# Steel Structures to Withstand the Elements: What Structural Engineers Need to Know about Corrosion

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## ABSTRACT

While regimented design processes for load-induced effects in structures are ubiquitous, similar design processes for considering corrosion resistance are lacking. This is a critical gap in the structural engineering profession as material degradation is the most common cause of diminishing structural condition for bridges and other infrastructure exposed to the elements. This results in both safety and financial consequences. This paper addresses this gap by reviewing basic principles governing corrosion, how these corrosion principles translate to real-world environments, commonly available corrosion protection systems, long-term field data assessing corrosion in varied quantified environments and associated conclusions, and practical design and maintenance strategies for improving corrosion resistance. These concepts are connected through a proposed framework for considering corrosion as a limit state that can be applied to all structures. Detailed consideration of uncoated weathering steel (UWS) bridges is provided as a pilot material and structure type for considering corrosion as a limit state. Thoughtful application of these concepts can be used to optimize corrosion resistance, improving life-cycle costs and service lives of civil engineering structures.


**Keywords:** corrosion, corrosions resistance, uncoated weathering steel.

## CORROSION AS A LIMIT STATE

Corrosion affects nearly every industry sector. In fact, the National Association of Corrosion Engineers (NACE) estimated (in 2016) the worldwide economic impact of corrosion to be $2.5 trillion annually, equating to 3.4% of the global gross domestic product. Furthermore, the most widespread problem affecting our national transportation infrastructure is material degradation. This fact is supported by examining the causal factors for diminishing conditions of highway bridges. So, increased understanding of corrosion is a timely need to enable more widespread implementation of design and maintenance choices that lead to more durable structures.

While presently, corrosion is typically considered in the design and maintenance of highway bridges, these considerations are generally qualitative. The most current national guidance on this topic is contained in the American Association of State Highway and Transportation Officials' (AASHTO) *Guide Specification for Service Life Design of Highway Bridges* (2020). This reference highlights that, with respect to corrosion, "there is no universal solution." For example, selections between alternative corrosion protection systems are typically limited to relative comparisons between cost and qualitative performance of different options. Another example of present reliance on qualitative processes is the descriptions of different environments that are frequently applied to make choices regarding situations in which some corrosion protection systems should or should not be used. In some cases, such qualitative considerations are the best available information. However, this paper will review recent progress to enable corrosion resistance to be approached from a more quantitative—and, therefore, engineered—approach.

Furthermore, it is proposed to develop an engineered approach that takes the form of considering corrosion as a limit state. This proposed framework is analogous to the limit state equations routinely used in structural engineering, where mathematical equations require the strength of various member types to be greater than the force effects of the loads that are applied to those members. Numerous mathematical equations have been rigorously developed over decades to ensure that such strength requirements are consistently satisfied with a uniform level of safety, generally having a format similar to Equation 1:

$$\phi R_n > \sum \gamma_i Q_i \tag{1}$$

where $\phi$ is a resistance (safety) factor; $R_n$ is the member resistance for a specific force effect and/or member type; and $\Sigma\gamma_i Q_i$ is the summation of the factored load effects from the governing load combination considering dead load,

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live load, wind load, etc. It is within reason as a long-term goal to think about corrosion as a similar concept, with the corrosion resistance of our materials being designed to be greater than the corrosive effect of the environment in which they are located. For example, Equation 2 shows an equation analogous to Equation 1:

$$\phi R_c > \sum \gamma_i C_i \tag{2}$$

where $\phi R_c$ could represent the corrosion resistance of a given material or corrosion protection system and $\Sigma \gamma_i C_i$ could represent the combined corrosion effect of environmental factors causing corrosion, such as average annual snowfall, atmospheric chloride concentrations, etc. The following sections review recent findings that can serve to develop a foundation for such equations and engineered approaches.

## CORROSION AND CORROSION RESISTANCE OF STEEL

### Corrosion Fundamentals

To progress the consideration of the corrosion resistance of structures from qualitative to quantitative approaches, a basic understanding of the fundamental chemical processes governing steel corrosion is necessary. Steel corrosion involves the transformation of iron (Fe) into what is typically referred to as "rust." Equations 3 through 6 illustrate one of the simpler of a few possible ways of forming rust. Equation 3 shows that the first reaction in the steel corrosion process is the dissolution of electrons from iron. This dissolution occurs quite readily when iron is exposed to any of the multiple sources of naturally occurring moisture (e.g., humidity, rain, snow) due to the natural oxidation state of iron being +2 (as in the example shown in Figure 1) or +3. Furthermore, the transformation to rust cannot proceed without moisture ($H_2O$) to produce hydroxide ions in the subsequent step (Equation 4) in the series of reactions leading to the formation of rust. Therefore, the presence of water is a critical factor affecting corrosion rates and thus an important factor in designing for corrosion resistance. More complicated means of forming rust similarly rely on the presence of $H_2O$.

