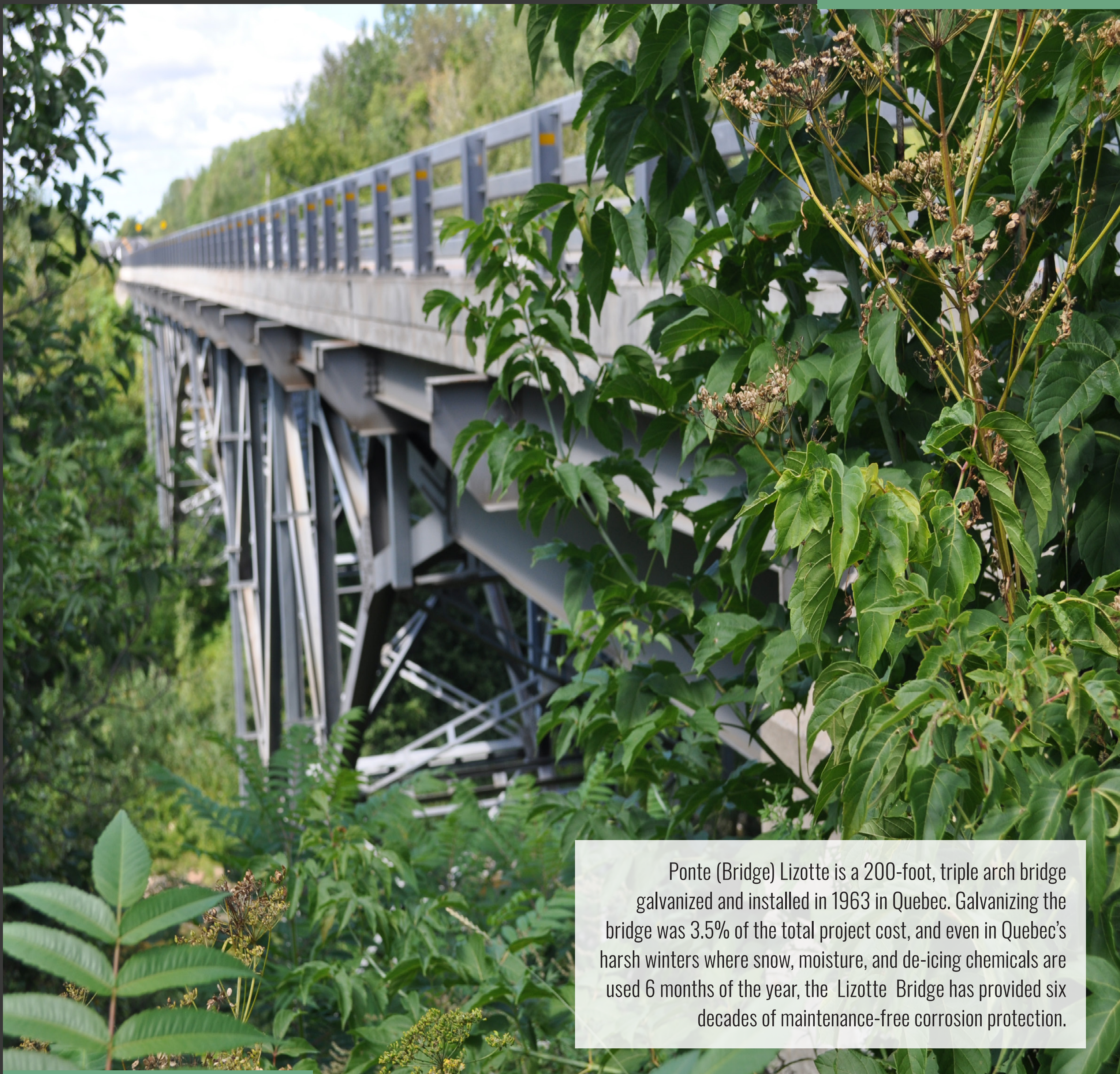
Hot-Dip Galvanized Steel

Bridge Design Guide

AGA Zn™
American Galvanizers Association
Protecting Steel for a Sustainable Future



Ponte (Bridge) Lizotte is a 200-foot, triple arch bridge galvanized and installed in 1963 in Quebec. Galvanizing the bridge was 3.5% of the total project cost, and even in Quebec's harsh winters where snow, moisture, and de-icing chemicals are used 6 months of the year, the Lizotte Bridge has provided six decades of maintenance-free corrosion protection.

> **"Easily the best decision of my career.**
> Emile Laurence, Senior MTQ Engineer when asked about his decision to HDG the Ponte Lizotte more than 60 years ago.

Executive Summary

This manual is intended to provide guidance to bridge owners and designers on utilizing hot-dip galvanized steel in bridge construction, and how to design, detail, fabricate, construct, inspect, preserve, maintain, and repair hot-dip galvanized steel bridges. This summary provides an overview of the information contained in the guide. Readers should consult the full content for detailed guidance.

Hot-Dip Galvanizing (HDG)

Hot-dip galvanizing (HDG) is a corrosion protection system where steel is fully immersed in molten zinc at 820–850°F [438-454°C], forming a metallurgically bonded coating. Unlike paint, which is mechanically bonded to the surface, HDG creates intermetallic layers that become part of the steel itself, offering robust, uniform protection even in hard-to-reach areas. To maximize quality, specific design and detailing considerations should be implemented to ensure HDG delivers long-term durability and minimal maintenance across a wide range of bridge applications.

Benefits of HDG

Designing 100-year bridges is a practical approach to sustainable infrastructure. Selecting materials that meet long-term performance goals without excessive cost or maintenance is essential to achieving this vision. Galvanized steel has a proven history in bridge applications, offering durable, economical corrosion protection. When specified and detailed appropriately for the service environment, HDG enables engineers to meet design life expectations with minimal upkeep.

When to Use

Hot-dip galvanizing is suitable for most bridge applications due to its durability, uniform corrosion protection, and minimal maintenance requirements. HDG has a proven track record in varying environments throughout bridge and highway infrastructure, including bridge superstructure and substructure, reinforcing steel, buried structures, overhead sign structures, guiderail, and more. However, its use should be carefully evaluated in more aggressive conditions such as coastal regions (within 1–2 miles of the ocean), areas with excessive road salting, frequent flooding, buried structures, and retrofits involving dissimilar metals. In these cases, additional design considerations or protective strategies may be necessary to ensure long-term performance.

Design

Designing for hot-dip galvanizing (HDG) requires attention to process-specific considerations due to the immersion process and temperature of the zinc bath. When designing for HDG, steel components are constrained by the size of galvanizing kettles; oversized items should be designed for modular assembly or evaluated for progressive dipping. Connections design must account for increased coating thickness to ensure proper fit and structural integrity. To minimize distortion, engineers should use caution when designing with significant thickness variations and asymmetrical designs. For high-strength or heat-treated steels, careful evaluation of steel chemistry and fabrication methods is recommended to mitigate risks such as embrittlement and excessive coating buildup.

Detailing

Detailing for hot-dip galvanizing requires minor but essential adjustments to ensure coating quality and structural performance. Key considerations include proper venting and drainage, connection details, lifting points, and product identification. These details support proper zinc flow during immersion and withdrawal, minimize distortion, and ensure uniform coverage. Addressing them early in the design process helps avoid costly rework and ensures successful galvanizing outcomes.

Fabrication & Construction

Following best fabrication practices for hot-dip galvanizing is essential to produce high quality coatings. Electrode selection, cleanliness of the weld area, and venting of overlapping surfaces are important considerations when welding prior to HDG. Structural bolting requires practices tailored to HDG fasteners to account for coating thickness during fit-up and the coefficient of friction for faying surfaces. Some steel chemistries, designs and fabrication practices may require additional surface preparation to remove contaminants or control coating buildup. While HDG coatings provide durability during transport and installation, proper storage is recommended to minimize aesthetic concerns such as wet storage stain.

In-Service Inspection

Inspection of HDG steel is straightforward, whether performed at the galvanizing facility or in the field. While the process is simple, inspectors should be aware that HDG coatings can exhibit varied appearances and minor surface irregularities unfamiliar to those new to galvanizing. The vast majority of these visual surface conditions are cosmetic and do not impact corrosion performance. Recognizing these intricacies of hot-dip galvanized coatings is essential to avoid misinterpreting acceptable cosmetic variations as defects.

Maintenance

Hot-dip galvanized bridges are relatively maintenance free, with coatings designed to perform for decades when properly designed and fabricated. While routine maintenance is minimal, certain environments or design elements may warrant more scrutiny such as overlapped surfaces with rust bleeding as well as HDG bridges placed in coastal areas and those exposed to excessive road salting. Although not required, some owners may choose to rinse or wash components in high-salinity or flood-prone environments to preserve aesthetics and performance. Regalvanizing and reuse of components is also viable, offering extended service life and cost savings over replacement.

Repair

Repairing HDG steel is straightforward using readily available materials in accordance with ASTM A780: zinc-rich paint, zinc-based solder, or metallizing (thermal zinc spray) . When repairing in the field, zinc-rich paints are most practical and easy to apply to maintain coating integrity over time.

Duplex Systems

Utilizing a duplex system of hot-dip galvanized steel with a paint or powder coating provides a solution for bridges in highly corrosive environments to increase the longevity of the steel. Alternatively, duplex systems may be specified to achieve specific aesthetics, such as matching surrounding elements, blending with the environment, or branding to a specific color.

Contents

> **"Hot-dip galvanized (HDG) steel has decades of proven performance in diverse bridge structures.**
>
> **From the first fully galvanized US bridge in 1966 to today, HDG steel provides bridge owners a durable, low cost, minimal maintenance solution.**

1.0. Benefits

> “The Stearns Bayou Bridge in Ottawa County, Michigan, the first fully galvanized bridge in the US, was HDG in 1966.

1.1 Cost

One of the key benefits of hot-dip galvanized (HDG) steel is its low life-cycle cost. HDG has been used on bridges for more than 100 years proving its ability to provide maintenance-free protection for decades in many environments. In fact, inspection and coating thickness measurements on galvanized bridges in service confirm this could continue for up to or beyond 100 years.

Initially, hot-dip galvanizing costs more than uncoated weathering steel (UWS) and some paint systems. However, it is an outdated misconception HDG steel is cost prohibitive. Fabricator surveys by the Federal Highway Administration (FHWA) and National Steel Bridge Alliance (NSBA), found hot-dip galvanizing increases initial costs 20-30% over uncoated weathering steel. However, by eliminating costly field maintenance, hot-dip galvanizing recoups this premium after one maintenance cycle, and saves an average of 70%-90% over paint systems throughout the bridge's life-cycle.[1]

Minimizing maintenance results in direct savings on material, labor and equipment while also reducing indirect costs such as traffic detours and losses to surrounding businesses which can be 5-11 times the direct costs. In summary, hot-dip galvanizing saves time and money for new construction rather than investing in the costly, time-consuming maintenance of existing structures.

1.2 Environmental

Hot-dip galvanized steel is made by coating steel with zinc, both of which are natural, abundant elements found in the Earth's crust. Unlike other corrosion protection systems that rely on man-made chemicals and release volatile organic compounds (VOCs), the galvanizing process does not create VOCs and generates minimal waste, as most by-products can be reused or repurposed.

Zinc and steel are both 100% recyclable without the loss of properties, making them infinitely renewable resources. Outside of reclamation of steel and zinc at the end of life, which is the standard of practice, galvanized steel can be reused without reprocessing or re-galvanized and returned to service (*see Section 8.0 Maintenance*). This sustainable versatility reduces resource consumption, minimizes waste, and promotes reuse.

Stearns Bayou Bridge

1 American Galvanizers Association (2025). *Life-Cycle Cost Calculator*. lccc.galvanizeit.org

Finally, the durability of hot-dip galvanized steel leads to low maintenance longevity, reducing the need for repair or replacement. Reducing maintenance minimizes the consumption of resources and energy as well as unnecessary emissions and waste. Bridge maintenance is not only frustrating for drivers in the area but also potentially dangerous for workers repainting steel near traffic or in difficult-to-reach locations.

1.3 Durability

Hot-dip galvanized steel's durability in harsh environments is key to its low maintenance performance (*see Section 2.3.2 Time to First Maintenance*). When steel is immersed in molten zinc, it forms tightly-bonded, abrasion-resistant intermetallic layers. These layers are metallurgically bonded to the steel, providing robust protection against corrosion. Unlike other coatings, HDG's intermetallic layers grow perpendicular to all surfaces, ensuring uniform coverage and protection, even for corners and difficult-to-access areas. This complete coverage means there are no weak points for corrosion to attack.

1.4 Schedule/Availability/Turnaround

Hot-dip galvanizing offers quick turnaround and widespread availability. The galvanizing process is factory-controlled allowing for rapid production regardless of weather - minimizing delays in delivery. Galvanizers are readily available throughout North America ensuring materials can be sourced without long lead times. Furthermore, it is possible to stock standard pieces for quick installation or replacement. This efficiency and availability make HDG steel ideal for projects with tight schedules.

1.5 Aesthetics

Hot-dip galvanized steel has a natural gray finish that blends seamlessly into its surroundings. Initially, it may appear shiny, matte, spangled, or a combination of these. As it weathers, it develops a neutral, non-reflective, matte gray patina (*see Section 6.0 Appearance*). Galvanizing standards prioritize long-lasting corrosion protection over a uniform appearance. Elevated aesthetic requirements are achievable but require early collaboration with fabricator and galvanizer. If the natural gray finish does not suit the project, a duplex system of paint or powder coating over galvanizing offers endless aesthetic options and extended coating life (*see Section 9.0 Duplex Systems*).

2.0. Site-/Application-Specific Design

2.1 Location Factors

Hot-dip galvanizing (HDG) is a widely used method for protecting steel from corrosion in various environments. The performance of HDG coatings that meet industry standards is consistent and reliable, regardless of the galvanizing applicator. Process variables affecting performance have remained stable for more than a century and do not vary meaningfully between galvanizers. However, different environments (atmospheric, buried in soil, embedded in concrete, etc.) present unique challenges and corrosion mechanisms that must be considered to ensure the longevity.

For instance, areas with heavy use of deicing salts, coastal regions, and certain types of soil can be particularly challenging for HDG. In such cases, additional protective strategies may be necessary to ensure long-term performance. Understanding the specific corrosion mechanisms in each environment is crucial for predicting the life of hot-dip galvanized steel and whether any additional protective measures are warranted.

2.2 Longevity & Performance

Since 1926, ASTM Committees A05 (Metallic Coated Iron and Steel Products), G01 (Corrosion of Metals) and others have systematically collected data on zinc corrosion under various atmospheric conditions. These atmospheric exposure tests – conducted throughout North America – have helped quantify corrosion rates and identify key environmental influences, depending on the environment.

Although corrosion rates vary, actual observed rates rarely exceed 0.3 mils per year in the most aggressive environments. For a vast majority of bridge applications, hot-dip galvanized steel protects against corrosion for 50 to 100 years or more.

2.2.1 Relationship Between Coating Thickness and Longevity

Field exposure tests indicate longevity is largely a linear function of the applied coating thickness. Although environmental factors affect the corrosion rate, a thicker coating will last longer in the same environment. It is normal to experience variations in the coating thicknesses achieved, as coating thickness is greatly influenced by the steel's chemical composition rather than the techniques used by the galvanizer. For these two reasons, North American specifications include minimum thickness requirements for galvanizing but do not impose maximum limits.

Considering thicker coatings mean longer life, it is common for specifiers to ask if thicker coatings can be specified to maximize longevity. However, there are practical limitations to this strategy. Although actual coatings often exceed the minimum average coating thickness requirements of ASTM A123/A123M[2], requesting additional thickness is not considered a reliable strategy to increase service life. For planning purposes, it is recommended to evaluate projects initially using the minimum average coating thickness requirements in A123/A123M Table 1 and consider the as-achieved coating thickness for maintenance planning only. Projects requiring greater longevity can also consider a Duplex System (*see Section 9.0 Duplex Systems*).

2 ASTM. (2024). Standard Specification for Zinc (Hot-Dip Galvanized) Coatings on Iron and Steel Products.

2.3 Atmospheric Environments

The corrosion rate of zinc is directly influenced by atmospheric conditions. Key environmental factors include:

- Temperature
- Humidity
- Rainfall
- Pollutants (sulfur dioxide)
- Sheltering Condition
- Air Salinity

None of these factors can be singled out as the main contributor to zinc corrosion, but their combined effect determines the longevity hot-dip galvanized (zinc) coatings provide in various environments.

When exposed to natural wet and dry cycles, galvanized steel forms a protective layer of zinc corrosion products known as the zinc patina. When the patina has stabilized, the passive layer significantly slows further reactions between the coating and the environment. Its formation is essential to the long-term corrosion resistance of HDG coatings.

For nearly a century, both independent and industry testing of galvanized steel samples in industrial, urban, rural, and marine environments have been conducted. These tests – which included varying degrees of chlorides, sulfides and other corrosive elements have yielded an extensive database of real-world performance data for galvanized steel. This database has been used to develop the Zinc Coating Life Predictor (ZCLP) and AGA's Time to First Maintenance (TFM) Chart to predict HDG performance with relative confidence on a macroscopic level.

