Uncoated Weathering Steel Reference Guide

NEED FOR SPEED

NATIONAL STEEL BRIDGE ALLIANCE NSBA FOUNDED 1995

Smarter.
Stronger.
Steel.

Uncoated Weathering Steel Reference Guide

National Steel Bridge Alliance

Printed in the United States of America

Executive Summary

This manual is intended to provide guidance to bridge owners and designers on when it is appropriate to utilize uncoated weathering steel (UWS) in bridge construction, and how to design, detail, fabricate, construct, inspect, preserve, maintain, and repair weathering steel bridges. This summary document provides an overview of the information contained in the manual. Readers should consult the content of the manual for detailed guidance.

Benefits of UWS

The primary benefit of using UWS is reduced cost, both in terms of initial fabrication and construction costs as well as long term maintenance costs (life cycle costs). Additional benefits include reduced fabrication time for structural steel, and potentially enhanced aesthetics. Initial cost savings over painted systems are estimated to be approximately 10%, while the savings in life cycle costs may approach 30%. The elimination of the painting steps, including drying time, during fabrication reduces the time needed to fabricate girders and other structural components, accelerating the construction schedule.

When to use UWS

In general, UWS is appropriate to use in the vast majority of locations. There are two main factors that in combination warrant further evaluation of use: high atmospheric humidity, and high concentration of chlorides. Depending on the conditions present at a specific site, the usage recommendations are:

- to use UWS
- to use UWS thoughtfully, that is, to carefully consider the conditions and possible mitigation factors, or
- to not use UWS at that site

In general, multiple factors need to be near their extreme before UWS would no longer be a viable option for a site.

These main factors of atmospheric humidity, chloride concentration, and moisture traps are a function of the general climate at the site (the macro-environment), and the local conditions at the site (the micro-environment). The particular combinations that may result in UWS not being recommended are:

- A coastal environment or one with an extremely high time-of-wetness, in combination with either:
- A low vertical clearance over water, or close-in vegetation or shelter preventing the steel from drying.

For all other site conditions, UWS is either recommended, or recommended to be used with some forethought. Coastal environments are defined as being within 2 miles of the shoreline, with average monthly relative humidity exceeding 75% for 8 or more months of the year. High time of wetness locations are limited to isolated locations in the pacific northwest, where rainfall rates can be extreme.

Highway crossings with deicing salt use are of a concern only when the amount of salt used, in combination with the amount of traffic under the bridge, approach extreme values. For the vast majority of highway crossings in areas of the country where deicing salts are used, UWS should perform well provided the design recommendations are followed.

Design Recommendations

The most important design recommendation is to prevent water from continuously flowing or ponding on the steel surfaces. A primary method to achieve this goal is to eliminate or minimize the number of joints on a bridge. Experience has shown drainage that directly contacts weathering steel girders (as well as those of other material types) through a leaking or failed joint results in poor performance and that adequate joint maintenance cannot be reliably guaranteed. Elimination of deck joints through the use of jointless bridges should be employed where possible. Long continuous girder lengths, link slabs, and other methods can be utilized to minimize the number of deck joints. When deck joints must be present, positioning them at abutments, and locating them on the back side of the backwall can prevent drainage from reaching the girders and diaphragms.

Careful consideration of the drainage system, either at joints or through scuppers, is needed to ensure the water is carried as desired off of the structure and does not cause corrosion. Key considerations when designing drainage systems is the prevention of clogging, ease of inspection and cleaning, and ensuring the bottom of any free-drop pipe is well below the lowest steel elevation.

For closed components, like box girders or box section truss members, provision for drainage of any moisture or water that enters the member should be provided. Design approaches that minimize the amount of water entering box members should be utilized, but should not be relied upon entirely. Past experience has shown it is difficult to completely seal a member against all moisture ingress.

Detailing

Appropriate detailing should consider the flow of water on a structure and can help minimize the collection of debris. Minimizing horizontal flat surfaces, and providing drip plates, bars, and pans are other methods to direct debris and moisture off of UWS surfaces. Adequate copes at the corners of stiffeners, which prevent debris and drainage from collecting, should be provided with ideally 2 inches or larger minimum dimensions.

When joints cannot be avoided, a detail that can be used to mitigate presumed future joint failure is the targeted painting of steel members (e.g., girder ends, diaphragms, etc.) beneath and near the joints. A length of painted area equal to 1.5 times the depth of the girder has been used successfully in the past. Another location where targeted painting should be considered is where a steel girder is embedded in concrete. Due to thermal effects causing condensation and capillary effects, the area of steel near the interface can remain wet for long periods, and painting should be used to protect this area.

Galvanic corrosion can be a concern when dissimilar metals are in contact with weathering steel in the presence of moisture. Problems can occur when the area of the more corrosion resistant metal (cathode) is large compared to the less corrosion resistant metal (anode) and in areas where frequent wetting is expected. Mitigation measures could include electrical isolation of the dissimilar metals.

Fabrication and Construction

The fabrication and construction of UWS generally follows the same procedures as for other steel types. However, the fabrication, storage, and construction practices adopted can affect appearance of the UWS. It is a recommended best practice to blast clean weathering steel girders in the fabrication shop to remove mill scale, which promotes a uniform formation of the protective patina that therefore aids in later visual inspections as well as aesthetics. Preventing ponding on steel and protecting it from long term exposure to soil are also recommendations.

Construction practices that can improve the aesthetics of UWS include limiting the staining of substructures by using temporary protection in the form of plastic sheeting over the substructure concrete during the first few months the weathering steel is in place. This, in combination with protective coatings on the concrete surface, have proved successful in preventing significant staining. The use of drip pans at the top of piers and abutments to collect and divert run-off from the girders has also proven successful.

Inspection

A properly formed patina on weathering steel can present a wide range of appearances due to a number of factors. Inspectors need to be aware of what signs to look for to identify poorly performing weathering steel. Color alone has proven to be a poor indicator of weathering steel performance. Rather, focus should be on the adherence of the patina and it's texture, in addition to color. Aside from typical inspection techniques such as close visual inspection or light abrasion with a putty knife, there are quantitative methods of evaluation available, such as ultrasonic thickness measurements or the tape test.

Maintenance and Preservation

The maintenance of joints and drainage systems to prevent direct contact between runoff and UWS should be the highest maintenance priority. Additional activities that have shown to be beneficial include periodic washing of the bridge.

Repair

Like all steel structures, UWS is easily repaired should the need arise. In the unlikely event that the weathering performance is not what was expected, weathering steel can be painted in the field, even if substantial weathering of the steel has already occurred. Other than a possible increase in the quantity of primer required, paint processes and expected performance are similar to recoating of typical steel structures.

TABLE OF CONTENTS

1.0—INTRODUCTION

Weathering steel as a material for use in bridges has a long successful history of excellent performance in a diverse mix of environments. Uncoated weathering steel (UWS) bridges have been used in the United States since the 1960s, reducing both the initial and long-term maintenance cost to owners while providing aesthetic crossings and minimizing disruptions to traffic due to decreased maintenance needs. While not every bridge location is ideal for the use of UWS, the vast majority of crossings can take advantages of what UWS has to offer owners, designers, contractors, and the public.

1.1—BENEFITS OF UWS

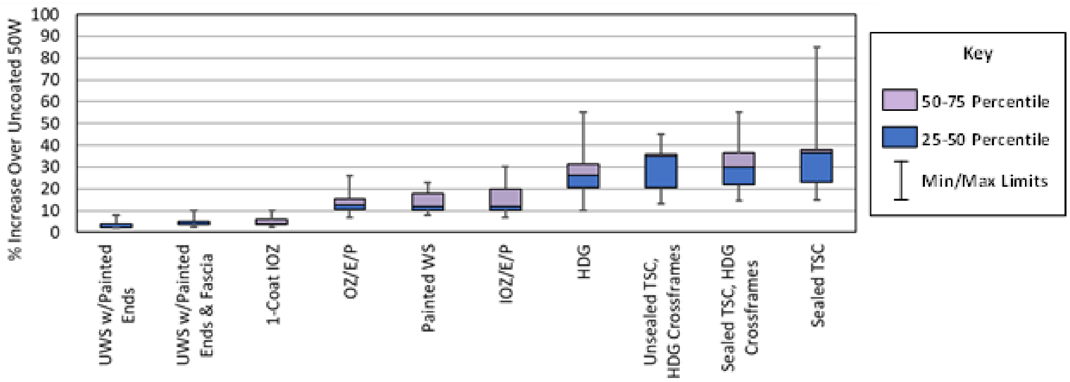
1.1.1—Cost

The most significant benefit of UWS for most owners is that it provides favorable and cost-effective performance in many environments. Because UWS has now been in use in highway bridges for more than 50 years, many best practices for achieving favorable performance are well established. Numerous studies have demonstrated UWS' favorable performance resulting from the use of these best practices based on various performance metrics (e.g., Jobes, 1996; McDad et al., 2000; Barth et al., 2005; Nelson, 2011; Nelson, 2014; McConnell et al., 2014; and Granata et al., 2017; CHA, 2021, which are further discussed in the following section). Based on this experience, El Sarraf et al. (2020) conclude that "[a]ssuming that there is no significant change in the environment, and with regular inspection to determine and treat any isolated problem areas if they occur, the life of a [UWS] bridge can be more than 100 years." It should also be stated that having the appropriate environment and incorporating modern detailing are necessary to achieve this longevity.

Figure 1.1.1-1—This 30-year-old bridge two miles from the Atlantic coast is one of thousands of examples of UWS bridges performing well after decades of service.

While the material cost of weathering steel is typically more expensive than that of traditional (non-weathering) steels, this increased expense is relatively small, on the order of 2 to 6% based on fabricator surveys by the Federal Highway Administration (FHWA) (Kogler, 2015). However, eliminating the cost of painting causes weathering steel to generally be the most cost-effective option. In terms of initial cost, eliminating painting reduces fabrication costs through reduced labor cost and reduced shop time. These reductions more than compensate for the increased material cost. Based on a national survey of fabricators, the median initial cost of a properly detailed UWS option is approximately 10% less than an equivalent structure with traditional three-coat paint options (see Figure 1.1.1-2) (Carlson, 2021).

In terms of life-cycle cost, eliminating or reducing the need for maintenance painting during the service life of the structure further increases the cost advantages of UWS by avoiding or decreasing costs associated with materials, labor, equipment, and maintenance of traffic. Based on these factors it has been estimated that a UWS bridge could provide up to a 30% savings in life cycle cost compared to a painted steel alternative (El Sarraf and Mandeno, 2010; American Iron and Steel Institute, 2020). In short, UWS provides equivalent mechanical properties to traditional steel at both lower initial and long-term costs.



Source: NSBA (2020)

Figure 1.1.1-2—UWS provides the minimal first cost (shown here using box and whisker plot of 2020 data) and life-cycle cost for typical girder bridges.

1.1.2—Other

In addition to the cost savings offered, implementation of weathering steel provides environmental benefits such as preventing the release of volatile organic compounds into the atmosphere by avoiding maintenance painting. Eliminating the need for maintenance painting also eliminates concerns with containment and disposal of removed paint and the abrasive blast media used for surface preparation. There is also an argument to be made for increased worker safety by eliminating the need for painting in elevated and/or awkward locations in close proximity to the driving public. Similarly, there is increased roadway safety and reduced traffic delays (and associated time and environmental savings) for the driving public.

The lack of painting also benefits the fabrication schedule for UWS structures. Eliminating the need to paint in the shop speeds up fabrication time and the overall project schedule.

A more subjective benefit of UWS is aesthetics. UWS provides a preferred aesthetic in locations where a natural appearance is desired. UWS can often be seen in parks for this reason (Figure 1.1.2-1). UWS can also provide a relatively uniform appearance over the life of the structure.

Figure 1.1.2-1—UWS is regularly selected for its aesthetics, particularly in scenic areas.

2.0—DESIGN RECOMMENDATIONS

The design of an UWS bridge needs to take into account the general geography in which the bridge is located, referred to as the macro-environment, as well as the local, site-specific characteristics of its location, known as the micro-environment. The macro- and micro- environments interact to define the environmental conditions to which the bridge is exposed.

In order to achieve the performance expected of UWS, prolonged exposure to wetness and/or high levels of chlorides (Cl^-), without the opportunity to dry, needs to be prevented. This condition can occur when one or more of the following occurs:

- High humidity due to either the general climate or local effects such as surface water or vegetation growing against the bridge,
- Roadway or marine salts that slow the drying process and accelerate corrosion, and
- Debris that traps moisture

The goal of design and detailing is to prevent the above conditions from occurring. In the vast majority of cases, this can be readily accomplished. However, there are locations where it may not be advantageous to utilize UWS: where high chloride content, persistent wetness, or both are likely to occur.

2.1—OVERVIEW OF MACRO- AND MICRO-ENVIRONMENT

In terms of bridge location, most macro-environments, micro-environments, and their combinations result in favorable performance of UWS. Severe combinations of macro- and micro-environments can result in situations where UWS is not recommended or where UWS is not recommended without a thoughtful maintenance plan and / or sacrificial thickness for a corrosion allowance.

Table 2.1-1 provides a broad overview of such considerations. Here it should be emphasized that the vast majority of bridge sites will fall into the “All Others” categories of both macro- and micro-environments, such that UWS is recommended for direct use following the design guidance provided in this manual.

Table 2.1-1 highlights two macro-environments – those with high time of wetness and coastal environments – where the use of UWS should be more carefully considered. Later sections of this document (see table footnotes) provide guidance for determining whether a given site should be categorized into one, both, or neither of these environments. Table 2.1-1 also highlights four micro-environments where the use of UWS should be more carefully considered, and similarly, later sections of this document (referenced in the table footnotes) provide criteria to be considered in determining whether a given site should be classified into any of these micro-environments.

Depending upon the interaction of the macro- and micro-environments, there are generally three alternative recommendations possible, summarized by Figure 2.1-1 and Table 2.1-1:

- Use UWS, following the design guidance provided in this manual. This applies to the vast majority of locations and occurs when neither the macro- nor micro-environment is severe.
- Use UWS thoughtfully. This includes consideration of providing a sacrificial thickness and/or a regular maintenance plan. A sacrificial thickness consists of adding a small margin (e.g., 1/16 in.) of additional thickness to selected horizontally oriented plates as a corrosion allowance (see Section 2.4.3). A regular maintenance plan could consist of activities such as bridge washing at regularly prescribed intervals, dedicated programming for joint maintenance, and/or planning for future painting if found to be warranted (as further discussed in Section 5). This recommendation generally applies when either the macro- or micro-environment contains features that increase the humidity or chloride exposure at site.
- Do not use UWS. This recommendation generally applies when features of both the macro- and micro-environments increase the humidity or chloride exposure at site.

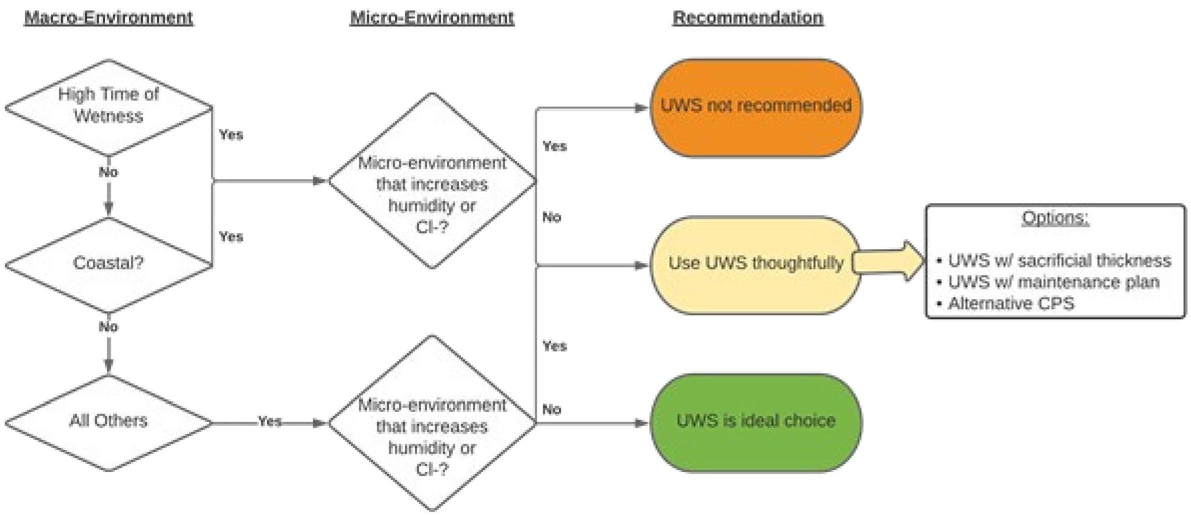


Figure 2.1-1—General Concept for UWS use Based on Macro- and Micro-Environment

Table 2.1-1 provides a more detailed summary of the recommendations for specific combinations of macro- and micro-environments. Furthermore, Table 2.1-1 also presents the concept for considering minor alterations to the site that would improve the performance of UWS. These include:

- Increasing low clearances over waterways, where feasible based on site geometry.
- Clearing and maintaining the clearance of vegetation, where doing so is not detrimental to the surrounding environment and environmental regulations permit doing so (further discussed in Section 5).

Table 2.1-1—Overview of Recommendations for UWS use in Various Environments

Micro-Environment	Macro-Environment		
	All Others	High Time of Wetness[1]	Coastal[2]
All Others	UWS is ideal choice	Use UWS thoughtfully	Use UWS thoughtfully
Highway Crossings with Extreme Salt Use[3]	Use UWS thoughtfully	Use UWS thoughtfully	Use UWS thoughtfully
Water Crossings with Low Vertical Clearance[4]	If minimal vegetation[5], use UWS thoughtfully; if dense vegetation[5], UWS not recommended	UWS not recommended	UWS not recommended
Sites with Dense Vegetation or Shelter[5]	UWS is ideal choice, if vegetation can be maintained and, for water crossings, adequate vertical clearance over water[4] provided	UWS not recommended	Depending on severity, UWS not recommended or UWS with sacrificial thickness[6] recommended

[1]See Section 2.2.3.1 for guidance on defining a high time of wetness environment.
[2]See Section 2.2.3.3 for guidance on defining a coastal environment.
[3]See Section 2.3.3 for criteria to be considered in categorizing this micro-environment.
[4]See Section 2.3.4 for criteria to be considered in categorizing this micro-environment.
[5]See Section 2.3.2 for criteria to be considered in categorizing this micro-environment.
[6]See Section 2.4.3 for detailed recommendations on providing a sacrificial thickness.

Table 2.1-1 is offered as a framework for considering the use of UWS in various environments based on the performance observed of UWS in various environments throughout the U.S. While Table 2.1-1 represents many possible combinations in order to be comprehensive, the vast majority of locations are not exceptional and fall into the "all others" category for both macro- and micro-environments. The guidance offered in Table 2.1-1 has considered many sites, but rational engineering judgment based on past experiences of usage of UWS in a given locale can be used to supplement such decision making.

The AASHTO Guide Specification for Service Life Design of Highway Bridges provides a table similar to Table 2.1-1 that considers macro-environment and service life. The macro-environments listed in Table 2.1-1, particularly when considered collectively with micro-environment, are considered to be a UWS-specific update to the more general categories intended for numerous steel types that are contained in that Guide Specification.

The service life categories contained in the Guide Specification are "normal," "enhanced," and "maximum." Service life considerations can be incorporated into the application of Table 2.1-1 by considering that the latter two service life categories (enhanced and maximum) are intended to represent longer service lives. Thus, in the situations identified in Table 2.1-1 that UWS is an ideal choice, it is an ideal choice independent of the service life. Similarly, for the situations in Table 2.1-1 that UWS is not recommended for a normal service life, it is not recommended for longer service lives. For the situations in Table 2.1-1 that are flagged as being ones where more thoughtful use of UWS is needed, these considerations can be expanded to also consider service life. Specifically, in these situations, providing a sacrificial thickness and a maintenance plan are the two primary recommended considerations, which can be pursued independently or in parallel. When a longer service life is desired, the sacrificial thickness may be increased or the maintenance plan made more robust. Further discussion on these topics can be found in subsequent sections on sacrificial thickness (Section 2.4.3) and maintenance plans (Section 5). Again, such recommendations should be considered as a general framework for decision making and may be supplemented with rational engineering judgment informed by increased familiarity with local environments and practices when available.

2.2—LOCATION (MACRO-ENVIRONMENT)

The first step in determining the appropriateness of UWS for a specific project is to consider the macro-environment in which a bridge will be located. The macro-environment has often been labeled as one of three relatively broad categories: rural, industrial, or marine. Urban is sometimes added as a fourth separate category in this classification framework. A consensus definition of these macro-environment labels does not exist, particularly one that is quantitative. An improvement to this concept is the International Standards Organization (ISO 9223, 2012) classification system, which quantitatively classifies the corrosivity of environments using an integer-based scale (of C1 to C5), with higher numbers indicating more severe environments. However, there is significant variation in environmental parameters influential to corrosion (e.g., humidity, chloride concentration) within any of these broad categories. For example, a marine environment in Texas is markedly different from a marine environment in Maine.

For these reasons, the considerations of macro-environment in these guidelines are presented in terms of the influential environmental parameters that may cause poor performance rather than purely categorical labels. Rural and urban environments have been considered relatively benign in terms of corrosivity (with the possible exception of deicing agents, which is considered as part of the micro-environment). The concern with industrial environments has been sulfur oxide concentrations while with marine environments it is chloride concentrations and high humidity. Excessively high humidity, in the absence of significant chlorides, is also a cause for concern. Thus, the recommendations in this section pertaining to general locations are organized in terms of the three influential environmental parameters – sulfur oxides, chlorides, and humidity. The combination of chlorides and humidity of concern for coastal environments is then discussed.

2.2.1—Sulfur Oxides

Levels of atmospheric pollution in the United States are typically low enough to have negligible effects on the performance of weathering steel, particularly since the adoption of clean air standards. All known existing standards that quantify a threshold on sulfate for the use of UWS either directly or indirectly refer to pollution levels above category P3 (per the ISO 9223 Standard), which equates to a sulfate concentration 250 $\mu g/m^3$. The current maximum sulfur dioxide emissions limit by the U.S. EPA is 200 $\mu g/m^3$.

While industrial environments have historically been mentioned as a cause for concern, the limited data underlying this concern originated from industrial locations in Europe. A prior review of this data from 1978 (Albrecht and Naeemi, 1984), attributed some of this data to a combination of high sulfur concentration and a higher relative humidity in the United Kingdom compared to the U.S. Similarly, in AISI's (1982) field studies, it was concluded that high sulfate levels (from industrial or automotive pollution) did not appear to have an effect on corrosion rates.

For these reasons, and the absence of any problematic UWS bridges being reported by bridge owners in the U.S. being attributed to proximity to industrial sites, previous considerations of "industrial environments" are not presently relevant to U.S. macro environments. Thus, for considerations of the use of weathering steel at a regional level in the United States, no concern regarding industrial environments remains.

One potentially severe and highly specific instance of a high sulfate environment that has raised concerns is bridges in rail yards. No special provisions are deemed necessary in these situations either, and this is discussed further as part of the Micro-Environment.

2.2.2—Chloride

There are two sources of chlorides that commonly affect bridges – airborne chlorides in coastal environments and chlorides from deicing agents used for winter roadway maintenance. The airborne chlorides in coastal environments are an important variable in defining a coastal macro-environment and are discussed in Section 2.2.3.3. Chlorides from deicing agents are considered a micro-environment characteristic and are subsequently discussed in Section 2.3.3.

2.2.3—Humidity

Three elements of humidity are relevant to the performance of UWS bridges: time of wetness, relative humidity, and coastal locations. Locations with both a macro-environment with an extremely high time of wetness and a micro-environment that further increases the time of wetness can result in poor performance of UWS.

As discussed below, time of wetness has been classified into five broad categories. These categories are convenient for considering whether the humidity is excessive or not and are recommended for use when humidity is the sole variable of concern. However, in coastal environments, the interaction between humidity and chlorides must be considered. In this case, the broad time of wetness categories lack sufficient refinement for practical use. Thus, for defining a coastal environment, the variation in relative humidity throughout the year has been shown to provide a stronger correlation with UWS performance. Relative humidity and associated thresholds are also discussed in this section.

2.2.3.1—Time of Wetness

Time of wetness is a quantitative measure of the amount of time during which atmospheric conditions are favorable for moisture to form on the surface of a metal or alloy. This is defined as the time when the relative humidity is greater than 80% and the temperature is above freezing (0 degrees Celsius, 32 degrees Fahrenheit) and is typically expressed in hours per year.

The FHWA TA on UWS states that "if the yearly average time of wetness exceeds 60 percent, caution should be used in the use of bare weathering steel." This is the quantitative version of the concept of "frequent high rainfall, high humidity, or persistent fog" that also appears in the FHWA recommendations. The 60 percent time of wetness threshold is generally agreed upon as a condition for additional evaluation, although some international standards (i.e., Australia and New Zealand) are based on higher limits.

Similarly, the ISO 9223 Standard defines five time of wetness categories, listed in Table 2.2.3.1-1. A time of wetness exceeding 5500 hrs/yr (i.e., approximately 60% of the year) represents Category T5 (the most severe). Figure 2.2.3.1-1 shows the ISO time of wetness category of various locations throughout the U.S. This demonstrates that Category T5 (i.e., a time of wetness of possible concern) is a very rare environment in the U.S., occurring only in isolated locations in the Pacific Northwest.

There are examples of UWS bridges that have and have not performed well in Category T5 environments. Those that have not are in a high time of wetness macro-environment as well as a micro-environment that causes local increases in humidity. Specifically, the bridges that have not performed well in T5 environments are waterway crossings (at least sometimes with limited vertical clearance), are in areas of high vegetation. Thus, the combined severity of the time of wetness, vertical clearance, and vegetation should be considered collectively. It is generally only when two or three of these variables are at their extremes that inferior performance of UWS has been observed in the United States.

