Hot-Dip Galvanized Reinforcing Steel

A Specifer's Guide

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Introduction

Repairing damage caused by corrosion costs billions of dollars annually. One significant contributor to the corrosion problem is decaying reinforcing steel bar (rebar), which causes staining, cracking, and spalling of concrete structures throughout North America. Corroding rebar leads to costly repairs, continual maintenance, and eventual structural deficiencies of the concrete.

Hot-dip galvanizing, commonly specified for its longevity and durability on exposed structural steel, is also effectively and economically used to protect rebar from corroding. Concrete is a porous material and corrosive elements from the atmosphere permeate the concrete, eventually reaching the rebar, and cause unprotected rebar to corrode. Galvanized reinforcing steel, with its tenacious, durable zinc coating, is uniquely suited to withstand these rigors without causing detriment to the concrete.

Rebar Corrosion

Concrete contains small pores and capillaries through which corrosive elements such as water, chloride ions, oxygen, carbon dioxide, and other gases travel into the concrete matrix, eventually reaching the steel reinforcing bar. As the concentration of these corrosive elements increases, particularly chlorides, steel's corrosion threshold is eventually exceeded and rebar starts to corrode.

Rust, or iron oxide, is the result of an electrochemical process. When iron corrodes, its corrosion products (rust) are 2-10 times more voluminous than the original steel. This increase in volume around the steel rebar exerts great disruptive tensile stress on the surrounding concrete. Concrete exhibits good compressive strength, but has poor tensile strength, generally about one-tenth of the compressive strength. As pressure builds, the concrete will begin to crack (*Figure 1*), creating a direct pathway for the corrosive elements, leading to accelerated rebar corrosion and eventual spalling of the concrete. Once cracking has occurred, the structural capacity of the element is compromised and costly repairs may be needed to extend its useful life.

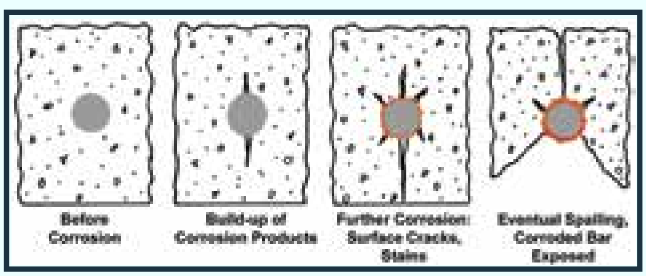
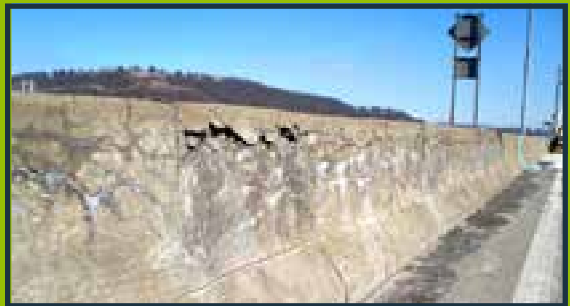


Figure 1: Spalling concrete

Veterans Memorial Bridge

The Veterans Memorial Bridge, which spans the Ohio River connecting Weirton, West Virginia and Steubenville, Ohio, opened on May 1, 1990. The bridge is an example of what can happen when reinforcing steel fails to withstand the environment in which it is placed. The photos below were taken in February 2009, and after less than 20 years in service, the rebar has corroded, leading to cracking and spalling of the concrete. Utilizing rebar able to withstand the moist river environment and damaging winter road salts would have kept the concrete intact, greatly reducing the economic and time concerning burden required to repair and replace the spalling concrete.



Corroded rebar causing concrete spalling

How Zinc Protects Steel from Corrosion

Zinc, applied to steel in the hot-dip galvanizing (HDG) process, has been used for more than 100 years to protect steel. While steel is immersed in the galvanizing kettle, the iron in the steel reacts with the molten zinc to form a series of metallurgically-bonded, zinc-iron alloy layers (*Figure 2*). These tightly-bonded (3,600 psi) intermetallic layers are actually harder than the base steel, thus providing superior impact and abrasion resistance.

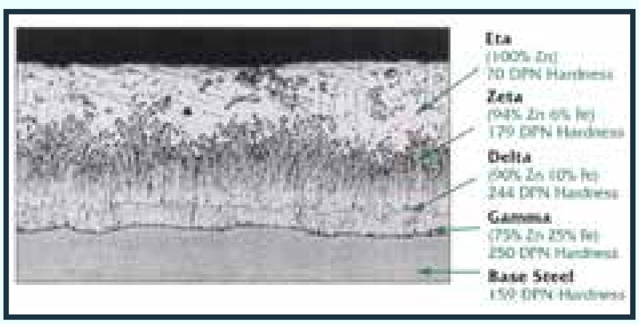


Figure 2: Typical zinc-iron alloy layers

During the reaction in the kettle, the alloy layers grow perpendicular to all surfaces ensuring corners and edges have equal protection (*Figure 3*). Additionally, the immersion process ensures complete coverage of the steel surface, including areas inaccessible or hard to reach with brush and spray applied coatings. This complete uniform coverage means the entire piece of steel is afforded barrier and cathodic protection – inside and out.

