Hot-Dip Galvanized Reinforcing Steel Performance Report

Longbird Bridge • Bermuda 1953 - 2020

American Galvanizers Association
Protecting Steel for a Sustainable Future

ZINC | international zinc association

Executive Summary

Over the nearly seven decades the Longbird Bridge stood, several inspections and corings were conducted to evaluate the performance of the hot-dip galvanized (HDG) rebar used in the bridge deck. In each of the studies, the average galvanized coating thickness was measured and found to exceed the requirements for newly galvanized rebar despite being exposed to a highly corrosive, tropical marine environment in Bermuda. The bridge was exposed to heavy salt-spray from tidal splash zones and was constructed in very close proximity to the ocean.

In 1995, when the bridge was 42 years old, the HDG rebar coating thickness was in excess of the requirement for newly galvanized rebar even though the measured chloride levels were 3 to 10 lbs/yd^3, well beyond the threshold limit of 1.1 lbs/yd^3 (0.65 kg/m^3) for black rebar. In 2020, after the bridge had been demolished, analyzed rebar samples showed HDG coating thickness still in excess of the requirement for new galvanized rebar after 67 years of service.

The performance of the Longbird Bridge, in part, led Bermuda's Ministry of Works and Engineering (MW&E) to exclusively specify hot-dip galvanized reinforcement in future bridge projects for more than 50 years and it is still standard practice today. If it were not for damage from multiple hurricanes over the years, including the devastating final blow delivered by Hurricane Fabian in 2008, the Longbird Bridge would have provided service for well over 100 years.

Concrete Corrosion Costs $20 Billion Annually

The deterioration and subsequent maintenance and replacement of reinforced concrete structures, such as bridges, is estimated to cost more than $20 billion annually in the United States. These costs are increasing by nearly $500 million each year, which has become a major liability for highway agencies. The direct costs of replacing and repairing the structures is obvious; however, the indirect costs resulting from traffic delays, business interruption, and structural failures further exacerbates the problem. As a result, finding a sustainable, corrosion-resistant reinforcing solution that lengthens the service life of reinforced concrete structures is paramount to decrease the burden these costs place on society. Hot-dip galvanized reinforcing steel has emerged as a viable solution to this problem.

Initial Construction

The Longbird Bridge in Bermuda, a swinging asymmetrical steel span, was built across Castle Harbor by the US Navy in 1953 to facilitate movements to St. David's Island near the Kindley Naval Air Station (now the Bermuda L. F. Wade International Airport). The US Navy maintained a military presence in Bermuda from the 1940's to 1995 and constructed many structures as part of its operations, including the Longbird Bridge. Due to the high chloride environment, hot-dip galvanized steel reinforcement was used in the concrete approach and bridge deck.

The single span concrete approach deck was approximately 18 ft (5.5 m) long by 20 ft (6.1 m) wide with 10 in (254 mm) thick concrete covered by 2 in (51 mm) of asphalt. Deformed, round, hot-dip galvanized #4 rebar was used to construct three layers each in an upper and lower mat of reinforcing steel. Top and bottom bars were longitudinal at staggered 16 in (406 mm) centers while the middle layer was transverse at staggered 8 in (203 mm) centers. An additional lower mat was constructed in essentially the same manner. Concrete cover over the top mat of the reinforcing bars was approximately 2 in (51 mm).

The parameters of the concrete mix are unknown; however, it is typical in the construction of bridges, seawalls, and buildings in Bermuda for concrete to be made with coral aggregates and mixed with seawater because fresh water is a rare resource. This introduces a high initial chloride concentration, amplifying the need to protect the steel reinforcement from corrosion.

Inspections & Studies

International Lead Zinc Research Organization - 1975

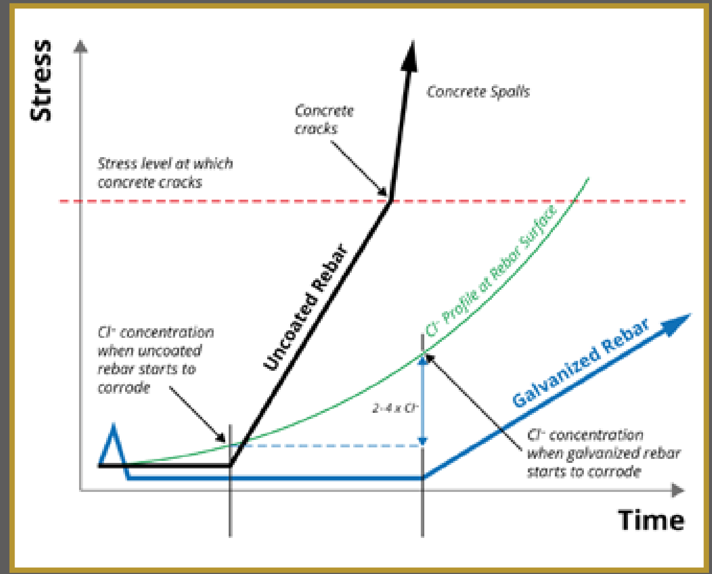
More than 20 years after the construction of the Longbird Bridge, the International Lead Zinc Research Organization (ILZRO) sponsored studies on the performance of galvanized reinforcement in concrete bridge decks in the United States, Canada and Bermuda. Concrete cores were drilled and samples of concrete and HDG rebar were pulled from various structures

About Bermuda

Bermuda lies in the northwestern Atlantic Ocean about 650 miles (1050 km) east of North Carolina. The main Island is about 23 miles (38 km) long and 1.25 miles (2 km) wide at its widest point. The climate is frost-free with temperatures ranging from 50°F to 90°F (10°C to 32°C) and an average relative humidity of 80%. No point in the archipelago of seven main islands and numerous islets is more than one kilometer from the sea, so salt spray and salt-laden air create a corrosive, tropical marine environment.