This past performance leads to the following recommendations for macro-environments with high (Category T5, i.e., > 5500 hr/year) time of wetness:

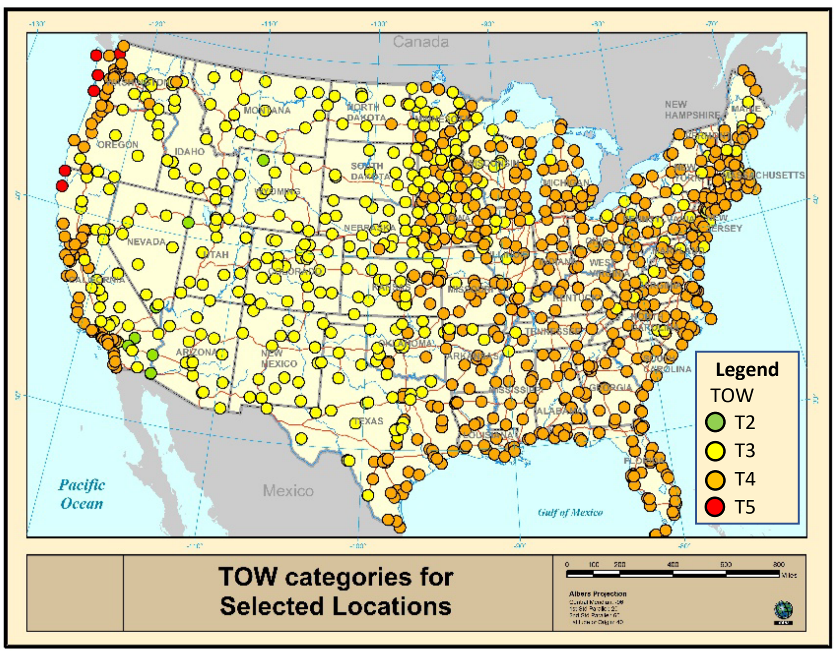
- UWS may be used if the micro-environment does not contain features that would contribute to a localized increase in time of wetness. Specific micro-environments of concern in this situation are water crossings with low vertical clearance (see Water Crossings – Vertical Clearance) and those with dense vegetation or other features that block significant sunlight (see Section 2.3.2). The use of a sacrificial thickness or development of a maintenance plan may be desirable for these situations.

- UWS is not recommended if the micro-environment contains features that would contribute to a localized increase in time of wetness – water crossings with low vertical clearance and sites with dense vegetation or other features that block significant sunlight.

For locations without high time of wetness (defined here as Categories T0 to T4), no special time of wetness concerns exist other than those stated elsewhere in this document (see discussion of coastal macro-environment and various micro-environments).

Table 2.2.3.1-1— Upper Bound Time of Wetness per ISO Environment Categories

Category	Time of Wetness hr / year
T0	NA
T1	10
T2	250
T3	2500
T4	5500
T5	>5500



Source: Adapted from Chase.

Figure 2.2.3.1-1—Time of Wetness Categories for Selected Locations in U.S.

2.2.3.2—Relative Humidity

While time of wetness provides a convenient metric for assessing humidity, time of wetness data is not typically readily available beyond the general time of wetness categories shown in Figure 2.2.3.1-1. From Figure 2.2.3.1-1, it is observed that most coastal locations in the U.S. are classified as T4. Thus, while time of wetness category T5 is convenient for defining an extreme time of wetness of concern, it is difficult to apply time of wetness data for defining a coastal environment due to the broad range of time of wetness represented by T4 (see Table 2.2.3.1-1).

A more readily available and specific metric that can be used for defining a coastal environment is relative humidity. However, similar to the concept of time of wetness, it is not just the average relative humidity that is of interest, but the amount of time that the relative humidity is high. One dataset that can be used to provide such information is the National Oceanic and Atmospheric Administration (NOAA) Climate Atlas of the United States (CAUS). This dataset provides contour maps of average relative humidity by month (Figure 2.2.3.2-1) and can be obtained through NOAA (https://www.ncei.noaa.gov/access/metadata/landing-page/bin/iso?id=gov.noaa.ncdc:C00121).

Decreased (but arguably still satisfactory) performance of a single UWS bridge was previously correlated with a location within one mile of the Gulf Coast and a location where 11 months of the year experienced an average relative humidity in Category H (average relative humidity between 76 and 80 percent per the NOAA CAUS dataset) (McConnell et al. 2016). In this same study, numerous coastal bridges with less severe combinations of distance from the coast and humidity performed well. A second study on coastal bridge performance quantified distance to the coast of many bridges in Florida (Granata et al., 2017). This study found decreased performance within two miles of the coast. Comparing these locations to the NOAA CAUS relative humidity data shows that these locations typically experience eight months of the year in Category H.

Thus, for the purposes of defining a coastal environment in the United States, it is recommended to consider distance to the coast (see later discussion in Section 2.2.3.3) and relative humidity per the NOAA CAUS database. The specific humidity level of concern is suggested to be one where eight or more months of the year experience average humidity in Category H (76 to 80 percent) or higher.

It should be clarified that relative humidity data is widely available, but also that there is great variability reported from various sources (e.g., local news outlets, personal smart phones, etc.). The significant variability in this data should preclude decision makers from extrapolating the recommendations made here based on the NOAA CAUS dataset to other forms of quantifying relative humidity. Thus, it is highly recommended to compare the NOAA CAUS data of a particular site to the recommended thresholds versus using relative humidity data from other sources. The NOAA CAUS maps in Figure 2.2.3.2-1 can be used for general reference or more precise data is readily available via NOAA.

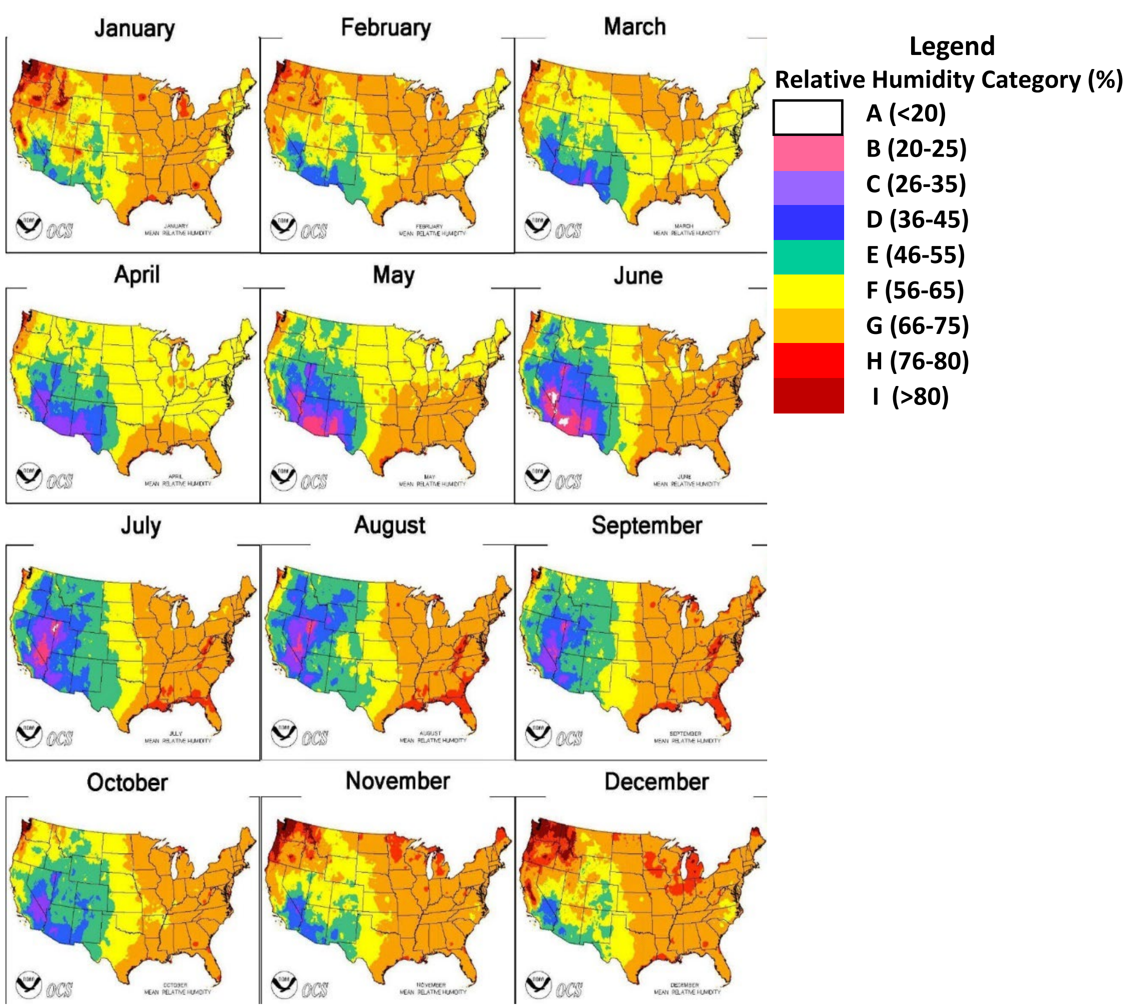


Figure 2.2.3.2-1—Monthly Relative Humidity Averages in the U.S.

2.2.3.3—Coastal

Coastal environments are harsh for all structural materials due to the combination of high humidity and high chloride concentrations that can occur. However, not all coastal environments are equally harsh and favorable performance of UWS occurs in many coastal environments.

The critical variables defining a coastal environment are the atmospheric chloride concentration and relative humidity. Because atmospheric chloride concentration data is not widely available, distance to the coast can be used as a general variable to represent this effect. Detailed information on relative humidity is given in the previous section. Therefore, and in the absence of more refined information, a general definition of a coastal environment of concern is an environment where both of the following criteria are satisfied:

- The bridge site is within two miles of the coastline. This includes the Atlantic, Pacific, and Gulf of Mexico coasts.

- Eight or more months of the year have an average relative humidity greater than or equal to 75 percent, as quantified by the NOAA CAUS dataset (see Section 2.2.3.2 and Figure 2.2.3.2-1).

The following recommendations are made for macro-environments meeting this definition of a coastal environment:

- The thoughtful use of UWS is recommended in most cases. The use of a sacrificial thickness or development of a maintenance plan may be desirable for bridges in coastal environments, particularly those crossing water.

- UWS is not recommended if the micro-environment contains features that would contribute to a localized increase in time of wetness. This includes water crossings with low vertical clearance, water crossings over salt water, and sites with dense vegetation or other features that block significant sunlight. See Sections 2.3.2, 2.3.4.1, and 2.3.4.2 for guidance on defining these micro-environments.

2.3—SITE CHARACTERISTICS - MICRO-ENVIRONMENT

Because of the lack of consistent poor performance in any of the qualitative macro-environment categories, the concept of a micro-environment has been developed to describe the variations in UWS performance within a given macro-environment. For organizational purposes, the micro-environment issues that may affect UWS performance can be considered relative to the crossing type and the type of service on the bridge. The crossing type is generally of greater importance than the type of service. This is because the steel superstructure typically is the critical UWS component of a bridge and is more directly exposed to what the bridge is crossing than the facility carried due to the shelter that is provided by a well-designed bridge deck and drainage system.

2.3.1—Site Evaluation

With more than 50 years of national experience with UWS bridges, there is now a significant knowledge base regarding sites where UWS can be expected to perform well. The designer should consider the macro-environment factors outlined in the previous section coupled with specific site features discussed in the remainder of this section to determine if the site of interest contains any severe features which makes the use of UWS not favorable.

For bridges in highly unique locations that may introduce uncertainty regarding the use of UWS, assessing the appropriateness of weathering steel through additional testing is practical and feasible given that the design process for highway bridges may last several years. Specifically, the tests that will be most beneficial in assessing the situation are corrosion penetration of UWS material samples, atmospheric salinity, atmospheric sulfur dioxide, and time-of-wetness. American Society of Testing and Materials (ASTM) standards exist for performing all of these tests and the American Iron and Steel Institute currently provides resources to perform such evaluations in some situations.

2.3.2—Vegetation, Shelter, and Moisture

The site topography should be evaluated to ensure that the site does not contain unique features that will cause the steel to be subjected to excessive periods of wetness. Two considerations are recommended to assess a specific site from this perspective:

- Natural topography that causes dense vegetation in, or nearly in, contact with UWS (as shown in Figure 2.3.2-1) has the potential to prevent the steel from having adequate drying time. This is most problematic in humid environments where the time of wetness exceeds 60% or there is low clearance over water (see Section 2.2.3.1 and Section 2.3.4.1). In other environments, the growth of vegetation at the site should also be considered during the maintenance of the bridge, as subsequently discussed in Section 5, to avoid accelerated corrosion of the type shown in Figure 2.3.2-2.

- Other unique obstacles that may shelter the site from sunlight and/or provide excessive moisture should be avoided. This is also most problematic in humid environments where the time of wetness exceeds 60% or there is low clearance over water. In these environments, scenarios where the structure is obstructed from receiving sunlight for at least 6 hours per day throughout the year may result in poor performance.

These considerations lead to the following recommendations for micro-environments with dense vegetation and/or other forms of shelter that severely limit sunlight (e.g., numerous immediately adjacent tall buildings, exceptionally steep mountainous terrain):

- UWS may be used if the bridge will not be subjected to close-in vegetation combined with high time of wetness (see Section 2.2.3.1), and for water crossings, where the vertical clearance is not considered low (see Section 2.3.4.1)
- UWS is not recommended if the previous conditions are not satisfied.

Figure 2.3.2-1—Example site characteristics where vegetation prevents drying of UWS bridge (credit: Google®).

Figure 2.3.2-2—Vegetation surrounding UWS bridges increases local humidity and can trap debris, leading to section loss.

2.3.3—Highway Crossings

Bridges that pass over roadways that are heavily treated with deicing agents for winter roadway maintenance cause a more severe micro-environment relative to their macro-environment. This is because airborne salt-laden road spray from the underlying roadway collects on the superstructure. In these situations, the primary influential variable appears to be the amount (and perhaps type) of deicing agent used, which is dictated by snowfall amounts and traffic volume. In the absence of large quantities of deicing agents, highway crossings do not present an environment of concern for UWS bridges.

Relatively small vertical clearances between the roadway and the superstructure and/or horizontal clearance between the roadway and the end of the bridge or other vertical site features exacerbate the effect of high quantities of deicing agent use. Sites with limited horizontal and vertical clearance have often been referred to as a "tunnel like" situation. However, such clearances do not appear to be detrimental to UWS performance in the absence of high amounts of deicing agents.

2.3.3.1—Deicing Agent Amounts

All of the UWS highway crossings with poor UWS performance have exceptionally high rates of deicing agent use. Few, if any, examples of poor UWS performance exist in this micro-environment when the deicing agent use is not at a very high rate and proper detailing and maintenance practices are implemented.

Unfortunately, deicing agent use is typically only quantified over large regions (state or county averages, for example). It is generally not possible to determine the amount of deicing agents beneath any specific bridge. This makes it difficult to provide threshold values on the amount of deicing agents that may be of concern.

Instead, what is known is that deicing agent use is largely a function of snowfall amounts and traffic volume. As either of these quantities increase, so does the amount of deicing agent use. These two metrics can be used to generally define a "extreme deicing agent use" environment. Using these two metrics, along with the engineering judgment and experience of local personnel, it is generally possible to determine if a given site will receive a high amount of deicing agents.

Guidelines for consideration in defining an extreme deicing environment are:

- Highway overpasses subjected to extreme amounts of deicing agent use on the roadway under the bridge. In the absence of refined quantification of deicing agent use amounts, the categorization of extreme amounts should be based on engineering judgment considering the past performance within the agency of interest or those with similar environments. The primary parameters that affect the amount of deicing agents used are intuitively snow and ice amounts and volume of traffic. Parameters such as vertical clearance between the superstructure and the roadway, bridge width, number of travel lanes, and travel speeds may also affect the amount of deicing agents transferred from the roadway to the superstructure. Micro-environment effects of deicing agent use only occurs in typical situations when the average annual snowfall exceeds 20 inches and other parameters (of those listed previously) are at their extreme values.

- Brine deicing solutions. As pre-treatment brines (applied prior to winter storms) become more popular, there is anecdotal evidence emerging that locations where a high percentage of the applied deicing agents are brines may see accelerated corrosion. Thus, it may be prudent to also consider the type of deicing agent use.

When the above criteria are met, the following recommendations are made regarding UWS use:

- The thoughtful use of UWS is recommended in most cases. The use of a sacrificial thickness and/or development of a maintenance plan may be desirable for bridges in extreme deicing environments. This is particularly recommended should the vertical and horizontal clearances contain features that exacerbate the effect of deicing agents, as detailed in these sections.

2.3.3.2—Vertical Clearance

Highway crossings over heavily salted roadways have sometimes been observed as having poor performance when relatively small vertical clearances have been provided. As one quantification of "small", the Ohio and Department of Transportation (ODOT) has evaluated the relationship between vertical clearance over roadways treated with deicing agents and UWS performance. As a result, ODOT restricts the use of UWS over such highways when the vertical clearance is 20 ft. or less. While this value may be conservative, in the absence of more refined data, it is recommended herein that when the micro-environment is defined as a "extreme deicing environment" and the vertical clearance is less than this threshold, it is recommended to provide a sacrificial thickness (see Section 2.4.3) and/or a regular maintenance plan (see Section 5).

An additional consideration on this topic is the ability to alter the vertical clearance based on other site considerations. Specifically, French guidelines give recommended vertical clearances between 14 and 25 feet based on the length of walls adjacent to the roadway per the following equation (Ungermann and Hatke, 2021):

Minimum Vertical Clearance = 14 ft. + L_{wall}(ft.) / 25 ≥ 25 ft. (Eq. 2.3.3.2-1)

where L_{wall} is the length of any abutment walls, wingwalls, retaining walls, noise barriers, traffic barriers, or other wall structure that are at least 6.5 feet tall and within 20 feet of the edge of roadway. Eq. 2.3.3.2-1 is empirical, based on observations that tall and long wall structures that are close to the under passing roadway tend to constrict airflow and amplify the tunnel effect.

2.3.3.3—Horizontal Clearance

At least 30 feet of horizontal clearance between the edge of the travelled way and the nearest substructure unit (pier, abutment, etc.), rigid barrier, or to the toe of a slope steeper than 1 to 3 is generally recommended for ideal roadway geometry. Highway crossings over heavily salted roadways have sometimes been observed as having poor performance when smaller horizontal clearances have been provided.

A specific example of this is represented in the VDOT specifications that restrict the use of UWS when the horizontal clearance is less than 22 feet and other criteria are met. French guidelines consider special provisions for the required vertical clearance when the horizontal clearance to obstacles more than 6.5 feet tall is less than 20 feet (Ungermann and Hatke, 2021; see Eq. 2.3.3.2-1).

Thus, if the horizontal clearance decreases below the recommended 30 feet and the micro-environment is defined as a "extreme deicing environment," increased consideration for providing a sacrificial thickness and/or maintenance plan may be prudent. If the horizontal clearance decreases below 20 feet and the micro-environment is defined as a "extreme deicing environment," a sacrificial thickness and/or maintenance plan is highly recommended. While both of these clearance recommendations are based on limited or empirical data, they are likely conservative and expected to result in good UWS performance.

2.3.3.4—Tunnel Effect

The combination of vertical and horizontal clearance combined with variation in roadway elevation can create what is known as a tunnel effect, which may also create a more aggressive micro-climate. The width of the overpassing structure has also been hypothesized as a variable influencing the tunnel effect, but definitive supporting evidence does not exist at this time. An ongoing research study funded by the FHWA Turner-Fairbank Laboratory is investigating the tunnel effect in bridges. However, the results are not available at this time. In the meantime, the recommendations contained in Sections 2.3.3.1 through 2.3.3.3 have been made considering realistic environments where tunnel effects are possible. These can be used along with engineering judgment to assess possible tunnel effects.

2.3.4—Water Crossings

2.3.4.1—Vertical Clearance

Limited vertical clearance over water can be problematic from two perspectives. One is that it can cause a localized increase in time of wetness relative to the surrounding macro-climate, which is of particular concern for UWS bridges as discussed previously. The other is the increased likelihood for flooding to affect the superstructure, which is a concern for all bridges. Engineering judgment should be used to determine whether or not the vertical clearance is of concern (i.e., is "low") for a given site.

From the time of wetness perspective, specific site conditions can result in small vertical clearances that cause localized humidity to be of concern. Thus, the following information is provided to assist in the determination of a "low" vertical clearance for a given site.

- FHWA guidelines currently recommend that weathering steel bridges should be used cautiously when there is 10 ft. or less of vertical clearance over stagnant, sheltered water or 8 ft. or less over moving water. Decades of applying these recommendations suggest that these limits are at least adequate, and most likely conservative, for providing good performing UWS.

- The alternative criteria for moving and stagnant water in the FHWA guidelines can also be thought of in terms of the size of the body of the water. Coastal plains, wetlands, and other bodies of stagnant water are also relatively large bodies of water. It is logical to provide larger vertical clearance in these situations, due to the greater likelihood for a larger body of water to cause a change in humidity than a smaller body of water. Conversely, small rivers, streams, creeks, and other small bodies of water (either based on metrics such as their flow rate, absolute width, or width relative to the size of the structure) likely have little impact on the time of wetness.

- In environments with low potential for flooding and lacking in excessive humidity (either from a macro-environment perspective as previously discussed in Section 2.2.3.1 or from a micro-environment perspective as previously discussed in Section 2.3.2), UWS bridges with as little as 6 feet of vertical clearance above water have demonstrated satisfactory performance (CHA 2021).

A recommended additional (or alternative) consideration is not only the vertical clearance in the typical flow state, but the propensity for flooding at the bridge site. Repeated or long-term flooding causes excessively wet environments. However, more significantly, flood events also frequently lead to trapped debris, and therefore trapped moisture, on the superstructure. The moisture trapped in this debris can cause a long-term continuously wet environment that greatly accelerates corrosion. Thus, it is recommended to consider the frequency of flooding that may occur at different elevations and develop plans that anticipate the potential need for debris removal following flood events.

If the vertical clearance is determined to be low, various actions are recommended based on other site features:

- UWS may be used if the macro-environment does not contain a high time of wetness (i.e., does not exceed 5500 hours/yr; see previous section on this topic) and minimal vegetation is present (see Section 2.3.2). The use of a sacrificial thickness or development of a maintenance plan may be desirable for these situations.

- UWS is not recommended if the macro-environment contains a high time of wetness or dense vegetation is present.

2.3.4.2—Crossings over Salt Water

There has not been clear evidence that the salinity of the water feature under a bridge has a significant effect on the performance of a UWS bridge. The one exception to this observation is if there is significant wave action and salt spray is present beneath the bridge. Bridges crossing over an environment with salt spray have significantly degraded corrosion performance.

2.3.5—Railway Crossings

In general, no special considerations are needed for UWS bridges crossing railways. However, two specific railway crossings that have been previously debated are bridges in rail yards and bridges over electrified rail.

Bridges in rail yards where diesel engines may idle beneath the superstructure have been a cause for concern previously due to sulfur emissions. However, there is no evidence to suggest that this theoretical concern leads to poor performance of UWS. Furthermore, the primary compounds present in diesel exhaust (carbon monoxide, nitrogen oxides, hydrocarbons, and volatile organic compounds) are not compounds known to cause poor performance of UWS. Lastly, while diesel fuel contains sulfur, which can lead to poor performance of UWS, the concentration of sulfur in diesel exhaust is believed to be negligible from the perspective of UWS performance. This is based on the fact that no historical problems in these situations are known to exist coupled with the fact that recent emission standards in the United States have dramatically decreased the allowable sulfur content in diesel fuel from 500 ppm to 15 ppm. Thus, no special provisions are deemed necessary for UWS bridges in rail yards.

A recent finding from a report on UWS bridges in Connecticut has suggested that stray current from electrified rail line crossings may affect the corrosion rate in existing bridges. Though the information to date is anecdotal, ensuring proper electrical insulation in such situations is recommended.

2.3.6—Railroad and Pedestrian Bridges

While the majority of UWS bridges are highway bridges, UWS is an ideal choice for railroad bridges due to the maintenance advantages they offer. Compared to highway bridges, railroad bridges are often in a more benign micro-environment than a corresponding highway bridge. One of the reasons for this is that deicing agents are not typically applied directly to railroad bridges. So, the likelihood for salt-laden runoff from the deck is minimal. If a railroad bridge is an overpass, salt spray from any roadways below should still be taken into consideration during design (see Section 2.3.3.2). A second reason is that railroad bridges are usually narrower than highway bridges. This is beneficial for improving air flow around the structural members and minimizing the tunnel effect.

UWS can also be an ideal choice for pedestrian bridges. Similar to railroad bridges, pedestrian bridges are often in less aggressive micro-environments than highway bridges due to a lack or decreased use of deicing agents. In these mild environments, the use of UWS is recommended. However, deicing agents may be applied to pedestrian bridge decks in colder climatic regions for pedestrian safety. In these more aggressive micro-environments, UWS pedestrian bridges should be designed and detailed to prevent corrosion. Common semi-permeable deck types used on pedestrian bridges, such as planking, should be avoided in aggressive micro-environments to prevent salt laden moisture draining directly onto underlying superstructure members. Similarly, pedestrian bridges often have open drainage over the sides of the deck that can allow moisture to drain directly onto adjacent and underlying superstructure members. This should be avoided, or the drainage should be directed in a manner to prevent contact with UWS members. In addition, HSS members and other closed sections that are commonly used for pedestrian bridges should be detailed to prevent chlorides and moisture from entering the interior of the section. Design considerations for these member types are discussed in greater detail in Section 2.4.1.3. Furthermore, like railroad bridges, the often-narrow cross section of pedestrian bridges aids in air flow around the structure.

2.4—STRUCTURAL DESIGN

Many of these recommendations are not specific to UWS but are detailed here for completeness. The guidelines given in this section address structural design issues that relate to corrosion performance. Other limit states should be considered and designed for accordingly depending upon the application. Appropriate references include but are not limited to the AASHTO *LRFD Bridge Design Specifications*, current edition for the design of highway bridges; the American Railroad Engineering and Maintenance of Way Association (AREMA) "Manual for Railway Engineering—Chapter 15," current edition for the design of railroad bridges; and the AASHTO *LRFD Guide Specifications for the Design of Pedestrian Bridges* in conjunction with the *LRFD Bridge Design Specifications*, current editions, for the design of pedestrian bridges.

It should be noted that the design of bridges utilizing UWS have no exceptions or restrictions from the design requirements found in the specifications identified above. The contents of this section are intended to supplement these specifications by communicating best practices and suggestions for improved corrosion performance. The use of ASTM A709 Grades 50W, HPS 50W, HPS 70W, and HPS 100W are highly recommended as the steels of choice for new construction in most situations, as described in Sections 2.1, 2.2, and 2.3.

2.4.1—Structure Type

2.4.1.1—I-Girder Bridges

The majority of steel bridges, and UWS bridges, in the United States are I-girder bridges. For this structure type, the primary considerations are as follows.

- The most frequent corrosion problems occur beneath leaking joints; see Section 2.4.2 for best practices.
- In extremely corrosive environments, it may be desirable to add a corrosion allowance (i.e., sacrificial thickness) to the bottom flange of I-girders and selected other horizontal surfaces; see Section 2.4.3 for recommendations.
- UWS I-girder bridges have the best performance when used with a continuous deck, such as a compositely connected reinforced-concrete deck. Discontinuous deck materials (e.g., timber decking, steel grid decks) lead to additional moisture, which can be problematic. See Section 2.4.4 for recommendations.

Other suggestions that may improve the performance of UWS I-girder bridges are given below on the topics of deck overhang width, girder spacing, flange transitions, and maintenance considerations.

2.4.1.2—Box Girder Bridges

Relative to I-girder bridges, box girder bridges have been observed as having better performance – when the interior of the boxes is kept dry. This enhanced performance is due to the absence of large exterior horizontal surfaces where water and salts can collect.