$$Fe \xrightarrow[\text{dissolution}]{(\textit{moisture})} Fe^{2+} + 2e^- \tag{3}$$

$$2e^- + ½O_2 + H_2O \rightarrow 2OH^- \tag{4}$$

$$Fe^{2+} + 2OH^- \rightarrow Fe(OH)_2 \tag{5}$$

$$Fe(OH)_2 \xrightarrow{\text{dehydration}} Fe_2O_3H_2O \tag{6}$$

Another element of concern is chlorine. Chloride ions ($Cl^-$) can be suspended as fine particulates in the air above bodies of salt water, which the wind can then drive onto structures in marine environments. Other sources of $Cl^-$ are deicing agents applied to roadways for winter roadway maintenance. From a chemistry perspective, $Cl^-$ is problematic because it serves as an electrolyte. Equation 3 shows that the first reaction for forming rust is an electrochemical reaction, with electrons traveling through films of moisture on the surface of the steel. Chlorides form dissolved electrolytes in this solution, which act as a catalyst, thereby increasing the rate at which rust forms. These facts regarding the effect of $H_2O$ and $Cl^-$ highlight that, while "the elements" is often thought of as a general phrase referring to weather, considering "the elements" as the chemical elements involved in quantitatively described corrosion processes provides a scientific foundation for designing for corrosion as a limit state.

### Influence of the Environment on Corrosion

The discussion in the previous section explains why corrosion rates depend on the environment in which structures are located, as the presence of $H_2O$ and $Cl^-$ vary dramatically between locations. These variations occur due to regional variations in climate, site-specific features within a given region, and differences in exposure to water and chlorides within a given structure. These variations can be considered relative to the existing framework of macro- and micro-environments. In this framework, all structures can be classified into at least one macro-environment. For example, one version of these classifications involves four categories: coastal environments, where the concern is exposure to chlorides; industrial environments, where the concern was previously exposure to sulfur dioxide, but this concern has been mitigated by modern Clean Air regulations now in place for decades; urban environments, where the concern was previously exposure to elevated pollutants in general, which is also a negligible modern concern; and lastly, rural environments that have been and continue to be defined as being relatively benign environments. Thus, of these four macro-environment categories, only the coastal macro-environment presents a modern-day corrosion concern as it is the only one with elevated $H_2O$ and/or $Cl^-$. Quantification of this category is discussed subsequently.

Micro-environments may exacerbate the corrosivity of the macro-environment due to the specifics of the bridge site, particularly due to the amount of $H_2O$ and $Cl^-$ at the site relative to the typical characteristics of the surrounding macro-environment. Examples of this include highway overpasses that cross over roadways treated with deicing agents for winter roadway maintenance. These bridges are exposed to higher amounts of chloride than other bridges in the same general location because road spray from the under passing roadway is transferred to the superstructure. Similarly, bridges that cross over waterways can experience localized increases in humidity. Alternatively, vegetation in such close proximity to the structure that it shelters the structure from sunlight for the majority of the day may also increase the local humidity. And lastly, as a final example, within the coastal macro-environment, the chloride effect is highly variable due to regional variations in atmospheric chloride concentrations, which are illustrated in Figure 1. More detailed consideration of these effects for the specific example of UWS bridges is given below.

Nano-environments are a third category of environment, proposed herein, to refer to differences in exposure to water and chlorides within a given structure. For example, details like leaking joints and discontinuous deck materials allow only some portions of the superstructure to be exposed to greater than normal amounts of $H_2O$ and possibly the $Cl^-$ dissolved in this water. Similarly, details that trap debris or provide inadequate drainage allow water and debris to collect on isolated areas of the structure, creating a continuously wet environment. While these effects are sometimes considered as part of the micro-environment, it is useful to distinguish between this classification of nano-environments compared to the definition of micro-environments given previously because owners, designers, and maintenance engineers have different levels of control over these two categories of environments. There is generally little to no control about the general site (i.e., micro-environment as defined herein) for a bridge. On the other hand, engineers and owners have full control of the nano-environment of the structure. Suggestions on best practices for exerting this control to achieve more corrosion resistant structures are described subsequently.

