CORROSION MANAGEMENT SERIES

Guide to Corrosion Management of REINFORCED CONCRETE STRUCTURES

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Guide to Corrosion Management of Reinforced Concrete Structures

1440 South Creek Drive
Houston, Texas 77084

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Sohanghpurwala, Ali Akbar.
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NACE International
1440 South Creek Drive
Houston, Texas 77084
http://www.nace.org

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Foreword

Considering the capital that bridge owners must invest to build their structures, it is imperative they make the structures last as long as possible. In the past few decades, the desired service life of bridge structures has increased from 50 years to 100 years. To preserve structures for that long, a concerted maintenance and repair program must be in place. All components of a bridge structure deteriorate and require maintenance and repair; however, corrosion of reinforcement is one of the most important and costly problems for which most bridge owners do not have a fully developed management system. Therefore, this guide was developed to assist bridge owners in understanding the basic requirements for managing corrosion of reinforced concrete elements. It is not intended to provide step-by-step instructions for managing corrosion; instead it provides an outline and identifies the essential components for a corrosion management program. Owners can develop their own programs based on their needs and the resources available to them.

The primary goal of this guide is to encourage bridge owners to implement a well-planned effort to control corrosion rather than perform necessary repairs after a structure has suffered critical damage and cannot be ignored any longer. It is understood that most bridge owners do not have the resources to allocate to a corrosion management program; however, not implementing a well-planned program for managing corrosion will result in a greater strain on the owners' resources as their structures age and reach the critical damage stage. To maximize service life and to minimize preservation costs, bridge owners need to change their modus operandi from responding to damage to preventing the damage.

To properly implement a corrosion control program, bridge owners need to acquire skill sets in this subject area. Without trained, experienced, and knowledgeable personnel it is not possible to implement such a program.

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CHAPTER 1

Introduction

Reinforced concrete is the material of choice for construction of the majority of highway bridge structures in the United States. This is evident in the records of the National Bridge Inventory (NBI) database maintained by the Federal Highway Administration (FHWA),[1] an agency of the U.S. government. This database is a compilation of records submitted to FHWA by all State Departments of Transportation (DOTs) for bridges located on public roads in the U.S. In 2009, this database had records of 586,000 bridges existing on public roads in the U.S. Of these, 235,000 are listed as reinforced concrete structures, and another 108,000 are identified as prestressed concrete structures. Thus, 59% of bridge structures in the database are reinforced concrete structures. The remaining 41% of the structures may not be listed as reinforced concrete or prestressed concrete; however, many are likely to contain one or more reinforced concrete elements.

Concrete is a very durable material; however, its durability is compromised by corrosion of reinforcement in certain environments or exposure conditions. Corrosion of conventional reinforcement results in cracking, delamination, and spalling of the cover concrete, and in extreme cases can result in significant loss of reinforcement cross-section, as is apparent in Figure 1. This degradation has an impact on the operation of the structure and/or results in the reduction of overall structural integrity. Consequences of corrosion on a stressed (both pre- and post-tensioned) reinforcement are far more severe and can result in the failure of the stressed high-strength steel element. Failure of a critical number of stressed elements can result in failure of that bridge element.

FIGURE 1 Loss of Cross-Section of Reinforcement as a Result of Corrosion

Corrosion of reinforcement significantly increases the cost of bridge preservation. With the limited availability of maintenance and preservation funds, controlling corrosion has become a top priority for many bridge owners. In addition, corrosion of the reinforcement can result in catastrophic failures, with accompanying loss of human life and significant impact on the local economy.

Several catastrophic bridge failures have occurred as a result of corrosion of metallic members of bridges that are classified as reinforced concrete bridges. The most tragic incident was the failure of the Silver Bridge over the Ohio River in 1967, when a total of 46 people died. This prompted President Lyndon B. Johnson's administration to mandate regular bridge inspections and the development of the NBI database. The death of a motorist resulting from the failure of the Anclote River Bridge in Pinellas County, Florida, in 1968 led the Florida Department of Transportation (FDOT) to start a corrosion group to preserve bridges in that state. In 1983, a 100 ft (30 m) section of the Mianus River Bridge in Connecticut collapsed, killing three people.

