

Fundamental Study of Corrosion of Prestressing Strands in Concrete Case Study: Collapse of the Lake View Drive Bridge over Interstate 70

Rilya Rumbayan, Geertje E. Kandiyoh

(Staf Pengajar Teknik Sipil Politeknik Negeri Manado)

Abstract; The Lake View Drive Bridge over Interstate-70 in Washington, Pennsylvania is a precast, prestressed concrete adjacent box-girder bridge. On December 27, 2005, the fascia girder of the 45 year old the Lake View Drive Bridge suddenly collapsed, resulting in minor injuries to three motorists on I-70 below. Bridge inspections of the bridge had been conducted on a biennial basis, with the most recent inspection being conducted in August, 2004. Some deterioration and corrosion of the prestressing strands and surrounding concrete was identified during the inspection, but the bridge remained opened. The corrosion and rupture of the prestressing stands was found to be the cause of the collapse. **The goals of this paper are** (1) to describe collapse of the Lake View Drive Bridge over Interstate 70 caused by corrosion of the prestressing strands, (2) to study the mechanisms of corrosion of steel in concrete, and (3) to introduce some engineering techniques to protect corrosion.

Keywords; *corrosion, prestressing strand, reinforcing steel, and concrete bridge.*

Abstrak; Jembatan Lake View yang terletak di atas jalan Interstate-70 di Washington, Pennsylvania adalah jembatan beton prategang pracetak yang terdiri dari balok-balok penopang utama yang berbentuk kotak berongga. Pada tanggal 27 Desember 2005, balok utama dari jembatan Lake View Drive Bridge yang berusia 45 tahun tiba-tiba runtuh dan mengakibatkan luka ringan bagi tiga pengendara pada Interstate-70. Pemeriksaan struktur jembatan ini telah dilakukan setiap dua tahun, dengan pemeriksaan terbaru yang dilakukan pada bulan Agustus, 2004. Beberapa kerusakan dan korosi dari kabel *strands* pratekan dan beton sekitarnya telah diidentifikasi selama pemeriksaan, namun jembatan tetap dibuka. Korosi dari kabel *strands* pratekan ditemukan menjadi penyebab keruntuhan. Tujuan dari tulisan ini adalah (1) untuk mendeskripsikan runtuhnya Jembatan Lake View yang disebabkan oleh korosi dari kabel *strands* pratekan, (2) untuk mempelajari mekanisme korosi baja pada beton, dan (3) untuk memperkenalkan beberapa teknik rekayasa untuk perlindungan terhadap korosi.

Kata-kata Kunci; korosi, kabel strand, baja tulangan, dan jembatan beton.

INTRODUCTION

Noncomposite adjacent precast prestressed concrete box beam bridge systems are a popular form of construction in the United States. These types of bridge designs started in the 1950's and continue today. The precast box girders have vertical shear keys in the webs intended to transfer force between adjacent girders. The box girders are typically post-tensioned with lateral ties that are fully grouted during assembly. An asphalt wearing surface is placed on the adjacent box girder bridge system. This type of bridge design is popular because it lends itself to a quick construction time, with most of the fabrication done offsite. As of 2007, over 19,000 adjacent box girder bridges were in service in the United States, with 3,291 in Pennsylvania (PA) [1].

Degradation problems have arose with the adjacent precast concrete box girder bridges due to the age, detailing practice, and heavy damage to the box girders and lateral tie

system of the first generation of these bridges. Inspections in 2007 indicated 590 adjacent box girder bridges to be structurally deficient in Pennsylvania alone. These inspections have indicated longitudinal cracking of the bottom flange, corrosion and fracture of prestressing strands, spalling, efflorescence, and leakage between beams. These problems potentially lower the dead load (asphalt wearing surface and structural dead load) and service live loads (truck and vehicles) that an adjacent box girder bridge can withstand without being overstressed.