The hot-dip galvanized zinc coating provides an impenetrable barrier, protecting the steel from corrosive elements in the environment. As the zinc coating is exposed to the environment, an additional barrier develops as zinc corrosion products form on the surface. This naturally occurring zinc patina is tenacious and relatively insoluble, creating a passive, protective layer on top of the zinc coating which inhibits ongoing exposure and corrosion of the underlying galvanized coating. This protective zinc patina is why zinc's corrosion rate is estimated to be 1/10 to 1/100 the steel corrosion rate.

In addition to the complete coverage and zinc patina barriers, hot-dip galvanizing also provides cathodic protection. Because of differences in electrical potential, zinc is anodic to steel, which means when the two metals are connected zinc corrodes preferentially, cathodically protecting the steel. Therefore, the hot-dip galvanized coating cannot be undercut by rusting steel, as is the case with paint coatings. Steel exposed at cut edges or from severe mechanical damage, will not corrode as the adjacent zinc will sacrifice itself and isolate corrosion until all of the surrounding zinc is consumed.

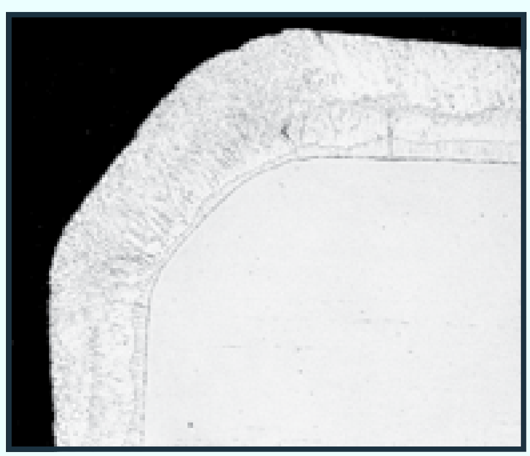
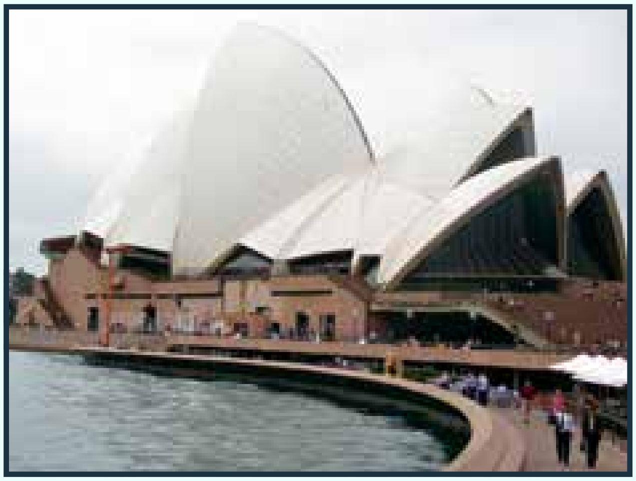


Figure 3: Full corner protection

How Galvanized Rebar Slows Corrosion in Concrete

The corrosion mechanisms and performance of black and hot-dip galvanized steel in concrete are different than when exposed in atmospheric conditions. Steel embedded in concrete is exposed to a highly-alkaline environment. Black steel is passive in alkaline concrete until the chloride level exceeds approximately 1 lb/yd^3, when steel becomes depassivated and starts to corrode. Zinc, on the other hand, can withstand chloride concentration at least four to five times higher than black steel, and coupled with its impervious barrier protection, delays the onset of chloride corrosion on galvanized rebar.

Chlorides penetrate the concrete through small pores and cracks that form on the surface through use and weathering. While black steel in concrete typically depassivates below a pH of 11.5, galvanized reinforcement can remain passivated at a lower pH, thereby offering substantial protection against the effects of concrete carbonation.



The Sydney Opera House in Australia utilizes galvanized reinforcing steel

In addition to the higher chloride tolerance, once the zinc coating does start to depassivate, the zinc corrosion products formed are less voluminous than iron oxides and actually migrate away from the galvanized bar into the matrix of the concrete (*Figure 4*). Unlike the development of iron oxide, the migration of the zinc corrosion products from the rebar prevents the pressure buildup and eventual concrete spalling.

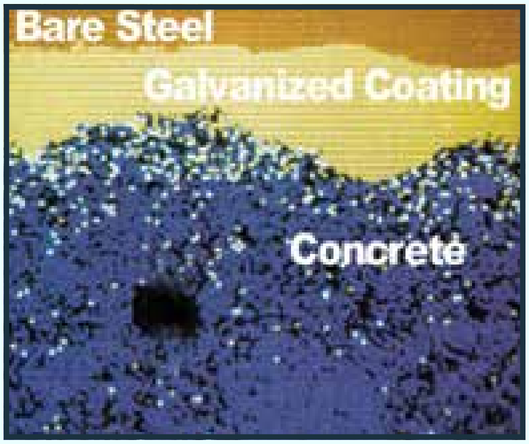


Figure 4: *This elemental map shows how corrosion products of galvanized rebar are less dense and do not build up pressure to cause concrete spalling. The zinc corrosion products (depicted in white), migrate away from the galvanized coating and disperse into the concrete matrix.*

