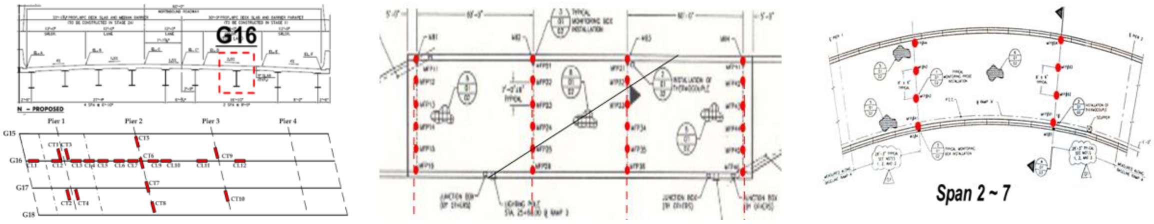


Figure 3. Sensor layout of Patcong Creek Bridge, Bridge No. 84.1 and Bridge No. 159.7A.

2.2.4 *Bridge No. 159.7A*

This bridge was reconstructed in 1999 using HPC and duplex SS for the new bridge deck. The same engineering consultants instrumented a number of MEPs (CPMP-2) on all spans of the bridge as shown in Figure 3 (c). The corrosion potential was monitored for the first 2 years by the NJTA engineers, and then by the authors since 2016.

3 FIELD MONITORING RESULTS

3.1.1 *Newark Bay Bridge (HPC with stainless steel and epoxy rebar)*

The monitoring has been performed over 5 years since 2013. Figure 4 presents the corrosion potential monitoring results of Ag electrode for two precast panels. Panel 1 has the SS, and Panel 2 has the epoxy rebar. Figure 4 shows that there is no corrosion activity in SS Panel over 5 years, however, there is some corrosion activity in epoxy rebar Panel from year 3 and the corroding area is getting large. Figure 5 depicts the monitoring results of ECI-2 MEP in Precast Panel 1. Based on Table 1, the results confirm that it is unlikely to corrode the stainless steel in Precast Panel 1.

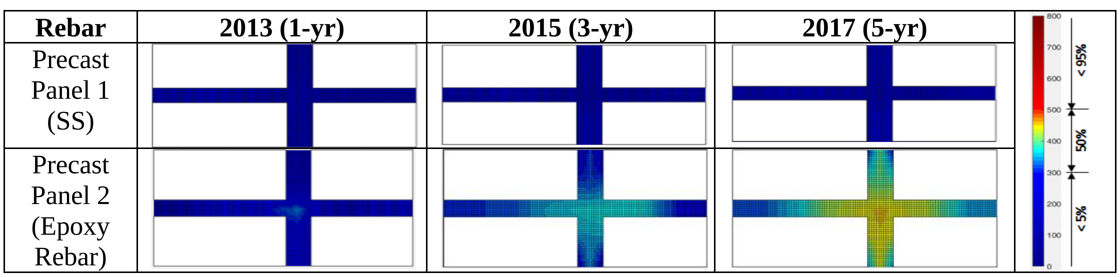


Figure 4. Newark Bay Bridge monitoring results 1 – Ag electrode.

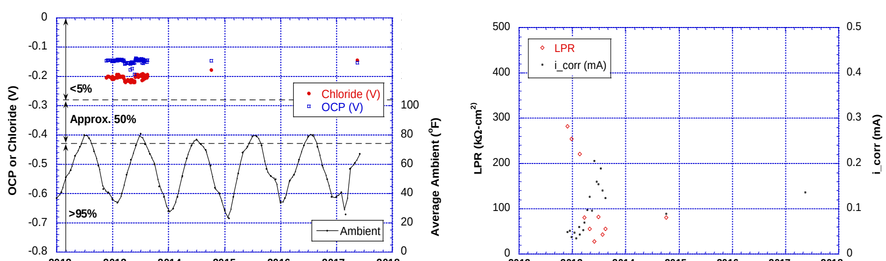


Figure 5. Newark Bay Bridge monitoring results 2 – ECI-2 MEP.

3.1.2 *Patcong Creek Bridge (HPC with stainless steel)*

The corrosion potential has been monitored over 5 years since 2013. Figure 6 and Figure 7 represent the corrosion monitoring results for Ag electrodes and ECI-2 MEP. Similar results as the Precast Panel 1 with SS were observed; no corrosion activity is monitored over 5 years.

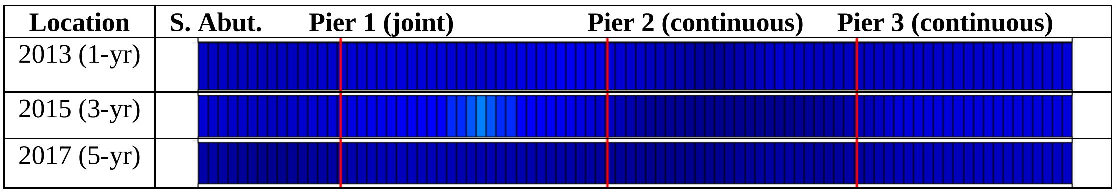


Figure 6. Patcong Creek Bridge monitoring results 1 – Ag electrode.