There are several cases of catastrophic failures of bridge structures in other parts of the world from corrosion of stressed reinforcement, both pre-stressed and post-tensioned. The first known failure occurred in 1967; the Brickton Meadows Foot Bridge collapsed in Hampshire, U.K., because of corrosion of post-tensioned tendons. Corrosion of post-tensioning also resulted in the failures of the Ynys-y-Gwas Bridge located in Wales in 1985 and the Malle Bridge in Belgium in 1992. Similarly, corrosion of prestressing strands resulted in the collapse of a five-year-old Lowe's Motor Speedway Bridge in Charlotte, North Carolina, in 2000. Figure 2 displays a photograph of the failed bridge. A 45-year-old overpass on Interstate 70 (I-70) located in Washington County, Pennsylvania, failed in 2005, as shown in Figure 3.

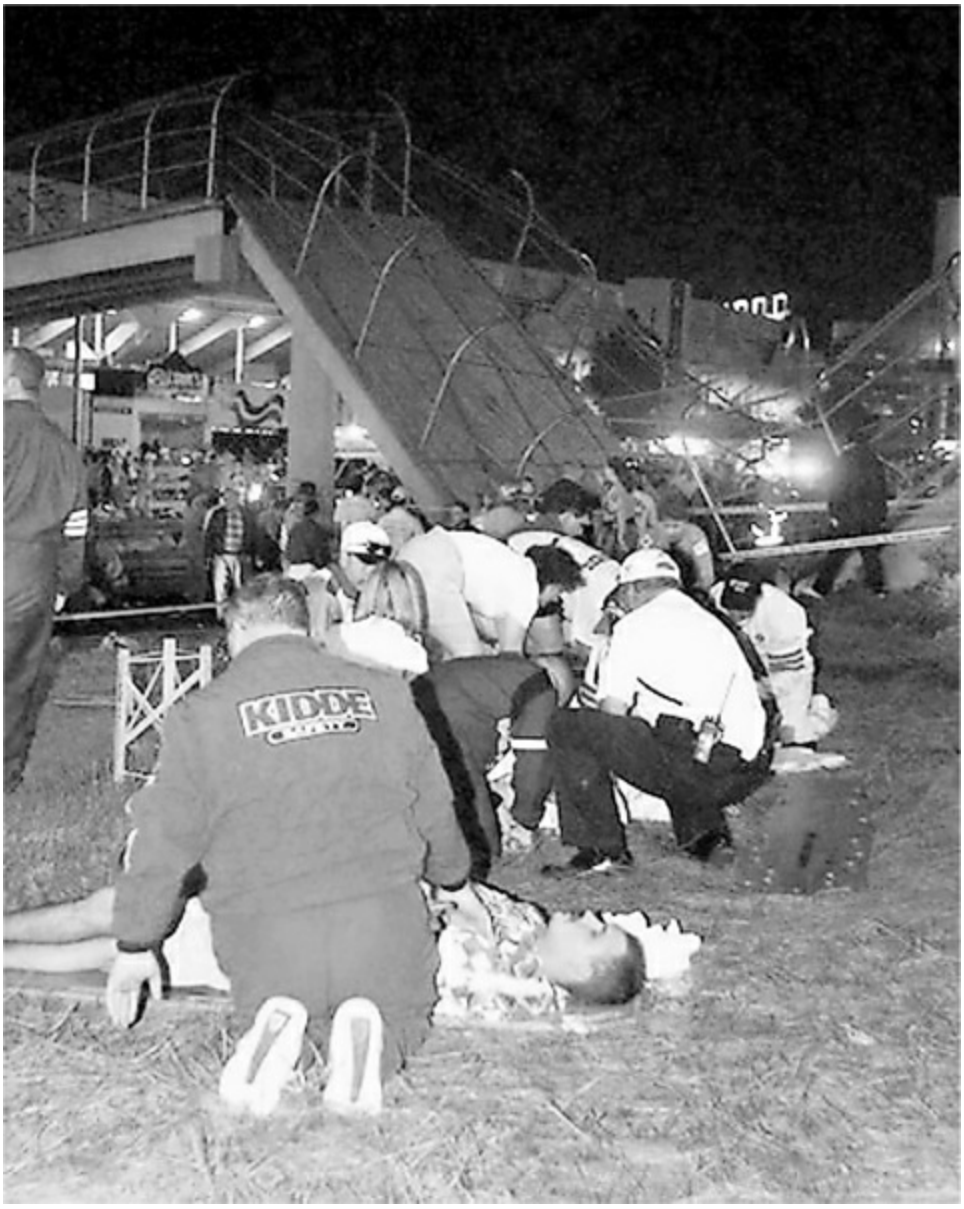

FIGURE 2 Lowe's Motor Speedway Collapse

These failures prompted many bridge owners to ascertain the condition of their post-tensioned structures. The state of Florida, one of the leading states in the construction of post-tensioned bridges, especially segmental concrete bridges, surveyed all of their post-tensioned bridge elements. Failed tendons were discovered on the Niles Channel Bridge near Key West and the Midway Bridge in Destin. On the Midway Bridge, two of the three tendons on one side of the segmental box girder had failed. Two failed tendons were also observed in the hollow columns of the Sunshine Skyway Bridge in Tampa.

FIGURE 3 Collapse of I-70 Overpass as a Result of Prestressing Cable Corrosion

Generally, corrosion of conventional reinforcement provides sufficient early warning to allow remediation measures to be implemented. For example, the superstructure of the historic Jefferson Street Bridge in Fairmont, West Virginia, shown in Figure 4, had developed significant corrosion-induced damage. Although the reduction in operating capacity and the resulting danger posed to the driving public is clearly observable, it was not expected to catastrophically fail. However, rehabilitation cost approximately $25 million.