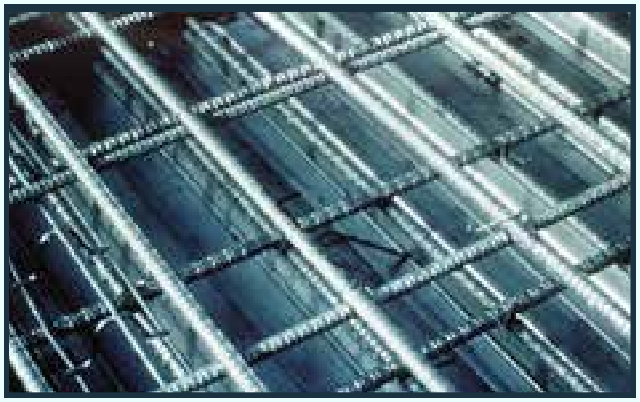
The total life of a galvanized coating in concrete is made up of the time taken for the zinc to depassivate (which is longer than for black steel, because of its higher tolerance to chloride ions), plus the time taken for the consumption of the zinc coating as it sacrificially protects the underlying steel. Only after the coating has been fully consumed in a region of the bar will localized corrosion of the steel begin.

Common Uses of Galvanized Reinforcing Steel in Concrete:

- Architectural building features
- Exposed beams and columns
- Coastal and marine structures
- Piers and breakwaters
- Transportation infrastructure
- Bridge decks
- Docks and marinas
- Water treatment facilities
- Lamp posts
- Power pole bases
- Power stations

Advantages of Galvanized Rebar:

- Low cost
- Cathodic protection
- Little to no concrete spalling
- Higher chloride concentration tolerance
- Performs well in aggressive environments
- Tolerates variable concrete quality
- Clean and easy to work with
- Longer service life for projects



Galvanized reinforcing steel

Mechanical Properties of Galvanized Rebar

Ductility and Yield/Tensile Strength

Studies of hot-dip galvanizing on the mechanical properties of reinforcing steel show little effect on the tensile or yield strength or the ultimate elongation of rebar, provided appropriate steel selection, fabrication practices, and galvanizing procedures are followed. When rebar is fabricated prior to hot-dip galvanizing, bend radius should follow Table 2 of ASTM A 767, *Standard Specification for Zinc-Coated (Galvanized) Steel Bars for Concrete Reinforcement*. If rebar is fabricated after galvanizing, standard industry practice, as per the Concrete Reinforcing Steel Institute's (CRSI) *Manual of Standard Practice*, should be followed.

Additionally, the effect of galvanizing on the ductility of steel bar anchors and inserts after being subjected to different fabrication procedures has been investigated. The study concluded with correct choice of steel and galvanizing procedures, galvanizing causes no reduction in the steel's ductility.

Fatigue Strength

An extensive experimental program examining the fatigue resistance of steel reinforcement shows deformed reinforcing steel, exposed to an aggressive environment prior to testing under cyclic tension loading, performs better when galvanized.

Strawberry Mansion bridge deck in Philadelphia

Bond Strength

Good bonding between reinforcing steel and concrete is essential for reliable performance of reinforced concrete structures. When protective coatings on steel are used, it is essential to ensure they do not reduce bond strength. Studies on the bonding of galvanized and black steel bars to Portland Cement concrete have been investigated. The results of these studies indicate:

- Development of the bond between black or galvanized steel and concrete depends upon cure time and environmental factors.
- In some cases, the full bond for galvanized rebar may take longer to form than for uncoated steel, depending on the zincate/cement reaction.
- As reported by Stephen Yeomans in *Galvanized Steel Reinforcement in Concrete*, there are a number of studies that have concluded the fully developed bond strength of galvanized rebar has no significant difference from black rebar bond strength.
- A study by C. Andrade in Spain monitored bond strength of galvanized rebar samples over 10 years immersed in sea water and found no deleterious effects on bond strength over that time.

Zinc Reaction in Concrete

During curing, the galvanized surface of steel reinforcement reacts with the alkaline cement paste to form stable, insoluble zinc salts accompanied by hydrogen evolution. This has raised the concern of the possibility of steel embrittlement due to hydrogen absorption. Laboratory studies indicate liberated hydrogen does not permeate the galvanized coating to the underlying steel and the reaction ceases as soon as the concrete hardens.

ASTM A 767 requires hot-dip galvanized reinforcement be chromate passivated after galvanizing. Many cement mixtures contain small amounts of chromate that may serve the same purpose as chromate passivating the zinc coating. The reaction between the alkaline cement paste and the zinc coating is dependent on the amount of zinc coated surface in the concrete with the potential for reaction increasing with more zinc metal in contact with the concrete.

Design and Fabrication

When galvanized steel is specified (see the AGA's publication, *Suggested Specification for Hot-Dip Galvanizing Reinforcing Steel*) the design requirements and installation procedures employed should be no less stringent than for structures where uncoated steel reinforcement is used. In addition, there are some special requirements to be observed when galvanized steel is used. The following suggestions are intended as a guide for designers, engineers, contractors, and inspectors. They are intended as a supplement to other codes and standards dealing with the design and fabrication of reinforced concrete structures, and deal only with those special considerations that arise due to the use of galvanized steel.

Steel Selection

Reinforcing steel to be galvanized shall conform to one of the following ASTM specifications:

A 615: *Specification for Deformed and Plain Billet-Steel Bars for Concrete Reinforcement*

A 706: *Specification for Low-Alloy Steel Deformed and Plain Bars for Concrete Reinforcement*

Detailing of Reinforcement

Detailing of galvanized reinforcing steel should conform to the design specifications for uncoated steel bars and to normal standard practice consistent with the recommendations of CRSI.