2.3.1 Zinc Coating Life Predictor (ZCLP)

The ZCLP is a web-based corrosion model (zclp.galvanizeit.org), requiring the input of environmental data such as temperature, airborne salinity, sulfur dioxide concentration, relative humidity, rainfall, and sheltering condition to estimate the corrosion rate. The tool will also predict a TFM of hot-dip galvanized steel using the corrosion rate of a given HDG coating thickness. The ZCLP is based on models developed using statistical methods, neural network technology, and a large international collection of real-world corrosion and environmental data published by ASTM committee G01 on Corrosion of Metals.

The ZCLP requires the user to gather and input environmental data for a particular region or project. In some cases, the data may be difficult to find. If needed, the AGA publishes a free guideline on locating the environmental data and using the ZCLP.[3]

To develop the AGA's TFM chart (*Figure 1,* next page), the ZCLP was used to model five cities each meeting the definitions of the ASTM environment classifications represented by each curve on the chart. Estimated corrosion rates were then averaged to represent environmental classifications and then used to develop each curve. These data points are based on macroscopic environmental data and, thus, may vary from the actual corrosion rate observed, due to site-specific environmental conditions.

Atmospheric Environment Classifications in AGA's Time to First Maintenance (TFM) Chart

Industrial environments are generally the most aggressive in terms of corrosion. Air emissions—such as sulfides and phosphates from vehicles, manufacturing plants, and other sources—accelerate the consumption of protective coatings. Most urban areas fall into this moderately industrial category due to the prevalence of such pollutants.

Tropical Marine environments are found in climate regions where the temperature rarely, if ever, falls below the freezing point of water. Warmer temperatures and high humidity combined with airborne chlorides from nearby bodies of water, intensify corrosion activity. Wind speed, direction, and proximity to the coast further influence the rate at which zinc coatings deteriorate.

Temperate Marine environments are less aggressive than tropical marine environments due to the lower temperature and humidity levels. Chlorides, wind speed, wind direction, and distance from the sea also affect the corrosion rate of zinc coatings in temperate marine atmospheres.

Suburban atmospheres are generally less corrosive than moderately industrial areas. As the term suggests, they are found in the largely residential perimeter communities of urban or city areas and therefore experience lower concentrations of pollutants.

Rural atmospheres are the least aggressive of the five classifications. The minimal presence of sulfur compounds and other pollutants contributes to the longevity of zinc coatings in these settings.

3 A. Fossa. (2022). *The Zinc Coating Life Predictor.* American Galvanizers Association.

2.3.2 Time to First Maintenance (TFM)

Time to first maintenance (TFM) is defined as 5% rusting of the base steel surface, which means 95% of the surface has some zinc coating remaining, and initial maintenance is recommended to extend the life of the structure. According to ASTM A123/A123M, structural shapes ¼-inch thick or greater must have at least 3.9 mils of zinc on the surface, but more often than not, there will be greater than the minimum requirement. Therefore, using the TFM chart (*Figure 1*), hot-dip galvanized structural shapes (>¼-inch thick) provides 70+ years of life to first maintenance even in highly corrosive industrial environments.

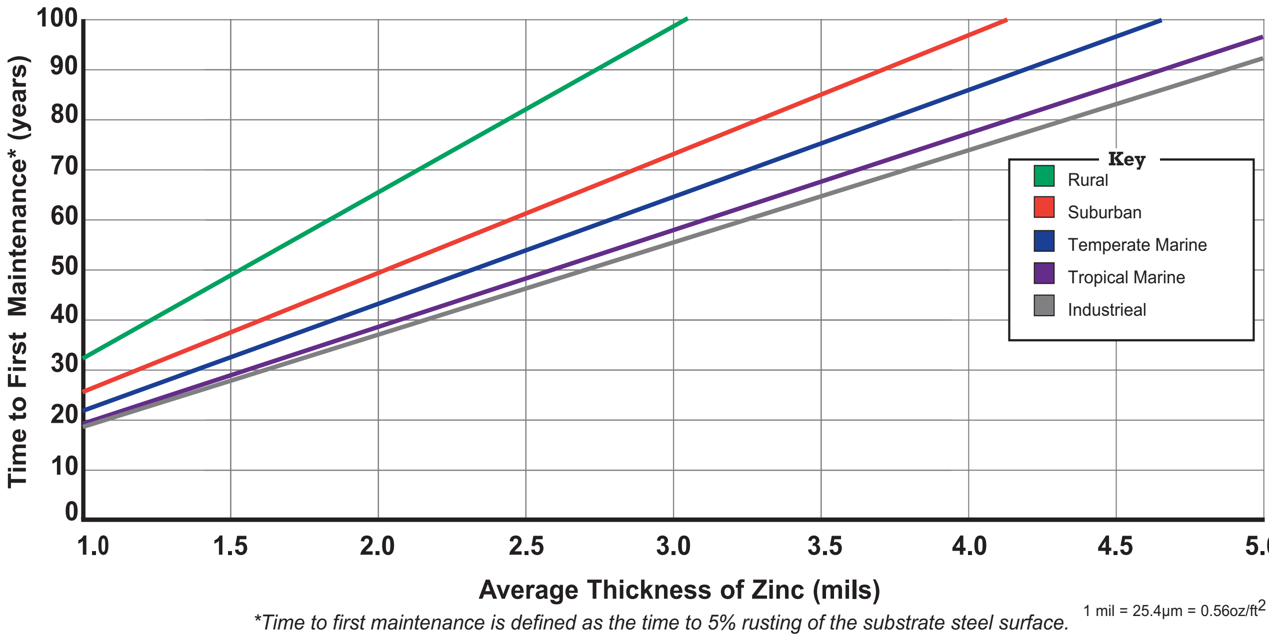


Figure 1: Time To First Maintenance (TFM) Chart

2.3.3 When to Use TFM vs. ZCLP

Both tools (TFM chart and ZCLP) allow specifiers to estimate the time to first maintenance of galvanized steel in atmospheric applications. Concrete embedment, coastal, immersion, heavy road salting, galvanic corrosion, and soil embedment applications are not represented by the TFM Chart or ZCLP.

Here's a quick recommendation for deciding between the tools:

- Use the TFM chart for quick, visual approximations of hot-dip galvanized steel's time to first maintenance based on five atmospheric classifications used by ASTM: rural, suburban, temperate marine, tropical marine, and industrial.
- Use the ZCLP for location-specific predictions of time to first maintenance by inputting environmental data from the project site.

2.3.4 Conservatism in Corrosion Rate Assessment

The continual collection of North American corrosion data since the 1920's has shown a substantial improvement in the corrosion rate of many metals, including zinc, due to anti-pollution campaigns. Modern corrosion rates are lower than historical averages, meaning the projected TFM values determined using the ZCLP and AGA TFM Charts are considered conservative estimates for the 21st century.

In North America, ISO corrosion categories for zinc are considered very broad, where most environments do not exceed an ISO C3 category classification. It is best to use the ZCLP or AGA TFM chart for corrosion rate estimates in this region. Zinc corrosion rates from ISO are available but should be used with caution. ISO 9223 provides

ISO Corrosivity Category	Exposure Time (years)					
	1	2	5	10	15	20
	Maximum corrosion attack for the extended exposure (μm) divided by the exposure time (years), μm/year					
C1	0.1	0.1	0.08	0.06	0.06	0.055
C2	0.7	0.6	0.52	0.45	0.42	0.4
C3	2.1	1.85	1.56	1.36	1.27	1.2
C4	4.2	3.7	3.10	2.73	2.53	2.4
C5	8.4	7.15	6.22	5.46	5.06	4.795

Table 1: Exposure Time Effect on Corrosion Rates ISO 9224

zinc corrosion rates for one year of exposure, while ISO 9224 provides an expanded table of corrosion rates for 1, 2, 5, 10, 15 and 20 year exposure times which shows the corrosion rate after 20 years is approximately half the rate observed after one year (*Tables 1 and 2*). This reflects real-world experience where it is proven zinc's corrosion rate decreases over time due to the development of zinc patina. Therefore, corrosion rates based on the one-year exposure data published in ISO 9223 or the maximum corrosion attack values for extended exposure published in ISO 9224 are considered highly conservative.

	General Desc	Typical Outdoor Environment	Corrosivity	Corrosion Rate
C2	Rural	Temperate zone (dry or cool) with minimal pollution (SO_2 < 5 µg/m^3), short time of wetness, e.g. rural areas, subarctic areas, some arid and desert areas, small villages or towns	Low	0.004 - 0.028 mils/yr 0.1 - 0.7 µm/yr
C3	Urban	Temperate zone, medium pollution (SO_2 > 5 to ≤ 30 µg/m^3) or some effect of chlorides, e.g. urban areas, between 1-30 km (depending on prevailing winds, buildings, vegetation and topography) from the ocean, or within 100 m of sheltered coastal areas with low chloride deposits	Medium	0.7 - 2.1 µm/yr 0.028 - 0.083 mils/yr
C4	Industrial	Temperate, subtropical to tropical, low to high pollution (SO_2 >30 to ≤ 90 µg/m^3) or substantial chloride effect, e.g. < 1 km of the ocean or within 100 m of sheltered coastal areas and outside the splash zone of salt water	High	2.1 - 4.2 µm/yr 0.082 - 0.165 mils/yr
C5	Marine	Subtropical to tropical, periods of time of wetness, very high industrial pollution (SO_2 90 to ≤ 250 µg/m^3) or significant chloride effect/deposits, e.g. industrial polluted areas, jetties and offshore structures, within a few hundred meters of the ocean and certain exposed areas along the coastline	Very High	4.2 - 8.4 µm/yr 0.165 - 0.331 mils/yr

Table 2: Conservative, One-Year Exposure Data According to ISO 9223

2.4 Coastal Environments

Zinc corrosion rates decrease with increasing distance from the shoreline. Hot-dip galvanized (HDG) steel structures located within one mile of the coast, but at least 250 feet away often retain effective corrosion protection for 15-25 years if sheltered from direct sea spray and salt-laden winds[4]. Because wind exposure and temperature further influence corrosion rates, specifiers should consider prevailing wind patterns and yearly average temperature when designing structures near the coastline. Structures within 250 feet of the coast require more detailed evaluation.

In coastal regions where increased or aggressive corrosion is probable, you can consider utilizing a duplex system (paint or powder coating over galvanizing) to extend the service life. A duplex system can provide maintenance-free corrosion protection for 1.5 – 2.3 times the sum of the paint life and galvanizing life (*see Section 9.0 Duplex Systems*). In these environments, some owners benefit from rinsing their HDG steel with potable water. This can be important for sheltered structures that do not benefit from rain rinsing.

Because corrosion behavior in coastal environments varies widely, it's essential to evaluate each project's microenvironment, including wind exposure and proximity to the sea[5] . Early collaboration between the galvanizer, customer, contractor, and duplex applicator (if applicable) can help ensure the desired service life is achieved.

4 A. Sheenan. (2013). *Performance of Hot Dip Galvanizing in Coastal Environments: A Review*. Galvanizers Association of Australia.

5 A. Fossa & T. Langill PhD. (2020). *The Performance of Hot-Dip Galvanized Steel in Water Environments*. American Galvanizers Association.

Coastal environments present challenges for all building materials due to their aggressive nature; however, hot-dip galvanizing remains a durable and effective corrosion protection solution for many coastal applications. Structures designed to facilitate drainage and provide adequate ventilation are known to perform suitably. As with all metals placed in coastal environments, efforts to prevent galvanic corrosion are important for maximum longevity.

2.5 Micro-environments

2.5.1 Vegetation

Galvanized steel develops its zinc patina through periods of wetness and dryness. As long as there is opportunity for the HDG steel to have periods of dryness, there is little impact to the zinc patina and therefore little change in performance. Hot-dip galvanized road components such as guiderail posts, sign posts, etc. are commonly in contact with vegetation and perform well.

2.5.2 Guano

High levels of moisture and ammonia, contact with abrasives, animal waste and urine, combined with dirt and other deposits create highly corrosive microenvironments. The durability and hardness of the HDG intermetallic layers stand up to harsh elements of animal waste, urine, frequent cleaning, rubbing and chaffing from animals and workers.

2.5.3 Deicing Salt

Hot-dip galvanized steel will stand strong against the daily onslaught of sun, rain, snow, and other natural elements, as well as fend off the damaging effects of chemicals from traffic pollution or deicing chemicals. As chlorides are used in all deicing agents, there is potential for increased corrosion rates and general best practices (not unique to galvanizing) should be employed to ensure good drainage away from the structure after a storm event, etc. Where bridges experience significant or heavy road salting, periodic rinsing of the deck, gutters, and bearings with fresh water is sometimes considered by owners (*see Section 8.0 Maintenance*).

2.6 Bridges over Water

When galvanized steel is not constantly exposed to water, but resting above it, corrosion rates tend to be more closely related to atmospheric corrosion rates. Occasional flooding is unlikely to significantly impact the performance of the coating unless the water lies stagnant over the galvanized steel for an extended period. Rinsing or washing the structure with fresh water after a major flooding event is sometimes considered by owners as a way to reduce exposure to corrosive salts left behind by flooding (*see Section 8.0 Maintenance*).

2.7 Railroad and Pedestrian Bridges

Hot-dip galvanized steel is a proven durability solution for railroad and pedestrian bridges. HDG steel is well suited for railroad bridges because its strength and ductility support heavy loads while providing greater stiffness and vibration resistance. Since these bridges are often located in remote or hard to access areas where regular inspection and repair are challenging, galvanizing offers a durable, low maintenance solution. For shorter spans in particular, HDG is advantageous, though design considerations such as progressive dipping and distortion control are key considerations for railroad projects (*see Section 3.0 Structural Design*).

Hot-dip galvanizing is also ideal for pedestrian bridges. Pedestrian structures size often can fit within galvanizing kettle dimensions. And though they often have less wear and tear or corrosivity than highway bridges, pedestrian structures in cold climates may still be subject to deicing salts.

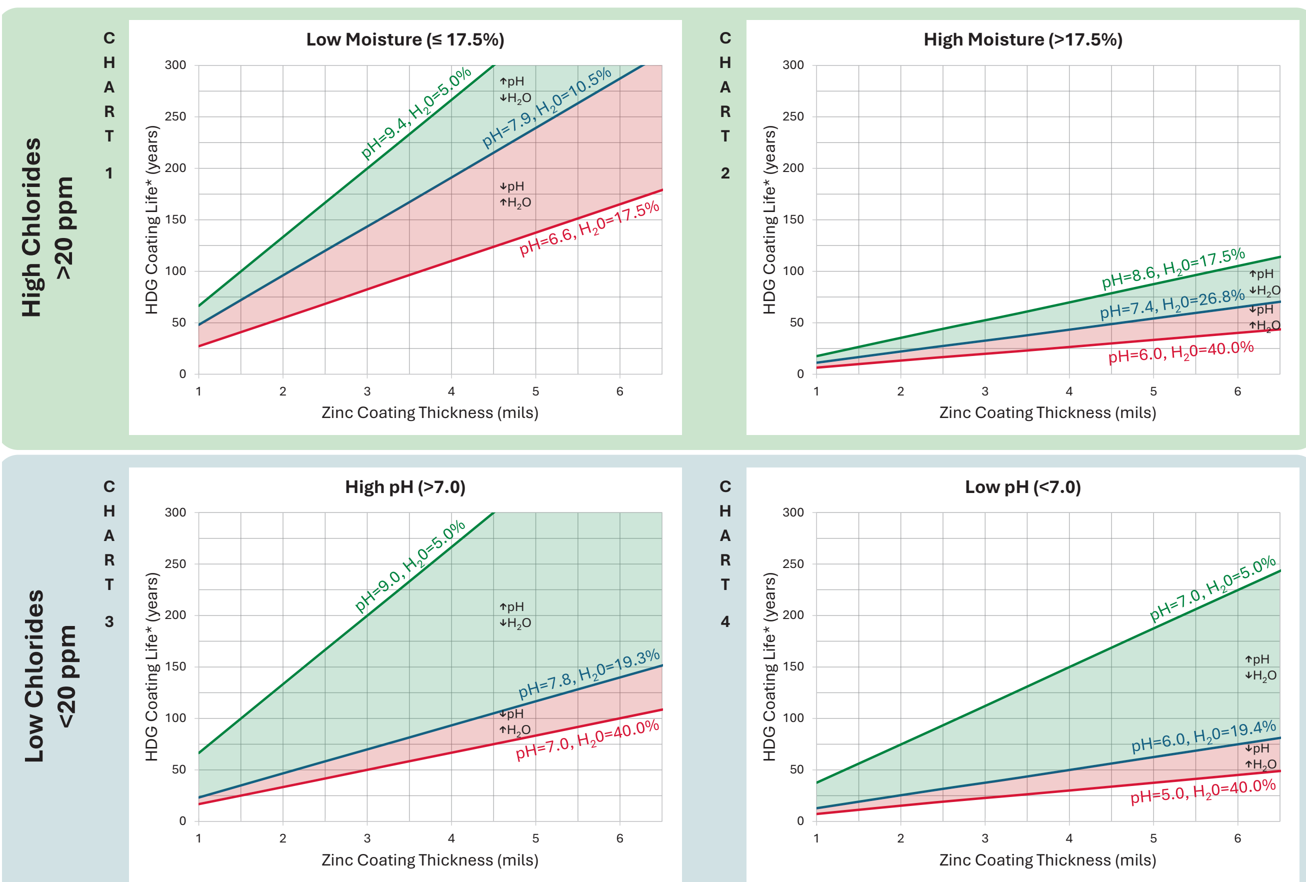
2.8 Soil Embedment & Buried Bridges

HDG steel elements such as H-piles, pipe piles, and sheet piles are commonly specified in bridge projects. In most soil conditions, hot-dip galvanized steel provides a maintenance-free service life of more than 75 years. As a rule of thumb, the best soil types for hot-dip galvanized steel are sandy, coarse soils with low moisture retention, while the worst soil types for HDG steel are dense soils with high moisture retention and swampy soils with high moisture and low pH values.