**Corrosion Protection Systems**

Corrosion protection systems for steel can be organized in three categories. These three categories apply to structural steel used in bridges and the exposed elements of buildings and include numerous types of paint that are typically formulated to be used in specific combinations to form multilayer paint systems. These are often termed "liquid applied coatings." Other coating types are categorized as "thermal applied coatings," with the most common examples of this being galvanizing and metallizing. In both of these coating systems, molten zinc or a blend of zinc and aluminum is used to provide corrosion protection. The third category is "uncoated steels," in which case the corrosion resistance is provided by additional alloying elements within the steel. There are two general types of uncoated steels presently specified for typical use in the United States. One type is known as weathering steel [or, when used uncoated

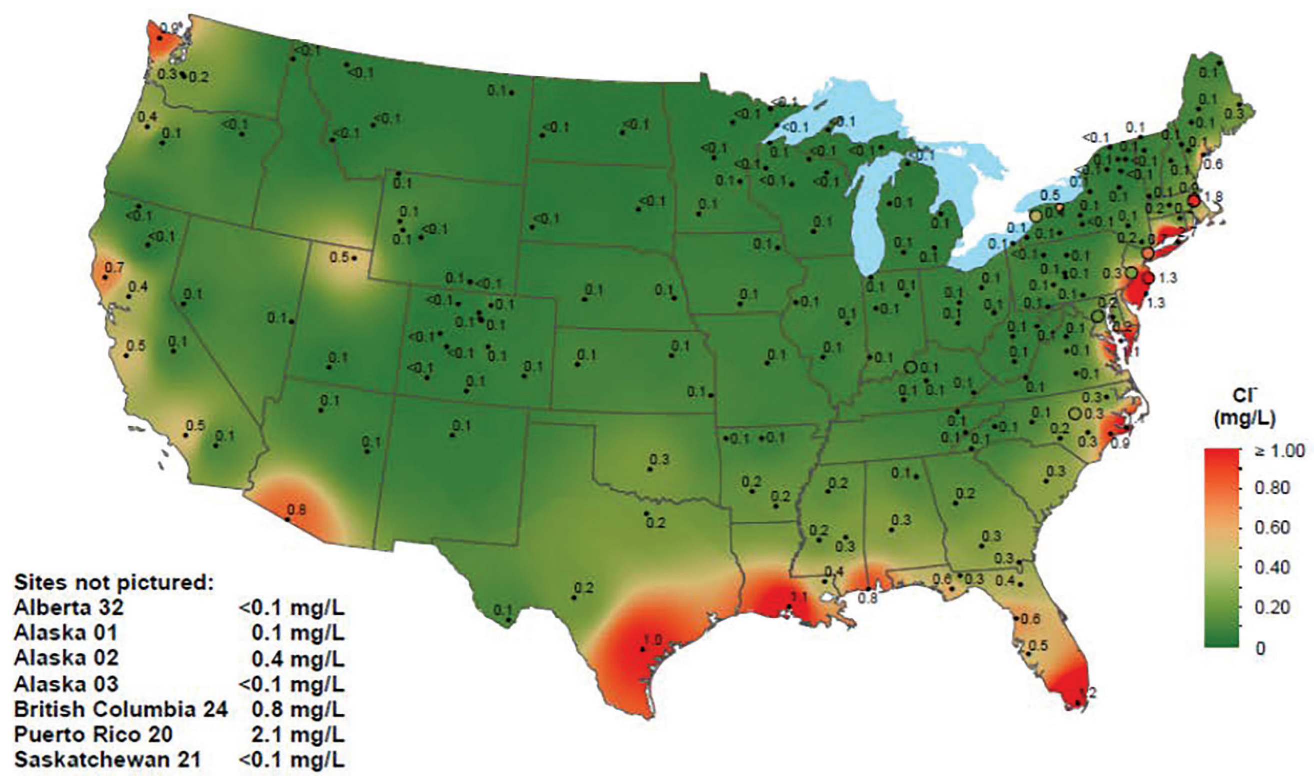


*Fig. 1. Chloride concentrations in the continental United States (NADP, 2020).*

as intended, uncoated weathering steel (UWS)], and there are specifications for several grades of UWS [e.g., via ASTM A588 (2019) for buildings and ASTM A709 (2021); AASHTO M 270 (2021) for bridges]. The other type of uncoated steel presently available is designated as 50CR (previously designated as ASTM A1010), due to the fact that corrosion resistance is provided by a relatively high percentage of chromium (Cr) (ASTM, 2021; AASHTO, 2021). Additional information on each of these types of corrosion protection systems is well summarized by Kogler (2015), who provides an overview of the scientific principles governing corrosion protection as well as practical considerations for each of these corrosion protection systems.