How does HDG Rebar Protect Steel in Concrete?

Zinc's chloride-induced corrosion threshold is 2-4 times higher than black steel. Black steel is passive in alkaline concrete until the chloride level exceeds approximately 1.1 lbs/yd^3 (0.65 kg/m^3); the point at which steel becomes depassivated and starts to corrode. Zinc, on the other hand, can withstand chloride concentration much higher than black steel and the corrosion of zinc will not initiate until concentrations of at least 2.2 lbs/yd^3 (1.3 kg/m^3) have been achieved and in some conditions even up to nearly 4 lbs/yd^3 (2.4 kg/m^3).



Even when the hot-dip galvanized coating begins to corrode, **zinc corrosion products have the unique property of diffusing into the concrete matrix** opposed to building up pressure at the surface of the rebar and causing cracking and spalling. The elemental map (left) is evidence of this migration. Bare steel is represented as orange, the hot-dip galvanized coating is yellow and the white spots in the concrete indicate zinc oxide which has migrated away from the galvanized rebar/concrete interface.

Longbird Bridge - 2015

The Longbird Bridge was put out of service in 2008 due to damage from hurricanes.

including the Longbird Bridge. Metallographic examination and petrographic analyses were performed on the concrete cores to examine the galvanized coating thickness on the rebar and the chloride concentration in the concrete near the bar surface.

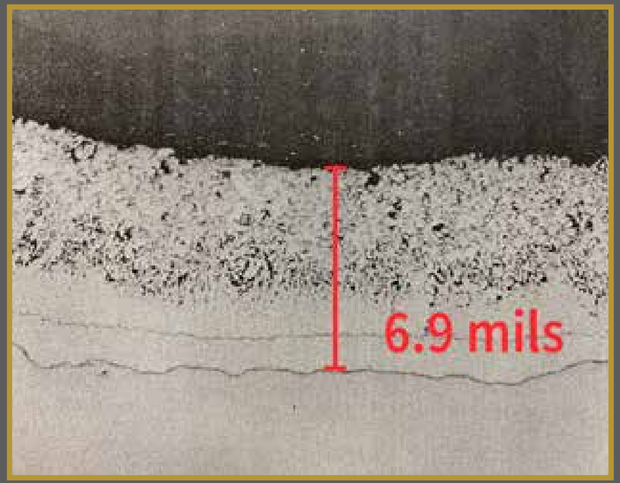
The results from the Longbird Bridge analysis revealed an average hot-dip galvanized coating thickness of 6 mils (152 µm) despite an extremely high concrete chloride concentration of 1.7 to 2.2 lbs/yd^3 (1.0 to 1.3 kg/m^3) present in the concrete at the level of the top mat of HDG reinforcing steel. This concentration is well above the 1.1 lbs/yd^3 (0.65 kg/m^3) to initiate corrosion of uncoated steel bars.

Coinciding petrographic examination and visual inspection showed the bridge was only slightly affected by corrosion and there were no visible signs of concrete deterioration observed since its construction 20 years prior.

In 1984, during an annual Bermuda Ministry of Works & Engineering (MW&E) inspection, cracks were observed in the soffit of the approach span. Initially, the cracking was thought to indicate deterioration of the reinforcing steel, however, no significant rust staining was visible near the cracks. In 1991, the US Navy repaired the bridge as part of a refurbishment of the main steel bridge. During the repair, additional inspections were performed in the inter-tidal zone, the splash zone and below water. Reinforcing bars uncovered during the repair clearly showed the HDG (zinc) coating was still intact thus disproving initial conceptions the reinforcing steel had begun deteriorating due to corrosion.

Construction Technologies Laboratory - 1995

In 1995, when the bridge was 42 years old, another investigation was commissioned by Bermuda's MW&E and carried out by Construction Technologies Laboratory (CTL) to determine the remaining useful life of the bridge. This study was partly prompted by the prior visual inspection in 1984 and subsequent repair by the US Navy in 1991. Again, the concrete was cored and samples of the concrete and HDG rebar were analyzed to gauge the performance and estimate remaining service life.



Photomicrograph from 1976 ILZRO report showing 6.9 mils (175 µm) of HDG coating thickness in one location after more than 20 years of service. Average thickness across all measurements in report was 6.0 mils (152 µm).

The results of the study (Appendix A) again showed extremely high levels of chlorides in the concrete ranging from 3.05 lbs/yd^3 (1.8 kg/m^3), taken horizontally into the side of the bridge with 6 in (155 mm) of concrete cover, to 10.39 lbs/yd^3 (6.11 kg/m^3), taken vertically into the sidewalk with 1.5 in (38 mm) of concrete cover. Despite the elevated chloride concentration levels, coating thickness measurements on the HDG rebar yielded an average coating thickness of 7.1 mils (180 µm) on the samples taken horizontally and 4.9 mils (124 µm) from samples taken from the vertical sections.