For a more detailed evaluation, the AGA publishes charts (*Figure 2*) for estimating HDG performance in soil based on real world corrosion data and variables known to have the most profound effect on the corrosion rate: moisture content, pH level, and chloride content[6]. In this context, service life is defined as the time required for total consumption of the zinc coating plus an additional 25%, indicating when structural replacement should be considered. Full soil corrosivity characterization is recommended to properly classify the soil and obtain the information needed to perform a comprehensive assessment using the soil performance charts. Use of in-situ resistivity and pH testing alone can lead to soil misclassification.

Courtesy of Contech Engineered Solutions LLC

For more specific guidance regarding the performance and specification of buried bridges, please contact the National Corrugated Steel Pipe Association (NCSPA) at www.ncspa.org.



*Time to total consumption of the HDG coating

1 mil = 25.4 μm = 0.56 oz/ft^2

Figure 2: Service Life Charts of Galvanized Steel Articles in Soil Applications

6 American Galvanizers Association. (2011). *Service Life of Galvanized Steel Articles in Soil Applications*.

3.0 Structural Design

3.1 Material Considerations & Heat-Treated Steels

Several studies have observed the effects of hot-dip galvanizing on the mechanical properties of various types of steels[7]. Generally, exposure to the galvanizing bath temperature ((820-850°F [438-454°C]) does not change the properties such as steel chemistry, tensile strength, yield strength, or micro-structure of the steel.

However, for articles that are heat-treated at or below galvanizing temperatures (820-850°F [438-454°C]), it may be necessary to test the parts to confirm mechanical properties. The American Institute of Steel Construction (AISC) prohibits hot-dip galvanizing of some high performance steels thermally treated to enhance strength such as ASTM A709/A709M HPS 70W and HPS 100W.

Hydrogen embrittlement is a concern for steels exceeding approximately 150 ksi [1,100 MPa] in ultimate tensile strength, and the galvanizing of ASTM F3125 Grade A490 and Grade F2280 bolts is prohibited. The susceptibility to hydrogen embrittlement is influenced by the type of steel, its previous heat treatment, and degree of previous cold work. The chemical cleaning process presents a potential source of hydrogen which is usually expelled due to the temperature of the zinc in the galvanizing kettle. In some cases, however, the grain size of the steel is too small to allow release of atomic hydrogen. This can later cause cracking due to increased stress at the location of the hydrogen between the grains. Though hydrogen embrittlement is rare, established best practices are provided in ASTM A143 and should be taken to avoid it. Contact the AGA Technical Department and communicate with the galvanizer if there are questions about a product's susceptibility to embrittlement.

3.1.1 Steel Composition & Reactivity

There are no requirements in hot-dip galvanizing specifications related to steel composition. However, it is important to acknowledge steel composition does influence the final galvanized coating. The recommended steel chemistry for hot-dip galvanizing is described in Section 3 of ASTM A385/A385M[8] (*Table 3*).

Element	Recommended % for HDG
Si	< 0.04 % or 0.15% - 0.22%
P	< 0.04%
C	< 0.25%
Mn	< 1.3%

Table 3: Recommended Steel Chemistry for HDG

Steels outside of the recommended ranges can be and are galvanized. However, they are more likely to produce atypical coatings – primarily in thickness and/or appearance. Silicon and phosphorus are two of the elements most likely to impact the coating thickness, finish, and initial appearance of HDG. Elements are not always evenly distributed throughout a steel member and Material Test Reports (MTRs) are one sample taken from the heat and do not exactly represent the composition of the steel surface. Furthermore, during fabrication, steels with different chemistries may be combined. All of these things can lead to localized areas of varying finish or initial appearance of hot-dip galvanizing (*see Section 6.0 Appearance*).

Although MTRs do not allow for precise predictions, they are an effective and economical way to estimate steel reactivity for hot-dip galvanizing. Galvanizers often request MTRs from fabricators to verify the material's chemical composition and configuration in advance. In some cases, this information can help the galvanizer exercise limited control over the coating thickness to minimize flaking associated with excessive coating thickness.

7 M.S. Ostrava & S.V. Banska. *Influence of Hot-Dip Galvanizing Technology on the Properties of Hot-Dip Galvanized Steels.*
BNF Metals Technology Centre & ILZRO. (1975). *Galvanizing Characteristics of Structural Steels and their Weldments.*
Industrial Galvanizers Corporation Pty Ltd. *Does Galvanizing Affect Steel Strength.*

8 ASTM. (2022). Standard Practice for Providing High-Quality Zinc Coatings (Hot-Dip).

Steel mills frequently meet the optimal chemistry ranges for steel to be galvanized. Generally it is not recommended to specify specific steel chemistry as doing so can add significant cost and time, especially for smaller projects. Service centers may have materials satisfying the desired range in stock if specifically requested.

3.1.2 Galvanizing of Weathering Steel

It is possible to successfully galvanize weathering steel, but it is rarely done intentionally to increase the corrosion protection or durability of bridge projects. Rather, weathering steel is typically galvanized for these reasons:

- General availability and cost from a steel supply center
- Individual components for fabrication were only able to be sourced as weathering steel
- An engineer specified ASTM A709 Grade 70W for increased minimum yield strength and not necessarily for the primary method of corrosion protection

Weathering steels exhibit heavier and darker galvanized coatings than traditional carbon steels. Weathering steels tend to have higher levels of silicon (up to 0.40% allowed, but 0.27% to 0.35% common) compared to traditionally galvanized steels. Therefore, thicker, matte gray coatings with little or no spangle are expected. To minimize the potential for excessively thick HDG coatings on fabrications such as girders, or articles >0.5" thick, which are subject to longer immersion times, blast cleaning prior to galvanizing is recommended.

To optimize cost, the galvanizer should be consulted regarding the choice to blast clean before galvanizing, and responsibility for the blast cleaning should be clarified between the fabricator and galvanizers as not all galvanizers have abrasive blasting equipment. The blasting method does not require the specification of a degree of cleanliness nor specific profile parameters, but Commercial Blast Cleaning in accordance with SSPC-SP 6/NACE No. 3 can be used as a guide.

Galvanizing Plant

> **"Where aesthetics are a primary concern, variations in initial coating appearance will become uniform and soft gray as the coatings weather naturally with time.**

3.2 Size Considerations & Options for Galvanizing Longer Spans

Hot-dip galvanizing is a complete immersion process, which means the parts must fit in the zinc bath to be coated. Ultimately, size is limited by the dimensions of the galvanizing kettle, but the kettle dimensions of galvanizers vary. When it comes to galvanizing items longer, wider, or deeper than the kettle, the question "will it fit" is important, but the answer is more nuanced than a simple yes or no. There are options to galvanize oversized pieces, and several AGA resources to guide specifiers through alternative solutions.

3.2.1 Kettle Size & Crane Capacity

In the design or bid phases of a project, it is wise to verify kettle constraints early on. However, for many projects the galvanizing facility is not always known at this stage. In such cases, it is helpful to consider galvanizing kettle sizes local to key project area(s). In North America, there are over 50 galvanizing kettles measuring at least 50 feet in length, and a few exceed 60 feet in length.

Utilize AGA's Galvanizer Locator to identify galvanizers in your area. Kettle sizes are listed along with contact information, making it easy to find an appropriately sized kettle and contact the galvanizer.

For very large items, it may also be necessary to discuss crane capacities with the galvanizer as they can vary between facilities. Additionally, building configuration constraints may factor into material handling at the galvanizing plant, but many have found creative solutions to accommodate oversized pieces using depth, diagonal positioning, and even kettle corners. For fabrications approaching the maximum length permissible by the galvanizer's kettle, these creative handling methods can impact the HDG finish. For example, handling rolled beams and plate girders in the H-orientation with a shallow dip angle is a common strategy to maximize fit within the galvanizing kettle; however, this method is associated with an increased occurrence of runs and skimmings inclusions along the web. Specifiers should carefully weigh these considerations in projects requiring elevated aesthetics to avoid misaligned expectations or additional cost for smoothing. Designers and fabricators are encouraged to discuss available methods and truck loading strategies directly with the galvanizer

3.2.2 Modular Design

Almost any component can be galvanized by designing and fabricating in modules or sub-units suitable for available galvanizing facilities. Designing structures in modules or sub-units to accommodate the galvanizing kettle often provides additional savings in manufacturing and assembly because they simplify handling and transportation. The sub-units can be connected after galvanizing by bolting or field-welding.

3.2.3 Progressive Dipping

If an item is too large for total immersion in the kettle, progressive dipping can be utilized. This process allows each end of the article to be sequentially immersed in the molten zinc[9] . If at least half the article can be submerged, it can be dipped at an angle, flipped, and re-dipped to achieve full coverage with a small overlapping area. In addition to size, the decision to progressive dip should also consider the handling capabilities of the galvanizer (plant layout and overhead crane capacity), the ability to mitigate the risk of warpage/distortion (*see Section 3.4 Avoiding Distortion*), and the acceptability of the finish near the overlap line.


Modular Tub Girder


Modular Truss


Modular Plate Girder

For slender articles or fabrications only a few inches tall, progressive dipping can nearly double the maximum length of steel articles that can be galvanized. However, for larger fabrications (rolled beams, plate girders), progressive dipping may only provide a 15-30% increase in lengths that can be galvanized.

To help in determining progressive dip feasibility, the AGA offers Progressive Dip Charts[10] for a quick estimation and a Progressive Dip Calculator[11] for a more detailed analysis using specific part and kettle dimensions. For example, according to the Progressive Dip Charts, a 40 ft long by 4 ft deep kettle will accommodate a 60 ft long item ≤ 1 ft in height. Still, it's always wise to consult directly with the galvanizer before assuming a large steel item will fit in their kettle[12]

Figure 3: Progressive Dip Line at Installation and after Weathering

9 B. Jones. (2024). *The Progressive Dip Process*. American Galvanizers Association.

10 A. Fossa. (2020). *Progressive Dip Charts*. American Galvanizers Association.

11 A. Fossa. (2020.) *Progressive Dip Calculator.* American Galvanizers Association.

12 A. Fossa. (2016). *Considerations for Progressive Dipping*. American Galvanizers Association.

Progressively dipped pieces often have an overlap area that is visible on the piece. The line or darker area will fade over time as the coating weathers naturally[13] (*Figure 3*). As the overlap area will most likely develop a thicker coating, it is important to consider if the excess zinc will impact a connection point with other pieces and should be avoided, such as for faying surfaces. If required, the excess coating thickness can be buffed or ground down even with the surrounding coating.

3.2.4 Hybrid Zinc Coating Systems

For projects containing a mixture of components suitable and unsuitable for hot-dip galvanizing due to size, a hybrid zinc coating system of HDG and thermal spray zinc (TSZ or metallizing) should be considered for maximum cost efficiencies while leveraging the benefits of both zinc coatings.

On a practical level, this could mean hot-dip galvanizing smaller or more complex components of a project that fit within the kettle while applying TSZ to components that are too large, but otherwise have accessible surfaces for zinc metallizing application. It could also mean hot-dip galvanizing each end of an oversized item, but zinc metallizing any mid portion which was unable to be coated due to size.

In rare instances, the feasibility of hot-dip galvanizing a large fabrication is not considered until after fabrication. At this stage, design changes such as adding a field splice can be difficult, so in most cases this challenge is resolved by changing the coating selection of the oversized component to TSZ or paint while the remainder of the project is hot-dip galvanized. To avoid this outcome, fabrication and kettle sizes should be discussed as early as possible in the design process.

3.3 HDG Process Temperature

During the hot-dip galvanizing process, steel is heated to approximately 820-850°F [438-454°C] for the galvanizing reaction to occur. Therefore, there are some design considerations that mitigate risks associated with exposing steel to the heat of the galvanizing process.

3.4 Avoiding Distortion

During the galvanizing process, steel progresses through a temperature cycle upon immersion into and withdrawal from the galvanizing bath. Because parts are immersed at an angle, uneven heating occurs, creating a temperature profile along the part being galvanized. If the steel has excessive internal stress, the temperature profile allows the stresses to be relieved at different points during the immersion cycle. These stresses may cause changes in the shape or alignment (distortion) exceeding acceptable dimensional tolerances.

Built-up structural members, bracing, expansion joints, fabrications with significant thickness differences between adjoining elements, and asymmetrical fabrications are examples of products with increased risk of distortion during hot-dip galvanizing.

13 B. Jones. (2024). *Examples of Natural Weathering on HDG Appearance*. American Galvanizers Association.

To minimize distortion, follow established, best design practices as much as possible; however, it is not necessary to eliminate every potential risk factor to successfully hot-dip galvanize. In addition to optimizing the initial design, strategies to reduce residual stress during fabrication can be employed as well as implementing specific material handling practices when galvanizing to further mitigate distortion risks.

ASTM A384/A384M[14] specifically outlines design best practices for minimizing distortion. Expanded guidance is provided in the AGA publication *Design of Products Galvanized After Fabrication*[15] and AASHTO/NSBA S8.3 Hot-Dip Galvanizing Specification[16]. Fabrications susceptible to distortion that would prevent their intended use should consider permanent or temporary bracing installed before galvanizing. Bracing options can rely heavily on the galvanizer's experience, meaning bracing options may not initially appear on the design plans or shop drawings. For fabrications prone to distortion, the designer should expect to discuss and approve project-specific strategies with the fabricator and galvanizer, with particular focus on the topics below.

3.4.1 Thickness Ratio

When two steels of different thicknesses are assembled and heated to galvanizing temperature, the thinner steel heats up and expands more quickly than the thicker steel. If the thicker steel restrains the thinner steel from expanding freely, warpage/distortion of the thinner steel can occur. Therefore, steel thicknesses should vary as little as possible throughout the assembly or wherever possible. Another option is to galvanize thick and thin portions separately and join them after galvanizing. Some susceptible fabrications where uneven thickness should be considered before fabrication include at joints, surrounding thinner material with thick framing, unsupported flat sheet assemblies, and plate girders where flange-to-web ratio is more than 3 to 1 (*Figures 4, 5,* and *6*).

3.4.2 Girders

The unique web and flange steel thickness in modern girder design can create specific challenges associated with galvanizing longer spans. These challenges must be considered by the design team to ensure the highest quality galvanized girder is delivered to the job site.

Requirements for additional mitigations intended for the galvanizer should be clearly stated in project documents. It is recommended to specify girders be air cooled after hot-dip galvanizing, and not water quenched, to minimize additional stress from the cooling cycle. Girders should also be laid flat after galvanizing to prevent sagging or bowing due to their weight.

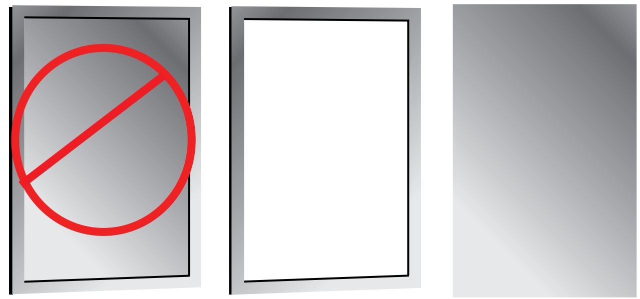


Figure 4
Avoid galvanizing frames containing thinner plates. These parts should be galvanized separately and assembled after galvanizing to minimize the potential for plate warpage and weld cracking.

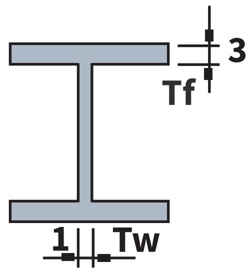


Figure 5
Flange-to-web thickness of fabricated beams (Tf to Tw) should be no more than 3 to 1

Figure 6
Avoid Uneven Thickness at Joints

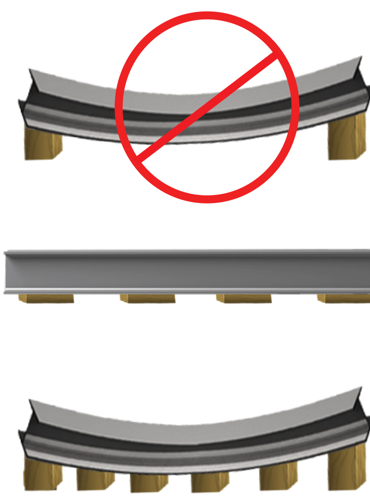


Figure 7
Avoid leaving the mid portion of long and slender products unsupported as sagging can introduce a permanent bow. Rather, use additional supports along the mid-sections to prevent sagging of straight beams. For cambered beams, lay on the strong axis and support with as many blocks as possible

14 ASTM. (2024). Standard Practice for Safeguarding Against Warpage and Distortion During Hot-Dip Galvanizing of Steel Assemblies.