Overlap lengths of hot-dip galvanized reinforcing steel are identical to uncoated steel rebar because of the equivalent bond strength to concrete.

Dissimilar Metals in Contact

Another design consideration when utilizing galvanized reinforcement is the possibility of establishing a bimetallic couple between zinc and bare steel (i.e. at a break in the zinc coating or direct contact between galvanized steel and black steel bars) or other dissimilar metals. This type of bimetallic couple in concrete should not exhibit corrosive reactions as long as the two metals remain passivated. To ensure no reactions occur, the concrete depth to the zinc/steel contact should not be less than the cover required to protect black steel alone under the same conditions.

Best practice dictates when using galvanized reinforcement, it should not be directly connected to large areas of black steel reinforcement, copper, or other dissimilar metals. Bar supports and accessories should be galvanized, and tie wire should be annealed wire – 16-gauge or heavier – preferably galvanized. If dissimilar metals must be used, polyethylene and other non-conducting tapes can be used to provide insulation between the metals.

Galvanized reinforcing steel in Townsville, Australia

Bending Bars

Hooks or bends should be smooth and not sharp. Cold-bending should be in accordance with the recommendations of CRSI. When bars are bent cold prior to galvanizing, they need to be fabricated to a bend diameter equal to or greater than those specified in *Table 1* (below). Material can be cold bent tighter than *Table 1* values if it is stress-relieved at a temperature from 900 F to 1050 F (482 C–566 C) for one hour per inch (2.5 cm) of bar diameter before hot-dip galvanizing.

Minimum Finished Bend Diameters - Inch - Pound Units				
Bar #	Grade 40	Grade 50	Grade 60	Grade 75
3, 4, 5, 6	6*d*	6*d*	6*d*	---
6	6*d*	6*d*	6*d*	6*d*
7, 8	6*d*	8*d*	8*d*	8*d*
9, 10	--	--	8*d*	8*d*
11	--	--	8*d*	8*d*
14, 18	---	---	10*d*	10*d*
d = nominal diameter of the bar				

Table 1: Minimum suggested bend diameters

When bending after galvanizing, some cracking and flaking of the galvanized coating at the bend may occur. The speed at which the article is bent may also affect coating integrity. The galvanized coating is best maintained at slower bend speeds. According to ASTM A 767, some cracking and flaking of the galvanized coating in the bend area is not cause for rejection. Any flaking or cracking can be repaired as described in ASTM A 780, *Practice for Repair of Damaged and Uncoated Areas of Hot-Dip Galvanized Coatings.*

Welding

Welding

Welding galvanized reinforcement does not pose any problems, provided adequate precautions are taken. Steps include utilizing a slower welding rate and maintaining proper ventilation (ventilation normally required for welding operations is adequate). More details are outlined in the AGA's *Welding and Hot-Dip Galvanizing* publication.

Inspection and Installation

After reinforcing steel has been galvanized, it should be inspected at the galvanizer's facility to ensure compliance with specifications. The standard specification for hot-dip galvanized rebar is ASTM A 767. However, when bars are fabricated into assemblies prior to galvanizing, the standard specification for hot-dip galvanized assemblies, ASTM A 123, *Standard Specification for Zinc (Hot-Dip Galvanized) Coatings on Iron and Steel Products,* applies.

Inspection of galvanized rebar

Coating Thickness

The thickness of the galvanized coating is the primary factor in determining the service life of the product. The thicker the coating, the longer it provides corrosion protection. For steel embedded in concrete, the relationship is approximately linear.

The minimum coating mass or weight requirements for reinforcing bars specified in ASTM A 767 are summarized in *Table 2*. The conversion of these weights into thickness values is shown in *Table 3*.

Class	Mass of Zinc Coating min gm/m² (oz/ft²) of Surface Coating
Class 1	
Bar Designation Size #3	915 (3.00)
Bar Designation Size #4 & larger	1070 (3.50)
Class 2	
Bar Designation Size #3 & larger	610 (2.00)

Table 2: ASTM A 767 Mass (weight) of zinc coating

Coating Weight		Coating Thickness	
oz/ft²	gm/m²	mils	microns
1.00	305.2	1.70	43
1.50	457.8	2.55	65
2.00	610.3	3.40	86
2.50	762.9	4.25	108
3.00	915.5	5.10	130
3.50	1068.1	5.95	153

Table 3: Conversion from zinc coating weight to zinc coating thickness

The minimum coating thickness requirements for reinforcing bar used in assemblies from ASTM A 123 are summarized in *Table 4*. The conversion of these grades into thickness and weight numbers is shown in *Table 5*.

Minimum Average Coating Thickness Grade by Material Category					
	All Specimens Tested				
Material Category	Steel Thickness Measurement in Inches (mm)				
	<1/16 (<1.6)	1/16-1/8 (1.6-3.2)	1/8-3/16 (3.2-4.8)	>3/16-1/4 (>4.8-<6.4)	≥1/4 (≥6.4)
Structural Shapes	45	65	75	85	100
Strip	45	65	75	85	100
Pipe & Tubing	45	45	75	75	75
Wire	35	50	60	65	80
Rebar		100	100	100	100

Table 4: ASTM A 123 Coating thickness requirements

Minimum Coating Thickness by Grade*				
Coating Grade	mils	oz/ft^2	µm	g/m^2
35	1.4	.08	35	2.45
45	1.8	1.0	45	3.20
50	2.0	1.2	50	355
55	2.2	1.3	55	390
60	2.4	1.4	60	425
65	2.6	1.5	65	460
75	3.0	1.7	75	530
80	3.1	1.9	80	565
85	3.3	2.0	85	600
100	3.9	2.3	100	705

*Conversions in this table are based on the metric thickness value equivalents from the next earlier version of this specification, using conversion factors consistent with Table x.21 in ASTM A 653 rounded to the nearest 5µ ξ 0.03937; oz/ft^2 = µm x 0.02316; g/m^2 = µm x 7.067.