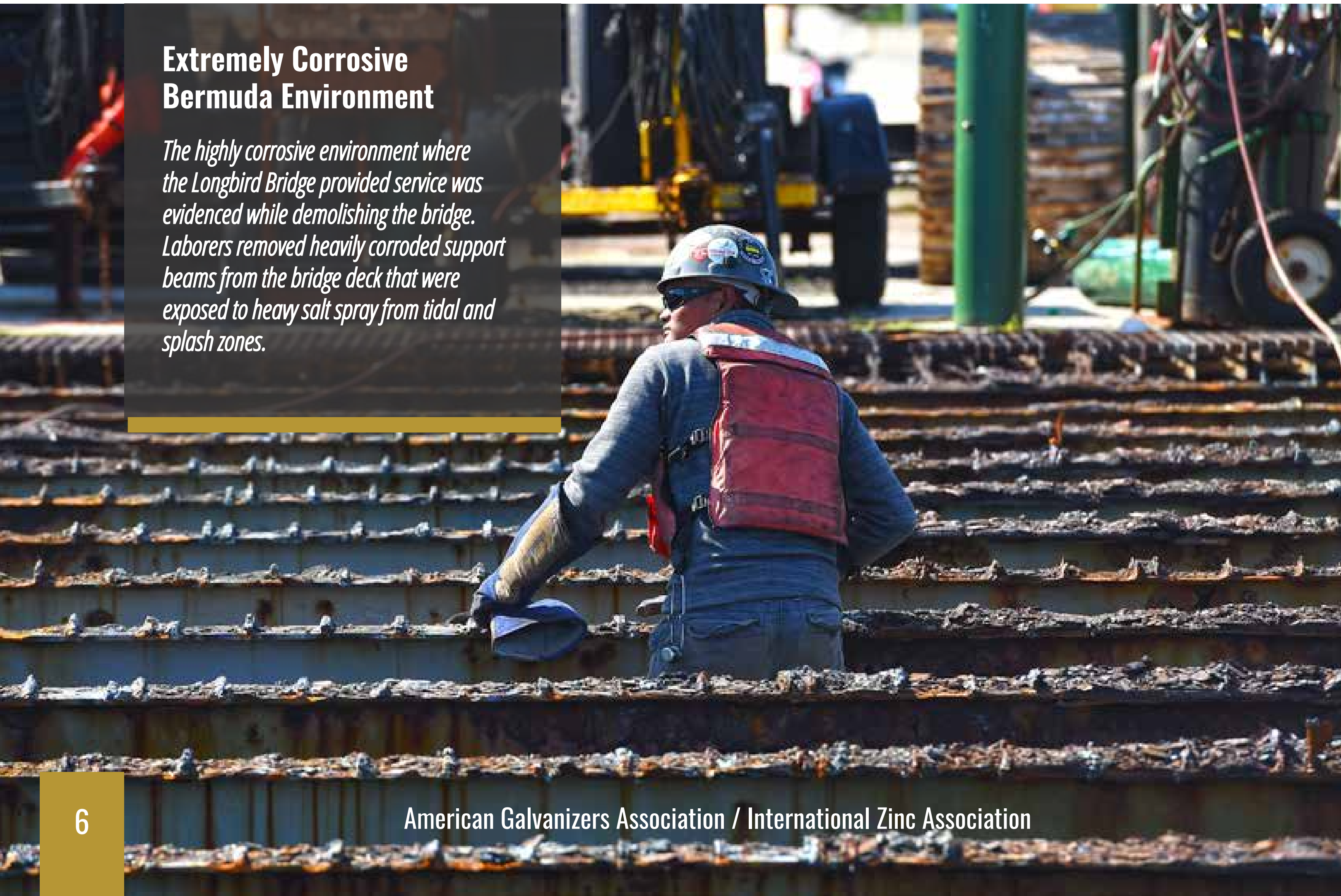
The results of this 1995 inspection confirmed the conclusions from the repair and inspection that was performed by the US Navy four years prior. The average zinc coating thickness exceeded the requirement for new HDG rebar galvanized to ASTM A767 (Class 1) even though the chloride levels were 3-10 lbs/yd^3 (1.8-5.9 kg/m^3), well beyond the threshold limit of 1.1 lbs/yd^3 (0.65 kg/m^3) for corrosion to initiate on black rebar. The performance of the HDG rebar in the Longbird Bridge supports the Bermuda MW&E's practice of exclusively specifying HDG reinforcement on all bridge projects.

American Galvanizers Association & International Zinc Association - 2020

In 2008, the Longbird Bridge was closed due to damage from hurricanes and subsequently bypassed by temporary twin galvanized steel bridges. In 2020, 67 years after its construction, Bermuda's MW&E began demolition of the Longbird Bridge to make way for a new, larger replacement structure.