15 American Galvanizers Association. (2023). *The Design of Products to be Hot-Dip Galvanized After Fabrication*.

16 AASHTO/NSBA Steel Bridge Collaboration. (2023). S8.3 Hot-Dip Galvanizing Specification.

3.4.3 Deformed Elements

Elements that were deformed (bent, straightened, curved, etc.) by force, heat, or their combination before galvanizing may distort during galvanizing due to the release of residual stresses from that previous work. Challenges more often arise with asymmetric geometries, such as curved T-sections and curved sections with stiffeners on one side only.

The hot-dip galvanizing process is not known to significantly affect sweep and camber unless there is significant rework during fabrication, increasing the risk of distortion. If needed, diaphragm members attached during construction can be used to draw the girder into place. This is done by welding or fastening the diaphragm steel members to the girder, starting at one end and working to the other.

Laydown after hot-dip galvanizing is also important to retain the camber. To support a positive or negative camber, lay the girder on the strong axis and support with as many blocks as possible (*Figure 7*).

3.4.5 Progressive Dipping

Progressing dipping alone does not cause distortion, but it increases the risk of distortion when other risk factors are involved since the part is exposed to a more extreme temperature gradient. One end of the construction will be in the molten zinc bath, while the other end is exposed to cooler air. When progressive dipping is required, the risk of distortion can be reduced by consulting with the galvanizer to consider the galvanizing bath dimensions and plan for thermal expansion conditions. Analyzing the conditions of the first dip is most critical as the temperature gradient will be greatest.

3.4.6 Tolerances

In rare cases, distortion during galvanizing can exceed acceptable tolerances. If this occurs, it is possible to propose corrections, use the item as-is, modify the item to allow use, or replace it. After correcting the distortion, damages to the coating can be repaired. Regalvanizing is generally not performed unless additional bracing is used because there is significant risk of repeated distortion.

3.5 Press Brake Tub and Folded Steel Plate Girders

Press Brake Tub Girders (PBTG) and Folded Steel Plate Girders (FSPG) are modular, shallow boxes fabricated using hydraulic press breaks or from cold-bent structural steel plate and then galvanized. Concrete deck or other deck options can be placed on the girder before shipping the unit to the bridge site to accelerate construction, or a deck can be cast in place. PBTG and FSPG are an economical, simple solution in short span bridge construction. Details will be available in an upcoming guide to be published by NSBA.

Girder Design Considerations for HDG

- Significant thickness differences between adjoining elements increase distortion risk. Specifically, the flange-to-web thickness ratio of plate girders should not exceed 3 to 1 to avoid distortion of the web during hot-dip galvanizing. Additional bracing stiffeners exceeding the design requirements are commonly specified to further reduce risk of distortion.
- Asymmetric fabrications increase distortion risk and should be avoided where possible. Examples include girders with different steel thicknesses for the top and bottom flanges, girders with flange width transitions, and girders with stiffeners placed on only one side of the web.
- Consider additional bracing for plate girders to resist lateral deformation during galvanizing. While typical rolled beams or plate girders usually do not require special bracing, lightweight plate girders might.
  - Bracing is typically achieved through permanent welded stiffeners, temporary bolted stiffeners using field splice bolt hole or other temporary bracing within 3 feet of girder ends.
- Temporary or permanent lifting points should be placed at quarter points to avoid permanent deflection caused by the self-weight of the product.
- Discuss a plan with the detailer to maximize the venting and drainage designs above the requirements specified in ASTM A385/A385M to assist the galvanizer in achieving best practices around immersion and withdrawal speeds.

Press Brake Tub Girder Bridge

3.6 Bolted Connections

Considerations for hot-dip galvanized fasteners vary according to the connection type, with specific requirements necessary to ensure quality and design requirements. There are also design choices available to ease installation and prevent galvanic corrosion.

3.6.1 Galvanizing Specifications for Fasteners

ASTM A153/A153M[17] and ASTM F2329/F2329M are similar specifications for coating fasteners with hot-dip galvanizing and centrifuging after. Fasteners are centrifuged to remove excess zinc from newly galvanized parts that could inhibit effective mating with complementary fasteners. ASTM F2329/F2329M covers galvanizing of threaded fasteners, washers, and nuts but does not cover galvanizing nails or rivets which are covered in the broader ASTM A153/A153M specification. Outside of this, the major differences between the two specifications are the sampling protocol, coating thickness requirements for various items, inspection procedures, provisions for embrittlement, and the documentation required from the galvanizer.

3.6.2 Bearing Connections

When using bolts < 1 inch in nominal diameter for bearing connections, standard clearance holes sized 1/16 inch larger than the bolt may need to be unblocked or reamed after hot-dip galvanizing to fit the galvanized bolt. For bolts 1 inch nominal or larger, standard clearance holes sized 1/8 inch larger than the bolt and are sufficient to accommodate a galvanized bolt without hole clearing. Therefore, it is common for engineers to receive requests from the fabricator and erector to use 1 inch galvanized bolts or holes sized 1/8 inch greater than the nominal diameter to reduce labor in the field (*see Section 4.4.2 Clearance Hole Sizing*).

3.6.3 Slip Critical Connections

For slip-critical connections, a clearance hole sized 1/8 inch larger than the nominal bolt diameter is recommended, where accounted for in the design, to accommodate a galvanized bolt without hole clearing. For unprepared hot-dip galvanized faying surfaces, it is currently accepted the surface will have a friction coefficient of 0.30, as specified by AASHTO LRFD Bridge Design Specifications[18] (Class C, *Table 4*) RCSC Specification for Structural Joints Using High-Strength Bolts[19] (Class A, *Table 5*). If AASHTO Class D is specified and the means of achieving the higher class is not shown in the plans, the means of achieving Class D must be discussed among the fabricator, the galvanizer, and the designer. Testing and qualification in accordance with Appendix A of RCSC Specification for Structural Joints Using High-Strength Bolts can take several months and is subject to laboratory availability.

According to the AASHTO LRFD Bridge Design Specifications, a creep reduction factor K_c = 0.80 is used in the equation for determining the nominal slip resistance (Rn) of a galvanized faying surface (Class C, μ = 0.30) or duplex-coated faying surfaces utilizing a coating applied over hot-dip galvanizing to produce a higher slip coefficient (Class D, μ = 0.45). This factor is intended to account for bolt relaxation due to creep in the galvanized surface. For all other surface conditions, K_c = 1.

Class C	HDG surfaces. Subsequent treatment (wire brushing) of the galvanized surface is prohibited.	μ = 0.30
Class D	Blast-cleaned surfaces with Class D coatings, such as zinc-rich coatings applied over HDG	μ = 0.45
Class D	HDG surface mixed with unsealed pure zinc or 85/15 zinc/aluminum thermal-sprayed coating (≤ 16 mils)	μ = 0.45

Table 4: AASHTO LRFD Bridge Design Specifications

Class A	HDG surfaces. Subsequent treatment (wire brushing) of the galvanized surface is prohibited.	μ = 0.30

Table 5: RCSC Specification for Structural Joints Using High-Strength Bolts

17 ASTM. (2023). Standard Specification for Zinc Coating (Hot-Dip) on Iron and Steel Hardware.

18 AASHTO. (2025) AASHTO LRFD Bridge Design Specifications, 10th Edition.

19 RCSC. (2020). Specification for Structural Joints Using High-Strength Bolts.

3.6.4 High Strength Fasteners

ASTM F3125 permits hot-dip galvanizing of high-strength structural bolts with the exception of Grades A490 and F2280. While Grade 144 ksi bolts can be hot-dip galvanized upon request, due to the AASHTO creep reduction factor (K_c = 0.80), they are typically offered mechanically galvanized.

3.6.5 Using Other Zinc Coated Fasteners

When possible, specify hot-dip galvanized fasteners for hot-dip galvanized connections to maximize corrosion protection. While other zinc coatings can be specified, differences in coating thickness and longevity should be considered if suppliers offer alternatives like thermo-diffusion galvanizing, mechanical galvanizing, or zinc-flake coating (*Table 6*). Other zinc coatings are often marketed as equal to or better than HDG fasteners. In reality, longevity is largely a linear function of zinc coating thickness, thus hot-dip galvanized steel has more zinc and lasts longer than mechanical galvanizing or thermal diffusion galvanizing. Marketing claims regarding performance are often based on salt spray testing which is unsuitable for evaluating metallic zinc coatings nor suitable for comparing different types of coatings[20].

Each zinc coating application process has advantages and disadvantages and may be appropriate for projects where factors such as precise fit-up, embrittlement and availability are relevant considerations. Do not mix and match zinc coatings on threaded components of a fastener assembly to avoid issues with fit-up and thread engagement.

Zinc Coating	Specification	Metallic Zinc Coating Thickness	Purchasing Considerations
Hot-Dip Galvanizing	ASTM A153/A153M AASHTO M232M/M232 ASTM F2329/F2329M	1.7-2.1 mils (43-54 µm) minimum 3.6 to 7.0 mils typical	Superior corrosion protection, adhesion, and abrasion resistance. Flat washers prone to sticking. Not allowed for F3125 Grade A490. Rotational capacity test considerations.
Mechanical Galvanizing	ASTM B695 Gr. 55	2.0 mils (53 µm)	Lower cost. Uniform, controlled thickness where galling is avoided. Coating thin near edges. Lower adhesion and abrasion resistance. Not allowed for F3125 Grade A490.
Thermal Diffusion Galvanizing	ASTM A1059/A1059M Class 40	1.6 mils (40 µm)	Uniform, controlled thickness. Higher cost. Not allowed for F3125 Grade A490.
Zinc-Flake Coating System	ASTM F3393	n/a – liquid applied coating	Suitable for ASTM F3125, Grade A490

Table 6 : Common Zinc Coated Fasteners for Bridges

3.7 Maintenance

While hot-dip galvanizing is typically considered maintenance free during its coating life (*see Section 8.0 Maintenance*), the AASHTO Guide Specifications for Service Life Design of Highway Bridges[21] includes details on a Service Life Report. This report details the maintenance activities needed to achieve the service life assumed in design.

20 American Galvanizers Association. (2025). *Salt Spray Testing of Hot-Dip Galvanized (HDG) Steel*.

21 T. Murphy et al. (2020). *Guide Specification for Service Life Design of Highway Bridges*

3.8 Avoiding Liquid Metal Assisted Cracking (LMAC)

Liquid metal assisted cracking (LMAC) may occur when a combination of steel characteristics, fabrication detailing and galvanizing processing variables create conditions for brittle cracking of a steel article during hot-dip galvanizing. Although such a combination of factors rarely occurs in practice, known contributing characteristics should be reviewed in the design of bridge superstructures, HSS fabrications and structural supports for signs, luminaries, and traffic signals.

Contributing characteristics include: steel quality, steel composition, abrupt geometric changes, substantial changes in material thickness, levels of residual stress, location of stress concentrations, quality of welding, position and finishing of drilled or punched holes and flame-cut surfaces, size and location of vent/drain holes, dipping speed, immersion times, and galvanizing bath composition.

Where the impact of contributing characteristics can be minimized, the risk of cracking will be reduced. A general approach to minimize risk includes the use of the minimum grade of steel to achieve the design requirements, eliminate design choices known to increase susceptibility to LMAC, optimize fabrication detailing (as achieved through compliance with A385/A385M, A384/A384M, and A143/A143M [22]), reduce the severity of stress concentrations, and follow galvanizing industry best practices.

For products susceptible to LMAC it may be impractical to control all known contributing factors, meaning the risk of cracking is greatly minimized through control of any remaining characteristics which are practical. Additionally, ASTM A143/A143M describes a thermal treatment procedure to relieve residual stress in cold-worked steel fabrications.

Examples of specific practices which may possibly be employed by a mixture of the designer, fabricator, or galvanizer to reduce risk of cracking for parts identified as susceptible to LMAC are in the list on the right.

Mitigations for Structural Steelwork Susceptible to LMAC

- Specify the minimum grade of steel necessary to achieve the design requirements.
- Reduce the severity of stress concentrations, such as increasing bend radii and reduce cold working.
- Drill instead of punch holes.
- Minimize combinations of thick and thin material in the same assembly.
- Reduce susceptibility of distortion according to ASTM A384/A384M.
- Discuss with the detailer a plan to optimize the location of vent/drain holes and maximize hole sizes above the minimum requirements in ASTM A385/A385, thereby enabling the galvanizer to maximize immersion speeds.
- Avoid progressive dipping when susceptible details will be positioned near the overlap region.
- For thermal-cut edges positioned near areas of high residual stress, grind to bright metal before hot-dip galvanizing.
- For thermal-cut edges with surface roughness above 50 µm (2,000 µin) grind to bright metal before galvanizing.
- Consider water jet cutting to avoid introducing a heat affected zone (HAZ) or internal stresses.
- Limit zinc bath tin (Sn) content to 0.1% and combined lead (Pb) and bismuth (Bi) content to 1.5%.
- Minimize galvanizing immersion time where practical.

22 ASTM. (2020). Standard Practice for Safeguarding Against Embrittlement of Hot-Dip Galvanized Structural Steel Products and Procedure for Detecting Embrittlement.

4.0 Detailing

4.1 Coating Thickness Requirements

4.1.1 Minimum Average Coating Thickness

Hot-dip galvanizing standards – ASTM A123/A123M, A153/A153M, and A767/A767M[23] – define the minimum zinc coating required for various steel classes. Coating thickness may be specified by either thickness (in mils or microns) or weight per surface area (oz/ft^2 or g/m^2). The specifications include tables providing specific requirements for thickness or weight per surface area based upon the steel part type and the measured steel thickness. There is no maximum specified coating thickness and it is not recommended or practical to specify one.

4.1.2 Thick Coating Requests

Requests for thicker coatings are possible but cannot be guaranteed by the galvanizer. There are practical limitations to this approach that should be considered prior to specification (*see Section 2.2.1 Relationship Between Coating Thickness and Longevity*). Projects requiring greater longevity can also consider a Duplex System (*see Section 9.0 Duplex Systems*).

4.2 Managing Reactive Steels

Steels containing silicon or phosphorus outside the recommended ranges for galvanizing are referred to as "reactive steels" in the galvanizing industry. These steels tend to develop thicker and rougher coatings compared to steels with the recommended chemical composition (*see Section 3.1.1 Steel Composition & Reactivity*). Reactive steels are often galvanized; sometimes this is intentional or seen as a benefit to achieve increased coating thickness and longevity. However, instances of excessive coating thickness (>20 mils) can potentially affect fit-up between parts or cause appearance concerns. Additionally, excessively-thick HDG coatings can sometimes exhibit a more brittle coating structure which can lead to delamination (flaking) of the coating during transport, assembly, and erection. As steel reactivity affects galvanizing, it is important to consider strategies employed during fabrication to avoid the occurrence of excessively thick coatings on susceptible fabrications (*Figure 8*).

Steel mills frequently meet the optimal criterion for galvanizing but specifying the steel chemistry is not recommended because doing so may add cost and delay delivery, especially for smaller quantities that may not be ordered directly from a mill. Service centers may have material satisfying the desired range in stock if requested. Section 3 of ASTM A385/A385M discusses recommended steel chemistry for galvanizing.

To help avoid excess coating thickness but improve uniformity when highly reactive steels are to be galvanized, abrasive blasting per SSPC-SP 6/NACE No. 3 prior to galvanizing can be used to slightly roughen the surface and reduce the tendency to develop thick coatings. Preblasting steel could be mandated by the contract or mutually agreed between the fabricator and galvanizer.

Fabricators should supply galvanizers with Material Test Reports (MTRs) for all steel to be galvanized. For bridge projects, the topic of steel chemistry can be especially relevant for beams, plate girders, cross-frames, diaphragms, and fabrications made from weathering steel. Knowing material chemical composition and configuration in advance can help the galvanizer prevent flaking that can occur if the coating is too thick, but it is not a guarantee.

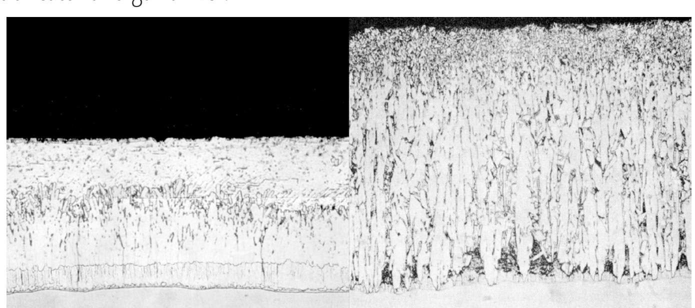


Figure 8: Recommended vs Reactive steel

23 ASTM. (2024). Standard Specification for Zinc-Coated (Galvanized) Steel Bars for Concrete Reinforcement

4.3 Product Identification

Permanent identification markings on fabricated items should be carefully prepared before galvanizing so they will be legible after galvanizing but not disrupt the coating integrity. For bridge projects, ASTM A385/A385M provides a list of acceptable marking practices, with the exception of weld marking unless allowed by contract or for ancillary items.