Should water enter a closed section such as a box girder, box section column, or box truss member, the time of wetness can be very long without proper drainage or air circulation. Strategies to avoid this include trying to prevent water ingress, providing appropriate drainage of all surfaces, or using a corrosion protection system on the interior of closed sections. For sections large enough to allow it, painting the interior with a single coat of a light-colored primer (e.g., organic or inorganic zinc, epoxy mastic) to facilitate inspection is a best practice.

Detailing to prevent water ingress into closed sections is necessary to achieve the desired performance of UWS. However, effectively sealing sections against water ingress can be extremely difficult, and past experience has indicated that even small openings can result in water accumulation over time as a result of condensation and/or capillary action. Similarly, providing drainage holes and other details to facilitate drainage is beneficial and encouraged. The size, spacing, and location of drainage holes should be carefully considered to balance the needs for drainage, for preventing clogged drainage, and for preventing wildlife from entering the closed sections. All drainage holes should be securely screened to prevent wildlife from nesting inside of closed boxes. Since drainage paths cannot always be predicted and accounted for in design, drainage holes should not be used as the sole moisture prevention method.

The lack of air circulation typical of closed sections may still result in long times of wetness. For sections large enough to need inspection access doors, providing vented doors can aid air circulation and is recommended where feasible (Figure 2.4.1.2-1).

In addition to these considerations for protecting box girders from accelerated corrosion due to ponded water collecting inside of boxes, additional considerations relevant to box girder bridges that are discussed in later sections are summarized as follows.

- Best practices for minimizing and eliminating joints should be followed.

- It is recommended to use a continuous deck type. Furthermore, deck joints above open boxes should be avoided.

- Maintenance considerations that may improve the performance of UWS box girder bridges can be found in Section 5.

- Because of a lack of any significant exterior horizontal surface for water and debris accumulation, the discussions below on deck overhang width, girder spacing, and flange geometry are not influential factors in the design of UWS box girder bridges.

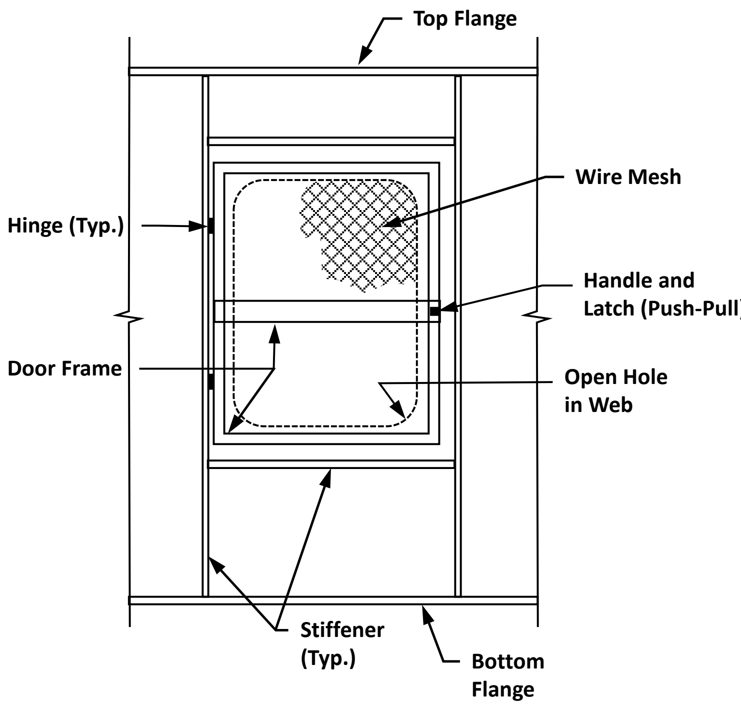


Figure 2.4.1.2-1—Example Vented Access Door.

2.4.1.3—Other Closed Sections

In addition to box girders, UWS bridges may contain other closed sections, such as boxes used for truss members, pier caps, straddle bents, and substructure components. The interior surfaces of built-up members should be painted with a single coat of light-colored primer at a minimum to protect against accelerated corrosion due to the potential for water accumulation and ponding.

Small, closed shapes such as HSS pose a challenge in that protection of the interior through a coating system is typically not practical and visual inspection is nearly impossible. Careful detailing to avoid any chance of moisture accumulation must be included in the design through adequately sized, properly spaced, and well-placed drain holes. Completely sealing small, closed sections to prevent all moisture ingress has proven ineffective in the past. At a minimum, drain holes or copes should be placed at the low points of all members. This should accommodate any expected accumulation of debris over the life of the structure. Improper detailing will lead to accelerated corrosion on the inside of closed shapes (Figure 2.4.1.3-1). In lieu of other guidance, the size, spacing, and location of drain holes can be determined using select provisions from ASTM A385 "Standard Practice for Providing High-Quality Zinc Coatings (Hot-Dip)." While this standard covers detailing for galvanizing baths, a logical thought process is that closed-shape UWS members properly detailed to drain hypothetical molten zinc should also be able to accommodate drainage of water for in-situ environmental conditions.

Source: VDOT

a. b.

Figure 2.4.1.3-1—Example of a poorly detailed HSS pedestrian bridge: (a) splices allow moisture to enter the inside of closed sections (b) drain holes are placed too high on the vertical and diagonal members, allowing water to pond on the inside below the drain holes.

If there is still concern for accelerated corrosion due to the potential for water accumulation and ponding inside of the members, then it is recommended that these members be galvanized.

2.4.1.4—Truss Bridge and Inclined Members

Trusses and other structure types including inclined members have the advantage that the majority of these members are boldly exposed, meaning that they are not sheltered by deck components. This provides the benefit of increased sunlight, air circulation, and exposure to rainwater that may provide a rinsing action for contaminants on the steel surfaces.

The tradeoff for this exposure to rainwater is that the drainage path for this moisture should be carefully considered and the potential for ponding eliminated (Figure 2.4.1.4-1). This often occurs when an inclined member connects to an adjacent member. Refer to Section 2.5 for drainage and other detailing considerations for truss bridges.

Figure 2.4.1.4-1—The drainage path of inclined members needs consideration. The middle and right photos show the consequences of water ponding at the termination of inclined members where no drainage was provided.

For the remaining members in truss bridges, which are sheltered by the deck, refer to prior Sections 2.4.1.1 through 2.4.1.3 on I-girders, box girders, and other closed sections for the information relevant to the member type under consideration. The information pertaining to I-girders is generally applicable to other open shapes.

2.4.1.5—Bent Plate Girder Systems

Because of the relatively thin plates used in bent plate systems, there is a smaller margin to protect against unanticipated corrosion in these structure types compared to other member types. Their geometry is also such that there is the potential for undetected water ponding. Thus, UWS should be used cautiously in bent plate systems and consider the recommendations for closed sections in this section.

2.4.2—Joints and Jointless Bridges

Because one of the largest performance problems of all bridge types is failed joints causing corrosion at ends of the superstructure, the best practice is to use jointless bridges wherever possible and otherwise minimize the number of joints to the extent possible. This statement is equally true for all bridge types, UWS and otherwise. Jointless bridges are a cost-effective option throughout the service lives of bridges, having both lower initial cost and maintenance cost than bridges with joints. FHWA (1989) states that "[t]o the extent possible, bridge joints should be eliminated. Jointless steel bridges have been used to lengths of 400 feet and greater (and up to 1600 feet with joints only at the ends) in some States with no problems identified due to lack of joints. Virtually every bridge with joints has problems (corrosion, rideability, maintenance) attributable to the joint." More recently, bridges with lengths of up to 500 feet have been constructed as fully jointless.

Jointless designs can be applied in most situations, with integral and semi-integral abutment bridges being the most common examples of jointless bridges. A 2002 report indicated that, at that time, most states that used integral abutments have an upper limit on skew, typically 20 to 30 degrees (WJE, 2002). Yet, there are integral abutment bridges with skews up to 45 degrees.

Elimination of joints through the use of link slabs is also an option that should be considered and is particularly well suited for rehabilitation projects where the structural system can accommodate them.

Pin and hanger connections in girder bridges, previously used to obtain the advantages of a continuous dead load moment diagram without introducing statical indeterminacy, have proven to be problematic from a durability perspective and therefore should not be used – particularly with UWS bridges. They are also prone to galvanic corrosion (discussed in more detail later) between the steel girder and the bronze washer used in the connection.

While jointless bridges are the preferred means of bridge construction and it is the desired norm for UWS systems, not all bridges can fit within the regime. When joints must be used, the focus must shift to means and methods to combat and eliminate roadway drainage from all sources impinging upon the supporting structural steel system, bearings and sub-structures. Strategies and details for protecting components under joints can be found in Section 2.5.

2.4.3—Sacrificial Thickness

When UWS bridges are designed, fabricated, constructed, and maintained in accordance with the guidelines contained in this document, thickness loss of steel over the life of the structure should be negligible and can be safely ignored for the purposes of designing member geometries in the vast majority of situations. In general, these strategies are highly preferable to designing and/or relying on a sacrificial thickness.

In environments where the corrosivity is unknown or known to be high (see Table 2.1-1), a sacrificial thickness may be added to insure sufficient structural capacity. It is typically the case that providing a sacrificial thickness of the magnitude suggested herein is more economical than the future cost of maintenance painting. Thus, a sacrificial thickness can be an economical option in environments where there is a significant uncertainty regarding performance of UWS.

When there is determined to be a need for a sacrificial thickness, the total thickness specified for a member is the thickness needed for the structural function of the member plus a corrosion allowance, i.e., sacrificial thickness. It is recommended that this corrosion allowance be added only to the thickness of components that are oriented horizontally. Most known instances of measurable section loss of UWS members have occurred in one of two situations: (1) from the bottom flanges of open sections where water and salts have the ability to pond on horizontal surfaces and (2) beneath leaking joints. Thus, only bottom flanges, horizontally-oriented cross-frames, and similar members – in limited environments – should be considered for a corrosion allowance. It is assumed that proper detailing, as recommended in this manual, will be followed, which will prevent the need for any additional thickness in girder webs or other vertical surfaces. The possibility for corrosion due to leaking joints should be mitigated through joint design and maintenance instead of sacrificial thickness. In short, the use of a sacrificial thickness cannot be relied upon in place of proper detailing or joint maintenance.

In cases where a corrosion allowance is determined to be warranted, the recommended corrosion allowance is 1/16 inch for a typical service life. This is the total increase in thickness, and accounts for section loss on both sides of a plate. Plate widths should be adjusted as needed to result in final plate thicknesses corresponding to those typically used and readily available. Designers should consider availability when specifying plate thicknesses. Additional guidance on proportioning flanges for corrosion performance can be found in Section 2.4.7. In no event should extra thickness be considered a replacement for good detailing. A patina that does not properly or fully form will not protect the steel, which will lead to corrosion and eventually section loss beyond the sacrificial thickness.

The recommendation of 1/16 inch as the typical value of sacrificial thickness, when deemed to be warranted, is based on comparing the performance of UWS bridges in the macro- and micro-environments listed in Table 2.1-1 with performance per the environment classifications established by the International Standards Organization (ISO, 2012), as adapted to UWS by Albrecht et al (1989).The situations identified as possible candidates for a sacrificial thickness in Table 2.1-1 can generally be considered as being a "high" corrosive environment, per the ISO classification system. Per this definition of a "high" corrosive environment, a UWS plate is expected to experience a section loss of up to 0.0008 inches/year (assuming both surfaces of the plate are exposed to the environment). Thus, a corrosion allowance of 1/16 inch in these situations is expected to provide adequate thickness over a 75-year service life (Figure 2.4.3-1). For a longer 100-year service life, the predicted additional thickness loss is less than 0.02 inches (relative to the base thickness without the corrosion allowance), or approximately 0.08 inches of total thickness loss. Such magnitude of thickness loss is considered negligible relative to the fact that this is within the fabrication tolerances of all plate thicknesses and widths codified by ASTM standards.

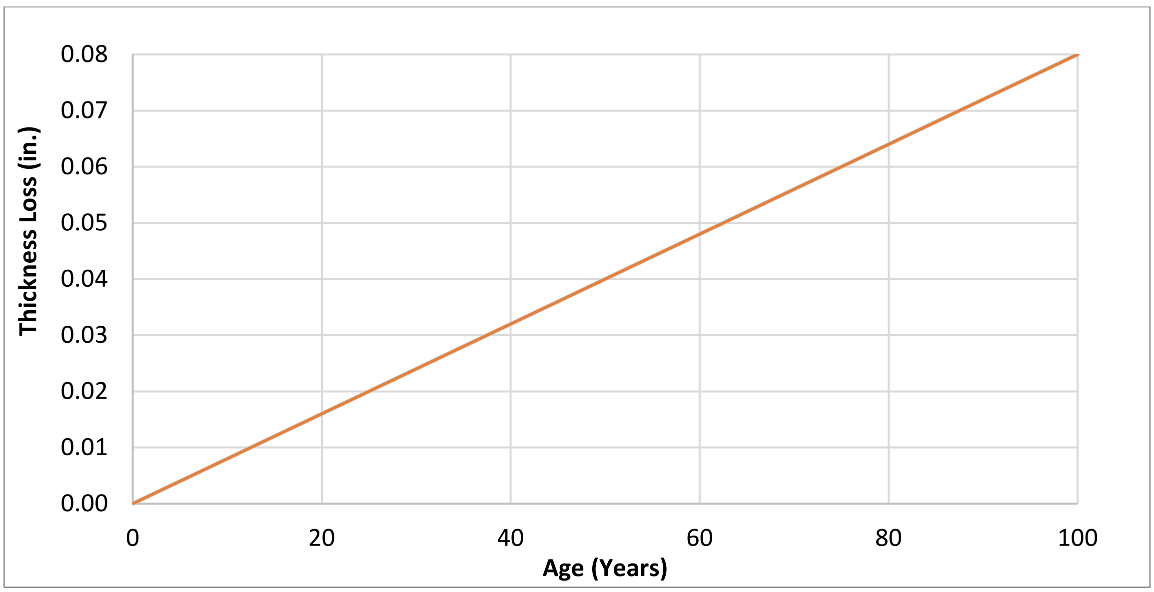


Figure 2.4.3-1—Estimated upper-bound section loss for fully-exposed UWS plates (i.e., total section loss on top and bottom surfaces) in "high" corrosive environments.

2.4.4—Deck Type

A deck type that provides a water-tight shelter for superstructure members is a best practice. This includes reinforced-concrete decks and other monolithic, impervious decks. This is in contrast to timber decking and open steel grid decks, which allow water to pass through the deck, producing a continuously wet environment, as exemplified in Figure 2.4.4-1. If filled grid decks are used, they should be used with an overfill or overlay to prevent leakage via the interface of the steel and concrete, which has been observed in cases without overlays (Figure 2.4.4-2).

An additional concern regarding the use of timber decks is that they are pretreated with chemicals that may be corrosive to UWS. In situations where the use of timber decking cannot be avoided, this concern can be alleviated if a mastic strip or damp-proof material is placed and maintained between the decking and the girders.

Figure 2.4.4-1—Timber decks retain moisture (as shown on the left), which can lead to blistering paint (middle) and accelerated corrosion of UWS (right).

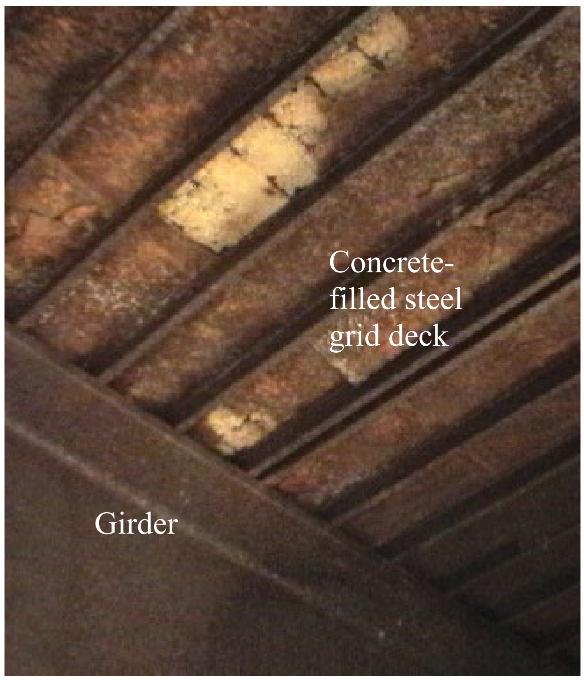


Figure 2.4.4-2—Concrete filled steel grid deck, without overfill, viewed from bottom, shows that bottom plate of deck has broken loose from water infiltrating between steel grid and concrete fill.

2.4.5—Deck Overhang Width

It is recommended that the deck overhangs be cantilevered to the greatest practical extent, consistent with the design parameters for deck design in the LRFD Specifications, and with consideration for the optimum dead load weight and constructability concerns. This is for the same reasons as previously discussed regarding deck type – to provide shelter to the UWS superstructure. Narrow overhangs can result in water ponding on the top side of bottom flanges due to windblown rain. Capillary action can then cause this water to be drawn up the web, leading to the potential for accelerated corrosion on both the bottom flange and web (Figure 2.4.5-1). Specifically, for I-girder bridges, it is recommended that the width of the overhang be at least equal to the depth of the exterior girder where practical, or as wide as practical otherwise. Also, drainage and drip beads should be provided in deck overhangs to prevent water on fascia girders (See Section 2.5 and Figure 2.5.1-8).

Figure 2.4.5-1—Relatively narrow deck overhangs (left) can cause ponded water on bottom flanges, which is drawn up the web by capillary action, and accelerates corrosion (right).

2.4.6—Girder Spacing Considerations

It is recommended to avoid girder spacings that limit air flow for drying actions, create areas where debris is more likely to become lodged, and/or impair inspections. To prevent these possible problems, where feasible, it is suggested to provide a minimum girder spacing that is approximately the lesser of 6 feet or the girder depth (e.g., 10 feet deep girders should be spaced at least 6 feet). For railroad structures with little exposure to chlorides, closer spacings have been used without negative effect.

2.4.7—Flange Geometry and Transitions

There are three primary considerations that should be made with selecting flange geometry: structural efficiency, constructability, and corrosion performance. The flange geometry will generally have larger impacts on strength and constructability than corrosion performance. For example, wider flanges will provide increased torsional and minor-axis bending resistance, which is of particular importance for curved girder bridges (Figure 2.4.7-1). Thus, flange width transitions may be preferred over flange thickness transitions in these situations. However, the recommended practice for general constructability (AASHTO/NSBA, 2020) is to favor flange thickness transitions instead of flange width transitions.

Therefore, it is recommended that the flange geometry be selected based on strength and constructability as the primary considerations, and secondarily for corrosion performance. The corrosion related considerations are:

1. To maximize plate thicknesses of bottom flanges so that the required widths are minimized, to the extent practical. This results in a smaller surface area where water and debris may collect, and a lower total loss of area for a given loss of thickness due to corrosion.

2. To provide flange thickness transitions instead of flange width transitions for bottom flanges (with the thickness added to the underside of the flange). This results in a greater ability to predict the drainage path of any water that may travel along the length of the top sides of bottom flanges (Figure 2.4.7-2).

Figure 2.4.7-1—Flange width transitions often result in the optimized design from a strength perspective, particularly for curved bridges.

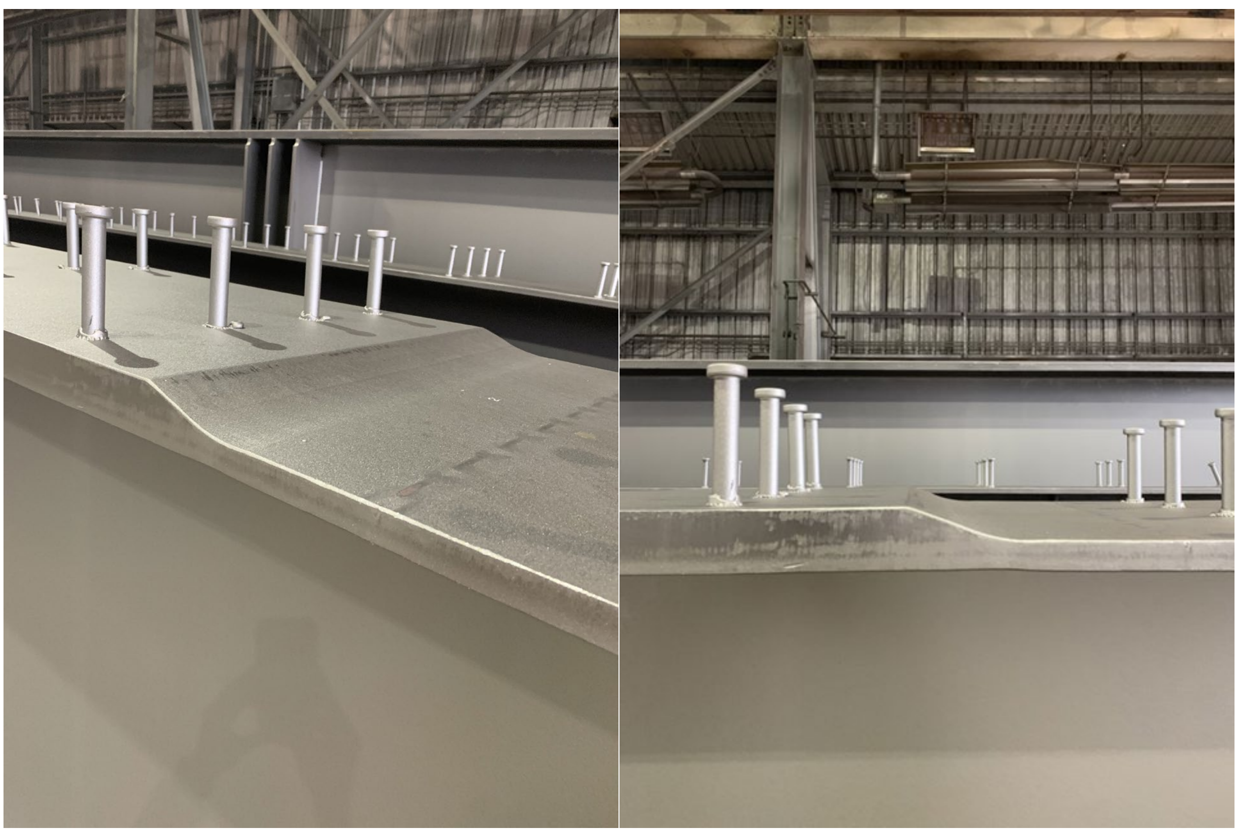


Figure 2.4.7-2—Where practical, flange thickness transitions are preferred for general constructability and corrosion performance.

2.4.8—Bolted Connections

Bolted connections between weathering steel members should use weathering steel specific fasteners. Appropriate combinations of bolts, nuts, and washers are listed in Table 2.4.8-1. For discussion of galvanic corrosion for bolts in dissimilar metal connections see Section 2.5.4.

Table 2.4.8-1—Fastener Combinations for Use with Weathering Steel

Bolts	Nuts	Washers
ASTM F3125 Grade A325 Type 3	ASTM A563 Grade DH3 or C3	ASTM F436/F436M Type 3
ASTM F3125 Grade A490 Type 3	ASTM A563 Grade DH3	ASTM F436/F436M Type 3

2.4.9—Maintenance Considerations

A broader consideration of maintenance needs over the life of a structure is also possible at the design stage. For example, Rhode Island requires designers to provide recommended corrosion maintenance procedures for coated steel structures (Ault and Dolph, 2018). While the maintenance needs of UWS are fewer, this is nonetheless a useful exercise for the designer as it may result in further optimization of the design from a corrosion perspective and providing clear expectations to the owner regarding assumed maintenance actions considered in the design. The AASHTO Guide Specifications for Service Life Design of Highway Bridges (Murphy et al., 2020) includes details on a Service Life Report, which contains details on what maintenance activities are needed to achieve the service life assumed in design.

2.4.10—Fatigue

The current AASHTO LRFD Bridge Design Specifications (2020) identify separate fatigue categories for the base metal of UWS and other base metals. The rationale behind this is that the corrosion process of UWS can result in greater surface roughness and/or pitting, which may result in decreased fatigue life (for example due to stress concentrations at pitting locations) (Albrecht and Cheng, 1983; Barsom, 1984). UWS base metal is classified as Category B with a constant amplitude fatigue life threshold of 16 ksi, while all other base metal is classified as Category A with a constant amplitude fatigue life threshold of 24 ksi. These categories have been in place for decades and continue to be supported as additional testing is performed.

However, this difference in fatigue life for the base metal is of little consequence in practical design, which is almost always governed by the fatigue life of welded or bolted details rather than the base metal. No difference is given in the fatigue categories for these details as a function of material type in AASHTO (2020) nor is it believed to be necessary based on experimental testing carried out by various researchers. The few cases in the literature where decreased fatigue performance of bolted and welded UWS specimens has been observed were carried out in severe environments in which UWS should not be used, as recommended elsewhere in this manual.

It is recommended that all connections and details be designed for the Infinite Fatigue Life (FATIGUE I) case, as well as qualify as fatigue Category C' or better whenever possible. However, it is allowable for the design of a bridge to be based upon a Finite Fatigue Service Life (FATIGUE II) per the current specifications.

While not expected on bridges designed according to the current fatigue provisions in AASHTO LRFD, fatigue cracking is a possibility once in service. The reader is referred to Section 4 for recommendations on inspection and crack detection.

2.5—DETAILING

2.5.1—Drainage

When the ends of beams are cast integral with the abutment backwall, the encased portion of the beam should be coated with a protective primer (Figure 2.5.1-1). The primer or primed and painted coating must project past the backwall-beam interface for sufficient distance to protect against moisture buildup (sweating) caused by the temperature differential between the backwall and beam exposed to the atmosphere.

Source: Ed Wasserman

Figure 2.5.1-1—Coating protection for portions of weathering steel embedded in concrete.

As indicated earlier, elimination of joints is probably the single most effective design detail to reduce corrosion. This can be achieved either with continuous beam design or single span beams with continuous deck, utilizing link slabs (Figure 2.5.1-2). Eliminating longitudinal joints in closely spaced bridges can be achieved by joining the two (Figure 2.5.1-3).