THE TIMELINE OF THE LAKEVIEW DRIVE BRIDGE

The Lake View Drive Bridge was built in 1960 and is a four span adjacent precast, prestressed concrete box girder overpass bridge that crosses I-70 in Washington, PA. The bridge has eight precast concrete box girders supported on two abutments and three piers, with pier 1 and 3 on either side of the four lane I-70 roadway and pier 2 in the median of I-70 as shown in Figure 1. The span lengths vary between 53ft 10 ½ in. to 88ft 9 ¾ in. and 88ft 9 ¾ in. to 42 ft. 1 ½ in.

The bridge was designed in accordance with the 1953 Standard Specifications for Highway Bridges [2]. The girders were fabricated with Grade 250 prestressing steel strands. Each precast concrete box girder span had 60 prestressed 3/8 in. 7-wire strand reinforcement in the bottom flange of the box girder as shown in Figure 2. The eight bridge girders were connected together with transverse posttensioning, utilizing 2 ¼ in. lateral rods (Figure 2). The posttensioning had to be staggered along each span to accommodate the 39 degree skew that existed in the bridge. The posttensioning with lateral rods or other reinforcement between prestressed concrete box girders is what makes this bridge a concrete adjacent box-girder bridge [2].

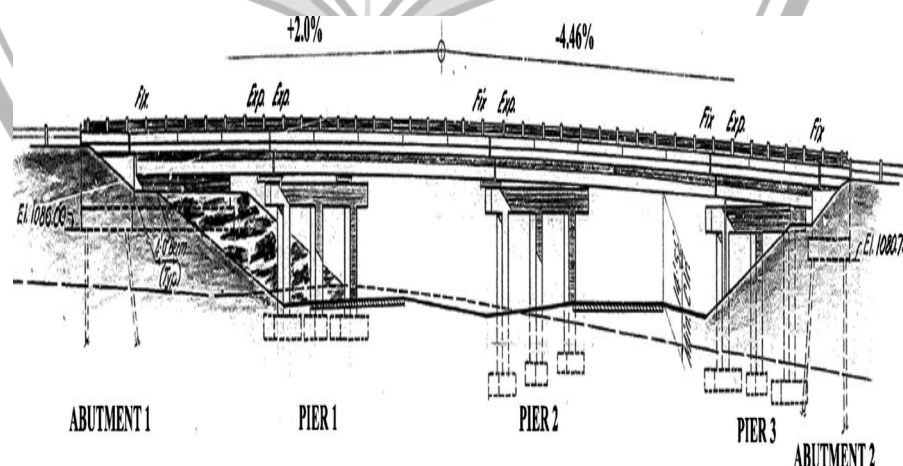


FIGURE 1 Bridge side elevation [3].