For temporary fabrication markings, alcohol- or water-based fabrication markers are widely available and designed to dissolve during the galvanizer's cleaning process. Cleaning solutions used in the galvanizing process will not remove paint stick, grease pencil, and other oil-based markers, so these products should not be used for applying addresses, shipping instructions, or job numbers (*see Section 5.1 Surface Preparation*).

4.4 Connections

4.4.1 Oversizing Nuts

Because hot-dip galvanizing is a coating of zinc over bare steel, the original steel becomes slightly thicker. For tapped holes and fasteners, the increased thickness is significant.

Bolts are completely galvanized, but internal threads on nuts must be tapped after galvanizing to accommodate the increased diameter of the coated bolts (*Table 7*). While tapping the nuts after galvanizing results in uncoated nut threads, the zinc coating on the bolt threads will protect both components from corrosion. For economy, nuts are usually galvanized as blanks and the threads tapped after galvanizing.

Nominal Nut Size (Inches) and Pitch	Diametrical Allowance (Inches)
0.250-20	0.016
0.312-18	0.017
0.375-16	0.017
0.437-14	0.018
0.500-13	0.018
0.562-12	0.020
0.625-11	0.020
0.750-10	0.020
0.875-9	0.022
1.000-8	0.024
1.125-8	0.024
1.125-7	0.024
1.250-8	0.024
1.250-7	0.024
1.375-8	0.027
1.375-6	0.027
1.500-8	0.027
1.500-6	0.027
1.750-5	0.050
2.000-4.5	0.050
2.250-4.5	0.050
2.500-4	0.050
2.750-4	0.050
3.000-4	0.050
3.250-4	0.050
3.500-4	0.050
3.750-4	0.050
4.000-4	0.050

Table 7: Overtapping Guidelines for Nuts

4.4.2 Clearance Hole Sizing

Depending on the type of structural connection, clearance holes may be oversized if they are to contain a galvanized bolt after assembly. Section J3.2 of the AISC Manual of Steel Construction: Load and Resistance Factor Design (LRFD manual) states oversized holes are not to be used in bearing type connections. Consequently, this may necessitate unblocking or reaming of the hole after galvanizing when standard holes are specified for bearing connections containing bolts sized < 1 inch in nominal diameter.

For slip-critical connections, a clearance hole sized 1/8 inch larger than the nominal bolt diameter may be specified for all nominal bolt sizes to provide a clearance hole to accommodate a galvanized bolt without hole clearing. Therefore standard clearance hole sizes in accordance with ANSI/AISC 360 Specification for Structural Steel Buildings[24] or AASHTO LRFD Bridge Design Specifications may be specified in slip critical connections involving bolts sized one inch or greater, as the standard hole is already sized 1/8 inch greater than the bolt diameter. For slip-critical connections where the specified bolt size is less than 1 inch, specify oversized holes which are 1/8 inch greater than the nominal bolt diameter (*Table 8*).

24 ANSI/AISC. (2022). Specification for Structural Steel Buildings

When oversized holes are used, the designer must evaluate the reduction in slip capacity due to the reduction in the connection area in order to ensure slip does not occur. Relevant specifications require the design slip resistance be reduced 15% for connections using oversized holes which can lead to additional bolts in the connection design. Furthermore, the use of oversized holes may not be allowed for certain designs such as bolted splices of bridge girders.

For other types of connections that require more hole clearance for alignment reasons, the maximum dimensions for oversizing can be found within Section J3.1, Table J3.3 of ANSI/AISC 360, or in *Table 8*.

Nominal Bolt Diameter (d_b) [in]	Standard Clearance Hole Diameter [in]	Hole Diameter for minimizing reaming after HDG [in]	Maximum Clearance Hole Diameter [in]
1/4	5/16	3/8	3/8
1/2	9/16	5/8	5/8
5/8	11/16	3/4	13/16
3/4	13/16	7/8	15/16
7/8	15/16	1	1-1/16
1	1-1/8	1-1/8	1-1/4
$d_b \geq$ 1-1/8	d_b + 1/8	d_b + 1/8	d_b + 5/16

Table 8: Clearance Hole Guidelines

4.5 Venting & Drainage

The positioning and dimensions of holes for venting and drainage are critical in steel detailing, significantly impacting both the quality and appearance of the galvanizing. For general information on the minimum requirements for venting and drainage, see ASTM A385/A385M and the AGA publication *Design of Products to be Hot-dip Galvanized after Fabrication*[25]. For example, stiffener plates require cropped corners or appropriately sized holes near internal corners (*Figure 9*) while hollow or tubular structures will require holes at intersections, elbows, and base plates.

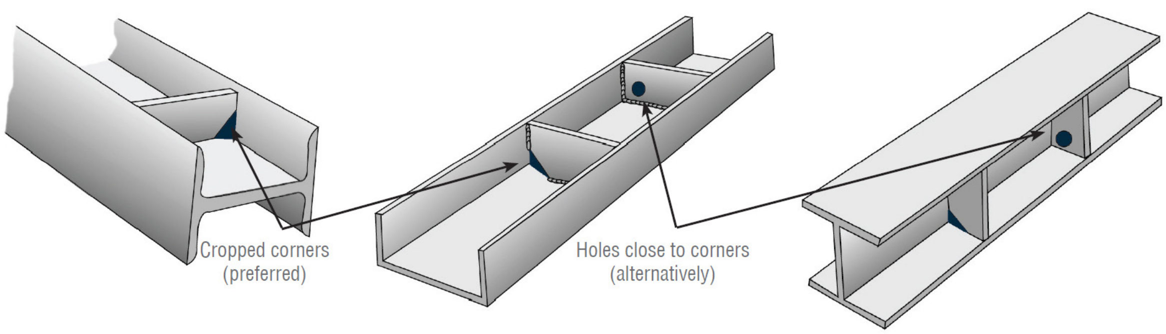


Figure 9: Example venting and drainage of stiffeners

4.5.1 Overlapping Surfaces

When overlapping surfaces with a narrow gap cannot be avoided, fabrications require special considerations to ensure structural integrity, galvanizing quality, and aesthetics near the overlapped area. The available methods are to:

- Seal weld overlapping areas < 16 in^2 (103 cm^2) of steel < ½ in thick or overlapping areas < 64 in^2 (413 cm^2) of steel > ½ in thick. These areas can be seal welded without venting or fear of weld blowout.
- Weld with sufficient venting as required to prevent weld blowout based on steel thickness and size of overlap area, as detailed in ASTM A385/A385M Tables 1 & 2. Then apply and maintain caulking to seal the joint after hot-dip galvanizing and prevent a cosmetic concern known as rust bleeding from the joint.

4.5.2 Rust Bleeding on Cross-frames

One example of a fabrication involving overlapping surfaces is the design of bridge cross frames which include an overlapping area at the connection between the angles and gusset plates. Depending on the steel thickness and size of overlap area, the specified holdback[26] or

25 American Galvanizers Association. (2023). *The Design of Products to be Hot-Dip Galvanized After Fabrication*.

26 FHWA. (2019). Bridge Welding Reference Manual. Figure 142.

otherwise unwelded lengths for this type of design (*Figure 10*) are typically sufficient to prevent issues with weld blowout during galvanizing per ASTM A385/A385MTables 1 & 2. However, rust bleeding is common after galvanizing.

Alternatively, seal welding may be performed in accordance with AASHTO/AWS D1.5M/D1.5 Bridge Welding Code[27] but achieving suitable weld quality can be difficult depending on welding method, part geometry, accessibility of the welding equipment, and welder skill. Any change to weld termination details should be discussed directly between the engineer, fabricator and galvanizer to discuss feasibility and known difficulties related to ensuring seal weld quality.

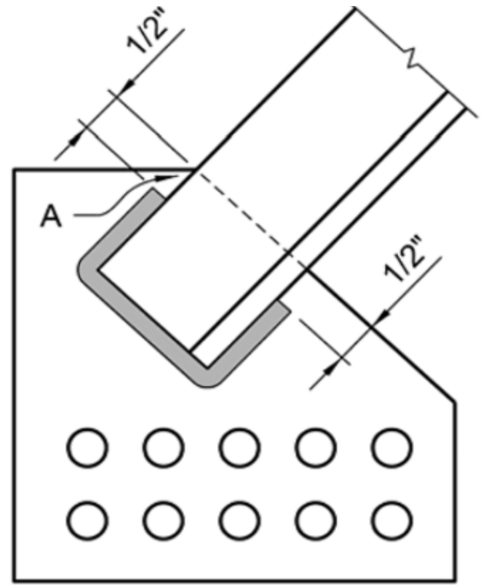


Figure 10: Example bridge cross frame design with weld holdbacks corners

4.5.3 Hole Plugs

If required, tapered plugs made from zinc or aluminum are the recommended method to fill vent/drain holes on galvanized hollow fabrications. Vent holes to be plugged should be drilled to ensure a relatively uniform circumference to accommodate the plug.

Aluminum plugs are considered more economical and any moderate impact on service life due to dissimilar metal interaction may be acceptable for most environments. They are available in sizes ranging from ¼" to 2" in 1/16" increments, although larger sizes are available upon request.

For galvanized products placed in coastal, high humidity, or high chloride environments where maximum longevity is also a primary design consideration, the use of zinc plugs is recommended. They are available from ¼" to 1-1/16" in 1/16" increments and from 1-1/16" to 2" in ¼" increments. Zinc plugs are recommended to achieve custom hole sizes or unique shapes upon request.

In certain circumstances, it may be necessary to create a waterproof or airtight seal. When vent or drain hole plugs are installed by hammering, they are compressed to form an initial seal. For a long-lasting seal, project plans may specify applying silicone caulk or polyurethane sealant around the hole prior to insertion of the plug and subsequent sanding to achieve a finished surface.

4.6 Lifting Points for Galvanizing

Large assemblies are usually supported by chain slings or by lifting fixtures. Special jigs and racks are also commonly used to simultaneously galvanize large numbers of similar items. Providing lifting points where possible will reduce or eliminate chain or wire marks that can be left on an item when no lifting points are present. If no lifting points are provided, any marks, which are usually fully galvanized, can be touched up if desired for aesthetic reasons. It is also good practice to discuss the weight-handling capacity with the galvanizer to ensure capability and optimal locations for lifting points which allow for highest galvanizing quality.

For longer articles such as girders, lifting should occur at the quarter points to avoid permanent deflection caused by the self-weight of the product (*Figure 11*). For smaller parts, extra holes or bolted attachments are used to provide appropriate lifting points.

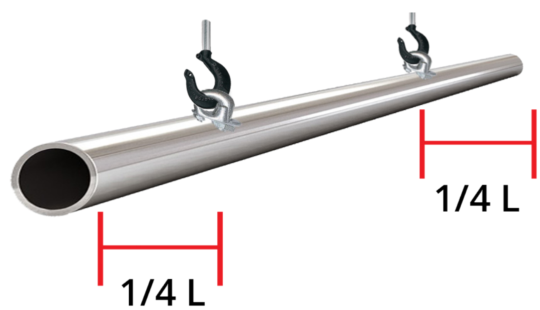


Figure 11: Lift at quarter points along the product

4.7 Dissimilar Metals

The HDG coating is primarily comprised of zinc and zinc alloys, but is sometimes placed in contact with other metals, including stainless steel, aluminum, and uncoated weathering steel. It is important to evaluate the combination of galvanized steel with other metals to determine if galvanic corrosion is of concern[28], although this topic tends to be most relevant to bridge/highway projects in the context of repairs and retrofit projects.

27 AASHTO/AWS. (2020). Bridge Welding Code

28 American Galvanizers Association. (2025). *Dissimilar Metals Corrosion with Zinc*.

There is no fear of galvanic corrosion when galvanized steel is in contact with other zinc coatings. Common examples in bridge/highway projects include the use of mechanically galvanized bolts to connect high-strength bolted connections, and connections between thermal sprayed zinc (TSZ) bridge girders and HDG cross-frames. As coating longevity is largely a linear function of zinc coating thickness, the component with the thinnest zinc coating will be the first to experience corrosion.

When HDG bolts are used in combination with UWS, zinc will initially sacrifice itself until the UWS patina develops. HDG parts have enough zinc thickness to last until the weathering steel patina develops with only minimal loss in coating life. As a result, UWS and HDG may be combined using any surface area ratio[29].

HDG steel may be successfully combined with painted steel if it is diligently maintained. Should painted surfaces combined with galvanized fasteners experience damage or weathering of the paint, the exposed galvanizing may corrode sacrificially to protect bare steel in direct contact while unexposed bolt surfaces (threads and the undersides of nuts or bolts) remain protected from corrosion.

4.8 Masking to Prevent the HDG Coating

For some purposes, intentionally ungalvanized areas are required. Masking products are high-temperature paints, caulks, and tapes applied to specific areas of steel when the galvanized coating on those areas would interfere with the end use of the product, or when additional work needs to be done on masked areas and a galvanized coating would make the work more difficult or expensive. Common examples in bridge/highway projects include:

- areas that will be welded after HDG
- field installation of shear studs after HDG
- faying surfaces

Masking materials should be applied in accordance with the manufacturer's instructions. Either the fabricator or galvanizer can apply masking, but best practice is to establish a communication plan regarding the location of masked areas.

Masking materials are known to remain mostly intact at high temperatures, but due to the relatively high galvanizing temperature it is not possible to ensure masked surfaces will be 100% free from the HDG coating. For critical surfaces, additional work may still be required to remove any unwanted galvanizing. AGA publishes a list of recommended masking materials, but it is recommended the galvanizer select the masking material[30].

Masked Beam

4.9 Shear Studs

There are some structure owners that allow or permit welding of studs prior to hot-dip galvanizing. When it is required to perform field installation of studs after hot-dip galvanizing, practical options include:

- Apply masking to the entire top flange, except for 1-to-2 inches along each edge
- Apply masking at each stud location or stud row
- Grind as needed for each stud in the field to remove the galvanizing

In these cases, it is not common to remedy or coat the top flange after shooting the studs. The concrete is poured, and little to no moisture is expected to travel all the way down to the flange surface. For this reason and to avoid staining, it is recommended to stop masking application 1-to-2 inches from the edges along the top flange surface.

AASHTO/NSBA S8.3 Hot-Dip Galvanizing Specification addresses additional considerations for field-applied shear studs in Section 6.5, and The Steel Construction Institute (SCI) publication Welding of Shear Studs to Galvanized Steel Beams[31] summarizes the history of technical challenges associated with stud welding through hot-dip galvanizing.

29 H.E. Towsend, et. al. (1998). *Atmospheric Corrosion Performance of Hot-Dip Galvanized Bolts for Fastening Weathering Steel Guardrail.* NACE.

30 B. Jones and B. Duran. (2025). *Masking Products for Galvanized Steel.* American Galvanizers Association.

31 Steel Construction Institute. (2011). *Welding of Shear Studs to Galvanized Steel Beams.*

4.10 Thermally cut edges

Thermally-cut edges satisfying the requirements of AASHTO/AWS D1.5M Bridge Welding Code are suitable for hot-dip galvanizing. However, the coating developed on the edge, particularly on thicker pieces, may be of aesthetic concern or present challenges (*Figure 12*) in preparing a Duplex System (*see Section 9.0 Duplex Systems*).

Where the additional cost to prepare cut edges can be justified, one method to achieve a higher quality galvanized finish along thermally cut edges is to grind select edge surfaces, which should be clearly indicated in the shop drawings. Grinding should be performed at least 1⁄16 inch into the parent material to remove hardness down to Vickers 275.

Figure 12: Example of HDG coating appearance formed over unprepared flame-cut edge

4.11 Flame Cut Copes

Flame-cut copes with small radii are prone to cracking due to residual stress and a rough surface (*Figure 13*). To reduce this risk, use a minimum radius of 1 in. (25 mm) or larger for cope cuts as required by ASTM A143/A143M. Additionally, ASTM A385/A385M includes information on a thermal treatment which can be used prior to galvanizing for large sections, but should be indicated on the shop drawings.

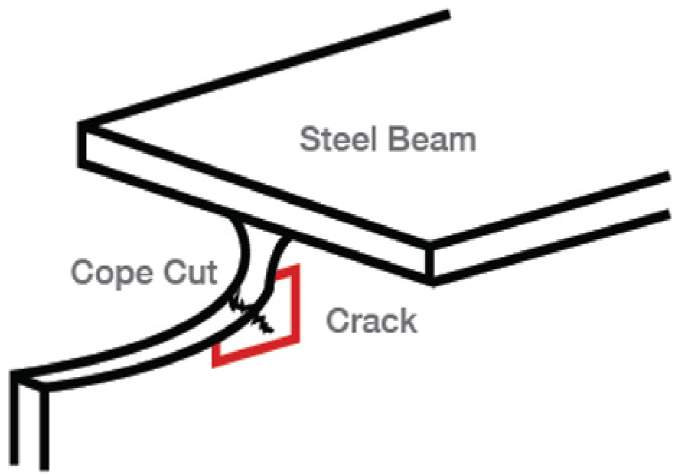


Figure 13: Cope cracks in structural steel beams after galvanizing

4.12 HDG Repair & Materials

ASTM A780/A780M[32] describes three acceptable materials for touch-up and repair of hot-dip galvanized steel: zinc-based solder, zinc-rich paint, or zinc-spray (metallizing). Each method can deliver durable results whether applied at the galvanizing plant or in the field (*see Section 8.1 Field Repair of HDG Coatings*). ASTM A780/A780M does not address aesthetics of galvanizing repairs, and repairs are not expected to match the surrounding HDG coating. Additional considerations may be appropriate for field repairs *(see Section 8.1 Field Repair of HDG Coatings*) or duplex systems (*see Section 9.0 Duplex Systems*).

