Design of Cathodic Protection of Rebars in Concrete Structures: An Electrochemical Engineering Approach

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Cathodic protection is an electrochemical technique that minimizes the corrosion of metals in contact with any ionically conducting medium. In this technique, the metal/electrolyte interface is electrically polarized by −200 mV, and a current is forced through the interface. For an ideal protection, however, the −200-mV polarization should be achieved uniformly all along the interface. Otherwise, where the interface is underpolarized, the metal will continue to corrode, and where it is overpolarized, it will fail catastrophically because of electrochemically generated hydrogen embrittlement. Nonuniform polarization is almost always caused by nonuniform distribution of the current across the interface, which can be traced to the design, installation, maintenance, and management of cathodic protection systems. These aspects have received very little attention in the 80-year history of the cathodic protection technique. This article describes an electrochemical engineering approach to designing, maintaining, and managing cathodic protection systems in concrete structures.

INTRODUCTION

Cathodic protection (CP) is a popular technique used to minimize the corrosion of metals in a variety of large structures, including bridges, pavements, parking lots, and pipelines. In concrete structures, CP is used to protect the reinforcing steel bars from corrosion; the reinforcing bars are commonly referred to as rebars. In North America, more than 350 bridges are protected from corrosion by this technique, several of them for over three decades.[1,2] Several more bridges in Canada, with approximately 60 in the Quebec Province alone, are under CP.[3,4] On bridge structures, CP has traditionally been used to protect only the deck sections, but recently, support structures have also been protected.

CP systems are by no means inexpensive compared with the cost of the bridge. The cost to install a CP system is estimated to be 15% of the bridge construction cost. In addition, the recurring expenses due to maintenance and management of a CP system over its lifetime can increase its cost severalfold.

Although the cost of implementing and maintaining a CP system on a concrete structure is relatively high, the benefits obtained in terms of protection from corrosion are not well resolved. If the past 30 years are considered in exploring CP as a viable technique to protect bridges from corrosion, then the results are somewhat mixed. During the past 10 years, numerous reports have been issued on the status of CP in several state and federal bridges.[4–11] These reports suggest that cathodic protection is more effective on some bridges[4,5] than on others.[6,10] The failures have been attributed to various causes, ranging from the inadvertent shutdown of the rectifiers to improper electrical connections. Studies correlating climatic and environmental factors to the effectiveness of CP have yet to be published. In essence, the CP technique for concrete structures is still evolving.

The continuing use of CP techniques is likely to be determined as much by cost considerations as by technical merit. Many options are available for reducing design and installation costs, as well as maintenance and management costs. The purpose of this work was to explore these options by using techniques that were not available or used in the present CP system designs.

PRINCIPLES OF CORROSION AND CATHODIC PROTECTION

The CP technique is based on the principles of electrode kinetics, which are briefly described as follows: In the absence of any polarization, a metal in contact with concrete or an electrolyte will remain at its corrosion potential (E_{cor}). At this potential, the metal surface sustains at least two reactions occurring at equal rates: a metal dissolution (or anodic metal oxidation) reaction, and a cathodic conjugate reaction, such as oxygen reduction or hydrogen evolution. If the metal is electrically polarized to potentials positive to E_{cor}, the metal dissolution reaction will be accelerated, whereas the cathodic conjugate reaction will be decelerated. The converse is true when the metal is polarized negative to E_{cor}. Thus, when the metal is polarized away from E_{cor} to a positive or negative value, a net anodic or a net cathodic current, respectively, will flow across the metal/electrolyte interface. A metal is under cathodic protection when it is polarized sufficiently negative to E_{cor} to reduce the metal dissolution rate by 3 orders of magnitude or more.