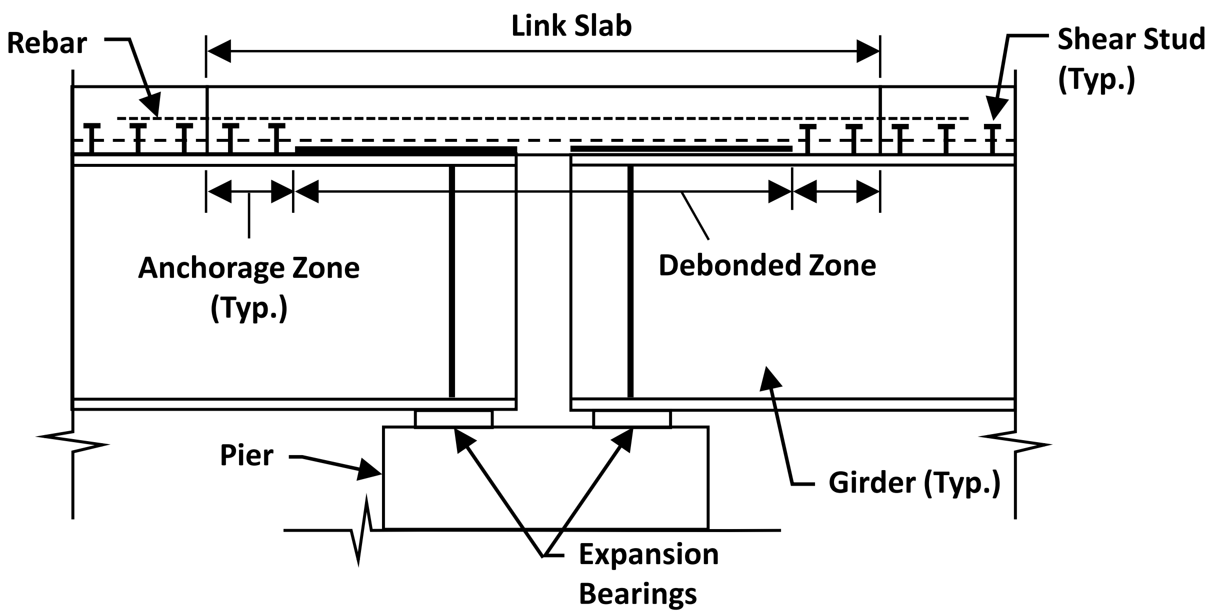
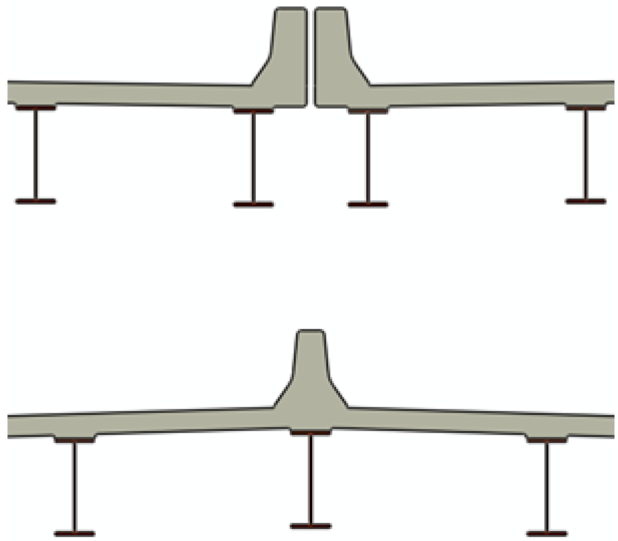


Figure 2.5.1-2—Example of a link slab to eliminate a joint at intermediate supports for simple span designed bridges. Expansion and contraction from thermal movements to abutment ends.



Source: Kogler (2015)

Figure 2.5.1-3—Example of eliminating closely spaced parallel structures or longitudinal joints.

Properly collecting and dispersing rain and snow run-off requires attention to details. The following methods are offered:

- The use of haunched girders complicates the efficient removal of run-off and can result in the collection of debris at the haunch (Figure 2.5.1-4a). Haunched girders should be used with care, with generous allowances for drainage through stiffener copes, snipes, and drain holes (Figure 2.5.1-4b).

Source: Kogler (2015) Source: Medlock et al. (2019)

Figure 2.5.1.-4—(a) Debris and moisture traps formed by bearing stiffeners without drain holes; (b) stiffeners fabricated with clips to reduce debris and moisture accumulation.

- Installing drip bars along facia girders can reduce the total discharge that reach connection details or prevent run-off onto substructures (Figure 2.5.1-5). Drip bars should not be welded to areas where the bottom flange is in tension or stress reversals, as a rule. If they are, the flange must be designed to meet the fatigue design rules that govern. Similarly, drip pans and trays can be installed at bearing locations over substructures to prevent concrete staining (Figure 2.5.1.1-6 and -7).

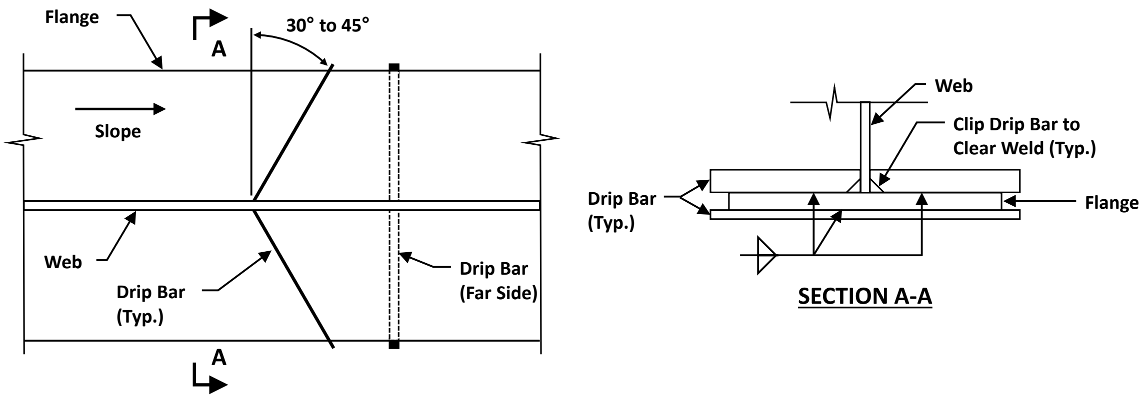


Figure 2.5.1-5—Example drip bar detail.

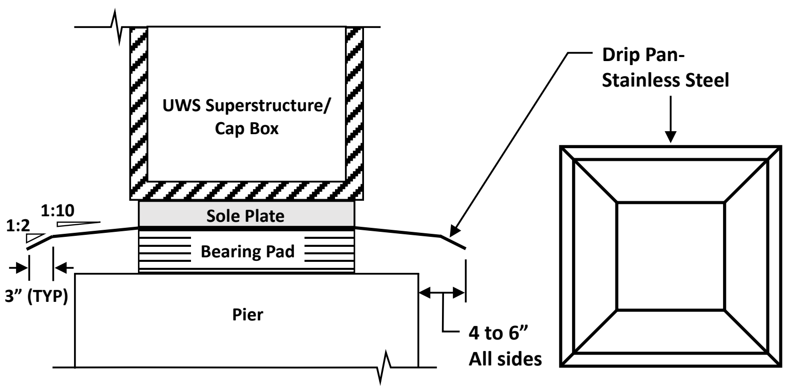


Figure 2.5.1-6—Example drip pan detail.

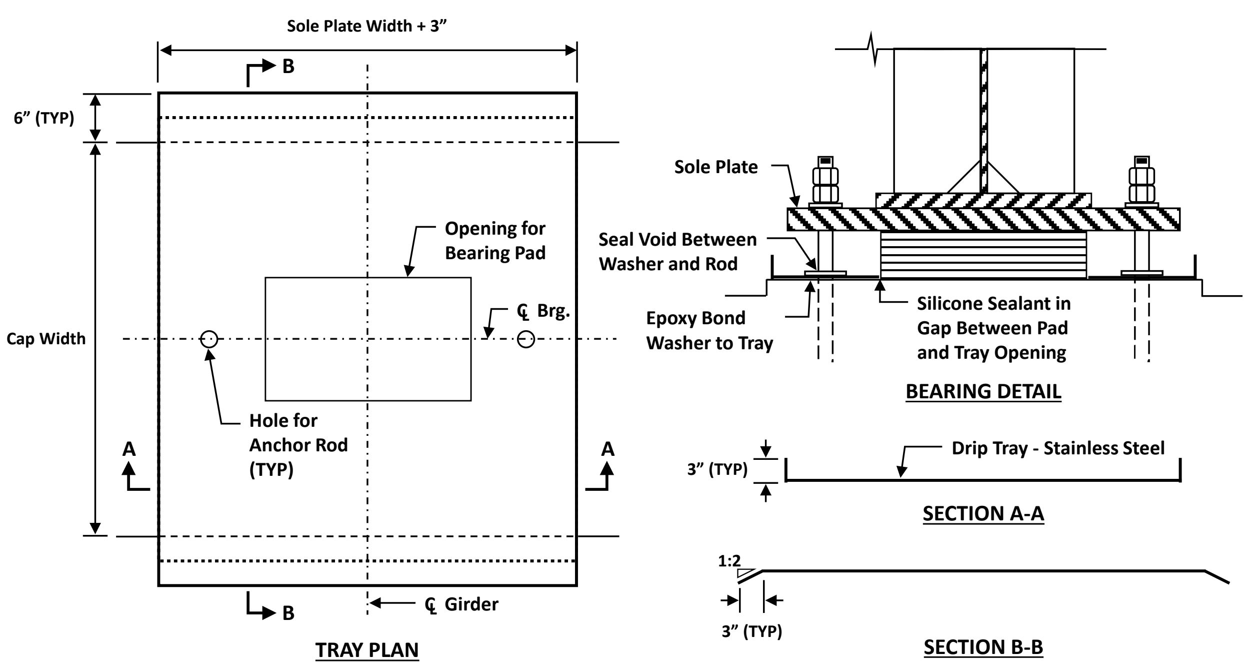


Figure 2.5.1-7—Example drip tray detail.

- Deck run-off should be routed into deck drainage scuppers. The outflow from the scuppers must be prevented from contacting UWS surfaces below deck (Figure 2.5.1-8). The distance below the bottom of the girder of the discharge end of the downspout needs to be sufficient considering the effects of wind on draining water. The use of closed drainage systems has proven to be problematic and should be avoided (Figure 2.5.1-9). Slot opening drains in parapets or curbs can be effective where the cantilevered deck overhang is of sufficient length to allow the discharge outfall to clear the fascia beam. On shorter structures, or larger ones with sufficient roadway grades, consider carrying deck run-off with no drains in shoulders and travel lanes, in conjunction with owner policies and conformance with pertinent FHWA Hydraulic Engineering Circulars, regarding design storm water spread. This works particularly well with jointless bridges.

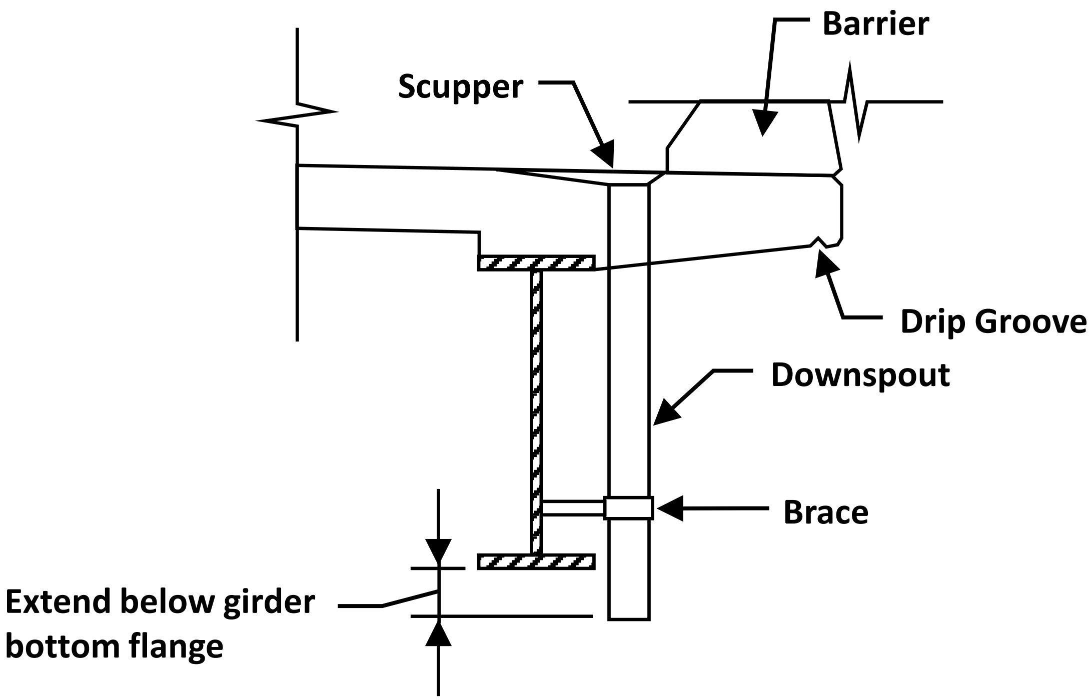


Figure 2.5.1-8—Example downspout detail.

Source: Kogler (2015)

Figure 2.5.1-9—Clogged and leaking drain.

- If transverse deck expansion-contraction joints cannot be avoided, placing the expansion joint at the back of the backwall is recommended (Figure 2.5.1-10). When potential leaking or greater discharge at substructures can or will occur, slope the tops to direct flow to outlet drains (Figure 2.5.1-11).

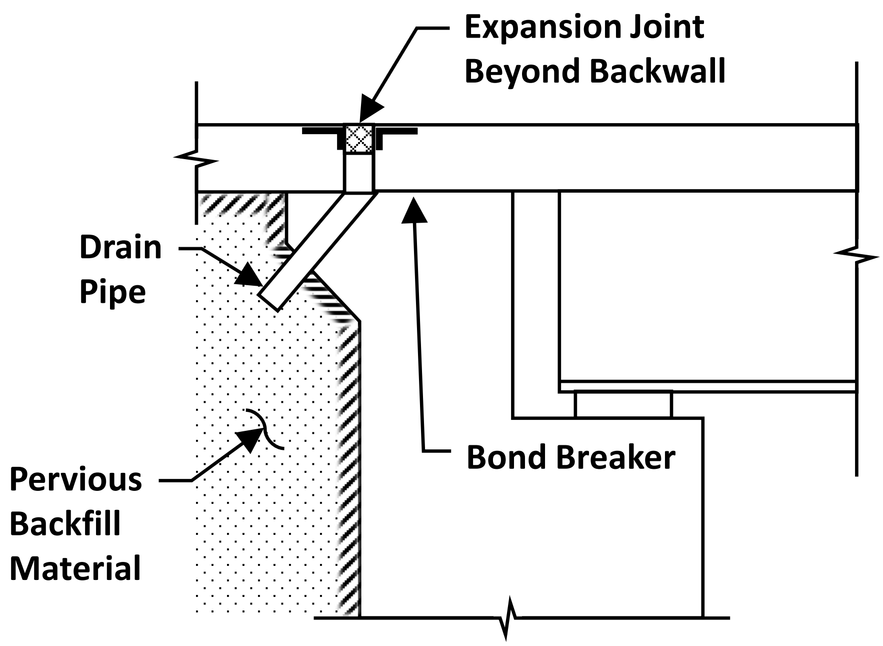


Figure 2.5.1-10—Example of locating the expansion joint at the back of the backwall.

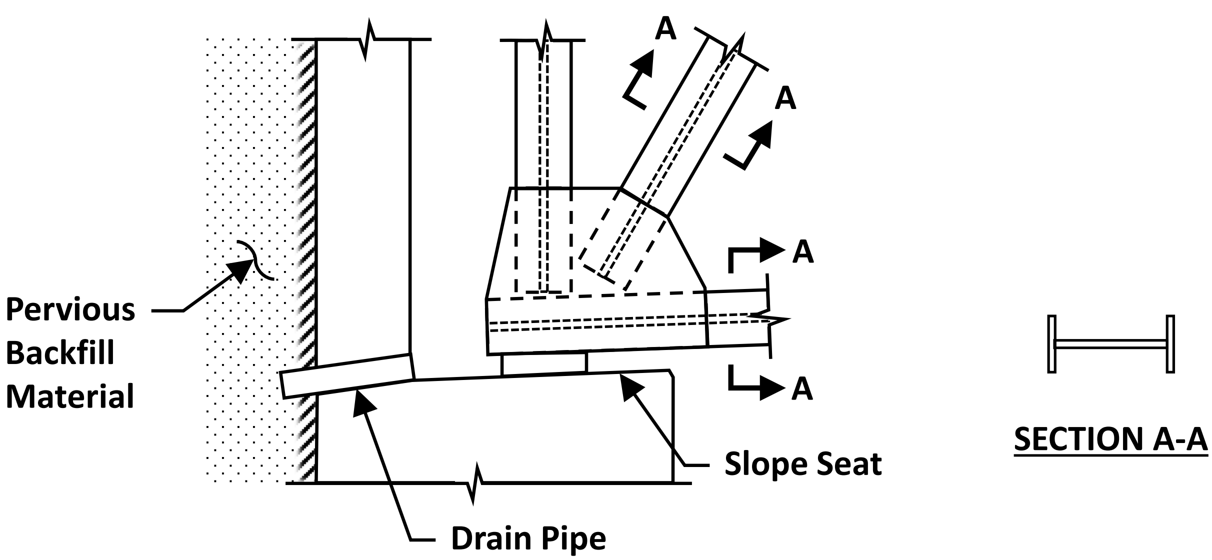


Figure 2.5.1-11—Example of sloping abutment seat and truss orientation for drainage.

- For overhead truss systems, orienting the open section in weak axis positions, that allows any flow to be channeled between confining flanges is recommended provided the horizontal members (chords) have sufficient slope to properly drain and prevent ponding (refer to Figure 2.5.1-11), and the run-off at the bottom of the member will not negatively affect the joint or other members.

- Tub and box girders should be detailed considering drainage as well as ease of fabrication. Two alternate connection details for bottom flange to web welds are shown in Figure 2.5.1-12. While the extended web option provides the best water shedding potential, the projecting bottom flange option avoids extensive fit-up challenges in the fabrication shop and has not been observed to be problematic from a corrosion perspective in typical scenarios. The extended web option is preferred from a corrosion perspective because there are no exterior horizontal surfaces or crevices for moisture to collect; however, it may require extra handling (e.g., rotating) during fabrication to make the welds. The projecting flange option is typically easier to fabricate especially for trapezoidal box girders, but it provides a continuous corner for moisture to collect. This surface is similar to, but less severe than, the bottom flange of an I-girder and the design guidance for I-girders would result in conservative recommendations for this scenario. The engineer should weigh the choice with the owner and potential fabricators before making a final decision on connection details. While tub and box girders are perceived to be free of water penetration, this is not likely the case, as leakage from construction cold joints and cracking in concrete decks will occur. Condensation caused by temperature change and temperature differentials will be present. All interior surfaces are recommended to be painted with one coat of a light-colored primer (e.g., organic or inorganic zinc, epoxy mastic) for protection and ease of inspection. Drains must be provided at low points within cells (Figure 2.5.1-13). Ventilation holes should be considered to promote air circulation and drying of interior surfaces (Figure 2.5.1-14) should water enter the box; however, locations of these holes must be carefully selected to prevent unintended infiltration of moisture from the exterior. For any type of hole introduced in closed sections, screens should be used over the holes to prevent wildlife from entering the interior.

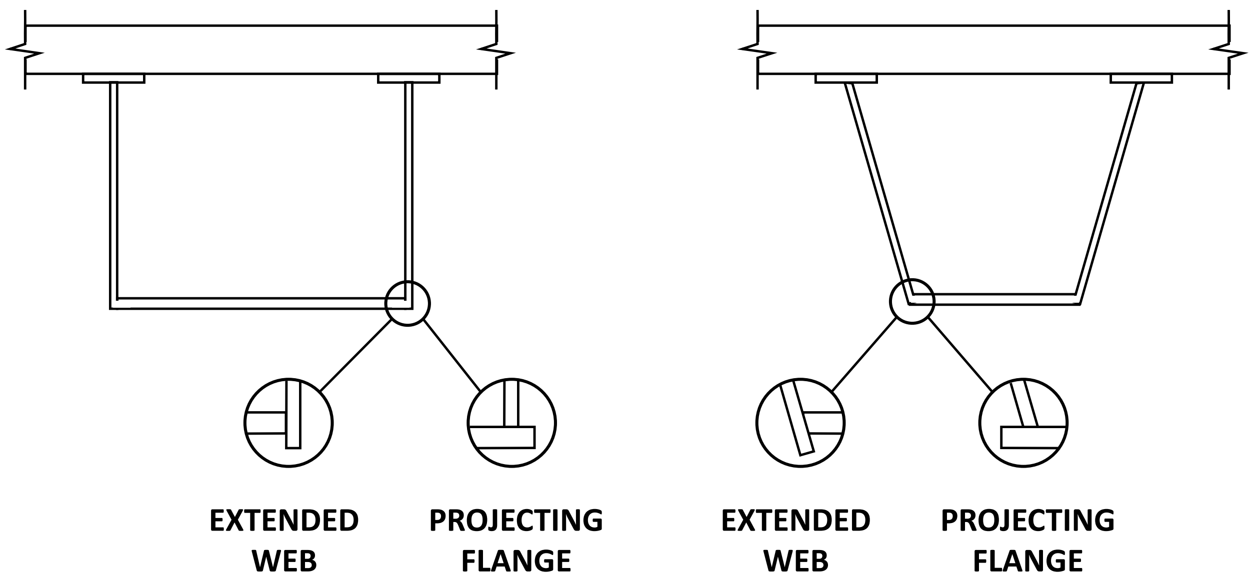


Figure 2.5.1-12—Example box girder fabrication details.

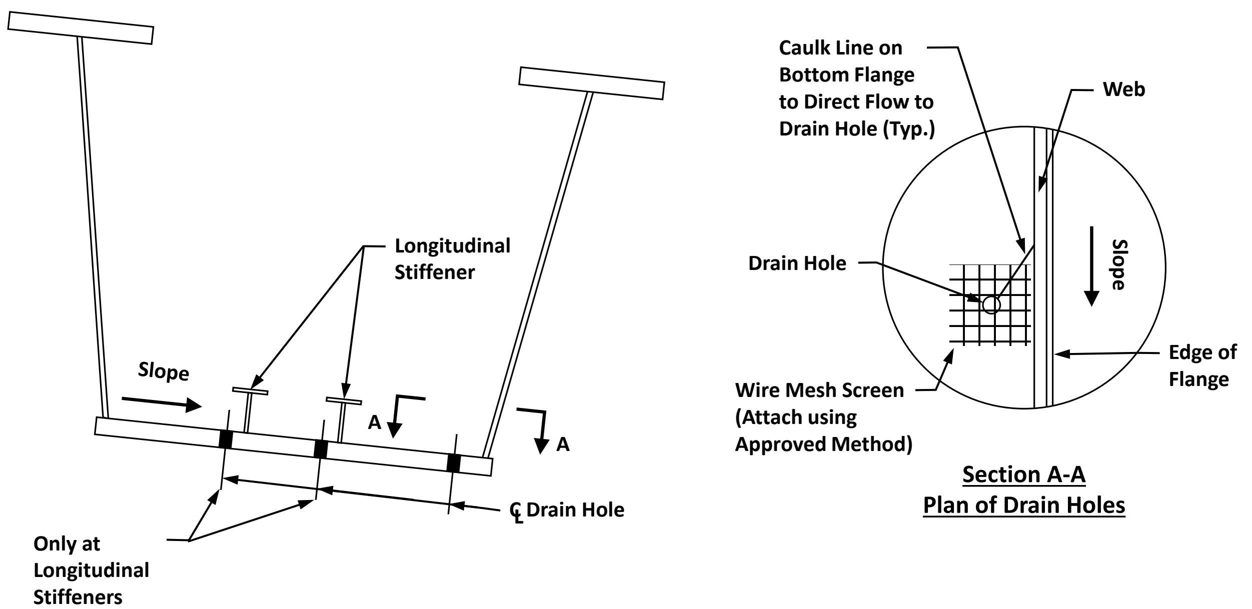


Figure 2.5.1-13—Example drain hole details

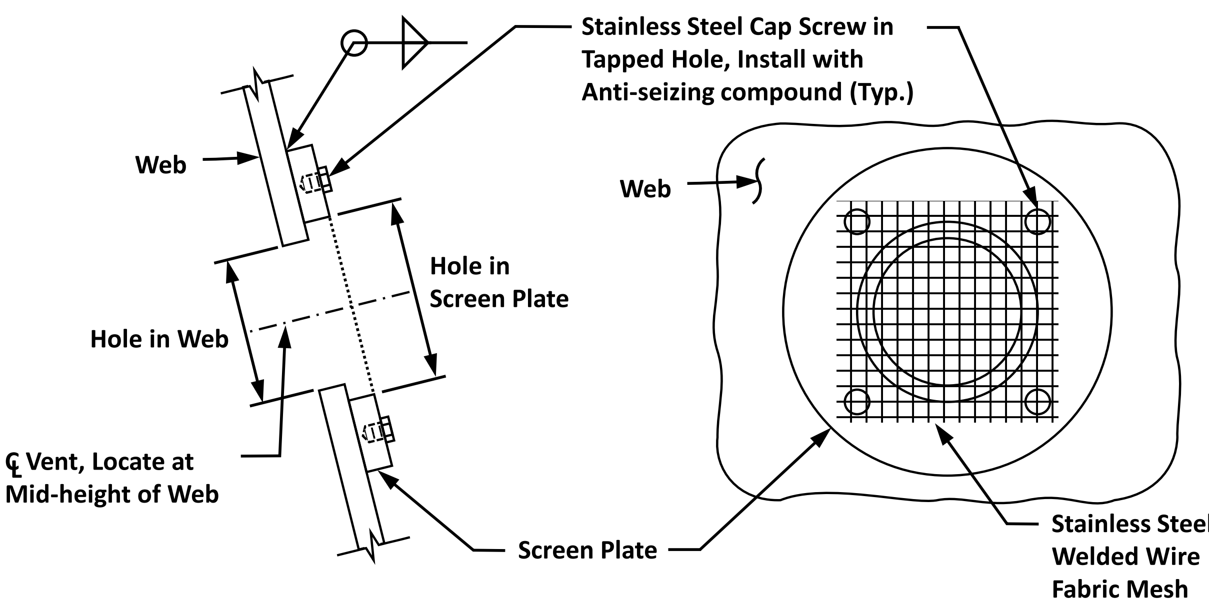


Figure 2.5.1-14—Example box girder screened vent hole detail.

2.5.2—Structural Connections

As stated in NCHRP Report 314 (ibid) "Water ponds and debris accumulate on horizontal surfaces and in corners formed by horizontal and vertical plates (reentrant corners), fostering excessive corrosion. In I-girder bridge members the most susceptible locations are bottom flanges, gusset plates for horizontal bracing, longitudinal stiffeners, bolted spices of horizontal and sloped members, and intersections of bearing and intermediate stiffeners with flanges and gusset plates."

Of course, these details are not exclusive to I-girders but apply as well to truss configurations constructed from open fabricated or rolled sections. It is worth noting that these facts apply to coated steel structural systems of similar design. Given these facts, design details should be approached with the mindset of minimizing the potential to pond and accumulate debris and instead promoting self-cleaning and easy discharge of water to the extent possible. To this end, a series of suggested details follow:

- For all vertical stiffeners that intersect horizontal surfaces, provide clips (snipes) of the largest dimensions practical considering the force carried to avoid trapping debris carried by water flowing on horizontal surfaces intersected Recommended clip details are provided in Figure 2.5.2-1; larger dimensions are preferred provided the design can accommodate them.