For more information on applying HDG repair materials in accordance with ASTM A780/A780M to achieve durable HDG coating repairs, refer to the AGA Touch Up & Repair video series[33]. These videos provide highly beneficial visual aids to those needing assistance with touch-up and repair, whether in the plant or the field.

4.13 Painting

To ensure proper adhesion and durability of paint over galvanized surfaces, shop drawings should refer to ASTM D6386[34] . This standard contains a list of surface conditions that need to be smoothed or remedied prior to painting. Additional guidance is available in the AGA publication *Preparing HDG Steel for Paint*[35] or *see Section 9.0 Duplex Systems*.

32 ASTM. (2020). Standard Practice for Repair of Damaged and Uncoated Areas of Hot-Dip Galvanized Coatings.

33 American Galvanizers Association. (2017). *Touch-Up and Repair of Hot-Dip Galvanized Steel*.

34 ASTM. (2022). Standard Practice for Preparation of Zinc (Hot-Dip Galvanized) Coated Iron and Steel Product and Hardware Surfaces for Painting.

35 American Galvanizers Association. (2021). *Preparing HDG Steel for Paint*.

5.0. Fabrication & Construction

5.1 Surface Preparation

Surface preparation by both the fabricator and galvanizer is critical to hot-dip galvanizing, as the zinc will not react with unclean steel surfaces. Any failures or inadequacies in surface preparation are immediately apparent when the steel is withdrawn from the zinc bath, as the unclean surfaces will not be coated.

The galvanizer's chemical cleaning process is used to remove mill scale, other surface oxides, and organic contaminants such as dirt, grease, and oils. However, there are some surface conditions the galvanizer's process is unable to remove or remedy. The materials (right) should be avoided or removed by the fabricator prior to delivery at the galvanizing facility to prevent bare spots in the coating.

Water-soluble markers, ink, and chalk stick are recommended for temporary identification and do not need to be removed prior to hot-dip galvanizing. Some solvent-based anti-spatter sprays are suitable such as Weld-Aid Weld Kleen HD.

5.1.1 Abrasive Blasting Before Galvanizing

Abrasive blasting prior to hot-dip galvanizing (either by the galvanizer or fabricator) is not required for successful hot-dip galvanizing, but is sometimes specified strategically for certain fabrications in bridge/highway projects:

- Fabrications containing contaminants which cannot be removed by the galvanizer's chemical cleaning
- Fabrications composed of weathering steel
- Built-up plate girders and rolled beams composed of reactive steel

For weathering steel and other reactive steel chemistries, abrasive blasting helps to avoid heavy coating thickness unless material test reports (MTRs) indicate the steel is potentially non-reactive (*see Section 4.2 Managing Reactive Steels*). This method does not require the specification of a degree of cleanliness nor specific profile parameters; however, Commercial Blast Cleaning in accordance with AMPP SSPC-SP 6/NACE No. 3 can be used as a guide. Any rust formed after abrasive blasting and before HDG is not an issue, because it is removed later during the galvanizer's chemical cleaning and does not significantly affect the anchor pattern.

Blast cleaning before hot-dip galvanizing may also be specified to enhance aesthetics or promote thicker galvanized coatings for low-silicon or aluminum-killed steels. These strategies are unusual for bridge/highway projects.

Avoid or Remove Prior to HDG

- Welding by-products (slag, spatter, and other residues)
- Anti-spatter sprays containing silicone
- Paint stick, grease pencil, crayon, or other oil-based paints and markers
- Stickers
- Burrs (could include excessively rough edges from flame cutting)
- Very heavy or extremely adherent mill scale
- Mill coatings such as varnishes or lacquers
- Epoxies, types of vinyl, and asphalt
- Sand and other impurities on castings
- Heavy deposits of wax or grease
- Rapid-dry ink (non water-based stencils)

Figure: Blasting Before HDG

5.2 Welded Connections

5.2.1 Welding Before HDG

When welding before HDG, a high-quality hot-dip galvanized coating is achieved through welding electrode selection, cleaning of welding residues from the weld area, and best practices regarding the venting of overlapping surfaces. For more information, see AGA Publication Welding & Hot-Dip Galvanizing [36].

Welding rods high in silicon may cause excessively thick and/or darkened galvanized coatings to form over the weld. AGA publishes a list of recommended welding electrodes known to promote standard coating thicknesses and a more uniform appearance (*Table 9*).

Welding residues and silicone-based anti-spatter sprays must be removed by the fabricator prior to delivery at the galvanizing facility. Alternatively, solvent-based anti-spatter sprays are suitable such as Weld-Aid Weld Kleen HD.

Best practice is to avoid large overlapping surfaces welded together with narrow gaps (*see Section 4.5.1 Overlapping Surfaces*). ASTM A385/A385M addresses specific details for overlapping surfaces and the necessary venting requirements. When these best practices are not followed, weld rupture, harm to galvanizing personnel, or rust bleeding may occur. With rust bleeding, entrapped cleaning chemicals can interact with the steel and moisture in the environment, causing oxides to seep from the joint later on. Rust bleeding is primarily a cosmetic concern and any associated staining can be cleaned. To prevent further staining, erectors may be asked to seal the joint using a silicone caulk.

Welsing Process	Lincoln Electric welsing Electrode	AWS Designation	Silicon (Weight%)
SMAW	Jetweld 2 Fleetwood 35 LS	E6027 E6011	0.22-0.26% 0.10-0.18%
SAW	L60-860	F6A2-EL12	0.24%
FCAW	NR-203 NiC+ NR 203 MP NR 233 NR 311	E71t8-K2 E71t-8j E71t-8 E70t-7	0.06% 0.22-0.26% 0.19-0.20% 0.12-0.13%

Table 9: Recommended Welding Electrodes For HDG

One example of a common bridge fabrication involving overlapping surfaces is the design of bridge cross frames which include an overlapping area at the connection between the angles and gusset plates (*see Section 4.5.2 Rust Bleeding on Cross-frames)*.

5.2.3 Welding After HDG

Welding after galvanizing is considered for planned field-welded connections, fabrications exceeding the dimensions of the galvanizing bath, and fabrications with higher risk of distortion.

Galvanized steel may be welded by all common welding techniques. American Welding Society (AWS) D-19.0, Welding Zinc Coated Steel[37], calls for welds to be made on steel free of zinc. The coating should be removed at least 1-to-4 inches from either side of the intended weld zone and on both sides of the workpiece. This is commonly achieved by masking (*see Section 4.8 Masking*). The coating removal can also be achieved by grinding in the field, but labor costs and difficulty verifying coating removal are often raised as challenges for the erector.

After welding, the HDG coating should be repaired with material in accordance with ASTM A780/A780M (*see Sections 4.12 HDG Repair & Materials and 8.1 Field Repair of HDG Coatings*). For more details and information on safety when welding HDG steel, see the AGA Publication *Welding & Hot-Dip Galvanizing*.

36 American Galvanizers Association. (2009). *Welding & Hot-Dip Galvanizing.*

37 AWS. (1972). Welding Zinc-Coated Steels

5.3 Bolted Connections

Considerations unique to HDG are necessary to ensure fit-up, coefficient of friction, and proper tensioning.

5.3.1 Hole Reaming

Standard clearance holes for nominal bolts sizes 1 in. or less may require reaming and touch-up on some holes to accommodate a galvanized bolt, particularly when ¾ in. or 7/8 in. galvanized bolts are specified. Reaming should remove excess coating thickness but not completely remove the coating.

5.3.2 Fit-Up

It is best practice to acquire nuts and bolts from the same supplier and request all nuts, washers, and bolts be pre-assembled and lubricated. This practice confirms proper fit of the bolt to the nut and washer and to ensure the nuts will turn freely on the bolt threads.

5.3.3 Faying Surfaces

Faying surfaces must be free of dross, runs, and other prominences exceeding 1/16 in. in height which interfere with sound contact between the connected plies. Even if the galvanizer is required to perform initial smoothing of these surface conditions, final smoothing may be necessary during installation.

Wire brushing for the purpose of roughening HDG faying surfaces is no longer required for slip critical connections, and is now prohibited.[38] For this reason, galvanized faying surfaces shall not be power wire-brushed to avoid polishing the surface. Hand wire-brushing is only allowable to remove areas of visible debris.

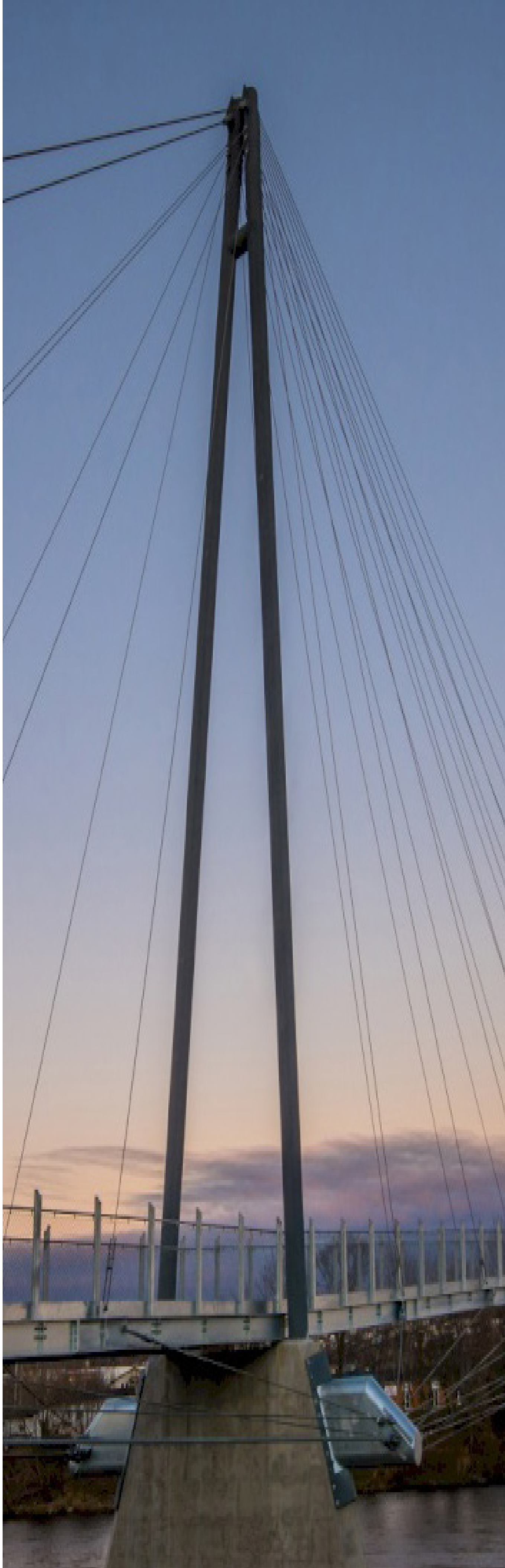
5.3.4 Rotational Capacity (ROCAP) Testing

HDG increases the friction between the bolt and nut threads and reliable tensioning can be difficult without proper lubrication. For HDG high-strength structural bolts, rotational capacity (ROCAP) testing in accordance with ASTM F3125 is specified for matched assembly lots (bolt, lubricated nut, washer) to ensure galling is prevented and the assembly will develop the desired pretension load. The ROCAP test is also required for most bridge projects under AASHTO or State DOT Bridge/Highway specifications. This test is in addition to the pre-installation verification testing for the installation method. Although bolt manufacturers can offer ROCAP testing prior to shipping when supplying matched assemblies, this does not necessarily relieve the contractor from performing this test at the job site. Individual DOT specifications address possible corrective actions in the event of a test failure.

5.3.5 High-Strength Bolt Storage

Some lubricants are water soluble, so it is recommended galvanized high-strength bolts and nuts be shipped and stored in sealed containers. Bolting components with wax-type lubricants should be kept away from high temperatures which could affect the lubricant.

38 AASHTO. (2025) AASHTO LRFD Bridge Design Specifications, 10th Edition. RCSC. (2020). Specification for Structural Joints Using High-Strength Bolts.



5.4 Material Handling

5.4.1 Wet Storage Stain (WSS)

When newly galvanized articles are deprived of adequate airflow, moisture can be trapped on the coating surface altering the natural development of the zinc patina. The trapped moisture presents a different set of conditions creating a reaction that will rapidly create a white powdery zinc corrosion product on the surface known as Wet Storage Stain (WSS). Although unsightly, it is not recommended to remove WSS unless necessary, such as in preparation for a Duplex System (*see Section 9.0 Duplex Systems)*. WSS is not detrimental to the hot-dip galvanized coating and will eventually weather out after installation to a uniform appearance over time[39].

For projects with heightened aesthetic requirements, avoid nested stacking and store HDG steel off the ground on dunnage. For wood it is preferable to use dry, non-resinous (poplar, ash, and spruce) and avoid acidic or resinous (sappy) wood (cedar, pine, fur) which will stain the coating.

Figure 14: Natural Weathering of Wet Storage Stain

The left photo shows two pieces of guiderail galvanized in the same batch in December. The guiderail section on the right was stored under cover with free flowing air, while the section on the left was exposed to moisture that was trapped and developed wet storage stain. Then the two pieces were hung side by side to weather naturally, Three months later, in March, the two pieces look identical as both pieces reacted with the environment to develop the zinc patina, which is matte gray and provides incredible corrosion resistance.

5.4.2 Superficial Rust Stains

Uncoated chains, banding, or other steel packaging techniques cause superficial staining when used without cushioning. Forklifts are another potential source, although difficult to avoid. Superficial rust stains can be cleaned and are not detrimental to the hot-dip galvanized coating but tend to cause unnecessary alarm at the jobsite.

5.4.3 Handling Damage

Flaking may occur when thicker HDG coatings, associated with reactive steel chemistry, are roughly handled (*see Section 7.2.1 Flaking*). Should flaking occur during shipping, handling, or bolt tensioning, best practice is to repair the coating in the field using a repair material in accordance with ASTM A780/A780M. Flaking is not known to continue after installation.

39 American Galvanizers Association. (2014). *Wet Storage Stain: A Guide to Minimizing and Treating Wet Storage Stain on Hot-Dip Galvanized Steel*.

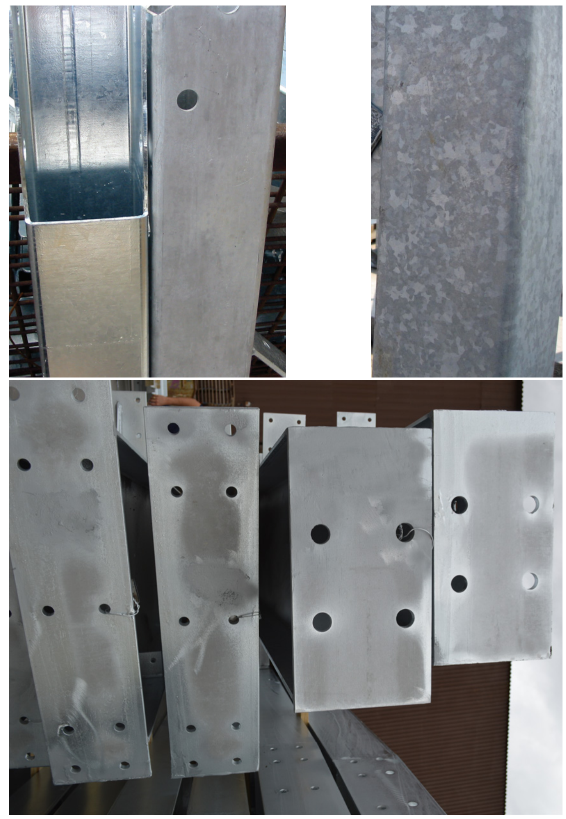
6.0. HDG Appearance

6.1 Initial Appearance

Several factors within and outside of the galvanizer's control can affect the finish and appearance of hot-dip galvanized coatings. In addition to variances in appearance (shiny, matte, spangled, or a combination), there are surface conditions unrelated to the HDG's quality or corrosion resistance which can be visible. The AGA offers a number of resources to understand these conditions and their impact on the coating including the *Inspection of Hot-Dip Galvanized Steel Products*[40], free online Inspection Course and Inspection App.

Steel chemistry, cooling rates, and steel processing/fabrication techniques are major factors influencing the final appearance of HDG steel. Steel chemistry, particularly silicon and phosphorus levels, plays a crucial role as these elements catalyze coating growth. Reactive steels typically develop thicker coatings that are initially matte gray or mottled in appearance. In contrast, steels with recommended steel chemistry for galvanizing generally develop coatings that are initially bright and shiny (*see Section 3.1.1 Steel Composition & Reactivity*). Additionally, steel processing methods like rolling, cutting, punching, and welding introduce stresses and impurities that can affect the initial galvanizing finish.