Under most conditions, a polarization of about -200 to -300 mV is sufficient to achieve cathodic protection. Excessive cathodic polarization should, however, be avoided to prevent onset of the hydrogen evolution reaction and to reduce the possibility of hydrogen embrittlement of the metal. Furthermore, cathodic polarization, like corrosion, is a surface process. Therefore, to achieve uniform protection at all locations on a given surface, it is imperative that the cathodic current density is uniform at all locations. Any nonuniformity in the current flow, especially with values less than some critical minimum, can cause localized variations in the metal dissolution rate. These variations can result in the structure corroding more severely in some places than in others. In a bridge, for example, if the CP current is nonuniformly distributed, those parts of the bridge that do not receive the current will continue to corrode, whereas those that do receive the current will be well protected from corrosion.

Typical CP systems used in protecting metal–concrete structures are described as follows: In these structures, the metal is usually steel, and the cement and water form the electrolytic medium. Generally, the CP system has a rectifier as the voltage source. The return electrode for the current is either a palladium-coated titanium mesh,[12] a thin layer of zinc,[7] or a conducting polymer mixed with concrete.[5] They are "inert" electrodes, not consumed or destroyed by the reactions associated with the cathodic protection, and are called ground beds. Generally, the ground bed is two-dimensional, is spread over the entire structure, and is covered with concrete and asphalt. All the rebars are electrically connected to one another, and the electrical connections between the rebars and the rectifier are made at one or two remote locations on the bridge. Similarly, the electrical connections between the ground bed and the rectifier are also made at one or two remote locations. Thus, in most cases, the ground bed is distributed evenly with respect to the rebars, whereas the electrical contact points are highly localized. Since the bridges are located in various geographical locations—from Washington to Maryland, and from Florida to New York—they are exposed to a wide variety of environmental and climatic conditions.

OPTIMIZATION OF CP SYSTEMS

The preceding description applies to conventional designs of CP systems. However, one can take several steps to improve these designs. For example, the CP system can now be designed with greater emphasis on uniform distribution of current and potential throughout the bridge. Using numerical techniques such as the finite-element method (FEM), one can predict the geometric arrangement of ground beds and the ideal points of electrical contacts for any given geometry of the bridge and the rebars. Variations in the electrical conductivity of the concrete overlayers, the presence of coated and uncoated (bare) rebars, and spatial variations in the level of exposure to moisture and salt can all be easily incorporated into the CP design. Furthermore, after implementation, the validity of the FEM results can be verified through mapping of the CP current over the entire bridge, which can be done noninvasively using magnetic sensors.

The goal of this work is to demonstrate the possibility of improving the CP technique, making it fully functional and completely automated. As a first step, we show the use of FEM to predict current and potential distribution in concrete, and magnetic sensors to map currents in prototypical models, as well as over the entire deck of a CP-protected, in-service concrete bridge.

NUMERICAL SIMULATION AND CP CURRENT MAPPING

Numerical simulation of current and voltage distribution, and mapping the current distribution in concrete structures, are the two most important steps demonstrated in this work. The former used FEM, and the latter used magnetometer sensors.

The FEM simulation can be performed in two or three dimensions. A wide range of geometric features, from the large size of a bridge deck to the fine thin coating on rebars, can be incorporated simultaneously into the versatile FEM models. Linear and nonlinear properties of several kinds of materials are simultaneously specified within a single model. The FEM analysis simulates potentiostatic (constant potential) or galvanostatic (constant current) conditions that are present in CP systems, and predicts potential, current, and magnetic field distributions in cathodically protected concrete structures. These predictions were used in this work only as the first step in the optimization of the CP system design.

Fluxgate magnetometer sensors are lightweight sensors powered by batteries that are used to map the current on concrete structures. They are totally isolated and insulated from their surroundings, and can operate while buried in concrete, immersed in water, or left under any condition that surrounds structures like a bridge. They are vector instruments that measure both amplitude and flow direction of AC and DC currents. Their spatial resolution decreases with an increase in the liftoff distance between the sensors and the rebars; when the sensor is 4 in. away from the rebar (which is the typical distance between the rebars and the top or the bottom surface of the concrete), it will measure the current that is present over an 8-in. length of the rebar. The most important feature of the magnetometer sensor, with respect to optimizing CP in large extended structures, is its capability to measure and map localized distribution of CP current noninvasively.