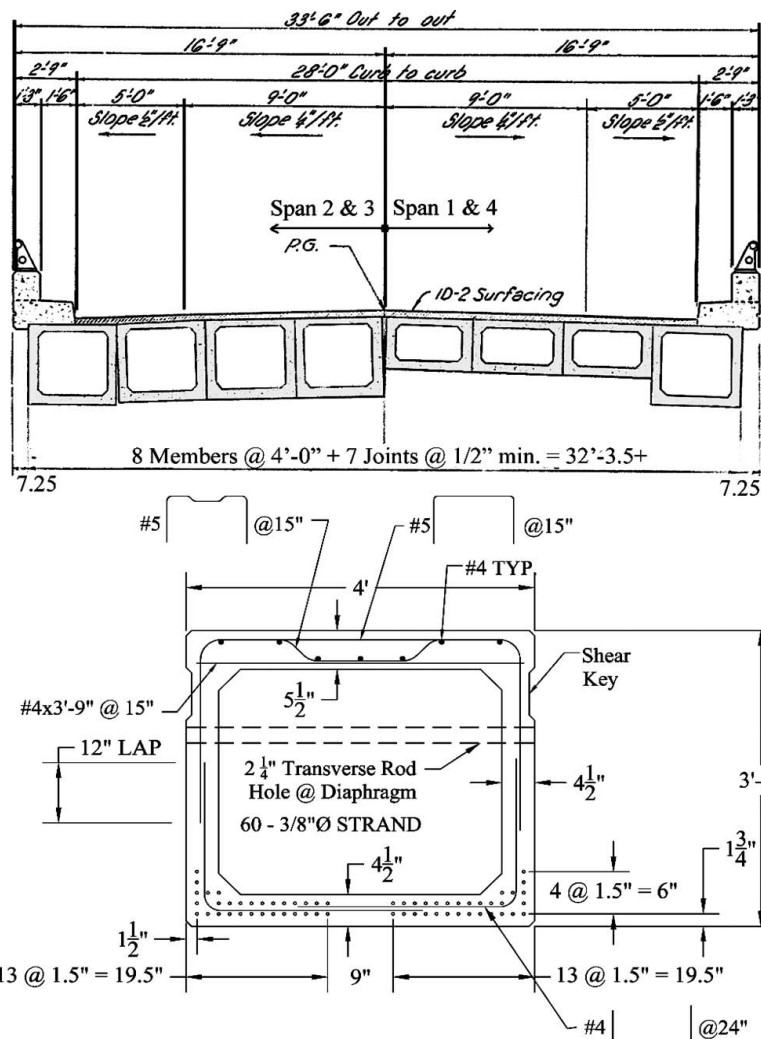


FIGURE 2 Box beam section, Span 2 and 3 [2].

In March 2004, Pennsylvania Department of Transportation (PennDOT) inspected the Lake View Drive Bridge in detail, and it was visually inspected again in August 2004. Those inspections of the bridge conducted in accordance with the PennDOT Bridge Safety Inspection Manual prior to the failure indicated that an impact to the beam may have occurred. From the visual inspection, it was noted that 20 of the 60 prestressing strands in the beam were corroded and fractured. The superstructure rating was based on the widespread condition of the bridge beams as opposed to an assessment of an individual member of the superstructure. Since only one member was heavily damaged and the remaining beam members were moderately damaged the superstructure was rated as poor, a value of 4 on a 0–9 scale, placing them in the structurally deficient category. The damage was clearly described and illustrated and beam replacement was recommended as a priority [3].

On Tuesday, December 27, 2005 around 6:00 PM, the Lake View Drive Bridge par-

tially collapsed onto the highway below, which is Interstate 70. The collapsed portion consisted of Beam 1 in Span 3 over the eastbound lanes of I-70, which is the north elevation fascia beam. The reinforced concrete bridge parapet and metal railing of Span 3 also fell with the beam, as shown in Figure 3 [2]. One vehicle carrying a driver and two passengers traveling on the highway below struck the collapsed bridge. However, the injuries sustained by the motorist did were minor in nature and did not require additional hospitalization after being taken to the emergency room for examinations.



FIGURE 3 Span 3 failure from the Lake View Drive Bridge [2].

In 2006, post-collapse inspection of the remaining beam by Michael Baker Inc. (Hartle 2006) revealed that in fact 39 of the 60 prestressing strands had exhibited corrosion related failure of individual wires or strands. Post-collapse inspection also revealed heavy spalling and corrosion of the strands on the bottom flange of the failed concrete box beam. This corrosion of the prestressing strands lead to the fracture of the strands and failure of Span 3 of the Lake View Drive Bridge. Similar damage was noted on the adjacent members and spans. As a safety precaution, the bridge was decommissioned and a number of beams were saved for forensic investigation and load testing. The bridge was repaired and reopened 6 months later.

TESTING AND RESPONSE TO THE COLLAPSE

In response to the collapse, PennDOT initiated and sponsored testing on the Lake View Drive Bridge. Dr. Kent Harries lead the investigation, which sought to further understand the mechanisms for collapse to prevent similar happenings. Dr. Harries, Assistant Professor, and his colleagues in the Civil and Environmental Department at

the University of Pittsburg conducted the testing of the girders. Two girders were selected for study: the girder directly adjacent to the failed exterior girder, called the interior girder, and the furthest-most girder, directly opposite the failed girder, called the exterior girder [2].