Table 5: Conversion from coating grade to thickness (ASTM A 123)

The galvanized coating thickness can be determined via several methods. The size, shape, and number of parts to be tested likely dictates the method of testing. The most common method for measuring coating thickness on reinforcing steel bar and assemblies is by magnetic thickness gauge in accordance with ASTM E 376, *Standard Practice for Measuring Coating Thickness by Magnetic-Field or Eddy-Current (Electromagnetic) Examination Methods*.

Factors Affecting Coating Thickness

There are several factors that affect the zinc coating thickness, some which are manageable by the galvanizer and others that are not. The two readily manageable by the galvanizer are the temperature of the zinc bath and the withdrawal rate of the reinforcing bar from the zinc bath. To a lesser degree, the roughness of the surface affects the coating thickness. Therefore, parts that have been over-pickled and are rough on the surface can develop thicker zinc-iron layers.

One condition, uncontrollable by the galvanizer, which significantly affects the outcome of the finished galvanized coating, is the steel chemistry – namely silicon and phosphorous content. Certain levels of silicon and phosphorous tend to accelerate the growth of the zinc-iron alloy layers so the coating continues to grow the entire time the reinforcing steel is immersed in the zinc bath.

The Sandelin Curve (*Figure 5*) shows the coating thickness produced by steels with different silicon levels immersed in the zinc bath for equal amounts of time. Following the Sandelin curve, there are two ranges of silicon content recommended for steels to be galvanized, below 0.04% OR between 0.15% and 0.22%, as detailed in ASTM A 385 *Practice for Providing High-Quality Zinc Coatings (Hot-Dip)*. Generally, steels with silicon content outside these ranges produce thick coatings characterized by a matte gray surface, indicating a predominately zinc-iron intermetallic coating with little or no free zinc outer layer.

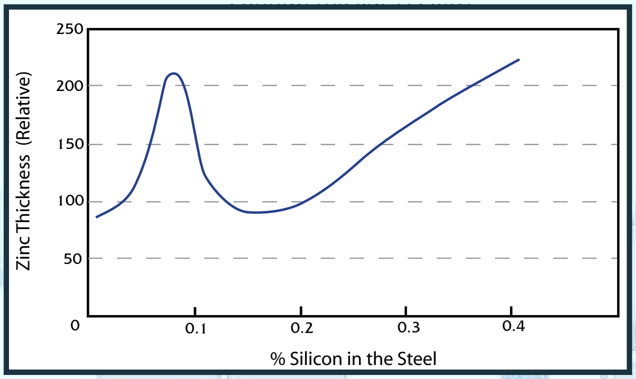


Figure 5: Sandelin Curve

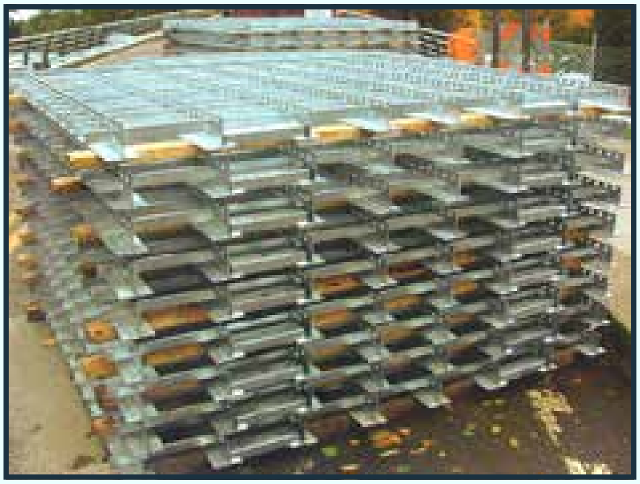
Though service life is linear to the amount of zinc coating, hot-dip galvanized coatings more than 12 mils (305 microns) thick can be susceptible to damage from rough handling. These thick coatings may experience flaking of the outer free zinc layer in areas where external stress is put on the bars. In more extreme cases, the coating can fracture at the interface between separate zinc-iron intermetallic layers, leaving only a fraction of the original coating thickness.

One other factor affecting coating thickness is the blend of various bar sizes in a reinforcing steel assembly. Different size bars will develop zinc coating at different rates. The assembly must be kept in the zinc bath for a longer time in order to develop the minimum required thickness on thicker sections; therefore, smaller bars in the assembly tend to have thicker than normal coatings, which will be more pronounced if the silicon levels are outside the recommended ranges.

Coating Appearance

ASTM A 123 and A 767 require the zinc coating have no bare spots and be free of blisters, flux spots, and large dross inclusions. The galvanized coating must be continuous to provide optimum corrosion protection. Handling techniques for galvanizing require the use of chain slings, wire racks, or other holding devices to lower material into the zinc bath. Chains, wires, and special fixtures used to handle pieces may leave marks on the galvanized item. These marks are not necessarily detrimental to the coating and are not a cause for rejection, unless they have exposed the bare steel or created a handling hazard for erection personnel. If needed, these areas can be repaired according to ASTM A780.