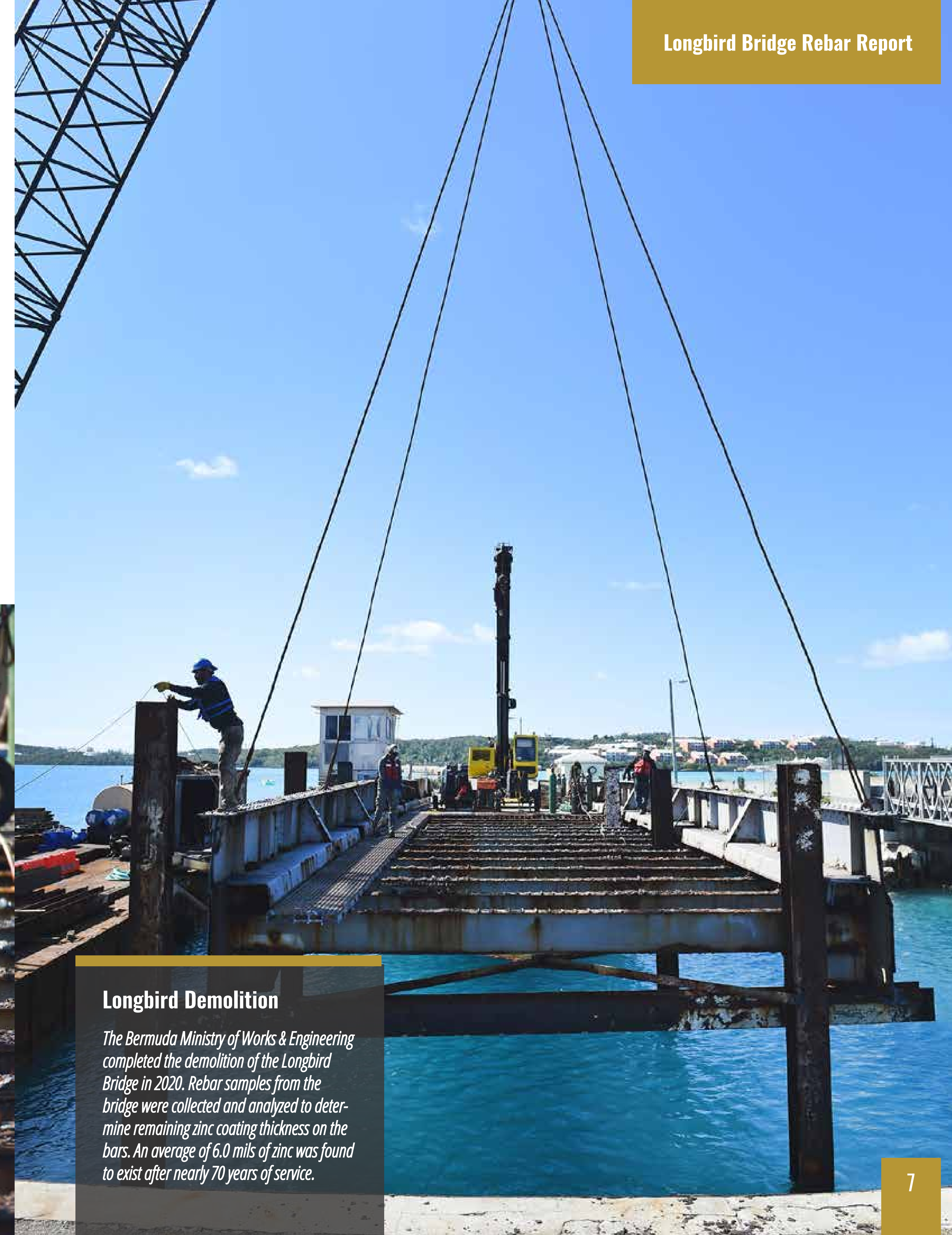
The American Galvanizers Association (AGA) in collaboration with the International Zinc Association (IZA) worked closely with the Bermuda MW&E to retrieve samples of both the rebar and concrete as the bridge was being demolished. Concrete samples were unable to be tested; however, it can safely be assumed that the concrete chloride levels would not have decreased, but rather increased from their elevated states in previous studies.

The salvaged HDG rebar samples were sent to a lab for detailed performance and metallographic analysis (Appendix B). For each sample, twelve separate test sites were optically examined and the coating thickness at each site was measured. The high and the low readings were discarded and the final ten measurements were averaged. The average of the four samples ranged from 3.8 mils to 11.6 mils and the average all of the samples together yielded a thickness of 6.0 mils which exceeds the minimum coating thickness for new rebar in ASTM A767 Class 1 (150µm or 5.9 mils). Visual observation of all the samples showed that only one small area on one of the samples had visible rust.



Extremely Corrosive Bermuda Environment

The highly corrosive environment where the Longbird Bridge provided service was evidenced while demolishing the bridge. Laborers removed heavily corroded support beams from the bridge deck that were exposed to heavy salt spray from tidal and splash zones.



Longbird Demolition

The Bermuda Ministry of Works & Engineering completed the demolition of the Longbird Bridge in 2020. Rebar samples from the bridge were collected and analyzed to determine remaining zinc coating thickness on the bars. An average of 6.0 mils of zinc was found to exist after nearly 70 years of service.

Conclusions

The performance of hot-dip galvanized rebar used in the Longbird Bridge was studied extensively over its life of nearly seven decades. In the most recent, final study in 2020, the average zinc coating thickness measured on the rebar exceeded the minimum coating thickness required for any type of new galvanized rebar according to ASTM A767, Standard Specification for Zinc-Coated (Galvanized) Steel Bars for Concrete Reinforcement.

These results show the corrosion benefits of galvanized rebar despite the remarkably high chloride concentration found in the concrete samples. The concrete was mixed with seawater as is/was the standard practice in Bermuda. Thus, the initial chloride concentration is assumed to have been at or near the chloride threshold at which corrosion is initiated on bare steel. Chloride concentrations increased over time showing chlorides had been diffusing into the concrete from ocean tidal and splash action.