The girders were tested until failure over a smaller span (84ft 2 in.) than the original bridge (88ft 10 in.). The load was induced by two frames placed 48 in apart across the midspan through four hydraulic cylinders, with two cylinders per frame. Loads were applied in cycles, with the interior girder being irreparably damaged at 41 kips, and the exterior girder having significant cracks and rupture of the prestressing strands at 60 kips [2].

Based on this testing, as well as detailed visual inspection, PennDOT developed a new, more detailed protocol for prestressed concrete box beam bridges. A moratorium was placed on new construction of certain types of prestressed concrete box beam bridges until more capable inspection technologies were developed. PennDOT developed and released detailed guidelines for rating existing bridges. The Department also adjusted rating protocol on box girder bridges so that the condition of a bridge is rated in respect to its weakest member. Thus, if one member is noted to be structurally deficient, the whole bridge is considered to be as structurally deficient [3].

CORROSION OF REINFORCING STEELS IN CONCRETE

Corrosion of steel in concrete is a relevant topic to the bridge engineer, as made evident in part by the Lake View Drive collapse. Some corroded members of the Lake View Drive Bridge were said to either be reduced in diameter or be lost entirely [5]. This loss is critically important to the overall strength of the bridge, because the prestressed strands are intended to provide compression and to reduce cracking in the concrete. Thus, to fully appreciate the mechanisms of the Lake View Drive collapse, it is necessary to understand the mechanisms of corrosion of steel in concrete [6] including electrochemical process, protective layer provided by concrete, rate of corrosion, carbonation, chloride and diffusion process, corrosion of prestressed steels, and protecting steel from corrosion.

Mechanical Properties

The corrosion process is important to the engineer, because many relevant physical properties are associated with corrosion, including an increase in volume and a de-

crease in strength. Corroded steel can grow in volume as much as 6x its original volume [7]. This increase in volume can result in cracking and spalling of the concrete, further exposing the metal to air and water, thus accelerating the corrosion process [7]. Corrosion is detrimental to a reduction in the cross-section area in prestressing steel due to general or pitting corrosion. In a cross-sectional area with partial corrosion, the corroded area contributes increasing the net stress in prestressing and possibly leading to local yielding and fracture [6, 9]. For instance, in the report of the Lake View Drive Bridge collapse by Naito et al. [6], prestressed strands were categorized by cross-sectional area lost due to corrosion. The corroded strands were categorized as: minimal, minimal to 20%, above 20%, and entirely corroded (or entirely lost).

Rate of Corrosion

The rate of corrosion of steel is governed by the current which results from rate of release of electrons from the iron. The rate is modeled by an equation called Faraday's Law which states:

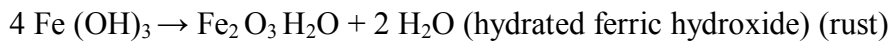
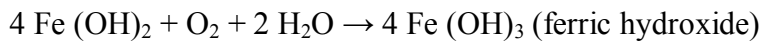
$$\frac{M}{t} = \frac{IA_w}{nF}$$

where M is the mass of the material corroded, t is time, I is current, A_w is the atomic weight, n is the valency, and F is Faraday's constant (96,500 C/m). Note that the rate of corrosion is directly proportional to current (or rate of electrons released from the iron) and atomic weight. For steel, the rate of corrosion, after M is divided by the density of steel, is calculated to be = 11.8 $\mu\text{m}/\text{yr}$ [8]. In concrete, the release of electrons from the iron, which is the current that affects the rate of corrosion, can be influenced by several factors such as heterogeneity of the steel and concrete, pH of the concrete pore water, and stray currents.

Electrochemical Process

Corrosion is primarily an electrochemical process which typically occurs in the presence of air and water. When an iron atom comes in contact with water, it is stripped from two of its electrons: $\text{Fe} \rightarrow \text{Fe}^{2+} + 2 \text{e}^-$. These two electrons freely travel across the conductor, but if water and oxygen are present along the steel, they will combine to create hydroxide: $\text{O}_2 + 4 \text{e}^- + 2 \text{H}_2\text{O} \rightarrow 4 \text{OH}^-$. These two equations are the most noteworthy to the engineer, because they show the necessary constituents which lead to corrosion. However, corrosion proceeds when hydroxide recombines with the positively

charged iron:



This set of reactions, set on simply by the presence of iron, water and oxygen, is one electrochemical example of how rust is formed. However, this is not the only way that rust developed. Many other acidic elements can corrode steel. For example, salt (chloride) used in icy conditions on roadways accelerates corrosion of prestressed strands in box girder bridges.