The same specifications state a matte gray finish is not cause for rejection. A matte gray finish, and sometimes rougher surface, is a sign of accelerated growth of the zinc-iron intermetallics due to steel with high levels of silicon. Cold-working may also result in a matte gray appearance. The ability of a galvanized coating to meet its primary objective of providing corrosion protection should be the chief criteria in evaluating its overall appearance and in determining its suitability. And the matte finish and/or rougher surface do not affect the performance of the reinforcing steel or the galvanized coating embedded in concrete.



The intermetallic layers of the galvanized coating are harder than the base steel, so galvanized rebar and other embeds are extremely resistant to damage from abrasion.

Because of its unique, tough coating, galvanized steel requires no special handling at the work site.

Storage and Handling

Galvanized reinforcing steel can be handled and placed in the same manner as black steel rebar because of its superior abrasion resistance. Galvanized bars can be stored outside without any degradation in corrosion performance from UV light. The ease of storage makes it feasible to store standard lengths of galvanized reinforcement so it is available on demand. (Please refer to the AGA's publications *Hot-Dip Galvanizing vs. Epoxy-Coated Rebar* or *Field Handling Guide: Hot-Dip Galvanizing vs. Fusion Bonded Epoxy* for additional information).

Local Repair of Coating

Local removal of the galvanized coating in the area of welds, bends, or sheared ends will not significantly affect the protection offered by galvanizing, provided the exposed surface area is small compared to the adjacent surface area of galvanized steel. When the exposed area is excessive and gaps are evident in the galvanized coating, the area can be repaired in accordance with ASTM A 780.

Removal of Forms

Metal forms should be electrically isolated from the galvanized rebar to prevent dissimilar metal reactions during the concrete curing. If metals forms are not isolated from the galvanized rebar, then zinc ions can be released from the galvanized coating to try to protect the metal form, resulting in a change in the concrete appearance near the galvanized bar placement.

Removal of galvanized rebar from the zinc bath

Testing Galvanized Rebar

In addition to visual and coating thickness inspection, different properties and characteristics of hot-dip galvanized rebar may be tested. These tests may need to be performed on specific lots of steel to ensure they meet relevant standards, or on trial lots before they are put into end-use. Accredited labs experienced with the individual test procedures should perform these tests.

Bond Strength Test

The bond of the hot-dip galvanized reinforcing bar to the concrete can be tested according to ASTM A 944, *Test Methods for Comparing Bond Strength of Steel Reinforcing Bars to Concrete Using Beam-End Specimens*. The bond strength relies heavily on the deformation of the bar and not as much on the actual bond between the zinc and the concrete. For plain bars with no deformation, the bond between the zinc and the concrete becomes very important. Pullout strength of hot-dip galvanized reinforcing steel has been tested many times, and the values of bond strength are equivalent to, or better than, black steel bond strength, as detailed on page 4.

Chromate Finish Test

If chromate coating is required, the existence of chromates may be verified using the method described in ASTM B 201, *Practice for Testing Chromate Coatings on Zinc and Cadmium Surfaces*. Because chromate conversion coatings will weather away fairly quickly, bars chromated after galvanizing may exhibit no chromate by the time they are embedded in concrete. The formation of zinc carbonate patina on the bar will begin as the chromate weathers away and serves the same purpose as chromates to prevent the formation of hydrogen during concrete curing.

Embrittlement Test

Higher strength bars that have had considerable cold working may be susceptible to embrittlement during the galvanizing process. Guidelines for fabricating bars to be hot-dip galvanized are provided in ASTM A 143, *Safeguarding Against Embrittlement of Hot-Dip Galvanized Structural Steel Products and Procedure for Detecting Embrittlement*, and ASTM A 767. When embrittlement is suspected, ASTM A 143 designates the appropriate test method to determine the presence of embrittlement.

Accelerated Aging Test

Efforts have been made in many zinc-coated steel applications to develop the correct test method to determine a proper accelerated lifetime. The most commonly used accelerated corrosion test is ASTM B 117, *Practice for Operating Salt Spray (Fog) Apparatus*.

There is no long-term exposure correlation between salt-spray testing and galvanized rebar field performance. Salt spray tests cannot accurately test zinc-coated steel because they accelerate the wrong failure mechanisms. Without a proper wet/dry cycle, the zinc coating cannot form patina layers; the absence of a patina layer allows constant attack of the zinc metal and results in a short zinc coating lifetime.

The galvanized rebar from the Route 66 Bridge Deck in Kittanning, Pennsylvania, after more than 30 years of service.

Bermuda

Hot-dip galvanized reinforcing steel in concrete has been used extensively since the early 1950s. One of the first installations occurred in the construction of the Longbird Bridge in Bermuda by the US Navy in 1953. Galvanized steel was used to reinforce the bridge deck in the construction of an 18-foot long, single approach span concrete bridge.

Longbird Bridge

The Bermuda marine environment is highly corrosive, as exhibited in a 1978 inspection of bridges and quays conducted by Construction Technology Labs. This inspection included the Longbird Bridge and showed chloride levels in the concrete up to 4.3 kg/m^3 (7.3 lb/yd^3). During this inspection, a low chloride ion gradient across the concrete cores indicated significant chlorides were already in the concrete at the time of placing (most likely from salt water used to mix the concrete). The internal chloride concentration, combined with salt spray from the nearby ocean, produce an extremely corrosive environment. According to this inspection, the galvanized coating had only been slightly affected by corrosion, as 98% of the initial galvanized coating remained intact.