CURRENT DISTRIBUTION ON A SIMULATED SECTION OF A BRIDGE

The concept of using numerical models to optimize CP system design was verified on a small, steel-reinforced, 4.0 × 3.0 × 0.8 ft block of concrete. The block (Fig. 1), which represents a small section of a bridge deck, contained two layers of No. 5 rebars (0.5-in. dia.), oriented orthogonally to each other. Each rebar extended over the entire length of the concrete block, and each layer of the rebar was parallel to the plane of the concrete. The two layers of the rebars were 5.5 in. and 6.5 in. below the top surface of the concrete overlay. A metallized layer depicting the anode mesh was incorporated in between the rebar layers and the top surface of the block. The metallized layer was covered with a layer of asphalt. Resistivity values of $0.18 \times 10^{-4}\ \Omega\cdot\text{cm}$ and $0.5 \times 10^{5}\ \Omega\cdot\text{cm}$ were assigned for the steel and concrete, respectively.

The surfaces of the rebars that are shown as circles in Fig. 1 were specified with identical electrical potential; this setup is equivalent to connecting the rebars electrically to the same source and polarity. The other ends of the rebars (not visible in Fig. 1) were not specified with any potential. Similarly, the surface of the metallized layer that is projecting out of the concrete surface was specified with an electrical potential of opposite polarity to that of the rebar surface. Electrical conductivity values, commonly known for steel, concrete, and steel/concrete interface, were also incorporated into the model. In essence, these parameters

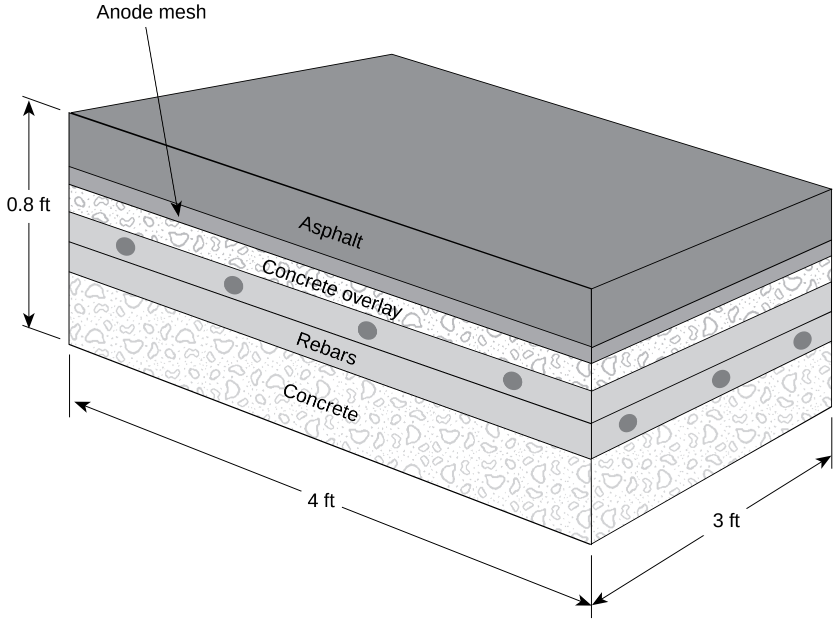

Figure 1. Diagram of the concrete block used in the FEM model to determine the current and potential distribution. The circles represent the cross-sectional areas of the rebars. The diagram is not drawn to scale in order to show the composition of the layers.

simulate a cathodically protected concrete surface, where the rebars are polarized cathodically and the metallized layer is polarized anodically. Furthermore, specifying the electrical voltages at only one end of the rebars (and the metallized layer) simulates an asymmetrical electrical contact, which is the most common practice used in the field on in-service structures. The objective of this simulation is to identify the effect of the asymmetrical electrical contact configuration on the distribution of the CP current and potential.