The cooling process also impacts the initial appearance. Thinner areas and outer edges cool rapidly, resulting in a bright/shiny free zinc (eta) layer, while thicker areas or connected pieces stay closer to bath temperature longer, leading to a matte gray finish.



Initial HDG Coating Appearances

Upper Left: Shiny vs Matte
Upper Right: Spangle
Bottom: Mixed/Mottled

6.2 Natural Weathering

Although HDG may have a variety of initial appearances from bright and shiny, matte, spangled, mottled or a combination of these, over time, all HDG coatings transition to a uniform, matte gray finish due to exposure to the atmosphere. This change typically occurs within six months to two years as the coating develops a protective zinc patina during exposure to natural wet/dry cycles. Once formed, the zinc patina has a uniform matte gray appearance, evening out any initial differences (*Figure 15,* next page).

> **"Variations in initial coating appearance will transition to a uniform, matte gray as the coating is exposed to the atmosphere and develops the zinc patina.**

Other surface conditions, such as oxide lines and progressive dip overlap lines, may also be observed but will weather out over time. Oxide lines appear when a product is not withdrawn from the kettle at a constant rate. This is typical for large articles, complex shapes, and items with poor drainage. Oxide lines are purely visual and do not impact the corrosion protection of the part. Articles which are galvanized by progressive dipping will result in a visible overlap area. Overlap areas often appear darker and have a thicker coating as the area is in

40 American Galvanizers Association. (2016). *Inspection of Hot-Dip Galvanized Steel Products.*

the kettle during the first and second dip. This difference in appearance will become less noticeable over time as the product weathers (*see Section 3.2.3 Progressive Dipping*).

Figure 15: Natural Weathering of Mottled Initial Appearance

The left photo shows the canopied walkway at Mark Twain Elementary in Riverside, CA at installation in October 2006. The right photo shows the same canopied walkway in June of 2009. The beams are now uniformly matte gray with little to no visible difference in appearance.

It is difficult to match touch-up and repair materials to the appearance of the galvanized coating. They are usually not an exact match initially but will provide a more consistent appearance once the galvanized coating develops the zinc patina and becomes matte gray. Specifiers and/or fabricators can discuss touch-up materials with the galvanizer before galvanizing to decide on the preferred aesthetic as there are options to try to match a brighter initial finish with the understanding it may not match the coating once it weathers.

Weathering of Repaired Materials

6.3 Maximizing Aesthetics

The galvanizing standard ASTM A123/A123M ensures hot-dip galvanized coatings provide consistent corrosion resistance, focusing on quality and performance rather than aesthetics. If elevated aesthetic requirements are needed, design, fabrication, and galvanizing techniques should be discussed in a pre-design meeting with the designer, fabricator, and galvanizer[41]. For highly visible pieces, consider a duplex system –painting or powder coating over the galvanized coating – for a uniform appearance, color options, and extended corrosion protection.

Discussion Points to Maximize Aesthetics

- Use Custom Category Requirements
- Identification & Marking of Parts
- Steel Chemistry
- Design & Fabrication for Optimal Aesthetics
- HDG Processing Methods
- Finish & Surface Smoothing
- Duplex Systems
- Handling, Storage, & Wet Storage Stain (WSS)
- Inspection
- Coating Repairs at the Galvanizing Facility
- Coating Repairs at the Jobsite

41 American Galvanizers Association. (2021). *Hot-Dip Galvanized Architecturally Exposed Structural Steel Specifier's Guide.*

7.0. In-Service Inspection Recommendations

Once in place, all bridges require periodic inspection and assessment of the bridge condition. When inspecting hot-dip galvanized steel in the field, the inspector should be aware of potential accelerated corrosion areas, and aesthetic surface conditions and whether they are a concern.

Inspection of HDG bridges is straightforward, primarily focused on the evaluation of coating thickness and a visual inspection of areas known to potentially experience accelerated corrosion. This section reviews information specific to hot-dip galvanized steel to be considered in addition to the requirements found in the National Bridge Inspection Standards, the AASHTO Manual for Bridge Evaluation, state specifications, or project-specific requirements.

7.1 Inspection Procedures

During routine maintenance inspection of galvanized steel in the field, you may observe differences in appearance. Typically, these are purely aesthetic differences and not cause for concern; however, others may require attention and/or maintenance. This section addresses practices and issues related to HDG structures that are already in service, rather than newly galvanized steel. For detailed information on a broader list of common surface conditions encountered during initial HDG inspection, refer to AGA publication *Inspection of Hot-Dip Galvanized Steel Products*.

7.1.1 Methods for Corrosion Protection Assessment

ASTM E376[42] provides information on acceptable instruments, measurement techniques, and factors interfering with accuracy of the measurement. Coating thickness measurements are used to estimate years remaining before the coating will require maintenance or full replacement (*see Section 2.0 Site*).

ASTM A896/A896M is the standard practice for conducting case studies on galvanized structures. It provides a framework for evaluating the performance of a galvanized coating over time.

7.1.2 Areas Requiring Visual Inspection

In addition to taking coating thickness measurements, the galvanized coating can be visually inspected for signs of accelerated corrosion in specific areas:

- Crevices
- Areas where water pools or road salts collect
- Previously repaired areas
- Dissimilar metals in contact

7.2 Common Aesthetic Concerns Observed During Maintenance Inspections

7.2.1 Flaking

Flaking (*Figure 16*) takes place when a brittle or excessively thick galvanized coating, usually associated with reactive steel chemistry, is impacted or handled roughly causing an area of coating to flake or delaminate. Shipping and installation are traditionally when most flaking occurs because this is when the steel is likely to

Figure 16: Flaking

42 ASTM. (2019). Standard Practice for Measuring Coating Thickness by Magnetic-Field or Eddy Current (Electromagnetic) Testing Methods.

experience impact forces. If flaking occurs, the flaked area can be inspected to determine the remaining coating thickness.. Areas of aesthetic concern or areas of insufficient coating thickness can be repaired using the materials and procedures specified by ASTM A780/A780M. Nearly all cases of flaking occur during or prior to installation. Flaking does not occur spontaneously and requires an impact force, so it is uncommon for flaking to occur after installation.

7.2.2 Brown Staining

Often mistaken for corrosion, brown staining (*Figure 17*) is an aesthetic concern occurring when iron in the zinc-iron alloy layers oxidizes and causes superficial staining. Brown staining does not occur with all HDG coatings, and it is typically associated with older structures. To distinguish between corrosion of the base steel and brown staining, clean a local area and test for coating thickness using a magnetic thickness gauge. If the gauge reading shows a coating thickness, then the condition is brown staining and the corrosion performance of the galvanized coating is not affected. It is not recommended to clean away brown staining as the staining will quickly return and frequent cleaning may compromise the coating. For projects with heightened aesthetic criteria, a thin layer of spray-applied zinc-rich paint can be used to help blend the appearance with the surrounding HDG coating.

7.2.3 Wet Storage Stain

Similar to the development of wet storage stain (*Figure 18*) when storing materials (*see Section 5.4.1 Wet Storage Stain*), galvanized products in place that are prone to collect moisture on the surface without the movement of free-flowing air can develop a build-up of zinc oxide and zinc hydroxide on the surface. Given normal wet/dry cycles once in service, this type of wet storage stain is uncommon after installation as wet storage stain occurs most often during the first months after galvanizing.

7.2.4 Rust Bleeding

Rust bleeding (*Figure 19*) is primarily a cosmetic concern. To clean and re-seal these areas, you can clean any staining from the outer area and apply a silicone caulk to the area to prevent bleeding from the crevices in the future.

7.2.5 Bare Spots

After final inspection and acceptance of a continuous coating from the galvanizer, the galvanized coating can be compromised during delivery, handling, erection, or while in use. Some cathodic protection is offered to bare areas (*Figure 20*) of the steel by the surrounding galvanized coating, but these areas can still rust if the area is too wide or corrosive elements frequently attack the steel. Research has shown the galvanized coating offers cathodic protection to bare areas between 1 mm - 5 mm wide depending on the environment.. Bare areas should be touched-up in accordance with the procedures described in this publication to ensure the longevity of the surrounding coating.

Figure 17: Brown Staining

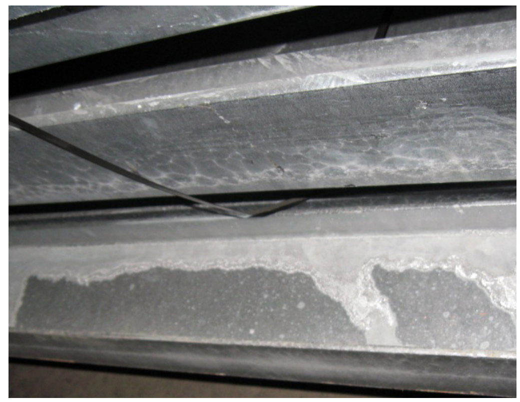


Figure 18: Wet Storage Stain

Figure 19: Rust Bleeding

Figure 20: Bare spots

8.0. Maintenance & Preservation

Hot-dip galvanized bridges designed, fabricated, and galvanized according to industry best practices and the guidance provided in this document will perform as intended in the desired service environment, often 75-120 years (*see Section 2.0 Site*). While owners often characterize hot-dip galvanized bridges as requiring minimal maintenance, the reality is all bridges require periodic maintenance and preservation measures.

FHWA Bridge Preservation Guide (2018) describes common bridge preservation activities. This section outlines additional considerations for HDG bridge maintenance plans, some of which may also apply to other bridge types.

8.1 Field Repair of HDG Coatings

ASTM A780/A780M defines three acceptable materials for field repair and the required procedures to ensure hot-dip galvanized steel will perform as intended: zinc-rich paint, zinc-based solder, or thermal spray zinc (metallizing). Each HDG repair material presents specific pros and cons[43], but it is possible to achieve a successful and durable coating repair using each method if the material meets the requirements specified by ASTM A780/A780M and is applied according to the manufacturers' recommendations.

Spray-application of zinc-rich paint (aerosol can) is recommended only for cosmetic touch-up. While it is theoretically possible to use this method for repairing bare areas in the coating, it is challenging to satisfy the requirements in ASTM A780/A780M. For this reason, brush- applied formulations are recommended for field repair of bare areas. Additional considerations such as compatibility between zinc-rich paint and subsequent coatings should be considered when field painting (*see Section 9.0 Duplex Systems*).

Zinc-based solders and thermal spray zinc cannot be used on certain surfaces in the field because of limitations related to their application methods. On projects where zinc-based solder or thermal spray zinc are specified as the preferred repair method, it is still necessary to specify a zinc-rich paint for addressing edges, overhead surfaces, and inaccessible areas.

ASTM A780/A780M specifies repair materials based on their corrosion resistance rather than appearance. Although it is not possible to guarantee HDG repair materials will precisely match the color of the HDG coating, material selection may consider aesthetics when necessary[44].

Some DOTs and local bridge owners maintain approved lists or additional requirements for galvanizing repair materials that may apply at the galvanizing facility, jobsite, or both. Review these lists and requirements before selecting materials for repairs, as some will restrict or mandate certain materials. Because galvanizing standards permit the selection of any material described in ASTM A780 unless otherwise agreed, any owner preferences should be clearly detailed and communicated to all contracting parties to avoid confusion.

8.2 Re-Caulking

Overlapping surfaces and previously caulked areas should be re-sealed using caulk, such as silicone to prevent rust bleeding (*see Section 7.2.4 Rust Bleeding*).

43 A. Fossa. (2018). *Evaluation of HDG Repair Materials*.

44 American Galvanizers Association. (2023). *Touch-Up and Repair of Galvanized Steel Product Suppliers*.

8.3 Sweeping & Washing

Although not required, some owners prefer to sweep and wash bridges after major flooding events or in spring following heavy use of deicing salts. Clean, and fresh water is used at ambient temperatures and various pressures but should not exceed 1,450 PSI to avoid damaging the HDG coating. Washing activity is typically limited to decks, bearings, drainage systems. Girders are rarely washed and limited to 6 ft at the ends. While there is no empirical data on the long-term benefit for HDG bridges, some owners report bridge washing every 2-to-5 years benefits all bridges by promoting drainage and reducing exposure to deicing salts. It is recommended the frequency and priority of this maintenance activity be determined based on road salting exposure and corrosivity of the environment. Consult Bridge Preservation Partnership Pocket Guide[45] for additional information on common procedures.

8.4 Cleaning

Cleaning HDG steel is straightforward. Begin with water and a nylon bristle brush. If needed, use chemical cleaners followed by thorough rinsing and complete drying [46].

CLR, lime juice, Naval Jelly Rust dissolver, Picklex 10G, and white vinegar effectively remove wet storage stain and other light contaminants without harming the zinc coating. For heavier contaminants like permanent marker, oil, grease, and spray paint use commercially available products: Klean-Strip Graffiti Remover, Goof Off, and Motsenbockers Lift Off.

8.5 Extending HDG Service Life Beyond Time to First Maintenance

When the hot-dip galvanized coating approaches its first maintenance, field painting and regalvanizing are the most common options for extending the service life of bridge components.

Success in field painting depends on careful surface assessment, material selection, and surface preparation, but is a great option for HDG components that cannot be removed from service. It is recommended painting be carried out before rust has formed on the surface to avoid painting over a mixed substrate, and preferably when the remaining HDG coating thickness is not less than 1 mil (25 μm) in preparation for roughening by sweep blasting. These methods will ensure greater longevity of the coating renovation. A material standard for this specific application does not exist, but the most common materials for bridge renovation include organic zinc-rich coatings and standard epoxy coatings, top coated if necessary on areas of the bridge where UV degradation is of concern.

Michigan Bridge Rail Reconstruction

Highway traffic damaged only 15-20% of the HDG bridge rail installed 52 years prior, so the Michigan Department of Transportation (MDOT) took the remaining rails and returned them to service after regalvanizing.

Commonwealth of Kentucky Guiderail

When guiderail and posts begin to display surface rust but the galvanizing preserves the integrity of the base metal from corrosion, the Commonwealth of Kentucky is known to refurbish the guiderail and posts by regalvanizing after minor adjustments to fit new mounting hole configurations.

45 NCPP Bridge Preservation Partnership. (2023). *Pocket Guide A User's Guide to Bridge Cleaning*.

46 American Galvanizers Association. (2010). *Cleaning Galvanized Steel*.

Organic contaminants must be removed prior to surface roughening, but the specific surface preparation requirements will depend on the selected coating system and should be advised by the coating manufacturer. The AGA offers *Preparing HDG Steel for Paint* as guidance in accordance with the general guidance of ASTM D6386. Additionally, AMPP Guide 19 Selection of Protective Coatings for Use Over Galvanized Substrates[47], provides additional guidance when painting over galvanized surfaces exhibiting rust on 10% or more of the surface area.

HDG steel that has not been severely corroded and can be removed from the job site can also be re-galvanized and reused, as the hot-dip galvanizing process is identical for new and refurbished steel. This process effectively restores the HDG steel to its initial condition. In North America, highway guiderails are often regalvanized (*see below*) but ancillary bridge components should also be considered to maximize cost savings[48]. An exception applies to high-strength fasteners, which cannot be re-used once they have been removed from service[49].

8.6 Graffiti Prevention and Removal

Graffiti is not detrimental to the HDG coating, therefore anti-graffiti topcoats or cleaning are not required. If needed for aesthetics, HDG can withstand scrubbing and chemical cleaners used to remove graffiti but high pressure washing or water pressures above 1,450 PSI will cause damage and should not be used. Aggressive solvents (acetone, MEK, commercial paint removers/thinners) or alkaline cleaners are suitable for removal of graffiti. Brief exposure to chemical cleaners will not harm the coating, but the area should be rinsed thoroughly with fresh water immediately after cleaning to remove any remaining chemicals from the surface.

47 AMPP. (2012). Selection of Protective Coatings for Use Over Galvanized Substrates.

48 A. Fossa. American Galvanizers Association. (2014). *Stripping and Regalvanizing*.

49 RCSC. (2020). Specification for Structural Joints Using High-Strength Bolts.

9.0. Duplex Systems

A duplex system refers to the application of a paint or powder coating over a hot-dip galvanized (HDG) substrate. This combination merges the barrier and cathodic protection of hot-dip galvanizing with the added protection and aesthetics of an organic topcoat. When applied and maintained, duplex systems significantly extend service life and reduce long-term maintenance costs, making them an ideal choice for exposed steel bridge components.

Clear coordination and pre-job conferences among the specifier, galvanizer, coating applicator, and inspector are essential for the effective implementation of duplex systems. While some galvanizers provide in-house duplex system services for bridge projects, many do not, meaning some surface preparation requirements must be shared and agreed among parties. When project responsibilities are divided among multiple parties, critical preparation steps may be overlooked, resulting in adhesion problems, coating defects, and increased remediation costs. Varying bridge owner preferences and the absence of industry-wide consensus have also contributed to the lack of a universal duplex system specification. Additionally, different coating systems often necessitate distinct surface preparation procedures, as recommended by the manufacturer. Therefore, detailed project specifications and clear assignment of roles and responsibilities are crucial to project success.