If it were not for hurricanes damaging the Longbird Bridge, the hot-dip galvanized rebar would have easily provided corrosion protection for more than 100 years.

Summary Results of Longbird Bridge Studies

Year	Study	Average Coating Thickness mils (µm)	Chloride Concentration lbs/yd^3 (kg/m^3)
1975	International Lead Zinc Research Organization	6.0 (152)	1.7 - 2.2 (1.0 to 1.3)
1995	Bermuda MW&E / Construction Technology Laboratory	7.1 (180)* 4.9 (124)**	3.05 (1.79)* 10.4 (6.11)**
2020	AGA - Rebar Focus Group & International Zinc Association	6.0 (152)	N/A***

**Samples taken horizontally into the side of the bridge with 6 in (155 mm) of concrete cover*
***Samples taken vertically into the sidewalk with 1.5 in (38 mm) of concrete cover*
****Unavailable - It can be safely assumed that the concentration of chlorides would be at least as high as previous studies due to the location of the bridge and the proximity to salt water.*

Acknowledgment

The American Galvanizers Association and the International Zinc Association would like to thank the Bermuda MW&E for their assistance in collecting the galvanized rebar samples during their demolition of the Longbird Bridge. This report would have not been possible without their cooperation.

Appendix A

Reproduced with permission from David Stark and CTL. Editorial Note: Equivalent SI values included for comparison.

Evaluation Of Galvanised Reinforcing Steel In The Longbird Bridge, Bermuda

April1995

by David Stark
Senior Principal Scientist
Construction Technology Laboratories (CTL), Inc.

Introduction

The present investigation was intended to evaluate the performance of the galvanised reinforcing steel in the Longbird Bridge, after 42 years of service. For this purpose, two concrete cores were extracted and forwarded to CTL. These cores were nominally 5-1/2 in (140 mm) in diameter and 12 in (300 mm) and 6 in. (150 mm) long. Core No 1 was taken horizontally into the bridge deck from an outer exposed formed surface, while Core No 2 was taken vertically through a curb-sidewalk component of the structure. Core procurement was done in the fall of 1994.

Scope of Work

Three lines of evaluation were requested to characterise the performance of the galvanised reinforcing steel in the concrete, as follows:

1. One core, No. 1, was subjected to petrographic examination in accordance with procedures in ASTM C856, " Standard Practice for Petrographic Examination of Hardened Concrete." Both finely lapped and freshly fractured surfaces were examined to characterise the quality of the concrete and identify any other features such as abnormal microcracking and secondary reaction products. Also, depth of carbonation was determined by phenolphthalein applications to freshly fractured surfaces.
2. Determine the total (acid soluble) chloride contents of the concrete at selected depths in the two cores. For this purpose, dry powder samples were obtained using a drill and ¼ in (6.4 mm) diameter bit, and saving the sample obtained from inside a ¼ in. wide outer ring of concrete in the cores. The holes were drilled into the cylindrical faces of the cores to avoid contamination from previous wet coring. Chloride contents were determined in accordance with procedures in ASTM C 1152, "Standard Test Method for Acid-soluble Chloride in Mortar and Concrete." Non-evaporable water contents also were determined for each sample and used to correct for differences in paste-aggregate ratios among the samples.
3. Metallographic analysis was done to determine the thickness and compositions of the galvanised coatings on the embedded reinforcing steel. This was done on one section of steel in each concrete core.

Results of the Investigation

The following sections describe the findings of this investigation.

Petrographic Examination

Results of the petrographic examination of Core No. 1 are reported below. The examination was conducted on both finely lapped and freshly fractured surfaces of the core.

The coarse aggregate is a crushed dense to porous limestone consisting virtually entirely of calcite. The colour ranges from light to orange-buff. Particles shapes are angular to subangular and blocky to elongate. Maximum particle size is one in (25 mm). The fine aggregate appears to be of the same type of limestone but more consistently of a dense, fine grained texture. Both coarse and fine particles are uniformly distributed through the concrete.

The concrete is well consolidated with tight, intimate bond between aggregate particles and the hydrated cement paste matrix. The matrix contains numerous voids, generally in the size range characteristic of intentionally entrained air. These voids are uniformly distributed through the matrix. A few, somewhat larger, voids are scattered throughout the matrix and are considered entrapped air voids. The air content of the concrete was estimated at 2.5 to 3.5%.

The microscopic examination revealed no abnormal microcracking through the full length of the core, including that due to drying shrinkage or processes that cause progressive deterioration of the concrete. Treatment of freshly fractured surfaces with phenolphthalein indicates no detectable carbonation of the cement paste matrix in the interior of the concrete, nor particularly at the exposed outer surface of the concrete. This surface carries a light grey to while painted coating, beneath which is a dark, dense surface zone in the concrete where the phenolphthalein caused the appearance of a bronze colour on fractured surfaces. This surface zone extends to a maximum depth of ¼ in. (6.4 mm) and may represent the application of a surface coating or sealant. It was not present in, nor typical of, concrete deeper in the core.