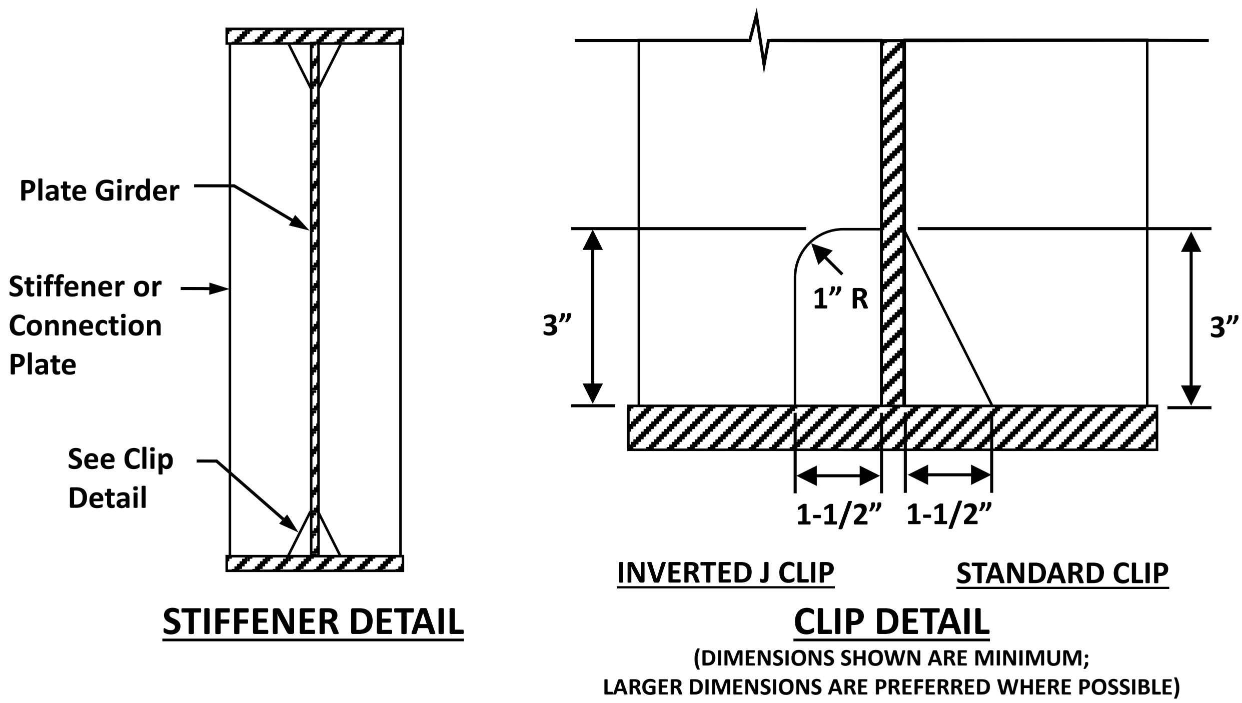


Figure 2.5.2-1—Size stiffener clips to avoid trapping debris.

- All bracing members should be oriented to promote the shedding of water and debris collection. For example, note that in Figure 2.5.2-2, the projecting legs of the angle members are oriented towards the top sides of these members to reduce the likelihood of water and debris accumulation in reentrant corners of these members. In addition to durability, the type (direct or gusset) and mechanism (bolting or welding) of connection should consider (1) constructability and (2) reducing the risk for distortion-induced fatigue cracking. Guidance on bracing system design can be found in the FHWA Steel Bridge Design Handbook (Helwig and Yura, 2015).

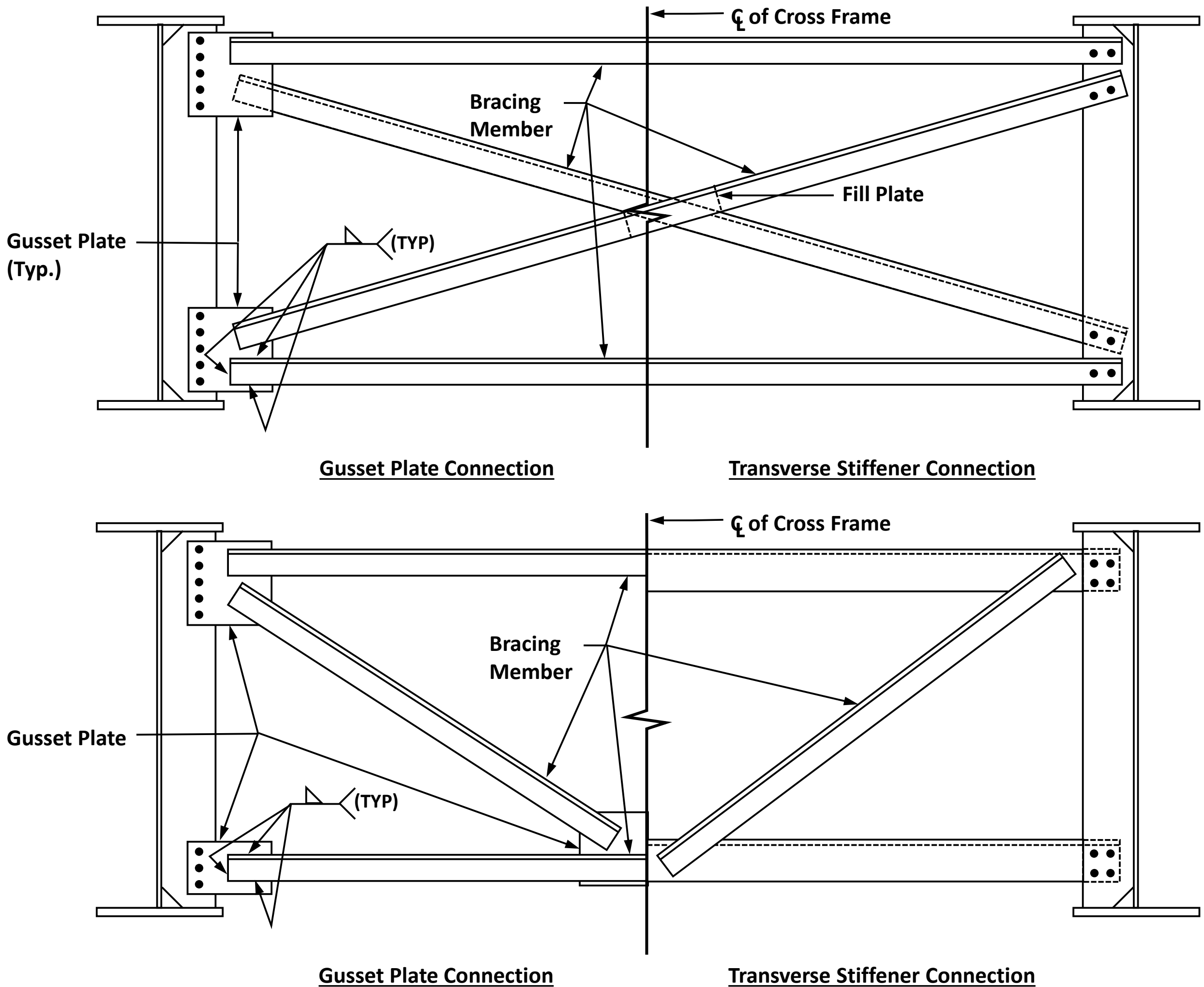
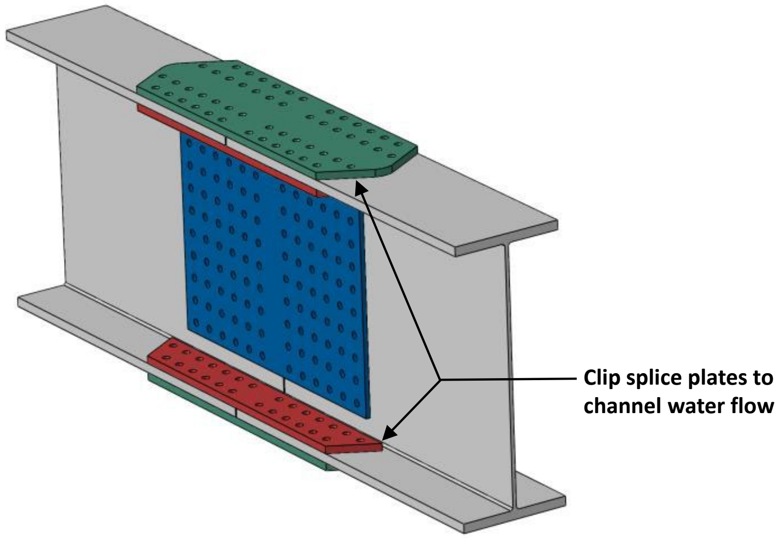


Figure 2.5.2-2—Preferred cross frame details.

- Flange splice plates at field splices should be clipped (sniped) at their leading and trailing ends to facilitate water shedding (Figure 2.5.2-3). This is not necessary for top flanges supporting a concrete deck.



Source: Kogler (2015)

Figure 2.5.2-3—Illustration of clipping splice plates.

- Similar to cross frames, lateral bracing members should be oriented to minimize debris and moisture collection. Connecting the laterals to the underside of the gusset reduces ponding and debris buildup. (Figure 2.5.2-4). As mentioned for cross frames, bracing design guidance can be found in the FHWA Steel Bridge Design Handbook (Helwig and Yura, 2015)

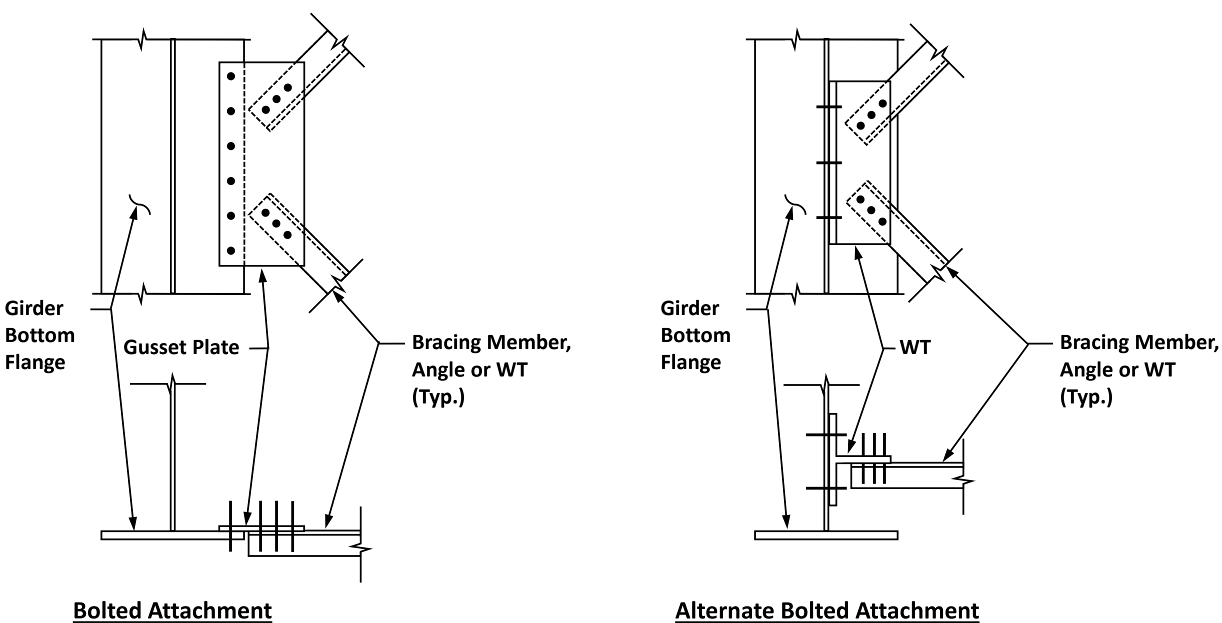


Figure 2.5.2-4—Preferred lateral bracing connection details.

2.5.3—Targeted Painting

There are situations where painting a limited area of UWS girders can provide a substantial benefit. These would include:

- The ends of girders near deck joints, where joints cannot be eliminated
- Area where a girder is embedded in concrete (excluding top flanges in decks)
- The interiors of closed members
- The outside visible surfaces of fascia girders for aesthetics

The most common situation of using paint on otherwise uncoated steel is beneath joints. Where possible, joints should be eliminated as leaking joints are a ubiquitous problem in the United States. However, when this is not possible, all UWS structures should be detailed assuming that joints will leak at some point during the lifespan of the bridge. The FHWA TA 5140.22 (1989) recommends painting all superstructure steel within a distance equal to 1.5 times the depth of the girder from bridge joints. This guideline has been generally used throughout the United States since it was recommended, although some agencies prescribe slightly different distances. The effectiveness of this practice is strongly supported by field observations.

As addressed elsewhere in this manual, the sections of girders or other structural members that are embedded in concrete should be painted, and for a short distance approaching the embedment as well. The difference in thermal mass can result in condensation forming at the interface, which can lead to extended times of wetness and increased corrosion rates. This recommendation does not apply to the top flanges of I-girders in contact with concrete bridge decks.

Another approach to controlling staining of concrete piers and abutments is to paint a short section of girder above the bearings. This should limit the amount of corrosion byproduct that is washed down onto the pier from precipitation. This approach is only effective if all other sources of drainage onto the substructures are controlled. As addressed elsewhere in this manual, there are other approaches to effectively control staining of substructure elements that do not involve painting of the steel.

Another situation where painting may be considered is the interior of boxes and other closed sections. These areas have a potential for long times of wetness, and a coating system in combination with appropriate drainage details will be effective in preventing excessive corrosion. This is discussed further in Section 2.4.1.2.

2.5.4—Material Interfaces and Compatibility of Dissimilar Materials

2.5.4.1—Galvanic Corrosion Mechanism

Galvanic, or bimetallic corrosion, can occur between metals with electrical potential differences that are in contact and exposed to an electrolyte source (NACE, 2008). This type of corrosion is an example of the electrochemical cell (Figure 2.5.4.1-1) in which the following factors are present:

1. Anode: where metal is lost and electrons are produced.
2. Cathode: where electrons from the anode are consumed.
3. Metallic Path: conducts electrons from the anode to the cathode.
4. Electrolyte: provides reactants for the cathodic reactions and allows ion flow.

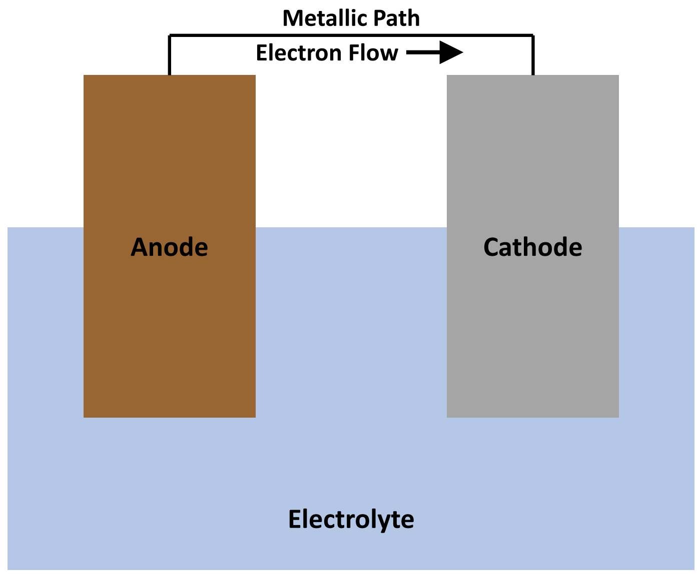


Figure 2.5.4.1-1—Galvanic corrosion mechanism.

In galvanic corrosion, electrons flow through the metallic path from the anode to the cathode. The electrical current flows through the electrolyte to balance the electron flow in the metallic path. The reaction occurs due to electrochemical potential differences between the metals in contact. This causes increased corrosion of the anodic metal compared to the same metal in the same environment but without dissimilar metal contact. The main drivers of galvanic corrosion are:

1. The electrochemical potential difference.
2. The relative surface area ratio between the metals.
3. The presence of a regularly occurring electrolyte connecting the metals (e.g., water).

Subsequent sections discuss each of these drivers. It should be noted that there are exceptions and that contact between dissimilar metals does not guarantee corrosion. Therefore, galvanic corrosion should be evaluated on a case-by-case basis whenever there is contact between dissimilar metals. Considerations and recommendations specific to UWS are included in the following sections.

2.5.4.2—Potential Difference (Galvanic Series)

The risk of galvanic corrosion should be evaluated considering the relative positions of metals in the galvanic series, which is a measure of electrochemical potential difference between metals. In general, corrosion of the anodic metal is exacerbated the further apart two metals are in the galvanic series (Figure 2.5.4.2-1). For further guidance, see Landrum (2012).

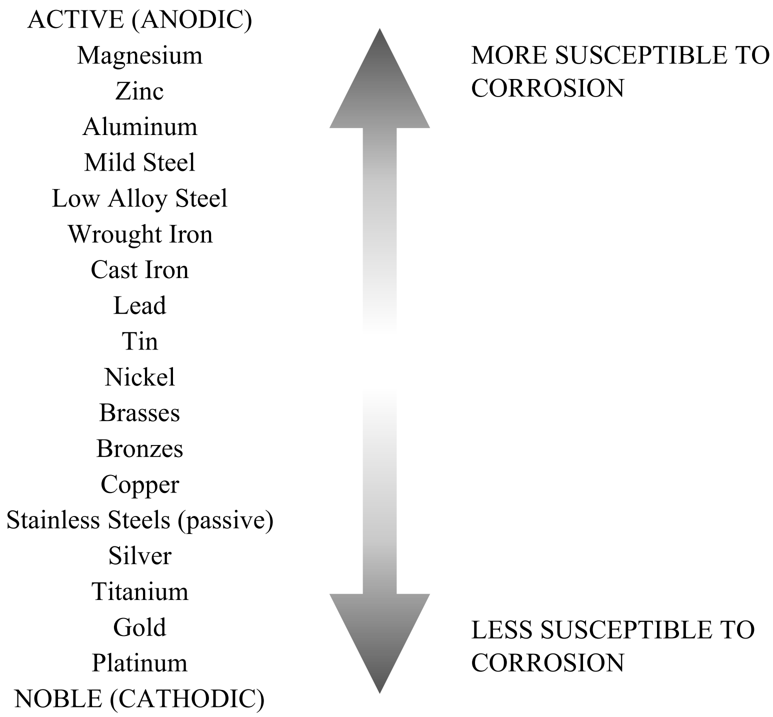
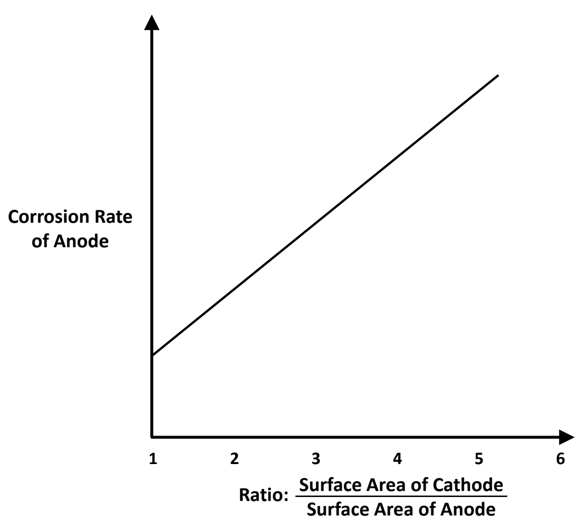
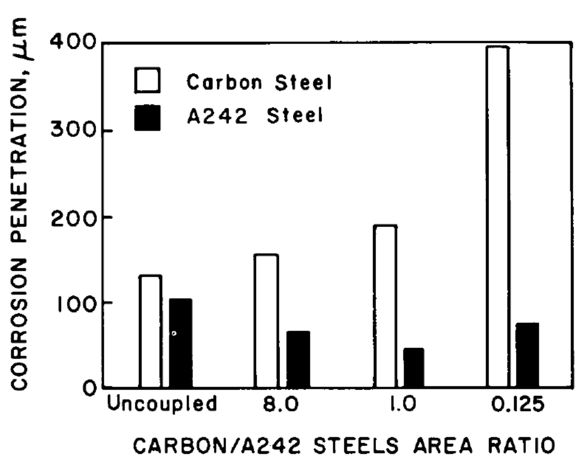


Figure 2.5.4.2-1—Galvanic Series of Metals in Seawater.

2.5.4.3—Area Ratio

The relative surface area of two metals in contact is critical to galvanic corrosion. As the surface area of more corrosion resistant metal (cathode) increases relative to that of the less corrosion resistant metal (anode), the corrosion rate of the less corrosion-resistant metal increases. Therefore, a small cathode to anode (or large anode to cathode) surface area ratio is more favorable, as illustrated by the graph in Figure 2.5.4.3-1 (a). A practical example is depicted by the graph in Figure 2.5.4.3-1 (b) for contact between carbon steel and ASTM A242 weathering steel (more corrosion resistant). As the area ratio between the carbon steel and A242 steel decreases, the corrosion rate of the carbon steel increases. The same concept holds true when UWS is the less corrosion resistant material in the couple, for example when in contact with stainless steel. Note that the results shown in Figure 2.5.4.3-1 (b) were observed in seawater and that the behavior could vary in other environments.





Source: Ellis and LaQue (1951)

b.

a.

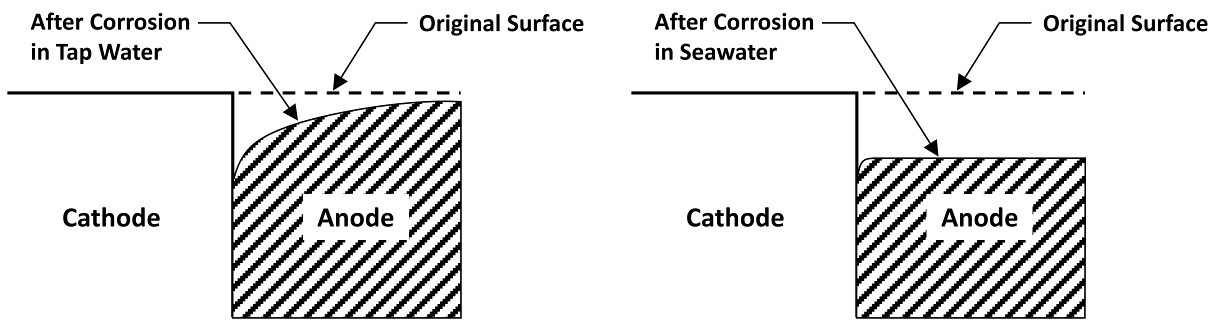
Figure 2.5.4.3-1—Effect of relative surface area on galvanic corrosion: (a) general concept; (b) corrosion of coupled and uncoupled carbon and A242 steel in seawater.

2.5.4.4—Electrolyte Presence and Resistance

The third main driver of galvanic corrosion is the presence and resistance of an electrolyte, typically water in the case of bridges. Without moisture, there is not an electrical path and galvanic corrosion cannot occur; however, that is not to say that other forms of corrosion will not occur.

In immersion conditions or where moisture remains for long periods of time, the extent of galvanic corrosion depends on the resistivity of the water (i.e., electrolyte). Water with high resistance (e.g., tap water) offers low current flow whereas water with low resistance (e.g., seawater) allows high current flow. Thus, galvanic corrosion is more intense in water with lower resistance, as depicted in Figure 2.5.4.4-1.

Under mostly dry atmospheric conditions, only a thin layer of moisture is expected to be present between the contact surfaces of the dissimilar metals. This means that the effective surface areas are approximately equal, and the pronounced area ratio effect introduced previously is not a factor under these environmental conditions. Minor galvanic corrosion can still be expected at the contact interface due to potential differences and the small amount of moisture.



a. b.

Figure 2.5.4.4-1—Effect of electrolyte resistivity on galvanic corrosion: (a) in tap water (high resistance) (b) in seawater (low resistance).

2.5.4.5—Prevention Methods

In cases where there is risk of galvanic corrosion, one or more of the following conceptual steps should be taken. See also Section 2.5.4.6.

1. Use compatible metals when in contact. The corrosion of the anodic metal is exacerbated the further apart two metals are in the galvanic series (refer to Figure 2.5.4.2-1). Table 2.5.4.5-1 provides design guidance for combinations of materials. For bridges, common plate and rolled shape sizes are readily available in weathering steel grades and should be specified for all steel members in contact when possible. In addition, Type 3 weathering steel grades of high strength bolts and corresponding nuts and washers should be specified for UWS connections. See also Section 2.5.4.6.1.

2. Use a small cathode to anode surface area ratio at contact surfaces.

3. Reduce and eliminate moisture using proper drainage and sheltering techniques, many of which are described in Section 2.5. Other less common methods to eliminate moisture include encasement or enclosure of structural steel. Increasing the electrolyte resistance can help as demonstrated previously; however, this is often a function of the environment and difficult to control in design.

4. Employ protection strategies. Two common methods are insulation by using an electrically insulated material between the two metals, or by coating one (cathode) or both (cathode and anode) contact surfaces. Insulation involves the use of nonmetallic material between the two (or more) metals which breaks the electrical path (Figure

2.5.4.5-1). Coating serves a similar electrical isolation purpose in which either one (cathode) or both (cathode and anode) contact surfaces are coated (Figure 2.5.4.5-2). When either of these options are employed they should be carefully considered for longevity of the insulation or coating in the given environment and over the lifespan of the structure, as well as meet all other requirements for the type of connection (e.g., slip coefficient).

Other protection methods include cathodic protection and enclosure but are less common because they are often impractical.

A simplified approach for design of UWS members in contact with other metals is as follows:

1. If the connection or contact surfaces are wet only infrequently, galvanic corrosion is of little concern (i.e., no electrolyte).

2. If there is any chance of significant or sustained moisture at dissimilar metal contact surfaces, it is not recommended to use dissimilar metals without employing one of the other prevention methods listed above. In addition, irrespective of dissimilar metals, corrosion of UWS at locations of moisture is a concern due to increased time of wetness.

Table 2.5.4.5-1—Risk of Galvanic Corrosion for Metals with Similar Surface Areas.

	Coupled Metal		
Corroding Metal	Less Corrosion Resistant Material (Anodic to UWS)	UWS	More Corrosion Resistant Material (Cathodic to UWS)
Less Corrosion Resistant Material (Anodic to UWS)	N	R	R
UWS	N	N	R
More Corrosion Resistant Material (Cathodic to UWS)	N	N	N

N No risk. R Risk of corrosion, severity dependent on potential differences.