To address ambiguities within bridge project specifications involving Duplex Systems, this section describes common areas requiring further clarity beyond the specification of a generic surface preparation standard.

9.1 Reasons for Duplex System

As more specifiers understand the importance of corrosion protection, the use of galvanized steel in conjunction with paint or powder coatings has increased. There are many advantages to specifying a duplex system, but in bridge projects, specifiers are most interested in the increased longevity and aesthetic benefits[50] .

9.1.1 Increased Longevity

When hot-dip galvanized steel is painted or powder-coated, the duplex system provides a more sophisticated manner of corrosion protection known as the synergistic effect. The exterior layer of paint or powder coating provides barrier protection for the zinc coating, while the galvanized coating prevents underfilm corrosion.

50 American Galvanizers Association. (2012). *Duplex Systems: Painting over Hot-Dip Galvanized Steel*

Cost Case Study Project Parameters

- Typical mix of size/shapes
  - 50,000 ft^2 project
  - 70-year design life
  - Moderately industrial environment (C3)
- Surface Preparation/Application
  - SP-10 automated (duplex to SP-16)
  - All coats applied in the shop

Initial Cost: System	$/ft^2	Total†
Epoxy/Polyurethane	$3.45	$172,350
Inorganic Zinc/Epoxy/ Polyurethane	$4.98	$249,050
HDG + Epoxy/ Polyurethane (Duplex)	$6.65	$332,600

† Expected Service Life and Cost Considerations for Maintenance and New Construction Protective Coating Work,. KTA-Tator, Inc.(2021)
American Galvanizers Association National Survey (2021)

Life-Cycle Cost (70 Years): System	$/ft^2	Total†
Epoxy/Polyurethane	$34.53	$1,726,500
Inorganic Zinc/Epoxy/ Polyurethane	$31.39	$1,569.500
HDG + Epoxy/ Polyurethane (Duplex)	$15.66	$783,000

† Expected Service Life and Cost Considerations for Maintenance and New Construction Protective Coating Work,. KTA-Tator, Inc.(2021)
American Galvanizers Association National Survey (2021)

This combination results in corrosion protection for 1.5 to 2.3 times the sum of the expected life of each system alone. The most corrosive environments with high pollution, salt, or humidity will be closer to the minimum limit, while mild and rural environments are more likely to achieve the 2.3 maximum.

As a guideline, it is possible to select the duplex multiplication factor based on the following environmental conditions:

- 1.5 for Extreme Marine and Extreme Pollution Environments
- 1.5-1.6 for Sea Water and Immersion Applications
- 1.7-2.0 for Industrial and Marine Environments
- 2.0-2.3 for Non-Aggressive Environments (Suburban, Rural, or Very Low Humidity)

This synergistic effect between HDG and liquid applied coatings is not just theoretical but practically observed on real-world projects, with modern applications from the 1960s, and excellent documentation since the 1990s[51]. Despite damage to or permeability of the liquid applied coating, the hot-dip galvanized substrate can extend maintenance cycles for paint and powder coatings by 50%[52]. If the topcoat is properly maintained over time, the galvanized substrate will remain protected.

9.1.2 Aesthetics

If hot-dip galvanizing provides sufficient protection, but the specifier or end user prefers a duplex system purely for aesthetic reasons, there are cost-saving strategies to consider. One approach is to keep internal steel galvanized and duplex only the steel exposed to public view. For example, steel girder bridges have internal girders only visible from underneath the bridge. By painting or powder coating only the fascia members, the overall coating costs can be reduced significantly.

9.2 Coating Selection

Bridge owner preferences regarding coating selection for Duplex Systems can vary widely. A successful duplex coating selection for a bridge will take a few factors into consideration.

- Environment
- Frequency of road salting
- Maintenance schedule
- Shop vs. field painting

When reviewing qualified coatings systems meeting the established standards of the bridge owner, these factors should also be discussed directly with a high-performance paint or powder manufacturer to further evaluate suitability for the bridge and discuss manufacturer recommendations for cleaning and roughening of the HDG surface. Common coating systems used for bridge Duplex Systems include but are not limited to:

- HDG/epoxy/polyurethane
- HDG/epoxy/acrylic urethane
- HDG/polyurethane/polyurethane
- HDG/epoxy powder coating/urethane

A zinc-rich primer is generally not applied between the HDG and epoxy because its main role is to provide barrier and cathodic protection, which the existing HDG coating already supplies. Further, epoxy and polyurethane coatings for bridges can be directly applied to HDG.

NCHRP Research Report 1048 from TRB's National Cooperative Highway Research Program, contains a compiled list of case studies illustrating the current state of duplex coatings use and the coating systems specified.

51 J. F. H. van Eijnsbergen. (1994). *Duplex Systems: Hot-dip Galvanizing Plus Painting.*

52 National Academies of Sciences, Engineering, and Medicine. (2023). *Corrosion Protection of Steel Bridges Using Duplex Coating Systems.*

9.3 Compatibility of HDG Repair Materials

When specifying zinc-rich paint for HDG repairs at the galvanizing facility or by the painter, evaluate the material compatibility of the zinc-rich paint and the selected coating system. Additionally, consult the manufacturer's product data sheet regarding re-coating intervals. It may be practically necessary to agree on whether the galvanizer should apply zinc-rich paint repair material if the galvanizer and painter are two different parties.

9.4 Considerations for the Specification of Surface Preparation

The following specifications contain information regarding the preparation of hot-dip galvanized surfaces for a Duplex System:

- **ASTM D6386** details recommended practices for preparing hot-dip galvanized surfaces for painting, including available practices for surface smoothing, cleaning, and profiling based on the identified initial HDG surface condition.
- **ASTM D7803**[53] details recommended practices for preparing hot-dip galvanized surfaces for powder coating, including available practices for surface smoothing, cleaning, and profiling based on the identified initial HDG surface condition. However, D7803 also provides guidance on a thermal pretreatment to be performed after surface preparation which is necessary to prevent outgassing of the HDG coating during the baking step in the powder coating curing process[54].

Proper surface preparation is critical to the success of a duplex system. While ASTM D6386 and D7803 describe established methods for cleaning and roughening the HDG surface, they do not address bridge-specific requirements. Due to variations in bridge coating systems and preferences among bridge owners and painters, it is necessary to clearly communicate all obligations to galvanizer and painter in the project documents.

Specifying ASTM D6386 or ASTM D7803 alone does not fully define surface preparation for duplex systems. Confusion arises on bridge/highway projects when the cleaning and roughening options are not clearly selected or agreed upon. To ensure best results, the paint manufacturer should be consulted when the methods from ASTM D6386 and D7803 are selected by the responsible party.

9.4.1 HDG Cooling Methods and Galvanizer Post Treatments

Galvanizing facilities may choose to immerse steel immediately after galvanizing in a water bath ("water quench") or passivation bath ("passivation quench") to cool the parts rapidly in preparation for handling and inspection. Alternatively, galvanizers may choose natural air cooling or forced air cooling using fans. If cooling requirements are not addressed by the project specifications nor communicated to the galvanizer, galvanizers will perform any cooling method of their choice as ASTM A123/A123M and AASHTO/NSBA S8.3 do not prohibit the use of passivation coatings.

Although there are exceptions, traditional industry best practice is to request the galvanizer avoid quench cooling (water quench and passivation quench). The most common passivation coatings used in hot-dip galvanizing are known to compromise the adhesion of coatings applied over HDG. If a passivation quench has been performed (or if use of a passivation quench is unknown), it can be detected and removed. Procedures for removing a passivation coating by sweep blasting (SSPC-SP 16) and an inspection to confirm removal of the passivation coating are provided in ASTM D6386 or ASTM D7803. Duplex Systems for bridges often utilize liquid coatings which require surface roughening by

Cooling/Post-Treatment Requirements in ASTM A123/A123M and S8.3

- Passivation coatings are not prohibited

Procedures for Passivation in D6386

- Passivation coatings are not recommended
- Provides available methods for removing organic contaminants, detection of passivation coatings (e.g. ASTM B201), and removing passivation coatings.

What Project Specifications Need to Further Clarify

- Requirements for galvanizer to avoid passivation quench and provide confirmation a passivation quench was not used.
- Whether water quenching is subject to mutual agreement or if it should be avoided.
- Requirements for detection and removal of organic contaminants and passivation coatings.

53 ASTM. (2025). Preparation of Zinc (Hot-Dip Galvanized) Coated Iron and Steel Product and Hardware Surfaces for Powder Coating

54 American Galvanizers Association. (2013). *Preparing Hot-Dip Galvanized Steel for Powder Coating*.

sweep blasting anyway, meaning a separate step for passivation removal is not necessary but removal should be confirmed.

Water quenching does not inherently cause the same issue with adhesion, but the quench bath naturally accumulates oil, dust, and other organic contaminants. Owners report painters have a bad habit of skipping the solvent cleaning to remove these contaminants before surface roughening despite requirements in SSPC-SP 16 or SSPC-SP 11, so the rationale is the galvanizer prevents a potential contamination source with bypassing the water quench.. In practice, water quenching and forced air cooling can be strategically employed by galvanizers for some but not all steel fabrications to promote the aesthetics and integrity of the HDG coating during sweep blasting. To allow for these potential benefits, correct surface preparation for a Duplex System should address the need for removal of organic contaminants during surface preparation by the painter.

9.4.2 Surface Smoothing

Some surface conditions and prominences present on hot-dip galvanized coatings do not affect the corrosion protection and are acceptable under ASTM A123/A123M and AASHTO/NSBA S8.3 (general roughness, small dross inclusions, skimmings, zinc runs, etc.). However, these same surface conditions are understood to affect adhesion of the top coating and must be smoothed or removed from the galvanized surface prior to cleaning and surface roughening. A description of these surface conditions is provided in AGA Publication, *Inspection of Hot-Dip Galvanized Steel Products.*

ASTM A123/A123M and AASHTO/NSBA S8.3 do not offer a list of specific surface conditions acceptable and rejectable for Duplex Systems. Instead, the level of surface smoothing before painting shall be mutually determined by the galvanizer and the purchaser.

If job specifications lack clear requirements and responsibilities, essential surface preparation may be missed due to poor communication, especially when the galvanizer and liquid coating applicator are different parties. Job specifications should include detailed instructions and clarify who is responsible for each surface smoothing requirement. Even if the galvanizer is assigned the primary responsibility for surface smoothing, painters will still need to fill indentations and smooth prominences resulting from transport or handling.

Hot-dip galvanizing does not cover or smooth out surface irregularities like burrs, raised areas, weld porosities, crevices, or thermally cut edges from fabrication. If these irregularities result in prominences taller than the surrounding coating, surface smoothing after HDG in preparation for painting will create a bare area. It is recommended to agree in advance on a method to address this concern. Alternatively, these irregularities can be smoothed prior to hot-dip galvanizing to avoid the need for smoothing and coating repairs after HDG.

> **“Galvanizer post-treatment to apply passivation should not be confused with surface treatments deliberately applied by the paint applicator or galvanizer to promote paint adhesion over HDG such as etching primer, acrylic passivation, or zinc phosphate treatment.**

Filing with Hand Tool

Smoothing with Grinder

Finish Requirements in ASTM A123/A123M and S8.3 Related to Smoothness

- Coating must be "reasonably smooth," and remove only plainly visible excess coating unrelated to design challenges described in ASTM A385/A385M and excess zinc that would make the parts dangerous to handle (edge spikes)
- For parts to be painted, further requirements concerning surface roughness shall be mutually determined by the galvanizer and the purchaser.

Procedures for Surface Smoothing in D6386

- High spots in the coating and rough edges should be removed by smoothing with hand (SSPC-SP 2) or power tools (SSPC-SP 3). Examples include zinc drips, dross pimples, and zinc oxide particles (known as HDG skimmings).
- High spots and roughness should be removed until level with the surrounding area without removing the coating.

What Project Specifications Need to Further Clarify

- Inspection requirements for smoothness (visual and tactile inspection).
- Surface conditions to be smoothed by the fabricator prior to hot-dip galvanizing.
- Additional surface conditions which may require smoothing after HDG, such as peeling, handling damage (flaking), or handling marks from wire, chain, forklifts, and tie-downs.
- Any restrictions or preferences on smoothing methods.
- Use and material compatibility of filler (caulk or putty) used to smooth gouges or indentations.
- Parties responsible for each requirement of surface smoothing.

9.4.3 Surface Roughening

ASTM D6386 describes five methods for roughening hot-dip galvanized surfaces: sweep blasting in accordance with SSPC-SP 16, surface grinding in accordance with SSPC-SP 11, and a variety of chemical surface treatments. Additional considerations for bridge projects are summarized below.

9.4.4.1 By Sweep Blasting (SSPC-SP 16)

SSPC-SP 16 Brush-Off Blast Cleaning of Coated and Uncoated Galvanized Steel is a surface preparation standard which details the method for brush-off blast cleaning (e.g. "sweep blasting") for hot-dip galvanized steel. It is the most common surface roughening method when applying industrial-grade paint and powder coatings over HDG. Unique methods for roughening the surface while avoiding damage to the HDG coating are described. The surface profile requirement in SSPC-SP 16 is minimum 0.75 mil unless otherwise specified in the project specification, procurement documents, or the product data sheet for the coating to be applied. There exists significant overlap between ASTM D6386 Section 5.4.1 on Sweep Blasting and SSPC-SP 16 regarding both mandatory and non-mandatory information.

AASHTO/NSBA S8.3 requires the coating thickness meet the original minimum average criteria for HDG after sweep blasting. ASTM D6386 and SSPC-SP 16 (appendix) also address coating thickness after blasting, with ASTM D6386 also allowing up to 1 mil of coating thickness removal. Several studies have determined sweep blasting reduces the HDG coating thickness from 0.4 to 1.0 mil. If the HDG coating thickness before sweep blasting is close to the minimum requirement, meeting this requirement may be challenging or impractical for the painter. Since it cannot be assured that the coating will consistently exceed the minimum, it is advisable to have a plan in place to manage this possibility.

Abrasive selection can be unclear for painters because research on abrasives tends to address performance or peak height capability with black steel. Abrasives are known to achieve different peak heights and peak densities when used on HDG surfaces compared to bare steel surfaces. General industry guidance recommends softer abrasives to avoid excessive removal or damage to the HDG coating during sweep blasting. However, abrasives of Mohs hardness five or greater such as mineral sands are more commonly specified when looking to achieve an "angular" surface profile 2.0 mils or greater as stated in a manufacturer's Product Data Sheets (PDSs) for industrial-grade coatings. Additional mitigations by the painter will significantly reduce the risk of HDG coating damage but come with a known tradeoff in blasting productivity. The most effective techniques include increased distance between blast nozzle and galvanized surface, reduced nozzle pressure, faster nozzle movement, and use of a finer abrasive size[55].

55 A. Fossa. (2019). *Abrasive Blast Media for Preparing Duplex Systems*. American Galvanizers Association.
AMPP. (2020). SSPC-SP 16 Brush-Off Blast Cleaning of Coated and Uncoated Galvanized Steel, Stainless Steels, and Non-Ferrous Metals.

9.4.4.2 By Surface Grinding

The surface profile requirement in SSPC-SP 11 is minimum 1.0 mil unless a higher value is specified. Any conflicting requirements regarding surface profile should be clarified with reference to other project documents, such as the coating manufacturer's Product Data Sheet (PDS).

Painters should start at the lowest air pressure or RPM to assess the tool's impact on the HDG surface. Higher RPM generally leads to a polishing effect, whereas lower RPM combined with light hand pressure encourages roughening while avoiding excessive removal of the HDG coating.

9.4.4.3 By Chemical Surface Treatment (e.g. Wash Primer, Zinc-Phosphate, Acrylic Pretreatment, or other)

Some bridge owners allow the use of qualified etching primers or other surface treatments to promote adhesion of coatings over HDG. Compatibility and use of surface treatments should be discussed directly with the paint manufacturer. ASTM D6386 and ASTM D7803 describe general material requirements and procedures, meaning more detailed application procedures or guidance from the surface treatment supplier are typically necessary to ensure best results. When considering surface treatments, it is recommended to address any conflicting specification requirements related to the application of HDG repair materials and inspection of surface profile prior to commencing work.

9.4.5 Time Between Surface Preparation and Painting

Painting should take place as soon as practical after surface preparation, no matter which method is used. ASTM D6386 and ASTM D7803 describe the influence of factors related to atmospheric conditions, including humidity and temperature. Any further requirements should be addressed in the project specifications.

Procedures for Sweep Blasting in D6386

- Preform according to SSPC-SP 16.
- Overlap differences from SSPC-SP 16 on recommended abrasive selection and blasting procedures.

Requirements for Sweep Blasting in SSPC-SP 16

- Minimum 0.75 mils surface profile (or per project docs)
- Cleanliness of abrasive and compressed air.
- Overlap with D6386 on removal of organic residues, debris, wet storage stain, and passivation before sweep blasting.
- Cleaning after sweep blasting.

What Project Specifications Need to Further Clarify

- Further surface profile requirements.
- Use of dry abrasive blasting methods only. Do not use wet abrasive blasting method option in SSPC-SP 16.
- Whether a job mock-up for sweep blasting is required.

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