The core also contained a section of galvanised reinforcing bar, ½ in. (12.7 mm) in diameter and located 2-7/8 in. (73 mm) below the coated external surface of the core. There was no evidence of corrosion of the steel substrate either on the surface of the steel bar or in the cast of the bar in the concrete. Treatment of the cast with phenolpthalein also revealed no evidence of carbonation. Most of the cast displayed sharply defined features of the embedded steel. However, an ¾ in. (19 mm) long section of part of the cast displayed a frothy texture that may represent either localised inadequate consolidation of fresh concrete along one side of the steel, or reaction coating with the highly alkaline solutions in the fresh concrete.

Chloride Contents

Results of the measurements for total chloride contents, corrected for variations in paste-aggregate ratios among the samples, are given in Table 1. Because there were no cement content determinations or mix design data available, results are expressed as mass per unit volume of concrete, wherein the unit mass of the concrete was determined in the 1976 investigation (2) to be 3765 lbs./cu yd (2240 kg/m^3). Also, all values were corrected for differences in past-aggregate ratios among the seven samples. The threshold acid-soluble chloride concentration above which corrosion is likely on untreated steel is 0.20% by mass of cement. For a concrete containing 500 lbs of cement per cubic yard (297 kg/m^3), which is estimated to be close to that in the Longbird Bridge concrete, the threshold chloride level would be 1.0 lb/cu yd (0.6 kg/m^3).

From Table 1, it is seen that chloride levels in the samples from Longbird Bridge are well above the threshold level for untreated steel. In Core No. 1, the chloride concentration at the level of the steel was 3.24 lbs./cu yd (1.9 kg/m^3). In Core No. 2, the concentration was 8.81 lbs/cu yd (5.2 kg/m^3) at the level of the steel. These concentrations were well above the threshold level, and therefore provide an environment favourable to corrosion of untreated reinforcing steel. However, it should be recalled that oxygen also must be present to sustain active corrosion. Whether this condition is met at these sample locations is not known.

Metallurgical Analysis

Metallurgical analyses were performed by the Zinc Corporation of America (ZCA) on a section of reinforcing steel in each of the two cores used by CTL for petrographic and chloride analyses. A summary of findings for each of the five types of analyses is given below.

1. Elemental mapping at paste-steel interface
   This work, using the scanning electron microscope, mapped the diffusion of zinc from the galvanised coating 15 to 20 mils (380-500 µm) into the surrounding cement paste. This diffusion is reported to help prevent a build-up of internal pressure that might lead to spalling of the concrete.
2. Metallographic examination of galvanised coating
   One examination of steel in Core No. 1 revealed a 7-10 mil (175-250 µm) thick coating consisting of a blocky delta layer of zinc-iron alloy adjacent to the steel, overlain by a columnar zeta alloy which, in turn, is covered by a layer of pure zinc. Another area revealed a mild attack on the coating which, at the time of examination, was 5.5 to 6.8 mils (140-173 µm) thick and displayed an irregular surface profile. The coating on the steel in Core No. 2 has undergone locally more severe corrosion which has exposed the steel surface at isolated locations. Coating thickness ranged from 0 to 2.0 mils (0-50 µm) at certain locations, and up to 1.3 to 10 mils (33-250 µm) at other locations.
3. Average coating thickness on bar circumference
   Optical microscopic determinations revealed average coating thickness of 7.1 (180 µm) and 4.9 mils (124 µm) on the reinforcing bars in Core Nos. 1 and 2 respectively. This was based on 12 equally spaced measurements along the full peripheries of the steel, with the greatest and smallest thickness measurements being discarded.
4. Semi-quantitative analysis of corrosion product
   Scanning electron microscope-elemental dispersive x-ray analysis revealed that, after normalising to 100% and expressing as oxides, 55% ZnO was present in corrosion products, together with 31% CaO. This confirms the other observations of localised corrosion of the galvanised coating.
5. X-ray diffraction analysis
   This examination revealed the presence of zinc oxide and calcium zinc hydroxide hydrate and major and minor corrosion products. Traces or possible traces of zinc hydroxide and iron oxide also were identified.

Summary and Conclusions

This project covers an investigation of the corrosion resistance of galvanised reinforcing steel in Longbird Bridge in Bermuda, built in approximately 1952. Petrographic examination of concrete cores, determination of acid-soluble chloride contents, and various metallurgical analyses of the galvanised coating were included in the investigation.

The petrographic examination revealed the concrete to be in good condition with no evidence of progressive degradation. There was no evidence of corrosion of the reinforcing steel substrate beneath the galvanised coating nor cracks associated with steel that might reflect corrosion of the steel.

Acid soluble chloride contents of the concrete near the reinforcing steel in the cores sampled indicate concentrations far greater than the threshold level generally considered necessary to induce corrosion of untreated steel. In these samples, the acid-soluble chloride concentrations were calculated as 3.24 and 8.81 pounds per cubic yard of concrete (1.93 and 5.24 kg/m^3), which is well above the 1.0 pound (0.6 kg/m^3) threshold level for active corrosion of untreated steel. It should be noted that, in these cases, moisture and chloride conditions may have been so uniform, or oxygen may not have been sufficiently available, that local differences in electrical potential could sustain active corrosion cells.

Metallurgical analyses indicated that minor localised corrosion of the galvanised coating has occurred on the reinforcing steel in Core No. 2, where acid soluble contents were calculated as 8.81 lbs. per cu yd of concrete (5.24 kg/m^3). Nevertheless, at this location, there was no distress observed associated with the steel.

Overall, the galvanised steel coatings on reinforcing steel in the samples of concrete from the Longbird Bridge have provided excellent service for more than 40 years without signs of impending or existing distress associated with steel, despite high levels of chloride ion adjacent to the steel.