These various corrosion protection systems have differing performance in different environments as well as different costs, making it difficult to optimize the selection of the corrosion protection system. While additional quantitative and objective information on both performance and cost is needed, recent work has started to provide quantitative comparative data. First considering performance, an aggregate view of comparative field performance was compiled by McConnell et al. (2022) as quantified by the superstructure condition rating (SCR) [Federal Highway Administration (FHWA), 1995] based on data from eight state departments of transportation that identified UWS, galvanized, metalized, and painted bridges within their agency. While the SCR takes several factors into consideration (such as for steel bridges, fatigue cracks and other visual signs of overstressed members, damage resulting from vehicular impacts, missing bolts in structural connections), corrosion is the most common cause of decreasing SCR. Thus, when reviewing these ratings for an extensive sample size, prior work has supported that SCR give a general indication of steel bridge durability (McConnell et al., 2024) despite their qualitative and subjective nature. Therefore, the SCR for the bridges identified by these departments of transportation was downloaded from the National Bridge Inventory (FHWA, 2022) and analyzed.

Figure 2 shows linear regression lines of the SCR versus age of each corrosion protection system considered (which were found to be a reasonable compromise between simplicity and accuracy compared to higher order curve fits). One notable observation from Figure 2 is that the slopes of the performance of the galvanized, UWS, and painted bridges are remarkably similar. Furthermore, Figure 2 shows that the relative performance of these three corrosion protection systems is such that galvanized bridges generally have the highest SCR ratings, painted bridges have the lowest SCR ratings, and UWS bridges have performance (as quantified by SCR) in between these two types. The metalized bridges in this dataset initially have the highest SCR, but the trend for this dataset deteriorates more quickly than the other corrosion protection systems. However, it should be noted that the sample size of the metalized bridges was very small, representing less than 1% of the dataset, and that older metalized bridges may not be representative of modern methods. Additional analysis of this data can be found in McConnell et al. (2022). The results in Figure 2 inform general trends but do not definitively determine the performance of a certain corrosion protection system at a given age or, more critically, a given environment given the significant effects of the environment on durability. Therefore, this data can be supplemented with the data compiled by Kogler (2015), who proposed deterioration rates and expected lives of different corrosion protection system options in environments where such data is available.

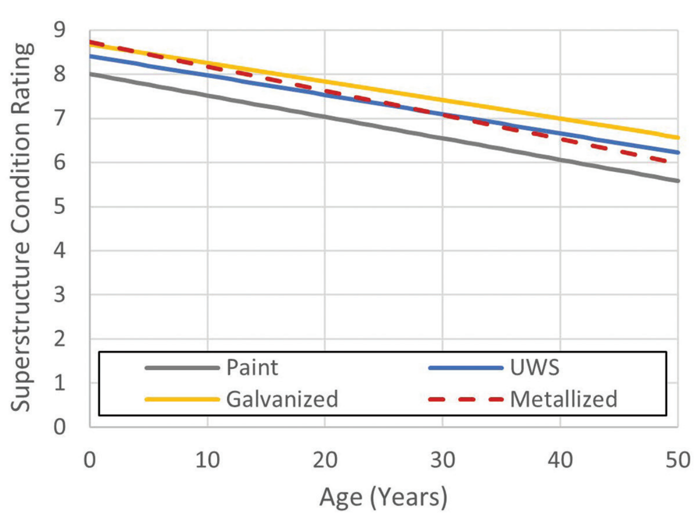


*Fig. 2. Linear regression lines of condition versus age for various corrosion protection systems (not for extrapolation).*

The ideal framework for choosing between alternative corrosion protection systems would be to compare such considerations of performance with the corresponding life-cycle cost, which accounts for both the first cost and maintenance costs over the lifetime of a structure. For example, materials with higher first cost are generally coupled with lower maintenance costs. However, sufficient data on longevity—and the multitude of factors that influence longevity—is not presently available to execute such an analysis. Yet, one aspect of cost for which there is presently relatively comprehensive high-quality data is the first cost of the most common corrosion protection systems. These have been quantified by a 2020 fabricator survey performed by the American Institute of Steel Construction (AISC), the results of which are summarized by Figure 3. This data indicates that the two UWS options [UWS with painted ends, which is recommended best practice for UWS (FHWA, 1989)], and UWS with painted ends and fascia (which is a preferred practice of some owners for aesthetic reasons) were consistently the lowest cost. The third lowest cost option is a single coat of inorganic zinc (IOZ) paint. It is noteworthy that even the maximum cost of these three minimum cost choices is lower than the minimum cost of the seven remaining choices. The two UWS options also have minimal maintenance requirements. Therefore, in situations where these three corrosion protection systems can provide adequate corrosion resistance, they are preferred options because they will also result in minimizing life-cycle cost. For this reason, the following section summarizes research related to specific analysis of the environments in which UWS provides adequate corrosion resistance.