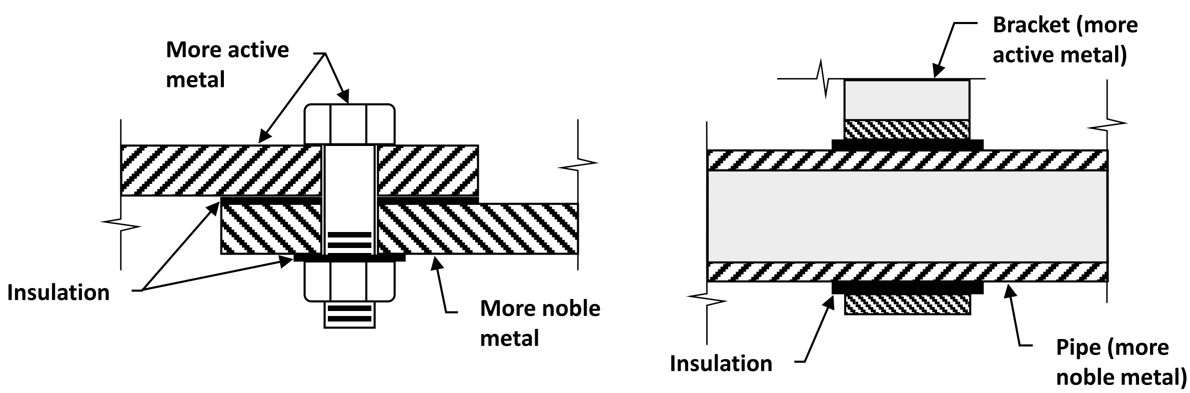


Figure 2.5.4.5-1—Insulation methods to prevent galvanic corrosion.

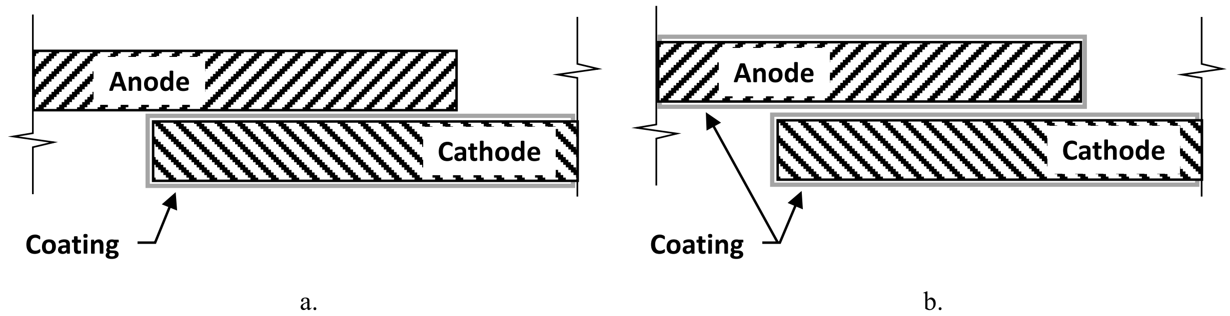


Figure 2.5.4.5-2—Coating methods to prevent galvanic corrosion (a) coat the cathode (b) coat both the cathode and anode.

2.5.4.6—Common Cases

The previous sections introduced the concept of galvanic corrosion and gave general guidance on prevention methods. The following sections highlight some of the most common cases of dissimilar metal contact on bridge structures with a focus on UWS, and how they can be resolved in design.

2.5.4.6.1—Fasteners

As mentioned previously, Type 3 weathering steel grades should be used in most connections involving UWS and should be used exclusively for connections between two or more weathering steel members, whether uncoated or coated. However, there are instances where UWS is connected to a dissimilar metal and the question of what types of fasteners to use often arises. Such instances include:

1. Appurtenance attachments (e.g., utilities)

2. Sign structure attachments

3. Bearing anchor rods

Fasteners made of a more noble material, such as stainless steel, may be used if area ratio and moisture effects have been evaluated and deemed negligible. Conventional mild steel fasteners should be avoided in direct contact with UWS members or fasteners. This problem is exemplified by the photo in Figure 2.5.4.6.1-1 in which a mild steel fastener was used in an UWS connection, most likely inadvertently during construction or as a replacement for a Type 3 nut that had threaded off the bolt.

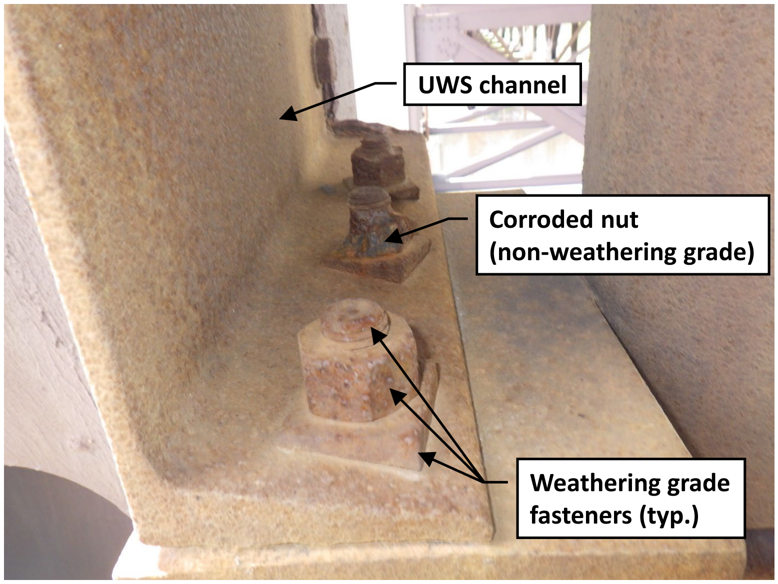


Figure 2.5.4.6.1-1—Corrosion of non-weathering grade nut.

Coated fasteners, such as hot-dip galvanized, should typically be avoided for UWS connections due to concerns over sacrificial corrosion of the coating and subsequent corrosion of the underlying carbon steel (Albrecht et al., 1989). Staining from coating corrosion can also be a concern. Others have suggested that galvanized fasteners are acceptable to use with UWS (Townsend et al., 1998; Langill and Fossa, 2009). The coating thickness of common batch hot-dip galvanized parts is typically sufficient to withstand sacrificial corrosion until the UWS protective patina forms with little loss in coating. In circumstances where hot-dip galvanized fasteners are often used, including sign structure and utility attachments, the risk of galvanic corrosion can be minimized using the previously introduced prevention methods.

If dissimilar metal fasteners are unavoidable or if there is any doubt about the risk of galvanic corrosion, isolation sleeves and washers are readily available and should be specified. Hardened isolation washers for use under structural bolts and nuts are commercially available and have been used successfully in the past. The cost of these items is negligible compared to the cost of having to address galvanic corrosion problems in service.

2.5.4.6.2—Bearings

Another common location for dissimilar metal contact is at bearings where different metals are often used. Contact between UWS and a dissimilar bearing metal should be evaluated for galvanic attack and any necessary prevention methods (e.g., intermediate insulating material, coating appropriate surfaces, optimizing relative surface area ratios) should be employed as described in prior sections.

An example bearing detail is shown Figure 2.5.4.6.2-1. Note the stainless steel plate used for a sliding surface that is welded to the UWS sole plate. There is little to no concern for galvanic corrosion at this contact surface because (1) the surface is mostly sheltered from moisture, assuming the joint detailing and maintenance recommendations outlined elsewhere in this document have been followed and (2) the weld joining the two plates prevents moisture intrusion as long as it is continuous and of an appropriate filler metal. Also note the materials for the anchor rod assembly. Galvanized anchor rods are common, and should there be the potential for moisture on top of the sole plate, isolation washers could be used in this connection.

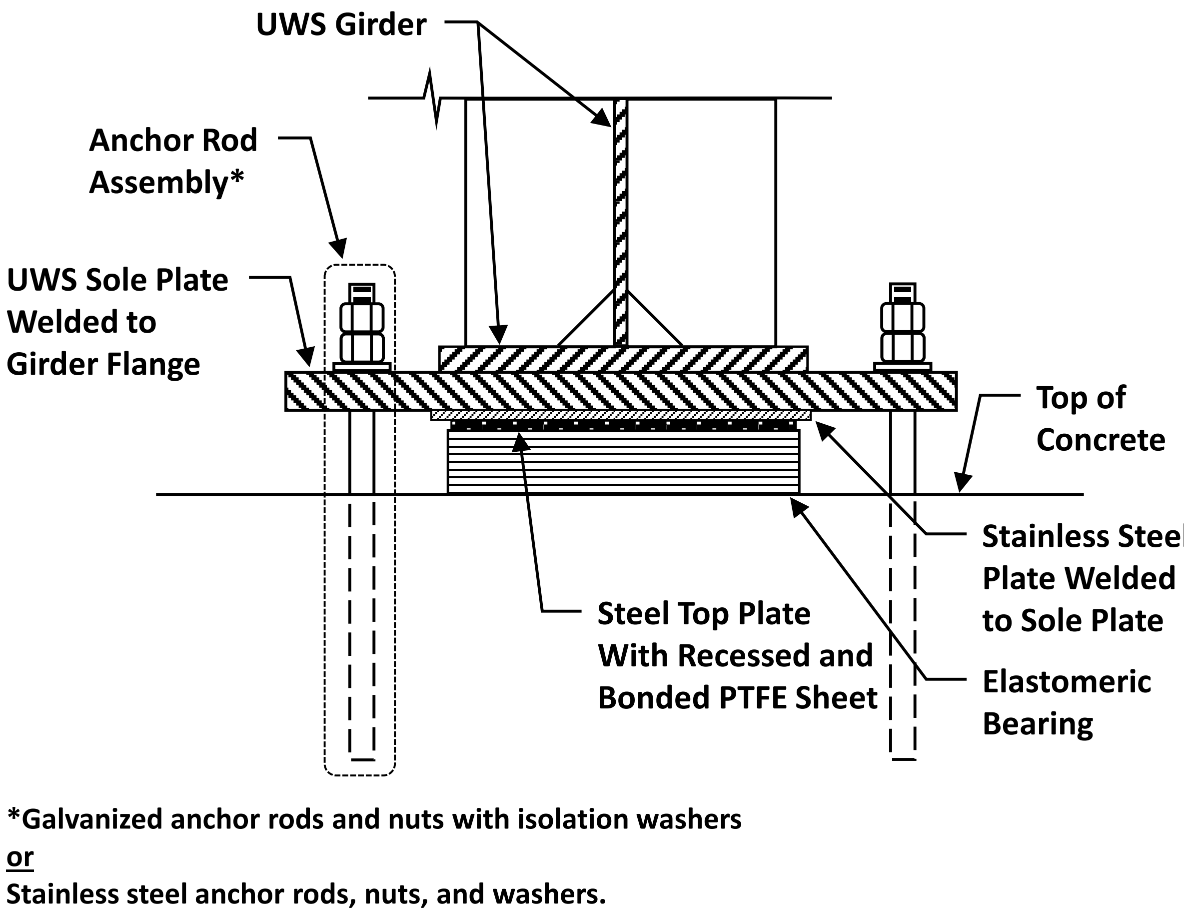
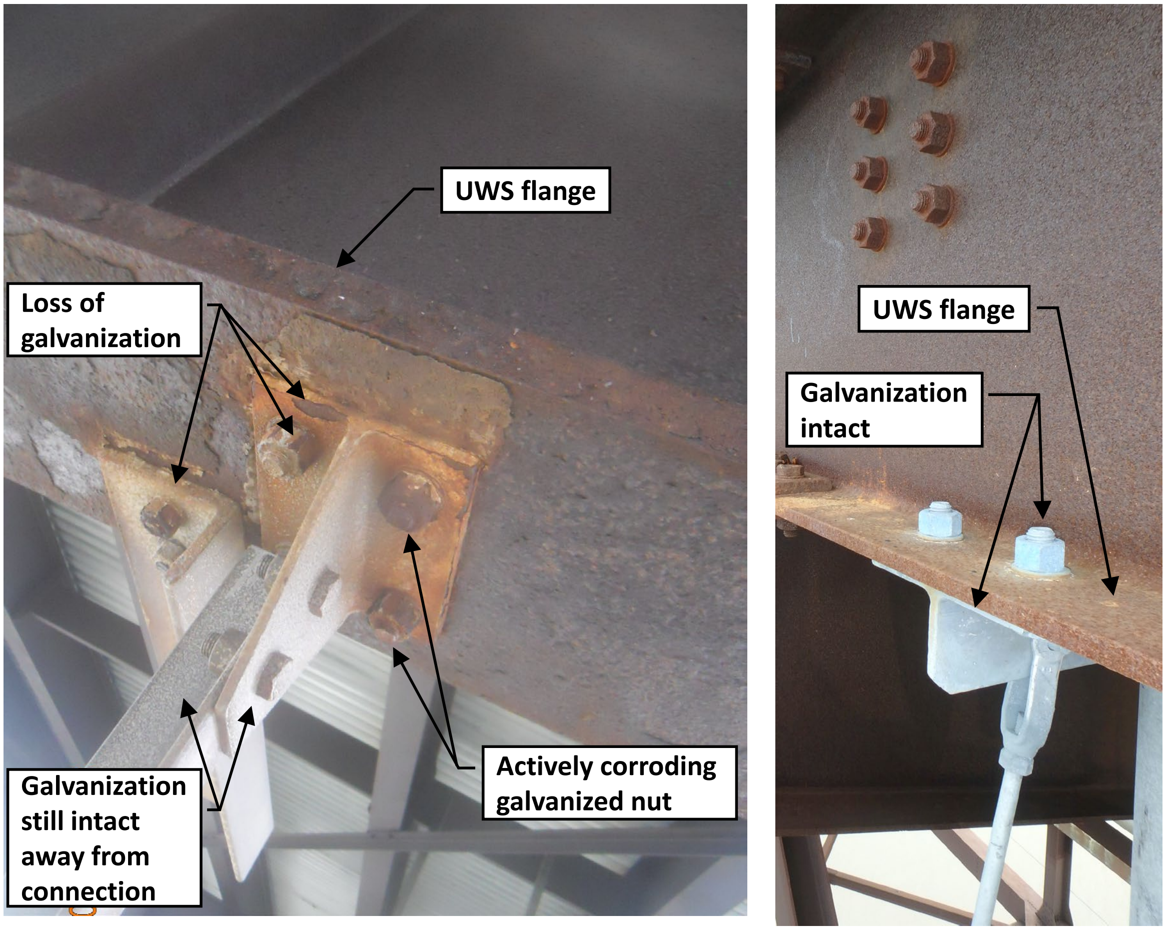


Figure 2.5.4.6.2-1—Example expansion bearing detail for UWS girder.

2.5.4.6.3—Appurtenances

Bridges are often used to carry more than just vehicle and pedestrian traffic across them, such as utility lines for water, gas, and electric. In addition, items like sign and luminaire structures are commonly supported by bridges. The supports for these appurtenances are often metallic, and the superstructure is a prime candidate for attachment locations (e.g., carrying utilities between girder bays by hanging them from cross frames). Therefore, there can be a number of locations on bridges where these appurtenances are in direct contact with structural steel members.

Examples of dissimilar metal contact in attachments to UWS are given in Figure 2.5.4.6.3-1. Both photos in the figure show the same metals in contact, UWS and galvanized steel, but with different corrosion performance. The connection in Figure 2.5.4.6.3-1a is experiencing galvanic corrosion, while the connection in Figure 2.5.4.6.3-1b shows no sign of galvanic corrosion. This can most likely be attributed to the design approach previously introduced in Section 2.5.4.5: the galvanically corroding connection is often exposed to moisture whereas the noncorroding connection has remained dry.



a. b.

Figure 2.5.4.6.3-1—Example of dissimilar metal appurtenance attachments to UWS: (a) galvanically corroding galvanized attachment (b) non-corroded galvanized attachment.

2.5.4.6.4—Shear Studs

There are other scenarios on bridges where galvanic corrosion is raised but often of little concern. One such instance is carbon steel shear studs welded to UWS flanges and embedded in concrete (e.g., composite deck systems); however due to the alkaline environment within the concrete, corrosion of the studs is not a concern (El Sarraf et al., 2017, 2020).

3.0—FABRICATION AND CONSTRUCTION RECOMMENDATIONS

3.1—SURFACE PREPARATION

Proper surface preparation is key to the development of the protective patina. Minimum requirements are provided below. Other additional best practices that can be used to further prepare surfaces and enhance the appearance are also discussed.

3.1.1—Minimum Requirements

Remove mill scale by blast cleaning all girders to SSPC-SP 6 "Commercial Blast Cleaning." In applications where aesthetics are important, care should be taken to prevent uneven appearance of the steel surface, which can result from variable or inconsistent mill scale removal due to incomplete blasting (Figure 3.1.1-1 and Figure 3.1.1-2) or spot re-blasting (Figure 3.1.1-3). Do not vary cleaning and/or blast cleaning requirements for members of the same structure. While requiring blast cleaning only on visible surfaces has been done in the past for aesthetics, it creates more difficulty during future inspections when assessing the condition of members of the same bridge.

If blast cleaning is not performed, then at a minimum, the following surface preparation practices should be performed (in general order of operation):

- Clean surfaces of oil, grease, and cutting compounds by solvent cleaning per SSPC-SP 1. Acids should not be used for any cleaning because they can cause corrosion (El Sarraf et al., 2017, 2020; AASHTO/NSBA, 2018).
- Perform power tool cleaning according to SSPC-SP 15 to remove weld spatter and residue
- Perform hand tool cleaning according to SSPC-SP 2 to remove rust deposits, rust scale, coating, or other foreign matter. Power tool cleaning according to SSPC-SP 3 or brush-off blast cleaning according to SSPC-SP 7 may be required if hand tool cleaning is insufficient.
- After fabrication, remove all shop markings by solvent cleaning again according to SSPC-SP 1. Markings not removed can inhibit patina formation and cause staining once the steel is exposed in the field (Figure 3.1.1-4).

Source: McDad et al (2000)

Figure 3.1.1-1—Non-uniform mill scale removal.

Source: McDad et al. (2000)

Figure 3.1.1-2—Incomplete blasting of a bent cap.

Source: McDad et al. (2000)

Figure 3.1.1-3—Non-uniform appearance caused by spot re-blasting.

Source: McDad et al. (2000)

Figure 3.1.1-4—Staining from not removing markings after blast cleaning.

3.1.2—Additional, Best Practices

The minimum requirements outlined above are intended to result in satisfactory UWS performance and should be considered bare minimum practices. To get optimum performance of UWS (both aesthetically and in relation to corrosion), additional best practices for surface preparation include (in general order of operation):

- Blast clean to SSPC-SP 10 "Near-White Blast Cleaning" in situations where aesthetics have high importance. If SP 10 is specified, use the same blast cleaning requirements on all members. See the previous discussion on consistent blast cleaning.

- After blast cleaning, subject the surfaces to wetting and drying cycles by periodically wetting to help initiate the patina formation and to aid in achieving a uniform finish (El Sarraf et al., 2017, 2020). It is thought that between 5 and 10 wet/dry cycles are sufficient. If this option is exercised, it is crucial to provide adequate drainage and prevent ponding (as described in the later discussion on material handling and storage). In addition, all environmental regulations regarding runoff should be followed.

- After steel erection and completion of all concrete work, solvent clean to SSPC-1.

- Seal depressed areas (i.e., water and debris traps) using an approved sealant. See Section 2.5 for additional guidance on these areas.

3.2—WELDED CONNECTIONS

All welding should conform to the requirements of the AASHTO/AWS D1.5M/D1.5 *Bridge Welding Code* (AASHTO/AWS, 2020 or current edition). Best practices for welding UWS include the following:

- Welded connections should be made using weld filler metal that is compatible with weathering steel. The appropriate type of filler metal depends on the welding process and the application.

- During the welding process, attention should be given to ensure welded connections do not result in areas where water may collect. Examples include using continuous rather than intermittent welds and grinding butt welds flush.

Additional guidance on welding and weld fabrication can be found in the FHWA Bridge Welding Reference Manual (Medlock et al., 2019) and the AASHTO/NSBA Steel Bridge Fabrication Guide Specification (AASHTO/NSBA, 2018).

3.3—BOLTED CONNECTIONS

There are three primary considerations for UWS bolted connections: (1) material compatibility, (2) providing a water-tight connection, and (3) the coefficient of friction. Each of these considerations is discussed in the following sections.

1. Material Compatibility

As discussed previously in Section 2, fasteners made of materials compatible with weathering steel should be used whenever possible to avoid galvanic corrosion, preferably Type 3 weathering grade fasteners.

2. Water-Tight Connection

Connections between faying surfaces of steel plates that are not water-tight provide locations susceptible to crevice corrosion that can ultimately result in prying of the joint and fastener tensile failure. To provide a water-tight connection and prevent crevice corrosion, bolts should meet the spacing for sealing requirements specified in the AASHTO LRFD Bridge Design Specifications (2020).

3. Coefficient of Friction

Slip-critical connections require a certain minimum coefficient of friction to perform properly. In order to achieve a sufficient coefficient of friction in UWS bolted connections, faying surfaces should be commercial blast cleaned according to SSPC-SP 6 and should also be free of any foreign material at the time of bolting. SP-6 is not necessary for a Class A surface condition, but is recommended to prevent crevice corrosion.

3.4—MATERIAL HANDLING

Methods of storage, transportation, and erection specific to UWS need to be considered to avoid potential problems and achieve the desired performance from a UWS bridge, as well as ensure good appearance of the steel, if that is a project goal. These primarily relate to reducing the amount of time the UWS remains continuously wet,. ensuring a uniform appearance and preventing substructure staining.

3.4.1—Storage

3.4.1.1—Minimum Requirements

After fabrication and prior to erection, members are often stored outside (at the shop or on-site). To prevent premature corrosion and promote patina development on UWS members, minimum practices include:

- To prevent ponding and excessive wetness, do not nest members together and place members at a sufficient slope to facilitate drainage.
- When storing on-site, do not place members within the limits of a floodplain or other body of water where immersion can lead to staining and accelerated corrosion.
- Do not allow direct contact with soil, or with timber blocking for extended time periods (beyond a few weeks).
- Do not cover members with moisture barriers that can cause condensation.
- Avoid contamination from concrete, mortar, asphalt, coatings, oil, and grease.

3.4.1.2—Best Practices

Best practices for storage include the following actions to promote patina development. For any efforts to promote patina development, it is crucial to provide adequate drainage and prevent ponding. This is similar to the guidance provided in Section 3.1 on surface preparation.

- To promote patina development, expose members to natural cycles of rain and sunlight or store them in an environment similar to in-service conditions. Examples of how this is accomplished include storing to weather for as long as practical (NHDOT, 2016) and storing on-site for 3 months prior to construction (WVDOT, 2017).
- Put members through wet/dry cycles by wetting during storage (El Sarraf et al., 2017, 2020). If this option is exercised, the members should be blast-cleaned prior to performing the wet/dry cycles.

See the AASHTO LRFD Bridge Construction Specifications (2017 or current edition) and AASHTO/NSBA (2018) for additional storage requirements.

3.4.2—Transportation and Erection

During transportation and erection, UWS members should be handled in a way that prevents damage to the initial patina and should be protected from any contaminants, such as chloride or chemical laden roadway water. Solvent cleaning (i.e., SSPC-SP 1) after transporting or erecting members may be needed to remove any contaminants. See the AASHTO LRFD Bridge Construction Specifications (2017) and AASHTO/NSBA (2018) for additional transportation and erection requirements for steel construction.

3.5—STAIN PREVENTION

Staining caused by UWS runoff is mainly an aesthetic concern for visible concrete surfaces. Stains alone do not harm concrete surfaces; however, they can be unsightly, significantly degrade the aesthetics of the bridge, and leave the false impression of a structure that is deteriorating. Attention to drainage control, as well as other techniques can eliminate the potential for permanent concrete staining. Thus, the presence of staining is an indication of poor drainage control and the potential for concrete deterioration due to the water, which is often salt-laden, permeating into the concrete.

Stain prevention is controlled at both the design and construction stages. See Section 2.5.1 for guidance on design and detailing for stain prevention over the life of the structure. The following sections discuss stain prevention during fabrication, and immediately pre- and post-construction.

3.5.1—Best Practices

The most effective methods at preventing staining of concrete surfaces during the fabrication and construction stages include:

- Follow the guidance in Section 2.5.1, particularly by installing drip bars, plates, pans, and trays (Figures 2.5.1-5 to 7).
- Performing proper blast cleaning of surfaces, which will promote early patina formation and reduce rust-laden runoff. Figure 3.1.1-2 provides an example of poor blast cleaning of a bent cap that will most likely result in staining of the underlying concrete substructure. See Section 3.1 for guidance on blast cleaning.
- Following the Storage guidance of Section 3.4.1 regarding natural or artificial wet/dry cycles will similarly promote early patina development and subsequently lead to reduced in-service staining.

3.5.2—Other Methods

Other methods have been used to prevent and/or remove staining. Two prevention strategies that are effective but are less common than the best practices listed above are:

- Prior to steel erection, wrapping substructure concrete members with temporary sheeting or other coverings as illustrated in Figure 3.5.2-1.

- Before and/or after steel erection, applying an approved silicone or epoxy-based sealer or other proprietary surface treatment to susceptible concrete surfaces after concrete substructure construction (Figure 3.5.2-2).

The best method to prevent staining post-construction is to follow the fabrication and construction guidance above. Removing stains after construction during in-service conditions can be difficult and costly and thus less practical than preventing its development. However, should staining occur, techniques that have been employed in the past include the following:

- At the completion of construction, allowing or requiring the contractor to remove staining with an approved stain remover (e.g., proprietary chemical stain remover, abrasive cleaner, acid-based stain remover).

- Other post-construction removal methods include water blasting and abrasive blast cleaning. Each of these methods has its own procedures and precautions that should be considered.

Source: Jeff Carlson

Figure 3.5.2-1—Example of wrapping a concrete pier during UWS girder construction.

Figure 3.5.2-2—Example of a concrete pier that was wrapped during construction and sealed post-construction. The bridge is approximately 20 years old at the time of the photo.

3.6—FINAL SITE CLEANING

After construction, a final inspection should be performed to look for contaminants that may have accumulated during construction. To remove any contaminants found, final cleaning should be performed by washing, chemical cleaning, or blast cleaning.

4.0—IN-SERVICE INSPECTION RECOMMENDATIONS

4.1—QUALITATIVE INSPECTION PROCEDURES

UWS bridges located, designed, detailed, fabricated, and constructed utilizing the guidelines provided in this document will perform satisfactorily for a service life of 75-years and beyond. However, all bridges, regardless of material type or structural configuration, require periodic inspection that thoroughly documents the condition of the bridge and identifies problem areas.

From a corrosion perspective, the inspection of UWS bridges should result in two types of information. The first is the surface condition of the UWS. It is imperative to ensure that an adherent protective oxide layer is forming or has formed. The second is an evaluation of the site conditions to screen for situations that are causing greater than expected residual moisture, debris, or contaminants (including the exposure to and/or retention of deicing agents). Any deleterious conditions identified should be clearly and promptly reported so that simple and satisfactory corrective measures (e.g., maintenance actions) can be undertaken. These two corrosion considerations are detailed in the following subsections. A third subsection below discusses inspection of UWS members from a fatigue perspective.