In electrochemistry and corrosion, the terms “voltage” and “potential” are not interchangeable. Whereas voltage refers to the electrical voltage applied between the rebars and the ground bed, potential refers to the potential drop incident across the rebar/concrete (metal/electrolyte) interface. This potential is not caused by a pure electrical drop alone, but by the sum of the differences in the electrical and chemical potentials between the metal and the electrolyte; it is commonly referred to as the electrochemical potential. That is the reason why electrochemical reactions, including corrosion, are affected by the chemical composition of the electrolyte (pH, oxygen concentration, ionic strength, and so on), as well as by electrical potentials (as in cathodic polarization). The term, electrochemical potential, is often loosely referred to as potential. However, since there is nothing like a chemical voltage, terms such as “electrochemical voltage” or its shortened form “voltage” are not used to refer to the potential drop across the steel/concrete interface.

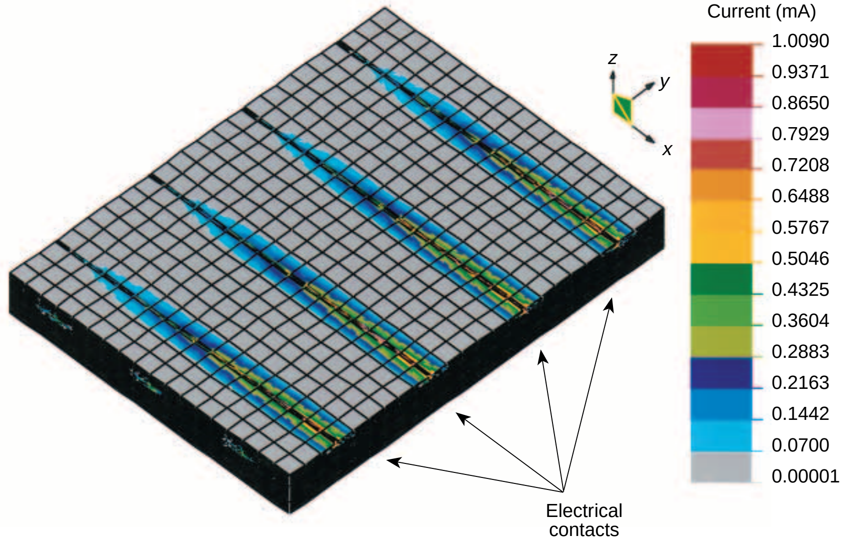

Figure 2. Current distribution near the rebar/concrete interface as obtained from the FEM analysis for the model shown in Fig. 1. Note that the currents are higher near the locations where the electrical contacts are made to the rebars. .

CURRENT AND VOLTAGE DISTRIBUTIONS

The current distribution near the rebar/concrete interface for the top layer of rebars, obtained by the FEM analysis for the model structure in Fig. 1, is shown in Fig. 2. The rebar surface where the electrical contacts were made is also indicated in the figure. The magnitude of the current is maximum at the end of the rebar surface where the electrical voltage was specified and is minimum at the far end. The potential distribution at a location close to one of the rebars is shown in Fig. 3; the spacing of the grids in this figure is on the order of centimeters. Close to the rebar/concrete interface, the drop in the potential is relatively small; most of the drop occurs over a distance of a few centimeters within the concrete. At all other locations of the interface, the potential distribution was found to be nearly identical to the one shown in Fig. 3. The relatively larger drop in the concrete is commensurate with its higher resistivity (0.5×10^5 Ω·cm) in comparison with steel (0.18×10^{-4} Ω·cm). This observation is in complete agreement with those made by other corrosion engineers on in-service concrete structures.[13]