Prestressed Steels

A loss of area due to corrosion is a particularly noteworthy issue in prestressed steels. First, these prestressed steels utilize a significant amount of their ultimate tensile strength (55% - 65%). A relatively small loss in cross-sectional will critically diminish the member's factor of safety. Furthermore, this cross-sectional loss due to corrosion is more rapid in prestressed strands. Strands are not made of a continuous piece of metal, but rather six supporting strands wrapped around a central, straight strand. Thus, the surface area of the prestressed strand bundle exposed to corrosion is higher than the surface area of a single bar. Consequently, corrosion rates are higher in prestressed steels than in single bars [9].

Protective Layer

Because metals corrode in acidic environments, a metal can be protected by an alkaline film which neutralizes the pH level. Such is the case with steel in concrete. Concrete pores contain elements such as calcium, sodium and potassium, which form alkaline hydroxides when water is present. The pH of this environment is between 12 and 13 [7]. However, this protective layer is not indestructible. Bridge engineers are able to plan accordingly, but if the lifetime of the bridge is miscalculated, or the weather brings unforeseen rain and snow, the protective layer will not withstand the ingress of acidic elements [8]. The success of corrosion protection is primarily a function of strengthening and sustaining this protective layer.

Corrosion by Carbonation

Carbonation is the general term given to the neutralization of concrete by reaction be-

tween the alkaline components of the cement paste and carbon dioxide (CO₂) in the atmosphere. Carbonation generally proceeds in the concrete as a front, beyond which the concrete not effected, but when the carbonation front reaches the steel, general de-passivation over large area or over the whole steel surface can occur and general corrosion can be initiated.

Carbonation has important effects on corrosion of embedded steel. The first consequence is that the pH of the pore solution drops from its normal values of pH 13 to 14, to values approaching neutrality (pH 8 to 9). A second consequence of carbonation is that chloride bound in the form of calcium chloroaluminate hydrates and otherwise bound to hydrated phases may be liberated, making the pore solution even more aggressive [7].

A carbonation front proceeds into the concrete roughly following diffusion phenomena. The rate of progress of carbonation is given by the equation:

$$d = At^n$$

where d is carbonation depth in mm, A is a carbonation coefficient, t is time in the years and n is an exponent, usually ½. This is a simple derivation of the Fick's laws of diffusion that says the rate of diffusion is proportional to the thickness being diffused through:

$$\frac{dx}{dt} = \frac{1}{kx}$$

where x is thickness, t is time.

The carbonation coefficient can be assumed as the measure of the rate of penetration of carbonation for given concrete and environmental conditions. The rate of carbonation depends on both environmental factor (humidity, temperature, concentration of carbon dioxide) and factor related to the concrete (alkalinity and permeability) [7]. The ingress of gases is higher at low relative humidity, but the reaction between the gas and the cement paste takes place in solution and is higher at high humidity. Therefore, the most aggressive environment for concrete neutralization will be that of alternate wet and dry cycles and high temperature [8]. The carbonation rate is a function of cover thickness, so good cover is essential to resist carbonation. A high cement content provides a good reserve of alkali to protect against possible carbonation. The diffusion process is made easier if the concrete has an open pore structure. On the macroscopic scale this means that there should be good compaction. On a microscopic scale well cured concrete has small pores and lower connectivity of pores so the CO₂ has a harder job moving through the concrete. Microsilica and other additives can block pores or

reduce pores sizes [7].