A later inspection of the galvanized reinforcement in the Longbird Bridge was conducted in response to the Bermuda Ministry of Works and Engineering's unilateral specification of hot-dip galvanized reinforcement. In this report, evidence of zinc coating integrity was found on exposed sections of rebar during repairs made in 1984, after 30 years of exposure to extremely high

The Reef Plaza in Bermuda

chloride levels. A third inspection was conducted in 1995 and core samples revealed after 42 years, the galvanized rebar still had a zinc coating thickness well in excess of specification for a new hot-dip galvanized coating.

For more than 50 years, Bermuda has hot-dip galvanized rebar exclusively on all reinforced concrete structures including docks, jetties, bridge decks, substructures, and industrial/commercial construction. The unmatched corrosion protection hot-dip galvanized steel provides for reinforcing materials in concrete caught the eye of many state DOTs and highway authorities. The New York State Thruway Authority, Penn DOT, and the Quebec Ministry of Transportation have all made extensive use of galvanizing's ability to protect rebar from corrosion.

The Magistrate Court and Hamilton Police Station in Bermuda have their foundations set in galvanized steel rebar.

New York State Thruway Authority

In 1995, the New York State Thruway Authority (NYSTA) began to specify hot-dip galvanized rebar for all of its bridge elements. The thruway consists of over 600 miles of toll roads comprising major sections of Interstates 87, 84, and 90, with sections connecting to other interstate highways and toll roads to four neighboring states and Canada. Most of the NYSTA's 810 bridges are installed in fresh water environments, with the exception of a few close to the Atlantic Ocean and qualify as located in a marine environment. In addition to the close proximity to water, the bridges undergo freeze-thaw cycles, and have heavy exposure to deicing salts and industrial pollution, all adding up to a highly-aggressive, corrosive environment.

The need to protect these bridges from corrosion became a major concern to the thruway authority during the early 1960s, when maintenance and inspection revealed extensive corrosion to previously installed bridge decks that incorporated bare steel reinforcement in the concrete. In the 1980s, the NYSTA seemingly solved its corrosion problem by implementing the use of epoxy coated rebar, partially based on the Federal Highway Administration's (FHWA) endorsement of the system. However, in as little as ten years, doubts began to rise regarding the protection provided by the epoxy-coated decks.

Within as little as four years cracks in the concrete had already begun to appear. Furthermore, the NYSTA began to have concerns about the bond strength of the epoxy-coated rebar to the concrete. When removing sections of concrete from epoxy-coated rebar during a repair of an improperly designed pier, the concrete was easily broken away from the epoxy-coated rebar exhibiting inferior bond strength.

Therefore, in the 1990s, the NYSTA conducted a study of the performance of its bridge decks in the pursuit to find an adequate corrosion protection system. During the study, they evaluated 197 bridges with varying types of reinforcing steel: 65 galvanized, 82 epoxy-coated, and 50 black. The following observations were made during the study:

Rusted epoxy-coated rebar

Tappan Zee Bridge in New York

- *Installed cost of galvanized steel was highly competitive with epoxy-coated rebar.*
  Though the initial cost of galvanizing was slightly higher than epoxy or bare steel on a per pound basis, the epoxy decks required more steel to compensate for greater overlap lengths, while galvanized rebar has overlap lengths equal to black bar. Therefore, the initial cost of galvanized reinforced decks was highly competitive.
- *Repair costs were minimized with hot-dip galvanized steel.*
  Not only was the initial cost of galvanizing competitive, but hot-dip galvanized steel also reduced field repair costs as it was able to withstand the rough handling and abrasiveness of placement; thus the overall cost of the bridge was reduced when galvanized rebar was utilized.
- *Installation of galvanized rebar was smooth, after an initial learning curve.*
  The installation of galvanized rebar was slightly different than for epoxy-coated rebar, and thus it took a little trial and error to determine the most efficient installation method. However, after the initial learning curve, the installation was speedy as the bar can be handled the same as black with the same overlap lengths and no touch-up required.

Based on these discoveries, the NYSTA decided to utilize hot-dip galvanized reinforcing steel unilaterally for corrosion protection. Galvanized steel's metallurgically bonded alloy layers which are impact and abrasion resistant helped withstand material handling damage. Furthermore, the cathodic protection of hot-dip galvanizing ensures any damage to the coating would not compromise the corrosion resistance, as any nicks or field cuts would be protected by the sacrificial action of the surrounding zinc. Because of these properties, coupled with the life-cycle cost analysis, the NYSTA concluded the performance of hot-dip galvanized rebar is unmatched.

Pennsylvania DOT

The Pennsylvania DOT has specified galvanized reinforcement for decades. One such bridge, the Athens Bridge, built in 1973, is an eleven-span, four-lane, divided bridge utilizing hot-dip galvanized reinforcing bars.

The Athens bridge deck was initially inspected eight years after installation. Concrete cores were drilled and an analysis of chloride contamination and coating thickness was conducted. The chloride levels found in the cores exhibited concentrations between 1.8 to 7.9 lbs/yd^3 of concrete. The high end of these concentrations is well above the threshold for active corrosion to occur on bare steel. Despite these extremely corrosive conditions, the coating thickness measurements indicated galvanized coatings in excess of 15 mils (approximately three times the coating thickness required on newly-galvanized rebar according to ASTM A 767).