References

1. Stark, David, and Perenchio, William, "The Performance of Galvanized Reinforcement in concrete Bridge Docks," Project No. ZE-206, International Lead Zinc Research Organisation, Inc., and American Hot Dip Galvanizers Association, Inc., October, 1975.
2. Stark, David, "Galvanized Reinforcement in Concrete Containing Chlorides" Project ZE-247, International Lead Zinc Research Organisation, Inc., and American Hot Dip Galvanizers Association, Inc., April, 1978.

Core No.	Core Location	Depth in Inches (mm)	Chloride lbs/yd³ (kg/m³)
1	Taken horizontally into side of bridge deck.	0.0 to 0.25 (0 to 6.4) 1.50 to 1.75 (38 to 45) 2.75 to 3.0 (70 to 76) 6.0 to 6.25 (152 to 159)	5.12 (3.05) 3.95 (2.35) 3.24 (2.10) 3.05 (1.81)
2	Taken vertically into sidewalk.	0.0 to 0.25 (0 to 6.4) 1.50 to 1.75 (38 to 45) 2.75 to 3.0 (70 to 76)	8.73 (5.18) 10.39 (6.18) 8.81 (5.23)

**Depth of reinforcing steel*

All chloride values are corrected for differences in paste-aggregate ratios among the individual samples.

Mass of chloride ion is based on a unit weight of the concrete of 3765 lbs/yd³ (2240 kg/m³), determined in the previous investigations.

Appendix B

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Evaluation Of Galvanized Rebar: Longbird Bridge, Bermuda

July 20, 2020

by Barry P. Dugan
Zinc Connections, LLC

Background

This report covers the metallurgical examination of galvanized rebar taken from the Longbird Bridge in Bermuda. The bridge was built in 1953 and had some unique construction details. It was one of the first bridges to use galvanized rebar, and it used seawater to mix the concrete, rather than freshwater. Theoretically, the chlorides in the seawater should have greatly degraded the service life of the bridge. Over the years the bridge has been core sampled and the concrete and rebar were tested. The bridge has been closed to traffic for the past 12 years due to deterioration and hurricane damage. Recently the bridge was demolished, and the remnants were moved to a storage yard for disposal. These bars were rescued from the ruble and will be the last available for examination and testing. Since there was no designation, the samples were randomly numbered 1 thru 4. In addition to the rebars, some pieces of concrete were also recovered; these will be tested at another lab.

The rebar samples were not labeled or identified as to their location. Figure 1 shows the as-received samples. The evaluation included metallographic examination of the coating cross sections, and optical coating thickness measurements.

Metallographic Examination

The rebars were cut at the locations shown in Figure 1 (arrows). Sections were taken from each of the four bars and prepared for metallographic examination of the coating cross sections. Sample 1 had two sections removed, since there were areas of coated and uncoated rebar (Samples 1a and 1b). The sections were mounted in epoxy, ground, polished, and etched to reveal the zinc coating. Two photos were taken for each coating cross section. However, since the coating microstructures were similar, only two of the photomicrographs were selected for inclusion in this report. In addition to the coating, the photos also show a layer of aluminum foil; this is NOT part of the galvanized coating. Foil is often used during the metallographic preparation to maintain flatness in the galvanized coating during grinding and polishing.

Figure 2 shows the coating cross section for Sample 2, where the coating consists of a diffuse delta layer next to the base steel, and a columnar growth of zeta crystals. These iron-zinc alloy layers are partially covered by remnants of the pure zinc layer (eta). The total coating thickness measures 6.7 mils.

Figure 3 shows the coating cross section for Sample 3. The coating structure is similar to the above sample, with layers of delta and zeta crystals. The sample has a much thicker pure zinc layer. The total coating thickness measures 12.0 mils.

Optical Coating Thickness Measurements

Optical coating thickness measurements were taken on the coating cross section for each of the five samples. This is the most accurate of all the measurement techniques, since it is done with a microscope at high magnification using a calibrated eyepiece. Twelve coating thickness readings were taken around the circumference of the rebar (at clock points). The twelve readings are reported as the range. For the average value, the highest and lowest reading are dropped, and the remaining ten values are averaged. This is done as to not skew the average value with excessively high coating readings around the rebar ribs. The following table shows the summary of those sixty thickness measurements.

Sample	Range, mils	Average, mils
1a	3.5 - 11.4	4.85
1b	0 - 12.9	3.81
2	1.5 - 16.5	6.52
3	7.2 - 16.4	11.63
4	5.5 -13.5	8.95

Summary

The Longbird Bridge was almost 70 years old before its recent demolition. Except for only a minor area, the galvanized coating on the rebar was in exceptionally good condition. In almost all cases the rebar had a coating thickness which exceeded the ASTM specification for new rebar.

*** Photomicrographs of the coating cross section and optical coating thicknesses measurements were performed by ATRONA Test Labs, Loves Park, Illinois, Project No.: 200515.*

Figure 1. As-received galvanized rebar sections showing the locations of the samples removed for metallographic examination and optical coating thickness readings.