Corrosion by Chlorides

This section discusses the role of chlorides in the corrosion process. The source of chlorides may be admixtures, contaminants, marine environments, industrial brine, or deicing salts. The use of calcium chloride (CaCl_2) as a set accelerator for concrete has been the most common source of intentionally added chlorides. Chlorides added to the mixture as accelerator for concrete have three additional effects on subsequent corrosion rates. First, it has been shown that the accelerating effect of the chlorides results in a coarser capillary pore-size distribution at a constant water-cement ratio (w/c), which allows faster ingress of additional chlorides, faster carbonation rates, and also reduces the resistivity of the concrete. Second, the chlorides increase the ionic concentration of the pore solution and its electrical conductivity. Both of these factors lead to an increase in the corrosion rate. Third, the chlorides alter the pH of the concrete pore solution, sodium chloride (NaCl) and potassium chloride (KCl) increase the pH whereas CaCl_2 , in high concentrations, reduces the pH.

Chloride also has been added in the concrete mixing water, aggregates (for instance by using sea sand and gravel without washing them with chloride-free water). The other main source of chloride in concrete is penetration from the environment. This occurs, for instance, in marine environments or in road structures in regions where chloride bearing deicing salts are used in wintertime.

The Diffusion of Chlorides

The transport mechanism of chloride is following the laws of diffusion

$$\frac{d[\text{Cl}^-]}{dt} = D_o \frac{d^2[\text{Cl}^-]}{dx^2}$$

where $[\text{Cl}^-]$ is the chloride concentration at depth x at time t . and D_o is the diffusion coefficient (usually of the order $10^{-10} \text{ m}^2/\text{sec}$) [7]. By using the parabolic approximation developed by Poulsen, the solution can be simplified using

$$C_{(x,t)} = C_i + (C_s - C_i) \text{erfc} \left[x / (4tD_o)^{1/2} \right]$$

where $C_{(x,t)}$ is the chloride concentration at time t and depth x , C_i is the initial chloride concentration, C_s is the surface chloride concentration and $\text{erf} ()$ is the error function of the value of the argument in brackets. The rate of diffusion depends strongly on a number of factors, including the water cement ratio, type of cement, temperature, and

maturity of the concrete [7].

In chloride environment, the initiation of corrosion occurs only when the chloride content is higher than the chloride threshold value. The consequence of chloride ions in the corrosion of steel in concrete has led to the concept of a chloride threshold level (CTL). The CTL can be defined as the content of chloride at the steel depth that is necessary to sustain local passive film breakdown and hence initiate the corrosion process [12]. It is usually obtained as the ratio of chloride to hydroxyl ions, the free chloride content or the percentage of the total chloride content relative to the weight of cement.

Assessment of the CTL is important in predicting the service life of structures exposed to chlorides. One possible definition of the service life is the time required for transport processes to increase the chloride level at the depth of the steel to the CTL. The measurement of CTL performed by using a synthetic concrete solution with a $[Cl^-]:[OH^-]$ ratio of 0.6. The relationship between chloride and hydroxyl ions is described by the equation

$$pH = n \log [Cl^-] + K$$

where n and K are constants. This implies that the ratio $[Cl^-]:[OH^-]$ represents a constant with n is 0.8 for corrosion prevention. The ratio of $[Cl^-]:[OH^-]$ has been considered functional, because it reflects the corrosion risk that is induced by either chloride alone, or carbonation and chloride in combination [12].

To measure the CTL, the time of initial of corrosion and the chloride content at the steel depth must be identified. The initial of corrosion can be detected by monitoring the macrocell current between an anode and a cathode, measuring half-cell potential or monitoring the corrosion rate measured by the polarization technique or AC impedance method [12].

Measurement of the chloride content or profile to determine the CTL is performed by adopting method for measuring total chloride content uses acid soluble extraction, in which it is assumed that both bound and free chlorides are soluble in acid. Measurement of acid soluble chloride (total chloride) may be made using a chloride ion sensitive electrode or by titration. X-ray fluorescence can also be used to determine the chloride content. The representation of the CTL by the total chloride level is the most widely used approach, and is the approach adopted in standards. Table 1 gives the chloride limits for concrete, expressed as a percentage by mass of cement, from each standard [12].