A significant conclusion drawn from the FEM analysis is as follows: For asymmetrical geometric configurations (of the rebars and the ground bed), with asymmetrical electrical configurations, the rebar/concrete interface that is farther away from the electrical contacts receives very little current. As described in the section “Principles of Corrosion and Cathodic Protection,” the degree of protection from corrosion is reduced as the current across the interface is reduced. Obviously, CP designs similar to the one described previously, if adapted for a real concrete structure, may not protect the rebars from corrosion over their entire length. Several of the 350 bridges mentioned previously, and many other structures that are presently under cathodic protection, are protected using asymmetrical electrical connections. An example of the effect of such protection on symmetrical geometric structure, under real field conditions, was demonstrated through current mapping on an in-service bridge in Maryland.

CP CURRENT MAPPING ON A CONCRETE BRIDGE

Figure 4 shows a steel-reinforced concrete bridge located in Maryland. The bridge is 93 ft long in the

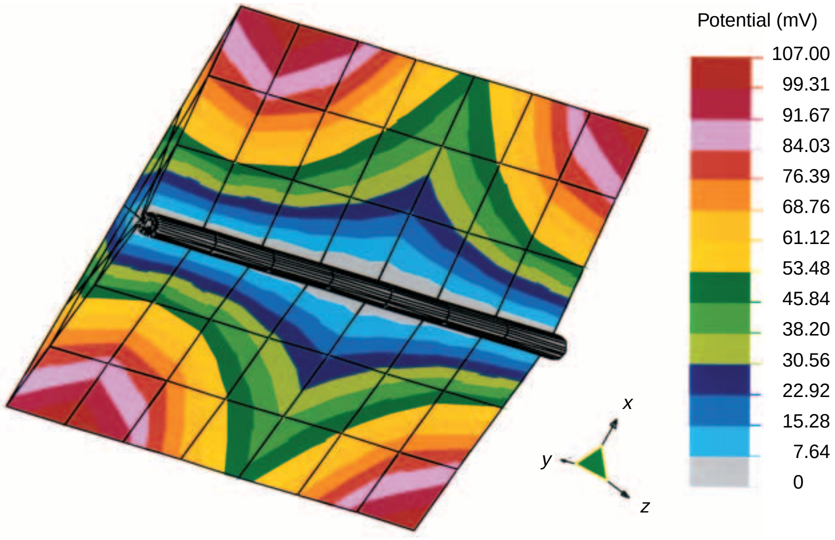

Figure 3. Potential distribution near a small section of a rebar/concrete interface as obtained from the FEM analysis for the model shown in Fig. 1. Note that the drop in the potential is higher in the concrete as compared to steel or the steel/concrete interface.

east–west direction and 133 ft wide in the north–south direction. The bridge deck is cathodically protected by a single rectifier. A schematic of the bridge is shown in Fig. 5. The deck has two layers of uncoated rebars, one on the top and the other on the bottom, with concrete in between. All rebars are shorted to one another. A palladium-coated titanium mesh, spread over the entire bridge, is placed over the top layer of the rebars and acts as the ground return. A latex–concrete mix covers the titanium mesh. A 133-ft-long conducting bar, placed along the north–south axis at about 46 ft from the west end of the bridge, is connected to the titanium mesh. A point contact made to the conducting bar at about 60 ft from the north

Figure 4. Picture of the 93 × 133 ft concrete bridge, which is CP protected. The CP current on this bridge was mapped using magnetic sensors over a period of 4 h.