Several cost analyses have been performed to estimate the cost of corrosion. In a 1986 report the National Cooperative Highway Research Program (NCHRP)[(2)] estimated that the unfunded liability to correct corrosion-induced distress in bridges in the United States was $20 billion and was increasing by about $500 million annually.[1] The U.S. Secretary of Transportation's report in 1982 estimated there were nearly 213,000 deteriorating bridges alone with a repair cost of $41.1 billion, with corrosion being the primary cause of the deterioration.[2] A recent cost-of-corrosion study determined that the annual cost of corrosion to all bridges is $8.29 billion, and the indirect cost to the user resulting from traffic delays and lost productivity can be more than 10 times the direct cost of corrosion. This study also estimated that of the $8.29 billion, $3.8 billion are for the annual cost to replace structurally deficient bridges over the next 10 years, plus $2.0 billion for maintenance and the capital cost of concrete bridge decks, and $2.0 billion for maintenance and capital cost of substructure elements.[3]

FIGURE 4 Corrosion-Induced Damage on Bridge Deck

Conventional reinforcing steel in concrete does not corrode unless the protection afforded by the high alkalinity of the concrete pore solution is compromised by chloride ions or carbonation. In North America, this primarily results from exposure to chloride ions from deicing salt and/or the marine environment. When the chloride ion concentration at the steel-concrete interface exceeds the threshold, corrosion is initiated. The time—from construction— required to initiate corrosion is termed *time to initiation*. Once corrosion is initiated, corrosion products are formed. The products of the corrosion process (iron oxides, such as rust) occupy a greater volume than the original steel.[4,5] The expansive productsubstructure elements of the corrosion process generate tensile stresses in the concrete. Because the tensile capacity of concrete is relatively limited, these stresses result in cracking, delamination, and eventually spalling. The time from corrosion initiation to formation of delamination is referred to as the *time to propagation*. The reinforcing continues to corrode even after the delamination has occurred and with time can incur sufficient cross-section loss to adversely affect the overall integrity of the element.