TABLE 1 Maximum chloride content values set by various ACI and BS documents [12]

Type	Maximum chloride content (% cement)			
	BS 8110	ACI 201	ACI 357	ACI 222
Prestressed concrete	0.10		0.06	0.08
Reinforced concrete exposed to chloride	0.20	0.10	0.10	0.20
Reinforced concrete that will be dry or protect from moisture in service	0.40			
Other reinforced concrete		0.15		

The representation of the CTL as the total chloride content as a percentage by weight of cement is the better representation of the CTL because (1) the inhibitive properties of cement matrix are reflected by its cement content and (2) the total aggressive potential of chloride ions is represented. The threshold value of 0.4% Cl^- by mass of cement proposed in Europe (approximately 1.4 kg/m^3 or 2.4 lb/yd^3 of concrete), however, is higher than the acid soluble chloride threshold value typically used in the United States, which is 0.6 to 0.9 kg/m^3 (1.0 to 1.5 lb/yd^3) of concrete [8].

Protecting Steel from Corrosion

Many options are available to avoid problems of steel corrosion in concrete, including applying coatings to the concrete (impermeable membranes), using corrosion-resistant reinforcing materials (stainless steels or non-metallic reinforcements), applying cathodic protection, or using coated reinforcement. Coated steel reinforcement particularly has been used widely in many areas. The two most common types are epoxies and galvanizing. Typically, coated reinforcements are used in bridges and highways. Fusion-bonded, epoxy-coated reinforcement was first used in 1973 in reinforced concrete bridge deck construction to fight the severe effects of deicing salts in North America. Fusion-bonded epoxy coating is containing pigments, thermosetting epoxy resins, crosslinking agents, and other additives, which is applied in the form of a powder onto a clean, heated metallic substrate and fuses to form a continuous barrier coating [8]. Epoxy coatings provide excellent corrosion protection to steel, and the coating is not consumed in performing its corrosion protection function. The coating has very low permeability to Cl^- , is highly chemically resistant, and is essentially unaffected in many environments. It protects the steel by isolating the metal completely from the local environment. Despite the excellent corrosion performance of epoxy-coated reinforcement in most situations, the effectiveness of epoxy coatings in very aggressive

environments has been questioned recently, primarily because the coating has naturally occurring holidays, which is discontinuity in a coating that is not visible to a person with normal or corrected vision, and may be damaged during transportation and fabrication. Consequently, a great deal of emphasis is placed on the careful handling and storage of epoxy-coated reinforcement to minimize abrasion and mechanical damage [10]. In addition, epoxy-coated reinforcement is smooth and concrete does not adhere well to its surface, bond strength develops primarily through mechanical bearing. Different studies have given different results, but most give values of 65 to 90% as the relative level of bond strength for epoxy-coated bar compared to black bar [10].

Galvanized reinforcement has been in use since the 1930s. Because the steel reinforcement is hot dipped into molten Zn at 460°C, galvanizing produces a metallurgically alloyed coating integrally bound to the steel substrate. The alloy layers are strong, resist mechanical damage, and afford sacrificial protection to the steel. Zn is passivated in concrete and can remain passivated to lower pH levels (as low as pH 9.5) than that which causes corrosion of black steel (pH < 11.5). Galvanizing thus offers substantial protection against the effects of carbonation in concrete. Galvanized reinforcement also can withstand exposure to Cl⁻ concentrations several times higher than that which causes corrosion of black steel in concrete [10].

CONCLUSION

The Lake View Drive Bridge was a four span adjacent precast, prestressed concrete box girder overpass bridge. The fascia girder that collapsed onto I-70 in Washington, PA on December 27, 2005 caused minor injuries to three motorists. The bridge was found to have extensive corrosion of prestressing strands in the bottom flange of the concrete box girders. This corrosion leads to the rupturing of the strands and collapse of the bridge onto I-70. Post-collapse inspection and testing was conducted to determine the cause of the collapse and to assist in development of new inspection protocol to be implemented. The failure of the Lake View Drive Bridge brought additional attention to the failure modes of pre-cast, prestressed concrete box girder bridges and the problems that corrosion of prestressing strands cause to these types of bridges.