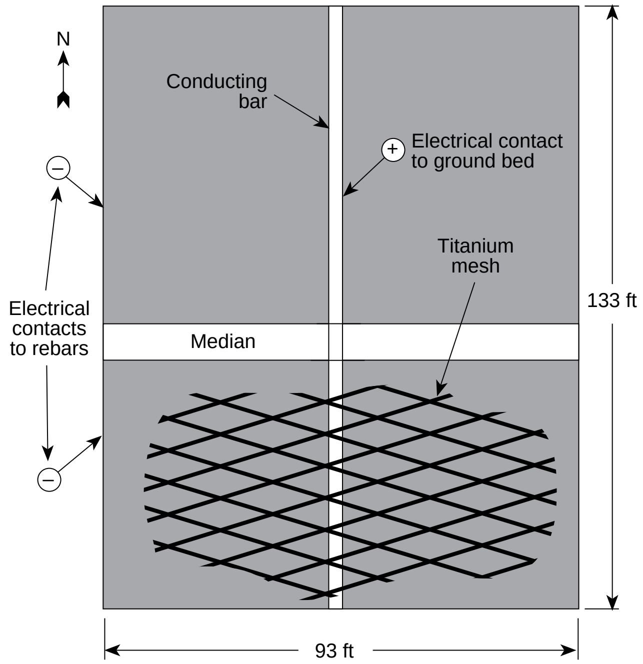

Figure 5. A diagram of the bridge in Fig. 4. The ground bed is a titanium mesh, is two-dimensional, is spread over the entire structure, and is covered with concrete and asphalt. Electrical connections between the rectifier and the rebars (negative) and the ground bed (positive) are made at remote locations as shown.

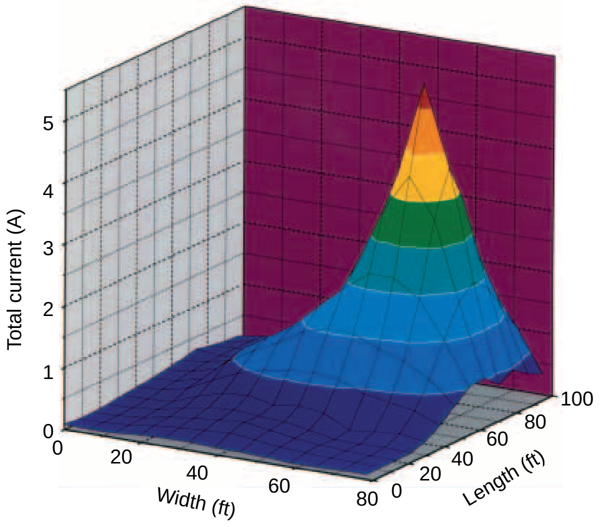

Figure 6. CP current distribution on the bridge in Fig. 4, as obtained by the magnetometer-based current mapping technique.

end of the bridge is connected to the positive terminal of the rectifier. The negative terminal of the rectifier is connected to the rebars at two locations along the west end of the bridge. Thus, the bridge is a textbook combination of a uniformly distributed ground bed laid over uniformly distributed rebars, with the non-textbook condition of remote electrical connections.

CP currents were mapped from the top of the bridge deck. For this purpose, the deck was divided into a matrix of several parallel and perpendicular lines at intervals of 10 ft. At each intersection point, the current flow along the east–west axis and the north–south axis was measured using magnetometer sensors. The resulting current distribution is shown in Fig. 6. This figure shows only an 80 × 80-ft part of the 93 × 133 ft area of the bridge deck; the amplitude of the CP current in the rest of the deck is less than 1 μA.

The CP currents are concentrated only in the northwest part of the bridge, where they reach a peak value of about 5 μA. The location where the maximum current occurred matches well with one of the points where the rebars are connected to the rectifier. This current distribution also confirms that while the distributed geometry of the ground bed, namely, a mesh spread over the entire deck, appears intuitively correct, it did not help to achieve uniform current distribution. The CP current, mapped with magnetometer sensors over the entire deck of the bridge, shows that more than 60% of the area did not receive any current.