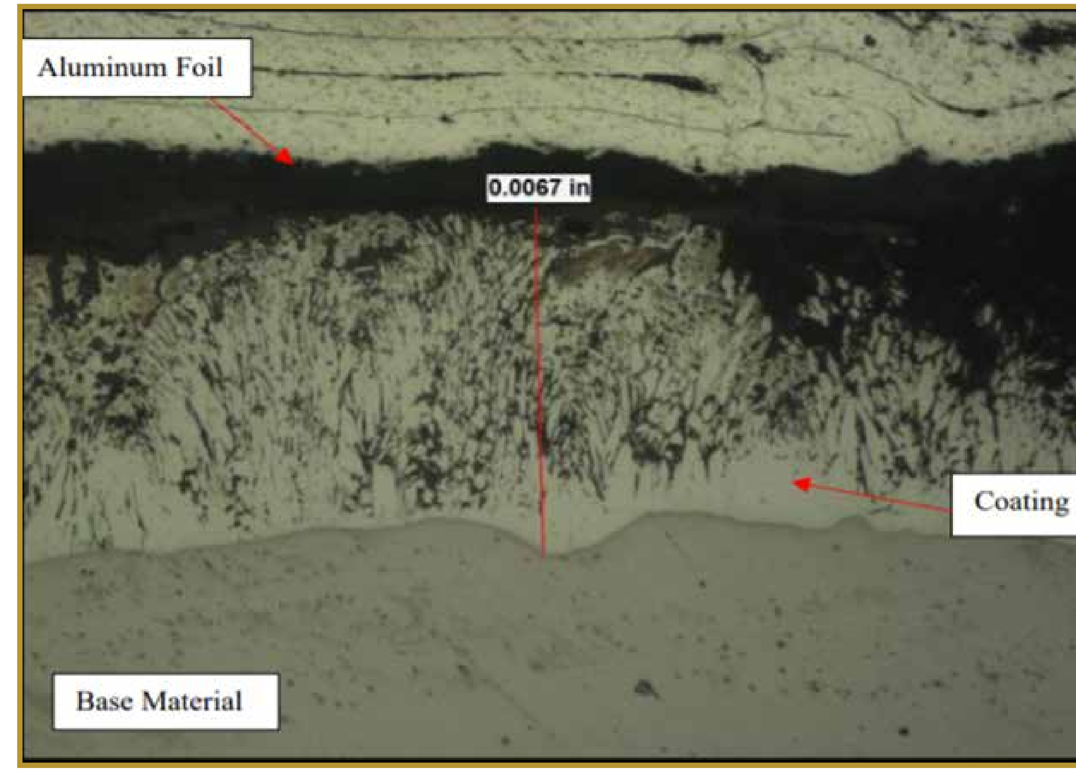

Figure 2. Coating cross section through Sample 2. The total coating thickness measures 6.7 mils.

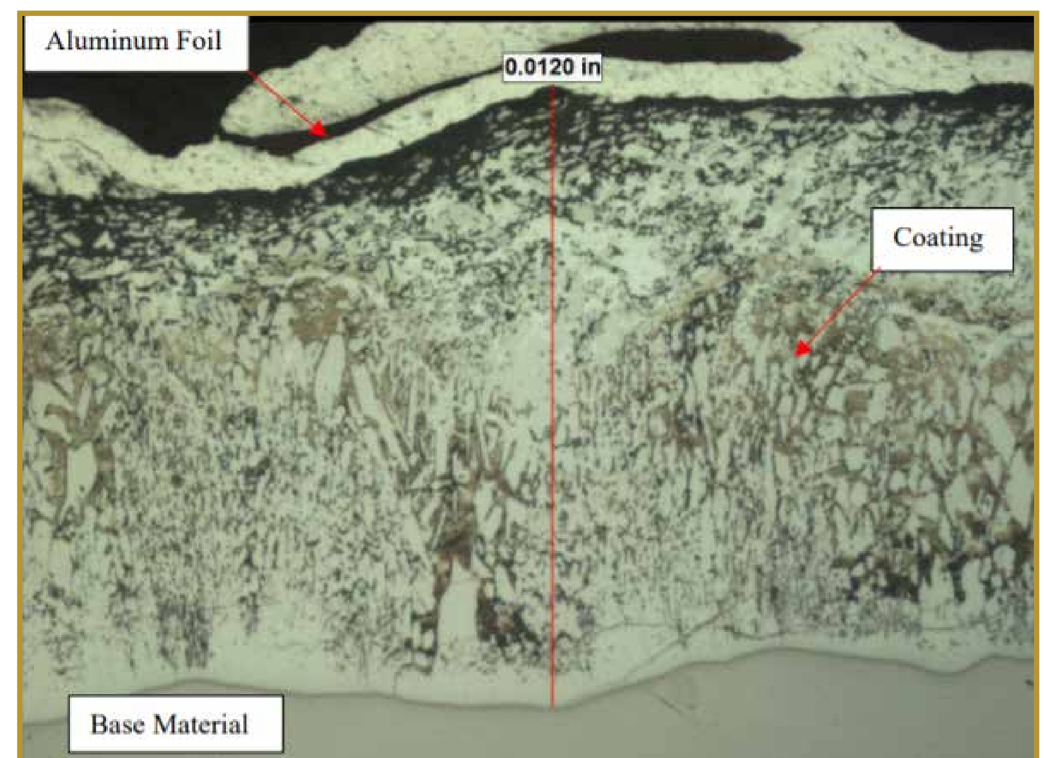

Figure 3. Coating cross section of Sample 3. The total coating thickness measures 12.0 mil

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