4.1.1—UWS Visual Condition for Corrosion Protection Assessment

4.1.1.1—Minimum Requirements

In accordance with the current requirements found in the National Bridge Inspection Standards, all bridges on public roads, as set forth in 23 CFR, Part 650, Subpart C of the Code of Federal Regulations, must be periodically inspected in accordance with the AASHTO Manual for Bridge Evaluation (MBE; AASHTO 2018 or current edition). The Code sets forth frequency intervals, depth (or level) of inspection, as well as a reporting system. In general, the inspections required by these regulations are qualitative, visual-based, inspections and are adequate for providing sufficient information to determine the structures or structural components in need of corrective action.

In the United States, more detailed, so-called element-level, inspections are required in some cases for all bridge types. These requirements are outlined in the Manual for Bridge Element Inspection (MBEI; AASHTO 2019 or current edition). While not specifically required to be performed for all bridges, element-level inspections can be useful in gathering more detailed and objective data than typical periodic inspections done in accordance with the MBE, even when not required. The general framework of the MBEI consists of assigning various percentages of specifically defined elements (e.g., girders, deck, etc.) to condition states. With respect to UWS members, there are four possible condition states for steel corrosion: (1) no corrosion; (2) freckled rust and corrosion initiation; (3) section loss or pack rust not warranting a structural review; and (4) corrosion that warrants structural review. While some of these condition states are easily distinguished from one another, the difference between Condition State 1 and Condition State 2 is less straightforward. The following section gives best practices for aiding in this determination.

4.1.1.2—Best Practices

Regarding the assessment of the visual surface condition of UWS, best practices consider the following three metrics: adherence, texture, and color, generally in this order of importance. To assess adherence and texture, and to some extent color, it is critical to be close to the steel. This concept is illustrated by Figure 4.1.1.2-1, which shows the contrast in appearance when a UWS superstructure is viewed from ground level compared to a similar elevation as the superstructure. While from a distance the patina appears adequate, from a closer distance there appears to be large flakes indicating less than desired performance.

a. b.

Figure 4.1.1.2-1—Sight distance is critical for an accurate determination of UWS performance. A view from ground level approximately 20 ft. in (a) could lead to a markedly different conclusion than the same structure inspected from a closer distance (b).

Specific considerations for assessing adherence, texture, and color are as follows:

- Adherence:

The protective layer should be tightly adhering. This metric is arguably the most reliable for determining UWS performance. Adherence can be confirmed by no change in surface condition occurring due to pounding with a rubber mallet or the inability of the patina to be rubbed off or pried loose by hand tools (e.g., putty knife). Examples of the surface texture of UWS meeting this criterion are shown in Figure 4.1.1.2-2.

In contrast, Figure 4.1.1.2-3 shows examples of easily disturbed patinas. The patina in Figure 4.1.1.2-3 (a) can be scraped loose with a putty knife. Figure 4.1.1.2-3 (b) shows a patina that readily crushed under light impact. Figure 4.1.1.2-3 (c) shows a patina that can be pried loose with a fingernail.

There are two exceptions to the above comments on adherence being indicative of performance. One is that in the first few years of service or in very benign environments where patina development occurs slowly, fine (< 1/32”) particles that are easily removed from the surface are not of concern (see comments below on texture). The second is that if the mill scale is not removed (departing from the recommended practice given in Section 3), the mill scale will likely be easily removed from the surface. It is because of the difficulty in distinguishing between mill scale and base metal corrosion for inspectors without significant experience that removal of the mill scale prior to erection is recommended.

If wire brushing is used to evaluate the weathering and aesthetics are of importance, this should be done at locations not viewed by the public, as the surface removal will leave a lighter color (that will re-darken with time).

a. b. c.

Figure 4.1.1.2-2—Photographs of good-performing UWS show a smooth surface of varying colors.

a. b. c.

Figure 4.1.1.2-3—Photographs of poor performance of UWS showing various textures: (a) rough "freckled" surface, (b) a relatively smooth surface that was easily crushed by tapping, (c) course surface with exfoliating rust layers.

- Texture:

The size of the particles forming the UWS patina often directly correlates to adherence, with larger particles being less adherent and more indicative of corrosion concerns. Such texture is often difficult to assess without adequate proximity to the surface, and thus such an inspection is essential for UWS structural members (see Figure 4.1.1.2-1).

Particle sizes of 1/8” or less are not of concern. Such particles sizes result in relatively smooth surfaces, manifesting in many different appearances as shown at close range in Figure 4.1.1.2-2. Granular rust flakes exceeding ¼” diameter are possible indications of a non-protective patina see Figure 4.1.1.2-3 (a). Sheet-like layers of rust (see Figure 4.1.1.2-3 (b) and (c)) are clear indications of a non-protective patina. Again, the importance of being of a sufficiently close distance for making such determinations is emphasized. Without a close-range inspection, nearly all UWS will appear to have a smooth texture (see Figure 4.1.1.2-1).

It should also be understood that when steel becomes rust, a significant volumetric increase occurs. This means that a relatively thick sheet of rust represents a much smaller amount of section loss. Recommended procedures for evaluating section loss are given in Section 4.2.

- Color:

Color of the surface of the UWS has been frequently suggested as a means for assessing UWS corrosion performance. While color can provide general information, due to the wide range of colors that can appear in both good and inferior performing UWS (e.g., refer to Figure 4.1.1.2-2 and Figure 4.1.1.2-3) and the subjectivity of evaluating color, it is recommended that greater consideration be given to the texture and adherence of UWS. In addition to basic color, the variation in color over close-up areas of UWS can be used as an indicator of performance. As can be seen from Figure 4.1.1.2-3, the texture of poor performing UWS also typically manifests as producing variations in color. An exception to this is vertically-oriented variations in color that are usually indicative of condensation patterns. Examples of this can be seen at a close-up scale in Figure 4.1.1.2-2 (c) and from a distance in Figure 4.1.1.2-4 (a).

In general, in good performing UWS in typical U.S. environments, the color of newly erected UWS begins as orangish brown after the initial stage of exposure, then becomes reddish brown and finally dark brown (often with a purplish hue). The specifics of these colors and the time scale over which these changes occur vary significantly in different environments, with Figure 4.1.1.2-4 showing representative colors of good performing UWS. Non-protective oxides generally appear dull gray to black in typical U.S. environments, as seen in Figure 4.1.1.2-3 (b) and (c). The dull gray color can often be found on poorly performing horizontal face-up surfaces where debris collects and mixes with the patina.

a. b. c.

Figure 4.1.1.2-4—Photographs showing typical color progression of good-performing UWS in U.S. environments: (a) relatively new bridge (less than 10 years), (b) bridge in early stages of service life (less than 25 years), (c) bridge with advanced patina development. Note: Color, perception of color, and rate of color change can be highly variable and dependent on environment, lighting conditions, etc.

4.1.1.3—Other Recommendations

In the absence of more formal guidelines, the following recommendations are offered for distinguishing between the various condition states:

- If there is no section loss, consider the criteria given in Table 4.1.1.3-1 to distinguish between Condition State 1 and Condition State 2. If the surface condition contains a combination of the attributes contained in the descriptions of both condition states, it is recommended to assign the surface condition to the category for which the majority of the attributes are in agreement.

- If there is section loss, defer to owner's typical practices for determining whether the severity warrants a structural review and assign the condition state to Condition State 3 or 4 accordingly.

Table 4.1.1.3-1—Recommended Criteria for Distinguishing Between Condition State 1 and Condition State 2 of UWS

Condition State	Section Loss[1]	Adherence	Texture	Color
1	None	Patina resists prying with hand tools; wire brushing results in no large particles	Smooth, particles generally < 1/8 in. width	Relatively uniform; not unexpected for age of structure
2	None	Patina easily pried loose with hand tools	Rough, some particles > ¼ in.	Varied colors at closeup scale

[1] If section loss is present, condition state is 3 or 4. See comments above.

4.1.2—UWS Crack Detection

A final qualitative consideration regarding the inspection of UWS relates to crack detection. As mentioned in Section 2.4.10, fatigue cracking is not expected in steel bridges designed in accordance with modern fatigue provisions but may occur in bridges designed prior to the implementation of these provisions. Cracks due to fatigue or other sources may be more difficult to discover in a UWS structure compared to a painted one, unless the crack is active and bright visible staining is evident from fretting corrosion or moisture in the crack. This is because in a coated structure, a fatigue crack typically causes a defect in the paint, which in turn causes localized rusting that has a visually obvious color contrast to the adjacent paint. Inspectors should be aware of this issue and adapt their processes for screening for fatigue cracks in UWS structures accordingly, if necessary. Inspection for cracks should follow the AASHTO MBE and Owner-specific protocols. Crack detection is typically performed visually, but nondestructive techniques may be used as well (e.g., magnetic particle testing, dye penetrant testing).

4.1.3—Site Conditions Assessment

The following checks should be made to assess the site for conditions that may contribute to an overly corrosive environment and to develop maintenance and/or remediation plans as warranted:

- Is there debris buildup or vegetation that causes surfaces to be frequently wet?
- Has the surface been contaminated by salt residue?
- Are expansion joints leaking?
- Are surface runoff drains dripping or spilling onto steel surfaces or substructures?
- Is water collecting and remaining on steel structures, bearings or substructures?
- Is there debris or corrosion at crevices, such as vertical stiffener to bottom flange intersections or at field bolted connections?
- Are any utility conduits leaking onto steel surfaces or substructures?
- Are steel to concrete interfaces corroding?
- Is there debris from waterway flooding?

4.2—QUANTITATIVE INSPECTION PROCEDURES

Quantitative measures have occasionally been used for the inspection of UWS bridge members. This is generally only performed for research purposes or when a significant performance concern is present. Three of the most common of these are ultrasonic thickness measurements, a tape test, and chloride measurements. Quantified color testing has also been explored, but is not yet at a sufficient state of development to provide information of significant value.

4.2.1—Ultrasonic Thickness Measurements

Ultrasonic thickness measurements have been used in several prior studies to determine the thickness of steel members. This can be performed using commercial handheld electronic instruments that require little expertise for their use. By comparing ultrasonic thickness measurements of small portions of the steel surface where the corrosion products have been removed to the original thickness, thickness losses can theoretically be determined. However, precise measurements of original thickness are typically not available and thus, when comparing measured thickness to original nominal thicknesses, little or zero thickness loss is typically found (e.g., McDad et al., Nelson 2014). Thus, the primary practical value of ultrasonic thickness measurements is to assess thickness loss relative to nominal plate thicknesses for the determination of sufficient structural capacity.

To perform an ultrasonic thickness measurement, the oxide (i.e., rust) layer should be lightly removed from the steel surface over a small area. The bare metal should be exposed only on the highest points of the corroded surface, leaving any depressions filled with oxide. Approximately one-third of the ground surface should have a metallic (i.e., shiny) appearance. The surface area where the oxide layer is removed only needs to be as large as the probe of the measurement device, which are typically circular with a diameter less than 1 inch. The oxide layer is easily removed with a mechanical wire brush fitted onto a drill, or similar device.

Once the oxide layer is removed as described above, a liquid biodegradable coupling agent is applied to the steel surface where the measurement is to be taken. The probe of the ultrasonic thickness device is then placed flush on the surface of the steel. The probe can be sensitive to slight changes in orientation and location, so it is recommended that multiple readings are taken to assess for reasonableness and that the minimum reasonable thickness that is obtained is the value recorded.

4.2.2—Assessment Using Tape Test

The tape test involves placing tape meeting the requirements of ASTM D3359 (clear packaging tape) on the surface of the steel and then evaluating the size and spatial density of the corrosion particles that adhere to the tape (Crampton et al. 2013). A fewer number of smaller particles indicates better performance than larger particles. This test is readily performed with minimal training and readily available supplies.

Images of the tape can be compared over time to assess qualitative changes. To perform such an assessment, strips of tape (approximately 6 in. in length) are applied with hand pressure to the steel. The tape is then gently removed and adhered to a contrasting background, such as a white sheet of paper for clear tape or clear plastic for white tape. The paper can then be photographed to aid digital record keeping.

Images of the tape can also be quantified using digital imaging processing techniques. However, such techniques rely on user-created computer code, which are not widely available at the present time. Furthermore, no clear thresholds on performance have been determined for making definitive conclusions from this test.

In prior work (McConnell et al., 2016), the percentage of the area of the tape sample that was occupied by particles greater than 1/8 in. was found to result in an efficient and effective metric that correlated with, but was more objective than, inspectors' qualitative visual assessments. Specifically, bridges rated as performing well by inspectors had an average of less than 4 percent of their sampled areas occupied by particles greater than 1/8 in. Conversely, bridges for which inspectors noted corrosion had tape samples with at least 8 percent of the area occupied by particles greater than 1/8 in. However, these values were found to be affected by the locations chosen for sampling, and otherwise have not yet been widely validated so they should be applied with caution.

While the application of tape sample data is less straight-forward than ultrasonic thickness data, it can provide earlier information on possible corrosion problems. This is because the progression of the size and spatial density of rust particles from tape samples can be obtained much earlier in the life of a bridge, before thickness losses relative to the nominal plate thicknesses become measurable through ultrasonic techniques.

4.2.3—Assessment Using Colorimeter

A colorimeter was used by Crampton et al. (2013) to quantify the color of the oxide layer. However, this method was abandoned due to the scale of the measurement being found to be too small to capture informative data given the wide variation in color on any given surface.

4.2.4—Measurement of Contaminants

Sulfate and, more often in recent studies, chloride measurements have been taken to evaluate cause and effect relationships between chemical concentrations and UWS performance or maintenance practices (e.g., Crampton et al. 2013, Palle et al. 2003, McConnell et al. 2016). Various commercial products and laboratory techniques are available for determining concentrations of these possible contaminants. Knowing the chloride concentration does not provide any direct information on UWS performance. However, chloride concentrations can be used to assess variations in site conditions, the influence of different maintenance strategies, or to provide context for observations regarding UWS performance.

One recommended technique for quantifying chloride concentrations that has been used successfully in prior studies is "CHLOR*TEST," manufactured by "CHLOR*RID" International, Inc. This test is relatively simple and low-cost and is appropriate in many conditions. Two conditions where it is not ideal is when chloride concentrations exceed 60 ppm (which is outside of the range of the test method) and when the patina has a course texture (i.e., does not have a relatively smooth surface that is needed to adequately seal the test kit onto the steel). Specific directions on the use of this test are available from the manufacturer.

When higher concentrations are present, QuanTab test strips, manufactured by Hach Company, Inc., are an alternative available testing method. Other commercial testing products for chloride testing include Bresle Test Kit manufactured by Paint Test Equipment, the Soluble Salt Meter manufactured by ARP Instruments, Inc., and the SaltSmart Sensor manufactured by Louisville Solutions Inc.

Results can be highly variable and dependent on sample location and test duration. When used to compare different bridges, contaminant tests should be performed at similar locations, for the same duration of time, and multiple times to replicate results.

5.0—MAINTENANCE AND PRESERVATION

5.1—RECOMMENDATIONS

As with other bridge types, maintenance of UWS bridges is a key aspect of bridge management. In a survey of bridge owners, only the presence and frequency of de-icing salt use ranked higher than maintenance frequency on the impacts on bridge service life (Murphy et al., 2020). While sometimes overlooked, proper and timely maintenance is vital to bridge service life. This section presents common maintenance considerations for UWS bridges; however, many of the practices mentioned are applicable to other bridge types as well.

5.1.1—General

General maintenance activities that should be performed on all UWS bridges include:

- Remove debris using compressed air or a vacuum system.
- Remove loose layers of rust where practical.
- Clean drainage pipes.
- Remove vegetation that is in contact with UWS components or has the potential to grow to be in contact with UWS components before the next maintenance period.

5.1.2—Joints

As discussed throughout this manual, deck joint failure is a primary source of long-term bridge performance problems. Where joints are present, their maintenance is of upmost importance to preserving underlying superstructure and substructure elements. Joint maintenance is particularly critical for UWS girder ends and end diaphragms, where joint failure allows deck runoff onto these elements, which increases time of wetness and accelerates corrosion.

5.1.2.1—Minimum Requirements

At minimum, the following maintenance activities should take place during every site visit:

- Require crews to inspect joints and associated drainage systems for leaks.
- Replace seals and drainage components where needed. An example is shown in Figure 5.1.2.1-1.

Source: FHWA (2018)

Figure 5.1.2.1-1—Joint seal replacement.

5.1.2.2—Additional Best Practices

Additional best practices for joint maintenance include:

- Hose the deck near joints during maintenance visits to better identify leaks.
- As a bridge management practice, replace joints on a predetermined schedule rather than performing repairs only when problems arise. Use inspection data, such as recorded condition state information, to establish typical service lives of joints which can then be used to determine appropriate replacement intervals. Where internal data is not available, published information on joint service life may be used, such as that shown in Table 5.1.2.2-1.

Rather than only performing maintenance when joints fail, also prioritize the maintenance of joints in good condition prior to failure and deterioration of the structural steel.

Many, if not most, bridge owners are unable to abide by a replacement schedule like the one in Table 5.1.2.2-1 due to their limited available resources and other asset management demands. An alternative approach is to accept that leaks cannot be prevented from joints and take the appropriate action to direct the drainage coming through the joint away from structural components, and to protect beam ends and pier tops through the use of coatings and other systems.

Table 5.1.2.2-1—Typical Joint Lifespans Reported by Owners (Milner and Shenton, 2014).

Joint	New Construction (yrs)	Replacement/Rehabilitation (yrs)
Asphaltic Plug Joint	10	5
Compression Seals	15	6
Poured Silicone	7	3
Preformed Silicone	7	3
Closed Cell Foam	5	2
Open Cell Foam	Unknown	Test joints in place, performing well after 3 years
Strip Seals	15	10

5.1.3—Washing and Cleaning

Washing and cleaning of bridge components should be considered an essential practice of bridge management and preservation. Generally, the methods can be split into two categories: dry methods (i.e., cleaning) and wet methods (i.e., washing).

The need for and benefit of cleaning is generally unquestioned. Given the wide range of numerous variables that can occur during bridge washing and the greater effort required, the effectiveness of bridge washing has been more difficult to ascertain and has been debated. However, anecdotal and quantitative evidence generally suggests that washing has positive effects including: visibly reducing the indicators of corrosion, reducing chloride levels, improving long-term performance, and/or reducing life-cycle cost. Furthermore, because the primary objective of washing is the removal of chlorides, when there is a need for prioritization, it is also logical to prioritize washing of the structures that are exposed to the highest levels of chlorides. In practice, this may mean highway overpasses over the most heavily salted roadways for a given maintenance region. The benefits of washing will be greatest for these structures.

This section provides an overview of the common methods and equipment and gives recommendations on the bridge components that should be cleaned and at what frequency.

5.1.3.1—Methods and Equipment

Various methods and equipment are often used to wash and clean highway bridges.

5.1.3.1.1—Dry Methods (Cleaning)

Dry methods include:

- Sweeping
- Compressed air blowing
- Vacuuming
- Shoveling
- Brushing, scraping, and other mechanical cleaning methods
- Vegetation removal

Typical equipment needed for dry methods includes street sweepers, brooms, air compressors, industrial vacuums, shovels, wheelbarrows, brushes, scrapers, and mowers. Example dry method operations are shown in Figure 5.1.3.1.1-1.

Source: MNDOT (2019) Source: NYSDOT (2008)

a. b.

Figure 5.1.3.1.1-1—Example dry methods of deck cleaning (a) sweeping (b) debris removal.

5.1.3.1.2—Wet Methods (Washing)

Wet methods include:

- Flushing
- Low pressure washing (< 1000 psi)
- High pressure washing (between 1200 and 6000 psi)

Associated equipment includes a large capacity water tank, water pump, hoses and nozzles, and a pressure washer. A number of variables can influence the effectiveness of pressure washing including the horizontal and vertical distance between the nozzle and target area, and the angle between the water stream and washing surface. The following are good rules of thumb when washing UWS bridges:

- Keep the spray nozzle at or above the target area elevation.
- Keep the spray nozzle within a reasonable distance from the target area, such as 1 to 5 ft.
- Use a nozzle with a 0 to 15° spray angle.

Site and access limitations may hinder these recommendations in certain scenarios. Examples of wet methods in use are shown in Figure 5.1.3.1.2-1.

Additional equipment to that listed above will be needed to carry out both dry and wet cleaning methods, such as mobilization and access equipment. See AASHTO/FHWA's *A User's Guide to Bridge Cleaning* (2019) for guidance.

Source: PennDOT (2016) — a.

Source: Crampton et al. (2013) — b.

Figure 5.1.3.1.2-1—Example wet methods of bridge cleaning (a) deck flushing (b) girder pressure washing.

5.1.3.1.3 —Environmental and Safety Considerations

While beyond the scope of this manual, all environmental and safety regulations should be followed while carrying out cleaning and washing operations. All federal and state environmental, waste disposal, and wildlife regulations should be consulted prior to performing work. In addition, all work should comply with Occupational Health and Safety Administration (OSHA) and state standards. See AASHTO/FHWA's *A User's Guide to Bridge Cleaning* (2019) for guidance.

5.1.3.2—Components to be Washed or Cleaned

Washing and cleaning of UWS components should be part of a larger bridge preservation program. Keeping all components of a bridge system clean and functioning helps to ensure that the UWS components can achieve the desired level of performance.

5.1.3.2.1—Minimum Requirements

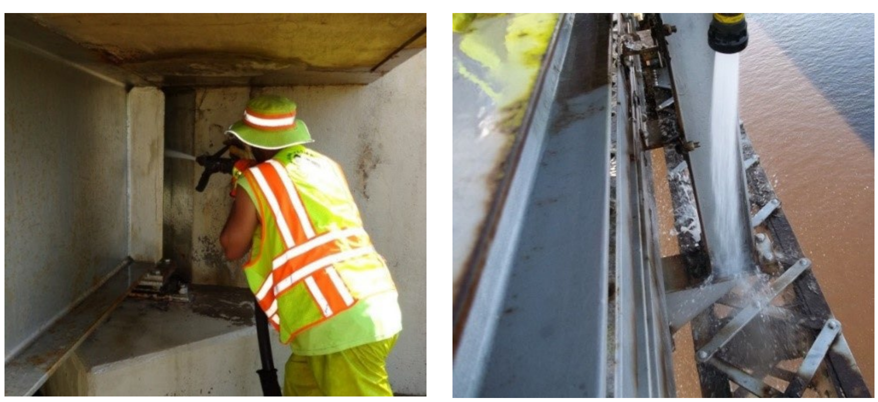
At minimum, the following components should be washed or cleaned on a recurring basis:

- *Decks*: roadways and shoulders, expansion joints, drainage components (e.g., grates, scuppers, troughs, pipes, etc.), sidewalks, medians, curbs, and railing and parapets. See Figure 5.1.3.2.1-1 for example photos.
- *Superstructure Elements*: Horizontal surfaces susceptible to debris accumulation (e.g., bottom flanges), elements or sections thereof beneath deck expansion joints (e.g., girder ends, end diaphragms), members in the splash zone or below the road level (e.g., truss members). Examples are shown in Figure 5.1.3.2.1-2. Monitor UWS members for delaminations that could pose a safety hazard (e.g., if they were to become falling debris) and remove them.
- *Substructure Elements*: Abutment seats and backwalls, pier seats, regions in the splash zone. An example is shown in Figure 5.1.3.2.1-3.

Source: MNDOT (2019)

a. b. c.

Figure 5.1.3.2.1-1—Deck component cleaning (a) roadway and parapet (b) expansion joint (c) drainage components.



Source: MNDOT (2019)

a. b.

Figure 5.1.3.2.1-2—Superstructure cleaning (a) beam ends (b) truss members.

Source: MNDOT (2019)

Figure 5.1.3.2.1-3—Substructure cleaning.

5.1.3.2.2—Additional, Best Practices

Other components should be considered for washing and cleaning depending on environmental and site conditions. These elements may include:

- *Superstructure*: entire lengths of girders, all diaphragms and cross frames.

- *Substructure*: all exposed surfaces particularly those susceptible to staining.

5.1.3.3—Frequency

The frequency at which cleaning and washing should occur depends on macro- and micro-environmental conditions. Elements that are subject to vehicular traffic and moisture (e.g., decks) or that are susceptible to debris accumulation (e.g., bottom flanges) should be maintained more frequently, whereas components that are sheltered from weather on a low trafficked bridge in a mild environment may be maintained less frequently.

5.1.3.3.1—Minimum Requirements

Minimum maintenance activities and frequencies for varies components are provided in Table 5.1.3.3.1-1. The Interval values listed in Table 5.1.3.3.1-1 are general suggested ranges and should be adjusted up or down based on site conditions. In addition, owners may have more stringent or specific requirements that should be followed.

Table 5.1.3.3.1-1—Cleaning and Washing Activity and Frequency Recommendations

Region	Component/Element	Activity	Description	Interval (Years)
Deck	• Roadway and shoulders • Expansion joints and drainage troughs • Drainage grates, scuppers, and pipes • Sidewalks, medians, curbs • Rails and parapets	Sweep / Compressed Air Blow	Remove and dispose of dirt, salt, and other debris using dry methods.	1-2
		Wash / Flush	Remove residual material after sweeping/blowing by washing. Flush all deck drainage systems.	1-2
Super-structure	• Bearings • Bottom flanges of beams and girders above roadways • Ends of beams and girders under deck joints within a distance of 1 to 1.5 times the girder depth on each side of the joint • End diaphragms and cross frames • Truss members in the splash zone; truss members at or below the road level	Compressed Air Blow / Brush / Dry Clean	Remove and dispose of dirt, salt, and other debris using dry methods.	1-2
		Wash	Remove and dispose of dirt, salt, and other debris by washing.	2-4
Sub-structure	• Abutment seats, backwalls, and pier seats • Pier and abutment regions in the splash zone	Compressed Air Blow / Brush / Dry Clean	Remove and dispose of dirt, salt, and other debris using dry methods.	1-2
		Wash	Remove and dispose of dirt, salt, and other debris by washing.	2-4
All	• As applicable	Vegetation Removal	Cut, remove, and dispose of vegetation that is in, or nearly in, contact with structure	1-2

5.1.3.3.2—Additional, Best Practices

While the activities and frequencies in Table 5.1.3.3.1-1 are good practices to follow, there may be situations where the guidance is either too tight or too lax. Ideally, washing and cleaning activities would be based on the type of bridge and the aggressiveness of its environment. These maintenance activities could then be prioritized and scheduled for a given bridge inventory. An example of such a washing guide for UWS superstructures is given in Table 5.1.3.3.2-1. Similar guides could be developed for other elements. In addition, a washing guide could be coupled with an inspection program to optimize maintenance actions, as exemplified in Table 5.1.3.3.2-2.

An additional consideration for cleaning and washing activities is the timing within a given calendar year. It is ideal to perform these activities at the beginning of spring after the conclusion of the winter road salting season, in locations where they are applied. Practically, this may not be achievable given the size of most state bridge inventories. This is another instance where a prioritization schedule similar to Table 5.1.3.3.2-1 could be developed and implemented.

Table 5.1.3.3.2-1—Example priority and washing intervals for UWS superstructures.