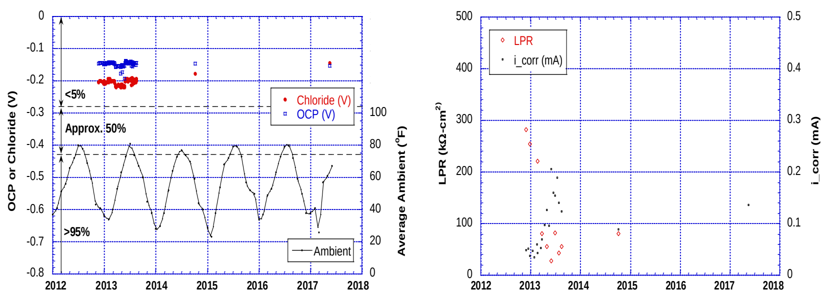


Figure 7. Patcong Creek Bridge monitoring results 2 – ECI-2 MEP.

3.1.3 *Bridge No. 84.1 (HPC with galvanized rebar)*

The bridge was initially monitored in 1999 and more frequently since 2016. Figure 8 shows the data for the corrosion potential and corrosion rate as measured by CPMP-2 MEP at Bridge No. 84.1. After 18 years, some areas (see Figure 8 near locations ① and ②) show some active corrosion in both corrosion potential and rate measurements; Location ① is in the left lane where the major traffic flows, and location ② is in the negative moment region of the bridge. These results indicate that the galvanized steel is in the phase of corrosion initiated within 18 years, and therefore a high probability that the outside Zinc coating layer is undergoing corrosion activity.

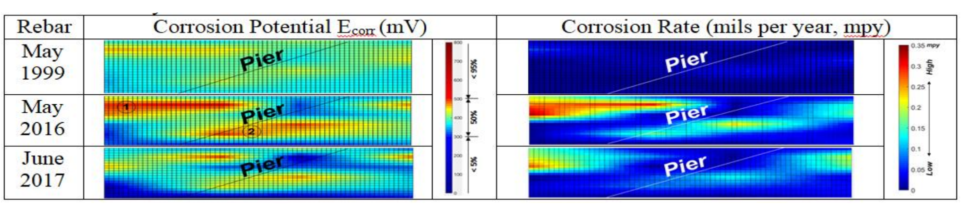


Figure 8. Bridge No. 84.1 monitoring results – CPMP-2 MEP.

3.1.4 *Bridge No. 159.7A (HPC with stainless steel)*

The ramp bridge No. 159.7A was initially monitored in November 1999, and more frequently since 2016. Figure 9 shows the corrosion monitoring results measured by the MEP. Corrosion potential results show that some locations had a 50% chance of corrosion since 1999. However, the data on corrosion rates show no corrosion or a very low corrosion rate. Therefore, it can be deduced that the SS withstands the corrosion activity after 18 years of service life.

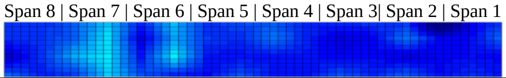
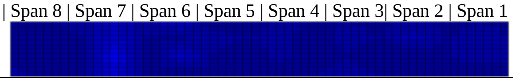
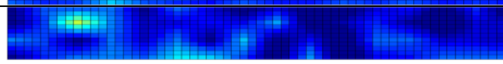
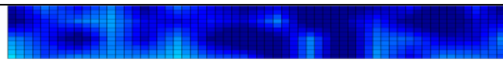
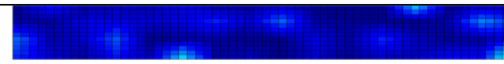
Rebar	Corrosion Potential E_{corr} (mV)	Corrosion Rate (mils per year, mpy)
Nov 1999	| Span 8 | Span 7 | Span 6 | Span 5 | Span 4 | Span 3| Span 2 | Span 1 | 	| Span 8 | Span 7 | Span 6 | Span 5 | Span 4 | Span 3| Span 2 | Span 1 | 
May 2016		
June 2017		

Figure 9. Bridge No. 159.7 monitoring results – CPMP-2 MEP.

4 SUMMARY AND CONCLUSIONS

Based on the field monitoring results, the following conclusions can be made:

1. The Ag electrode can provide the corrosion potential near the reinforcement, while the MEP can provide the corrosion onset as well as the corrosion rate.
2. The field monitoring of the Newark Bay Bridge indicates that the epoxy-coated rebar is not effective in mitigating the corrosion while the SS rebar can withstand the corroding activity. The precast panel with epoxy-coated rebar shows 50% of corrosion probability in 3 years, while the precast panel with SS shows no corrosion in 5 years. The monitoring results of the Patcong Creek Bridge also confirms the effectiveness of SS in resisting corrosion.
3. The monitoring results of Bridge No. 84.1 show that the corrosion onset and high corrosion rate were observed after 18 years for galvanized steel. For Bridge No. 159.7A, no active corrosion was observed after 18 years of service life for SS.
4. There is a need to correlate Lab-based accelerated corrosion results with field monitoring data to help establish these protocols.

Acknowledgments

The authors would like to acknowledge the New Jersey Turnpike Authority for their financial and logistical support for the RIME team during the instrumentation of the sensors and monitoring the bridges.

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