The damage mode of corrosion process for steel in concrete was explored. The study included: (1) electrochemical process, (2) protective layer provided by concrete, (3) rate of corrosion, (4) carbonation, (5) chloride and diffusion process, (6) corrosion of prestressed steels, and (7) protecting steel from corrosion. Based on this study on cor-

rosion of steels in concrete, the following conclusions can be made:

The corrosion of steel in concrete is caused by two electrochemical reactions: (1) an anodic reaction, capable of producing electrons, and oxidizing iron and (2) a cathodic reaction, capable of consuming electrons.

In general, an appropriately made concrete is very alkaline and exhibits a high pH. As a result the electrochemical reaction typically results in the formation of iron oxides which form a protective layer around the steel.

The major mechanisms of steel corrosion in concrete are localized breakdown of the passive film on the steel by chloride ions and general breakdown of passivity by neutralization of concrete, predominantly by reaction with carbon dioxide, namely carbonation.

The steel in reinforced concrete structures is susceptible to corrosion when penetration of chloride at the surface of the steel exceeds a chloride threshold level (CTL).

The effect of corrosion of steel in concrete is an increase in volume that may be sufficient to causing cracking and spalling of the concrete cover. The magnitude and consequences of corrosion in prestressing steels are much more severe than in reinforcing steels.

Fusion-bonded epoxy coated reinforcement and galvanization have been used to protect the embedded steel in concrete from chloride or carbonation attack. However, defects at the steel-concrete interface (i.e. a reduction of bond between steel reinforcement and concrete), which may be attributed to hydrogen evolution or smooth surface of coating, restricts the use of fusion-bonded epoxy coated reinforcement in concrete structures.

REFERENCES

- Hanna, K. E. "Transverse post-tensioning design and detailing of precast, prestressed concrete adjacent-box-girder bridges." *PCI Journal* 54 4 (2009): 160-174. Print.
- Harries, K. A. "Structural testing of prestressed concrete girders from the Lake View Drive Bridge." *Journal of Bridge Engineering* 14 2 (2009): 78-92. Print.
- Naito, C., et al. "Forensic examination of a noncomposite adjacent precast prestressed concrete box beam bridge." *Journal of Bridge Engineering* 15 4 (2010): 408-18. Print.
- Hanna, K. E. "Transverse post-tensioning design and detailing of precast, prestressed

- concrete adjacent-box-girder bridges." *PCI Journal* 54 4 (2009): 160-174. Print.
- Harries, K. A. "Structural testing of prestressed concrete girders from the Lake View Drive Bridge." *Journal of Bridge Engineering* 14 2 (2009): 78-92. Print.
- Naito, C., et al. "Forensic examination of a noncomposite adjacent precast prestressed concrete box beam bridge." *Journal of Bridge Engineering* 15 4 (2010): 408-18. Print.
- Broomfield, J. P. *Corrosion of Steel in Concrete, Understanding, Investigation and Repair*. Oxon: Taylor and Francis, 2007.
- ACI Committee 222, "Protection of Metals in Concrete Against Corrosion." *ACI 222R* (2001): 1-41. Print.
- ACI Committee 222, "Corrosion of Prestressing Steels." *ACI 222.2* (2001): 1-43. Print.
- Yeomans, S.R. "Performance of black, galvanized, and epoxy-coated reinforcing steels in chloride-contaminated concrete" *Journal Corrosion* 50 1 (January, 1994): 72-81. Print.
- ASTM. 2007. "Standard Specification for Epoxy-Coated Reinforcing Steel Bars," (ASTM A7751A775M-07b), 2007 *Annual Book for ASTM Standards*, Vol 01.04, American Society for Testing Materials, West Conshohocken PA.
- Ann K.Y, Song HW. "Chloride threshold level for corrosion of steel in concrete". *Corrosion Science* 49 (2007): 4113-4133.