The Athens Bridge was later inspected in 1991 and 2001, and the analysis generated similar results. No sign of active corrosion on the galvanized reinforcement was found and coating thickness measurements reported were in excess of 10 mils. These current coating thicknesses indicate an estimated 40-plus years of additional maintenance-free corrosion protection.

The Route 66 bridge deck refurbishment, south of Kittanning, Pennsylvania, provided a unique opportunity to assess the performance of galvanized rebar after more than 30 years of service. The bridge, built in 1973,

Athens Bridge in Pennsylvania

utilized galvanized rebar in the deck. Though the bridge deck was in excellent condition, Penn DOT wanted to replace the post and beam medial barrier with a more secure concrete Jersey barrier. They removed the entire middle section of the deck and exposed the galvanized rebar for inspection. Tests found the chloride content in the concrete surrounding the rebar to be 5 lbs/yd^3, far exceeding the chloride threshold for corrosion of black rebar.

Inspection of the rebar showed the coating was in excellent condition with thicknesses still exceeding ASTM A 767 specification for new galvanized rebar. Also noted during concrete removal was the tenacious bond of the galvanized rebar to the surrounding concrete, confirming the superior bond strength obtained from galvanized coatings. No refurbishment of the concrete deck was required and the original rebar remained in place when the Jersey barrier was poured.

The Egg

The Egg at the Empire Center Plaza in Albany, NY, was completed in 1978. The performing arts center was a massive undertaking of architecture, combining aesthetics and function in a concrete and steel form. The concrete and steel stem of the structure extends six stories into the ground. The Egg keeps its shape by wearing a girdle comprised of a heavily reinforced concrete beams utilizing hot-dip galvanized rebar.

The superior durability and corrosion protection of hot-dip galvanized steel made it the logical choice for the reinforcement of the concrete in such an integral factor of the structure's design. The reinforced girdle helps the egg keep its shape and directs the weight of the structure onto the supporting pedestal and stem. Housing two theaters, the building's curved exterior is continued on the interior. The walls are not square with harsh corners, but rather curve even up to meet the concave ceiling to give an appearance of endlessness and improved acoustics. Thanks to hot-dip galvanized reinforcing steel, The Egg's extravagant design has not only wowed citizens and visitors for decades, but it will remain a beautiful centerpiece of Albany for generations to come.

Other Installations

It is estimated over 500 bridge decks in the US use hot-dip galvanized rebar to resist rebar corrosion. Inspections on these bridges are continually conducted in order to evaluate the performance of the galvanized reinforcement. *Table 6* is a brief summary of some recent inspections that have been made. The table verifies the outstanding performance of hot-dip galvanized rebar. With concerns arising over the performance of other reinforcement in concrete and the desire to produce bridges that last 100 years, hot-dip galvanizing is more than an alternative—it is the premier corrosion protection system. The current inspections being done on existing bridge decks all report hot-dip galvanized steel is performing extremely well and estimates have shown most hot-dip galvanized reinforced bridge decks will provide at least 75 years of maintenance-free corrosion protection even in the most severe environments.

Boca Chica Bridge in Florida

Location	Installed	Inspection Date	Chlorides	Zinc Coating Thickness	
			(lb/yd^3)	mils	µm
Boca Chica Bridge, FL*	1972	1975	1.95	5.1	130
		1991	2.02	4.0	102
		1999	3.21	6.7	170
Tioga Bridge, PA*	1974	1984	0.58	5.9	150
		1991	1.06	8.8	224
		2001	2.23	7.8	198
Curtis Road Bridge, MI	1976	2002	6.88	6.1	155
Spring Street Bridge, VT	1971	2002	4.17	7.5	191
Evanston Interchange, WY	1975	2002	2.55	9.3	236

* Multiple inspections were made on these bridges. Since concrete cores are drilled out of the bridge, it is impossible to perform this inspection in the same spot. When performing subsequent inspections, the cores must be drilled in different areas which does not allow for corrosion monitoring in one particular area. Hot-dip galvanized coating thicknesses vary slightly over the length of the bars. This explains how a greater coating thickness can be read when measuring the same bridge at a later date.

Table 6: Bridge inspection summary

Additional Resources

Yeomans, Stephen R., *Galvanized Steel Reinforcement in Concrete,* 2004.

Development of the Bond Between Galvanized Rebar and Concrete in Beams Submerged in Natural Sea Water, C. Andrade, et. al.

Hot-Dip Galvanized Reinforced Steel: A Concrete Investment, International Zinc Association, 2006.

Hot-Dip Galvanized Rebar vs. Epoxy-Coated Rebar, American Galvanizers Association, 2006.

Field Handling Guide: HDG vs. Epoxy-Coated Rebar, American Galvanizers Association, 2000.

Suggested Specifications for Hot-Dip Galvanizing Reinforcing Steel, American Galvanizers Association, 2002.

The International Zinc Association's rebar website: **www.galvanizedrebar.com**

The American Galvanizers Association's website: **www.galvanizeit.org**

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American Galvanizers Association
6881 S. Holly Circle, Suite 108
Centennial, CO 80112
720-554-0900
aga@galvanizeit.org
www.galvanizeit.org