Factors that affect the initiation of corrosion on prestressing embedded in concrete are very similar to those of conventional reinforcement. The type of corrosion most likely to occur on prestressed tendon, however, is somewhat different. Pitting corrosion and environmentally induced cracking are more likely to occur rather than the general corrosion normally observed on conventional steel. Pitting corrosion can result in localized loss of cross-section, which results in a stress riser at that location. This can subsequently result in the failure of the wire and ultimately the tendon. Pitting corrosion can also generate hydrogen, which, when absorbed by the high-strength steel, can result in hydrogen embrittlement (HE). Environmentally induced cracking can result either from stress corrosion or HE and can result in the failure of the wire and eventually the tendon or cable. Corrosion of prestressed reinforcement has a more immediate and a greater impact on the structural integrity of the concrete element than that of conventional reinforcement.

In addition to the presence of chloride ions and lower pH, corrosion initiation on bonded post-tensioned tendons occurs because of voids in grouts where water and oxygen can collect, contact with dissimilar metals can occur, and excessive bleed water can be present. Corrosion on un-bonded

tendons results from inadequate or damaged sheathing where the tendon is exposed to a corrosive environment and/or contact with dissimilar metals is made. Pitting and environmentally induced cracking are most likely to occur on post-tensioned elements, which can result in the failure of the element. Failure of a post-tensioning tendon can result in a significant reduction of structural integrity of the concrete element.

All bridge components, from decks to footings, are susceptible to corrosion of the reinforcement. In the deicing salt environment, the deck, the superstructure, and the substructure are exposed to high levels of chloride ions, depending on the configuration of the structure. The deck is usually (depending on geography, traffic, volume, etc.) treated with deicing salt and has a direct exposure to chloride ions. Some of this salt may wash out through defective expansion joints onto the superstructure and contaminate it. The runoff can also contaminate the substructure elements. For structures that have a roadway under the bridge, the deicing of that roadway exposes the substructure elements adjacent to it.

In the marine environment, the substructure elements are directly exposed to salt water. Splashing of salt water against the reinforced concrete elements located in the splash zone introduces high concentrations of chloride ions into the concrete. The splash zone exposure is very severe, and in warmer climates such as that of Florida, without a *corrosion management program*, repairs are required approximately 12 years after new construction. Reinforced concrete elements located above the splash zone are exposed to airborne chloride ions. The airborne chloride ion exposure is generally less severe than the splash zone exposure; however, under the right circumstances this exposure can result in corrosion-induced damage in a relatively short time.

In a recent survey of 36 state and provincial Departments of Transportation (DOTs) in the United States and Canada, only one state DOT indicated that corrosion of metallic reinforcement in concrete was not a problem.[6] Of the remaining 35 agencies, 4, 23, and 8 rated their corrosion problem to be minor, moderate, or major, respectively. The survey also reported that of the 36 responding agencies, 21 had more than 70% of their bridge decks exposed to deicing salts, and 13 had all bridges exposed to deicing salts. One Canadian Province, Prince Edward Island, categorized all of its bridges in the deicing salt and marine exposure. When reporting on substructure elements, 6 of the 13 agencies that indicated that all their bridge decks were exposed to deicing salts also indicated that all of their substructures were exposed to deicing salts. This suggests the problem of corrosion is more severe than generally perceived by bridge owners.

Corrosion Management Program

Corrosion is one of the primary deterioration mechanisms that limits the service life of a reinforced concrete bridge structure. Because many bridge owners are now requiring bridges to be designed or rehabilitated to achieve a 100-year service life, a strategy to control corrosion and its impact is required. There are essentially two ways to deal with the corrosion problem. One is to have a corrosion management program, and the other is to respond to corrosion-induced damage when it reaches a critical level. Because of a lack of available resources, most owners resort to the latter. Even when they respond to the damage induced by corrosion, the repair or rehabilitation programs do not include any corrosion mitigation strategies or control systems; therefore, a cycle of corrosion-induced damage and repairs continues until the structure is replaced. The majority of the cost of a repair or rehabilitation is allocated to removal and replacement of damaged concrete. In addition, minimizing concrete repairs also reduces the carbon footprint of the construction. Therefore, if a