Micro-Environment	Priority / Washing Interval	Macro-Environment	
		All Others	Coastal
All Others	Priority	3	2
	Interval (years)	Maximum	Intermediate
Highway Crossings with Extreme Salt Use	Priority	2	1
	Interval (years)	Intermediate	Minimum

Table 5.1.3.2.2-2—Example maintenance actions based on UWS patina rating (Crampton et al. 2013)

Patina Rating[1]	Action
≥ 7	Continue periodic NBIS inspections to ensure patina is performing as intended
6	Continue periodic NBIS inspections to ensure patina is performing as intended, consider provisionary care such as periodic washing at baseline intervals.
5	Careful evaluation to determine if corrosion is advanced relative to age of structure and to determine cause of detrimental corrosion, if applicable, in areas of poor performance, routine washing at baseline intervals or more frequently.
4	Careful evaluation to determine cause of detrimental corrosion, routine washing more frequently than baseline intervals, monitoring, and consider painting if washing does not improve performance.
3	Washing will likely not improve patina performance, painting should be scheduled.

[1]Proposed Patina Evaluation Rating Scale from Crampton et al., 2013

5.1.4—Maintenance Plans

The concept of a "maintenance plan" for UWS bridges was introduced in Section 2. This may be desirable in cases where UWS performance is anticipated to be less than ideal or uncertain. While maintenance of all bridges is vital, the concept of a maintenance plan is to thoughtfully plan and program for potential maintenance needs, before there is an apparent problem. This will minimize deferred maintenance problems and improve UWS performance.

Concepts that may be considered in developing a maintenance plan include:

- Programmed joint maintenance at intervals not to exceed the anticipated life span of the joint. In the absence of more specific information, the time frames summarized by Table 5.1.2.2-1 can be used to guide this planning. However, for bridges in situations severe enough to warrant a maintenance plan, the recommendation for providing jointless bridges is especially emphasized.

- Washing and cleaning using the guidance in Table 5.1.3.3.1-1.

- Anticipation of painting after decades in service. If UWS fails to perform in an acceptable manner in a given situation, Section 6 outlines recommendations for rehabilitating the structure through painting. Situations where this may occur are likely to be ones where painted steel structures would need to be repainted in a similar time frame (and the performance of other material types is uncertain or costlier). Thus, the use of UWS effectively avoids one painting cycle.

5.1.5—Graffiti Prevention and Removal

Graffiti on UWS bridge elements is often aesthetically undesirable and, in some rare cases, can cause increased corrosion rates. Therefore, preventing and removing graffiti can be beneficial to long term performance of UWS.

5.1.5.1—Best Practices

The most effective anti-graffiti policies include:

- Preventing public access to the UWS elements using fences or anti-climbing plates or stiffeners (Figure 5.1.5.1-1). The best way to stop the problem is to prevent it in the first place. Security measures to prevent public access must allow for inspection and maintenance.

- A "do nothing" approach. Graffiti can be left if it is not publicly visible or objectionable and is not causing corrosion, as it will eventually be absorbed into the patina.

Source: Mandeno and El Sarraf (2020)

Figure 5.1.5.1-1—Example anti-climbing plates.

In cases where access cannot be restricted or where the owner wishes to remove existing graffiti, other methods should be employed.

5.1.5.2—Other Methods

The following alternative methods can be used to prevent or remove graffiti:

- Apply anti-graffiti coatings in areas most likely to be graffitied (e.g., near abutments) or to areas that have already been tagged. However, this prevents patina formation and somewhat defeats the purpose of using UWS.
- Remove using high pressure water jetting at 10,000 psi. However, this will also remove the underlying patina, resulting in a noticeable surface appearance difference until the patina reforms.
- Use other removal methods including dry ice blasting (Brush, 2010) or a combination of paint softener followed by steam cleaning (El Sarraf et al., 2020). These methods have shown varying levels of success and should be fully vetted prior to use.

6.0—REPAIR AND REHABILITATION RECOMMENDATIONS

UWS bridges, located, designed, detailed, constructed, and maintained utilizing the guidelines provided in this document, are expected to perform satisfactorily for a service life of 75 years and beyond (Refer to the AASHTO Guide Specifications for Service Life Design of Highway Bridges, current edition). Should the achieved performance of UWS not meet expectations, for example due to a more aggressive environment than anticipated, or unrepaired failures in a drainage system, there are many options for repair and rehabilitation that can be implemented.

Older UWS bridges may not have incorporated appropriate details during their design, and as such there may be a need for repair and rehabilitation where excessive corrosion has occurred.

6.1—REPAIR

Some modest amount of deterioration and damage can be addressed through recurring maintenance, such as debris removal, correcting leaking joints, and diversion of drainage outflow. Maintenance actions should follow the recommendations of Section 5. When conditions deteriorate beyond the repair capabilities of recurring maintenance activities, more assertive repair actions may be warranted. For UWS structures, common repair practices include sealing, strengthening, and painting, all of which are described in subsequent sections.

6.1.1—Painting

Early-age poor weathering performance can often be addressed by painting rather than more costly strengthening methods. In these instances of early detection, protective spot painting may be warranted, especially in the following areas:

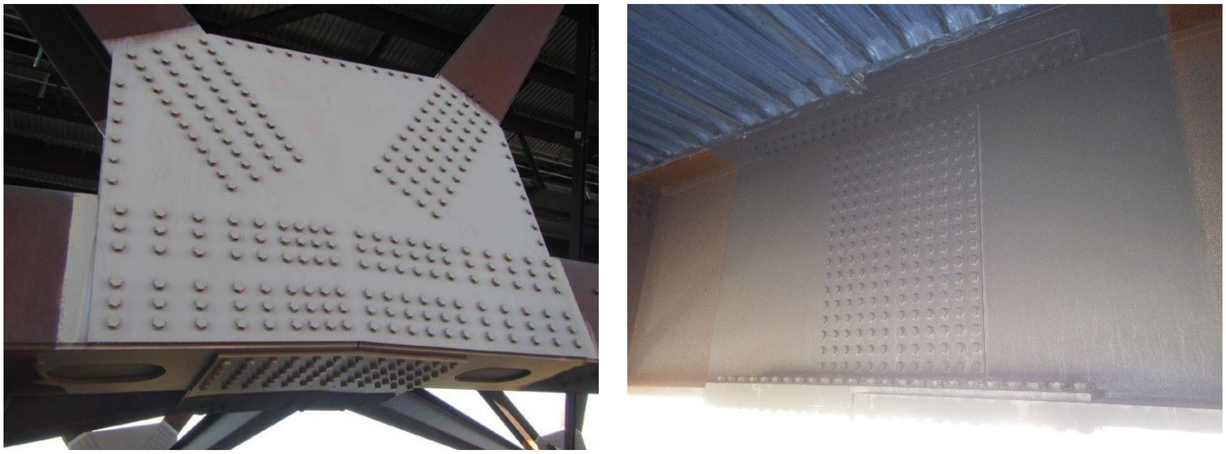
- Regions below deck joints (Figure 6.1.1-1)
- Around any non-performing crevices such as found around bolted connections (Figure 6.1.1-2)
- Poorly draining intersections of vertical stiffeners and bottom flanges (Figure 6.1.1-3)
- Ends of girders and along bottom flanges (Figure 6.1.1-4), which may or may not be caused by leaking joints.

Spot painting application should follow the guidelines for full painting application discussed in subsequent paragraphs.

Source: MNDOT (2014)

a. b.

Figure 6.1.1-1—Example painting of UWS members beneath deck joints.



Source: PennDOT

a. b.

Figure 6.1.1-2—Painted weathering steel bolted connections (a) truss gusset plate (b) girder splice.

Figure 6.1.1-3—Painted weathering steel around a connection plate without drain clips.

Source: MNDOT (2014)

Figure 6.1.1-4—Example spot painting of UWS girder end attributed to effects of a leaking joint.

In the rare case where a major portion or the entirety of a UWS bridge is not weathering satisfactorily, the entire bridge will require application of an appropriate protective paint system (Figure 6.1.1-5). In such instances, there are many similarities to the repainting of a typical painted bridge. However, there are also significant differences:

- Dry blast cleaning of all surfaces is necessary. Due to the rough surface and pitting, it will be difficult to economically obtain a high-quality finish. Specifications regarding the final finish should avoid setting an unachievable standard.

- The paint system selected must be able to accommodate large dry film thickness variations resulting from the rough surface of the steel substrate. This is notably applicable to the primer, as a larger quantity will be required to fill the dry blasted surface profile. To achieve a smooth surface finish, this can amount to as much as four times as much primer as needed in a typical application.

- The primer system should be resistant to rust residue or chemical residue, which are practically impossible to entirely remove from numerous pits in the substrate surface.

- The paint system must have a low water vapor transmission rate to prevent blistering of the paint film.

It is recommended that a certified coating consultant be employed to determine the most optimum protective coating system to be used.

Source: MDOT

Figure 6.1.1-5—Weathering steel bridge with entire superstructure painted.

6.1.2—Sealing

Crevice corrosion can be a deterioration problem on steel bridges, UWS bridges included, due to the tendency to trap debris and hold moisture (i.e., increased time of wetness) in these areas. This is more common on older existing bridges that utilized rivets or were designed during a time with more relaxed bolt spacing requirements. Bridges designed to modern sealing requirements do not suffer from this form of deterioration. If crevice corrosion occurs, sealing crevices can be a viable solution depending on the connection type and extent of corrosion.

For connections that are not critical to the structural stability of the bridge (e.g., certain cross frame and lateral bracing members), the connection may be disassembled, blast cleaned to the appropriate surface preparation grade, painted with a suitable coating, and reassembled. Prior to any connection disassembly, a structural stability analysis should be performed, and a disassembly and reassembly sequence should be developed.

For critical structural connections (e.g., girder splices), apply a penetrating sealer to displace moisture, caulk all edges with a compatible sealant (e.g., epoxy), and stripe coat the connection with a compatible coating. Figure 6.1.2-1 provides examples of sealing UWS members.

a. b.

Figure 6.1.2-1—Examples of sealing UWS: (a) penetrating sealer applied to the interior surface of a UWS box column base (b) caulking applied around the edges of a gusset plate connection.

6.1.3—Strengthening

In rare cases where severe section loss is found, it may be necessary to remove or replace damaged sections or supplement section loss by installing welded or bolted steel plates or shapes. Prior to any repair, the cause of the deterioration should have been determined and mitigated to prevent a reoccurrence. If the steel is to remain uncoated, new plates or shapes should also be weathering steel. Where supplemental material is added, it is important to perform proper surface preparation prior to installing the new section, which may include one or more of the following:

- Cleaning (e.g., hand tool cleaning, power tool cleaning, solvent cleaning) or blast cleaning to remove lost section rust residue.

- Applying an approved rust resistant, waterproof mastic metal putty to provide a smooth interface between the damaged material and the new plating.

- Priming the contact surfaces between the damaged material and new plating.

Figure 6.1.3-1—Bolted angle repair to strengthen a UWS beam bottom flange.

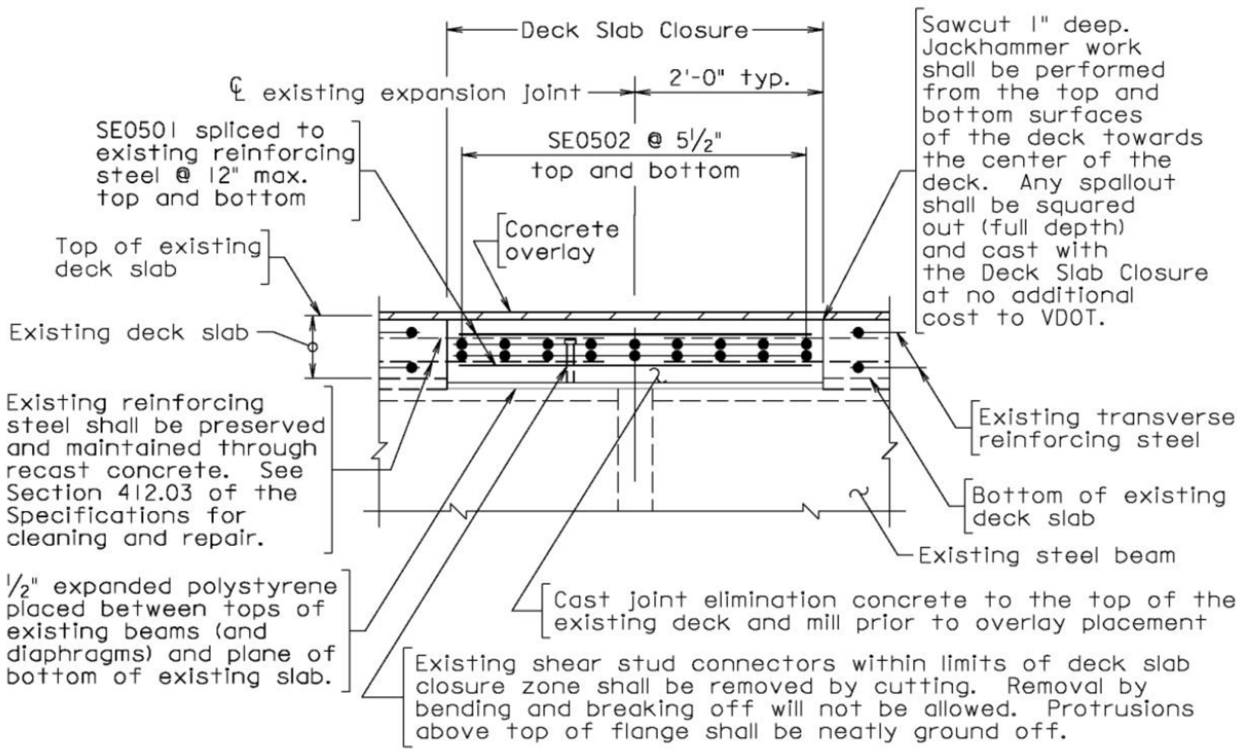
6.1.4—Joint Elimination

The elimination of deck joints through methods like link slabs has proven to be an effective rehabilitation strategy. This is particularly true for UWS bridges where time of wetness and de-icing salt runoff are critical concerns. See Section 2.4.2 for background on link slabs used for new design, as many of the same concepts apply to links slabs for rehabilitation of existing bridges.

Link slab construction over piers on existing bridges involves removing a calculated length of the existing deck concrete on each side of the joint (Figure 6.1.4-1). In addition, shear studs within the link slab limits are removed and replaced with a bond breaker (e.g., polystyrene, sheet gasket) to eliminate continuity between the link slab and the girders. An example link slab detail is shown in Figure 6.1.4-2. Bearing modifications may be necessary as well in order to accommodate changes in structural behavior. Design of link slabs is beyond the scope of this manual; information on link slab design can be found in Caner and Zia (1998) and Thorkildsen (2020).

Source: NYSDOT

Figure 6.1.4-1—Link slab construction on existing bridge.



Source: VDOT (2021)

Figure 6.1.4-2—Example link slab detail for existing bridges.

REFERENCES

AASHTO (2009), *LRFD Guide Specifications for the Design of Pedestrian Bridges*, 2nd Edition with 2015 Interim Revisions, American Association of State Highway and Transportation Officials, Washington, D.C.

AASHTO (2017), *LRFD Bridge Construction Specifications*, 4th Edition with 2020 Interim Revisions, American Association of State Highway and Transportation Officials, Washington, D.C.

AASHTO (2018), *Manual for Bridge Evaluation*, 3rd Edition with 2020 Interim Revisions, American Association of State Highway and Transportation Officials, Washington, D.C.

AASHTO (2019), *Manual for Bridge Element Inspection*, 2nd Edition, American Association of State Highway and Transportation Officials, Washington, D.C.

AAHTO (2020), *Guide Specification for Service Life Design of Highway Bridges*, 1st Edition, American Association of State Highway and Transportation Officials, Washington, D.C.

AASHTO (2020), *LRFD Bridge Design Specifications*, 9th Edition, American Association of State Highway and Transportation Officials, Washington, D.C.

AASHTO/AWS (2020), *Bridge Welding Code* BWC-8 D1.5M/D1.5, American Association of State Highway and Transportation Officials and American Welding Society, Washington, D.C.

AASHTO/FHWA (2019), "A User's Guide to Bridge Cleaning," American Association of State Highway and Transportation Officials Transportation System Preservation Technical Services Program (TSP2), Federal Highway Administration Bridge Preservation Expert Task Group (BPETG), Washington, D.C.

AASHTO/NSBA (2018), "Steel Bridge Fabrication Guide Specification," S2.1-2018, NSBASBF-4-OL, AASHTO/NSBA Steel Bridge Collaboration, Washington, D.C.

AASHTO/NSBA (2020), "Guidelines to Design for Constructability and Fabrication," G12.1-2020, NSBAGDC-4, AASHTO/NSBA Steel Bridge Collaboration, Washington, D.C.

AISI (1982), "Performance of Weathering Steel in Highway Bridges, A First Phase Report," Task Group on Weathering Steel Bridges, American Iron and Steel Institute, Washington, D.C.

AISI (2020), "Weathering Steel Bridges," American Iron and Steel Institute, Washington, D.C.
Taken from https://www.steel.org/steel-markets/bridges/resources/

Albrecht, P. and Cheng, J. (1983), "Fatigue Tests of 8-yr Weathered A588 Steel Weldment," ASCE *Journal of Structural Engineering*, 109 (9).

Albrecht, P., Coburn, S.K., Wattar, F.M., Tinklenberg, G.L. and Gallagher, W.P. (1989), NCHRP Report 314: Guidelines for the Use of Weathering Steel in Bridges, Transportation Research Board, National Research Council, Washington, D.C.

Albrecht, P. and Naeemi, A.H. (1984), NCHRP Report 272: Performance of Weathering Steel in Bridges, Transportation Research Board, National Research Council, Washington, D.C.

AREMA (2021), *Manual for Railway Engineering*, Chapter 15 Steel Structures, American Railway Engineering and Maintenance-of-Way Association, Lanham, Md.

Ault, J.P. and Dolph, J.D. (2018), "Corrosion Prevention for Extending the Service Life of Steel Bridges," NCHRP Synthesis 517, Transportation Research Board, National Research Council, Washington, D.C.

Barsom, J.M. (1984), "Fatigue Behavior of Weathered Steel Components," Transportation Research Record: *Journal of the Transportation Research Board*, No. 950, Transportation Research Board of the National Academies, Washington, D.C.

Barth, K., Albrecht, P., and Righman, J. (2005), *Performance of Weathering Steel Bridges in West Virginia*, West Virginia Department of Transportation, Charleston, W.Va.

Brush, M.B. (2010), "Using Dry Ice for Spray-Paint Removal on Weathering Steel," APT Bulletin, *The Journal of Preservation Technology*, XLI (1), The Association for Preservation Technology, Springfield, Ill.

Caner, A. and Zia., P. (1998), "Behavior and Design of Link Slabs for Jointless Bridge Decks." *PCI Journal*, Vol. 43, pp. 68-81.

Carlson, J. (2021), "Modern Corrosion Protection Systems (Part 1)," Summer 2021 Webinar Series, Short Span Steel Bridge Alliance, Washington, D.C.

CHA (2021), *Study of Corrosion Performance of Weathering Steel Bridges*, Connecticut Department of Transportation, Project No. 170-3301.

Crampton, D.D,, Holloway, K.P., and Fraczek, J. (2013), "Assessment of Weathering Steel Bridge Performance in Iowa and Development of Inspection and Maintenance Techniques," Final Report SPR 90-00-RB17-012, Iowa Department of Transportation, Ames, Iowa.

Ellis and LaQue (1951), "Area Effects in Crevice Corrosion," *Corrosion*, Vol. 7, No. 11, pp. 362-364.

El Sarraf, R. and Mandeno, W.L. (2010), "Design for Durable Structural Steelwork in New Zealand," *The Structural Engineer Magazine*, The Institute of Structural Engineers, 88(19).

El Sarraf, R., Mandeno, W., and Hicks, S. (2017), "Weathering Steel Design Guide for Bridges in Australia," New Zealand Heavy Engineering Research Association, Auckland, New Zealand.

El Sarraf, R., Mandeno, W., and Karpenko, M. (2020), "New Zealand Weathering Steel Guide for Bridges," HERA Report No. R4-97:2020, New Zealand Heavy Engineering Research Association, Auckland, New Zealand.

FDOT (2017), FDOT Structures Manual Volume 2: Structures Detailing Manual. Florida Department of Transportation (FDOT), Tallahassee, FL.

FHWA (1989), "Uncoated Weathering Steel in Structures," Technical Advisory 5140.22, Washington, D.C., Updated 2017.

FHWA (2015), Steel Bridge Design Handbook: Corrosion Protection of Steel Bridges. Publication No. FHWA-HIF-16-002, Vol. 19. Federal Highway Administration, U.S. Department of Transportation, Washington, D.C.

FHWA (2018), Bridge Preservation Guide. Publication No. FHWA-HIF-18-022, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C.

Granata, R., Presuel-Moreno, F., Madani, M., and Tran, B. (2017), "Environmental Suitability of Weathering Steel Structures in Florida – Material Selection, Phase 2," Final Report No. BDV27-977-04, Florida Department of Transportation, Tallahassee, Fla.

Helwig, T. and Yura, J. (2015), "Bracing System Design," Steel Bridge Design Handbook, Vol. 13, Report No. FHWA-HIF-16-002 – Vol. 13, Federal Highway Administration, Washington, D.C.

Idaho Transportation Department (2004), "LRFD Bridge Design Manual," Idaho Transportation Department, Boise, Idaho.

ISO (2012), "ISO 9223:2012: Corrosion of metals and alloys -- Corrosivity of atmospheres – Classification, determination and estimation," ISO, Geneva, Switzerland.

Jobes (1996), "Evaluation of Unpainted Weathering Steel Bridges in Idaho," Final Report, Idaho Transportation Department, Boise, Idaho.

Kogler, R. (2015), "Corrosion Protection of Steel Bridges," Steel Bridge Design Handbook, Vol. 19, Report No. FHWA-HIF-16-002 – Vol. 19, Federal Highway Administration, Washington, D.C.

Landrum, R.J. (2012), "Fundamentals of Design for Corrosion Control, A Corrosion Aid for the Designer," NACE International, Houston, Texas.

Langill, T., and Fossa, A. (2009), "Dissimilar Metals in Contact with HDG." American Galvanizers Association (AGA). Taken from https://galvanizeit.org/knowledgebase/article/dissimilar-metals-in-contact-with-hdg.

Mandeno, W.L., and El Sarraf, R. (2020), *Protective Coatings for Steel Bridges, A Guide for Bridge and Maintenance Engineers*. NZ Transport Agency, Wellington, New Zealand.

McConnell, J., Shenton, H., Mertz, D., and Kaur, D. (2014), "National Review on Use and Performance of Uncoated Weathering Steel Highway Bridges," ASCE *Journal of Bridge Engineering*, 19(5), p.01014009-1 1014009-11.

McConnell, J., Shenton, H., and Mertz, D. (2016), "Performance of Uncoated Weathering Steel Bridge Inventories: Methodology and Gulf Coast Region Evaluation," ASCE *Journal of Bridge Engineering*, 21(12).

McDad, B., Laffrey, D.C., Dammann, M., and Medlock, R.D. (2000), "Performance of Weathering Steel in TxDOT Bridges," Texas Department of Transportation, Project 0-1818.

Medlock, R., Gilmer, H., Miller, D., and Ream, A. (2019), "Bridge Welding Reference Manual," Publication No. FHWA-HIF-19-088, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C.

Milner, M. and Shenton, H. (2014), "Survey of Past Experience and State-of-the-Practice in the Design and Maintenance of Small Movement Expansion Joints in the Northeast," Report 242, AASHTO Transportation System Preservation Technical Services Program, Washington, D.C.

MnDOT (2014), "Report of the Condition of Weathering Steel Bridges in the State of Minnesota – 2013 Reassessment." Bridge Office, Bridge Safety Inspections, Minnesota Department of Transportation, Oakdale, Minn.

MnDOT (2019), Bridge Maintenance Manual, Minnesota Department of Transportation (MnDOT), St. Paul, Minn.

Murphy, T., Hopper, T., Wasserman, E., Lopez, M., Kulicki, J., Moon, F., Langlois, A., and Samtani, N. (2020), "NCHRP Web-Only Document 269: Guide Specification for Service Life Design of Highway Bridges," NCHRP Project 12-108 Final Report, Transportation Research Board, National Academy of Sciences, Washington, D.C.

NACE (2008), "Designing for Corrosion Control," NACE International, Houston, Texas.

National Oceanic and Atmospheric Administration (2002), "The Climate Atlas of United States," National Climatic Data Center, Asheville, N.C.

Nelson, W. (2011), "Report of the Condition of Weathering Steel Bridges in the State of Minnesota," Minnesota Department of Transportation, Oakdale, Minn.

Nelson, W. (2014), "Report on the Condition of Weathering Steel Bridges in the State of Minnesota – 2013 Reassessment," Minnesota Department of Transportation, Oakdale, Minn.

NHDOT (2016), "Standard Specifications for Road and Bridge Construction," New Hampshire Department of Transportation, Concord, N.H.

NYSDOT (2008), *Fundamentals of Bridge Maintenance and Inspection,* Office of Operations, Office of Transportation Maintenance, New York State Department of Transportation (NYSDOT), Albany, N.Y.

Palle, S., Younce, R., Hopwood II, T. (2003), "Investigation of Soluble Salts on Kentucky Bridges," Kentucky Transportation Center, University of Kentucky, Lexington, Ky.

PennDOT (2016), PUB 370J, Bridge Maintenance and Cleaning, Pennsylvania Department of Transportation, Harrisburg, Pa.

Thorkildsen, E. (2020), "Case Study: Eliminating Bridge Joints with Link Slabs – An Overview of State Practices." Report No. FHWA-HIF-20-062, Federal Highway Administration, Washington, D.C.

Townsend, H.E., Gorman, C.D., and Fischer, R.J. (1998), "Atmospheric Corrosion Performance of Hot-Dip Galvanized Bolts for Fastening Weathering Steel Guiderail," Paper No. 344, CORROSION/98, NACE International, Houston, Texas.

Ungermann, D. and Hatke, P. (2021), "European Design Guide for the Use of Weathering Steel in Bridge Construction," 2nd edition, European Convention for Constructional Steelwork, AC3 Bridge Committee, Report No. 143, Brussels, Belgium.

VDOT (2020), "Road and Bridge Specifications," Virginia Department of Transportation, Richmond, Va.

VDOT (2021), "Maintenance and Repair," Manual of Structure & Bridge Division, Part 2, Chapter 32, Virginia Department of Transportation, Richmond, Va.

WJE (2002), "Synthesis of Technical Information for Jointless Bridge Construction," State of Vermont, Agency of Transportation, Montpelier, Vt.

WSDOT (2015), WSDOT Bridge Standard Drawings. Bridge and Structures Office, Washington State Department of Transportation (WSDOT), Olympia, Wash.

WVDOT (2017), "Standard Specifications Roads and Bridges," West Virginia Department of Transportation, Division of Highways, Charleston, W.Va.

Smarter. Stronger. Steel.

National Steel Bridge Alliance
312.670.2400 | aisc.org/nsba

B302-22