Visual observation made on the top and the bottom of the deck revealed a significant amount of cracks in the structure in the east and the southeast locations (Fig. 7). Figure 6 shows that these regions received little or no CP current. The northwest locations that received significantly larger currents showed no evidence of cracking. It is possible that in the east and the southeast locations, the rebars are corroding because of a lack of cathodic current. Direct confirmation of the corrosion of the rebars through visual inspection is yet to be obtained. If the rebars are indeed corroding, that could be causing spalling and cracking of the concrete.

DISCUSSION

The key to success in cathodic protection is the ability to achieve uniform distribution of current over the entire metal/electrolyte interface. Generally, it is easy to achieve such uniformities under the controlled conditions of a laboratory, using relatively simple electrode geometry. However, CP under field conditions is difficult to achieve, as indicated by the several reports mentioned earlier on the corrosion status of over 350 bridges in North America currently under CP.[4–11] The reasons for the failure of CP in these bridges, and by extension, future bridges, should be critically evaluated in terms of the uniformity of distribution of the CP current, the design of the ground bed vs. rebar geometry and the locations of electrical contacts, and the effects of the environment and climate on the distribution of the CP current.

We have demonstrated that a uniformly distributed ground bed spread over the entire deck does not ensure uniform distribution of the CP current. We used a magnetometer to map the CP current on an in-service

Figure 7. Cracks found on the bridge in Fig. 4. Regions of low CP current in Fig. 6 can be matched with locations of cracks on the bridge deck.

bridge in Maryland. In this case, the nonuniformity in the current distribution appears to be due to the improper choice of locations for the electrical contacts. This observation is in complete agreement with the results of an FEM analysis of a rectangular concrete block, which is similar to the deck of the Maryland bridge. By extension, it is possible to optimize and design the electrode configurations for the entire structure through the use of FEM.

To ensure proper CP, the design of a CP system should include not only electrode geometric parameters, but also the spatial and temporal effects of microenvironmental and microclimatic factors that affect the cathodic reaction. For example, temperature, humidity, wetness, oxygen and chloride concentration, and pH all affect CP currents and should be considered in the design, maintenance, and management of CP systems. The performance of optimized CP systems can be verified by mapping the CP current with magnetic sensors.

The same sensors can also be used to monitor system performance on a continuous basis. Thus, future CP systems should incorporate sensor-based feedback systems that use microprocessor-controlled rectifiers, which we call "expert" CP systems. The use of sensors to manage CP systems in concrete structures is now beginning to emerge.[14,15] Earlier designs used potential-measuring sensors, such as reference half-cells, to monitor the level of electrochemical potential drop across the rebar/concrete interface. In practice, these sensors can only be kept at a finite distance from the interface; hence, a large resistive drop due to the resistance of the concrete is always included as part of the measured potential.[13] This condition has posed serious limitations on both monitoring and maintaining appropriate levels of CP for the rebars. Besides, using potential to monitor CP systems requires measurements to be made at short intervals, i.e., 4 ft or less.[16] This situation could mean installation of virtually hundreds of reference electrodes, especially for large structures such as bridges. In contrast, monitoring the current does not involve errors from resistive drops, and only a very few sensors are needed to monitor CP. Using magnetometers means that effective feedback controls can be developed to design expert CP systems.

SUMMARY

An electrochemical engineering approach to optimizing the design of CP systems for steel rebars in concrete structures has been demonstrated. The limitations of the conventional approach in implementing CP systems in concrete structures was demonstrated by mapping the CP current on an in-service bridge in Maryland. The distribution of the current was found to be highly localized, leaving most portions of the bridge unprotected from corrosion. The nonuniformity in the distribution of the current appeared to be associated with the electrical design of the CP system. This explanation was confirmed by an FEM-based numerical simulation of a concrete block representative of the bridge deck.

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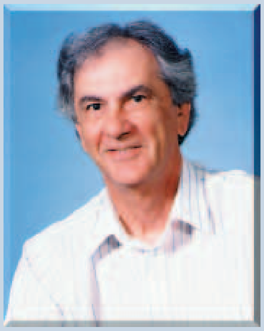

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