## QUANTIFIED ENVIRONMENTAL EFFECTS FOR UWS BRIDGES

### Introduction

Prior to the start of the research summarized herein, an existing resource for quantifying the corrosivity effects of different environments was the International Standards Organization (ISO) Standard 9223 (2012), which can be applied to any structure type (e.g., buildings, bridges, and other infrastructure types). This standard categorizes the corrosivity of all environments into six categories, labeled C1 to C5 in terms of increasing severity and with the sixth, most severe, category labeled as CX. The classifications into these categories are a function of the average temperature, average relative humidity, and average annual chloride and sulfur dioxide deposition rates, which are mathematically related to the corrosion rates for carbon steel, zinc, copper, and aluminum.

Figure 4 shows the classification of locations in the continental United States and portions of Mexico and Canada into these ISO categories. From Figure 4, it is observed that the majority of the continental United States is in category C2 (low corrosivity), most of the remainder is in category C3 (medium corrosivity), relatively small areas are in category C4 (high corrosivity), and no areas are in any of the remaining categories (very low, very high, or extreme corrosivity). In other words, the ISO 9223 classifications are relatively coarse, such that the observed performance of UWS bridges (and perhaps other corrosion protection systems) does not correlate well to these classifications. This is not particularly surprising considering that UWS is not a material type explicitly considered in this specification.

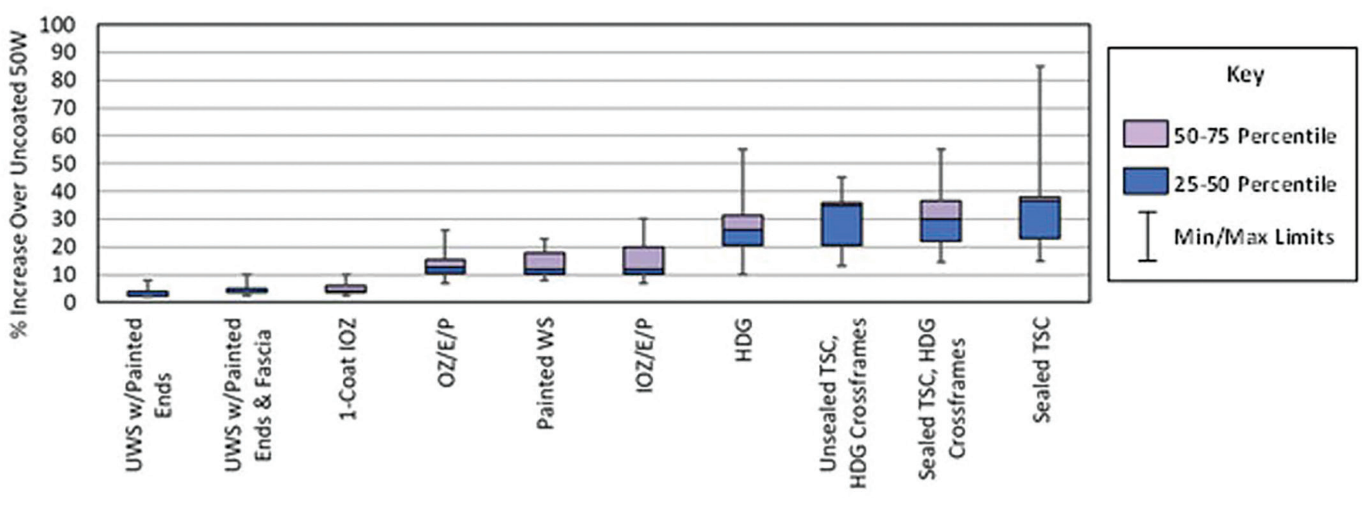


*Fig. 3. Box and whisker plot of relative first costs of common corrosion protection systems (AISC, 2022).*

Furthermore, this classification system lacks the ability to consider the influences of the micro-environment, which has been shown to be of significant importance. Therefore, while this classification system has general usefulness for describing the corrosivity of an environment, the results below advance this concept by being specific to UWS and considering micro-environment effects.

## Methodology

The quantifications of environments that are discussed subsequently are based on three types of data: field data for 34 bridges that was collected as part of research specifically focused on the performance of UWS; in-depth review of owners' reporting of UWS condition (as quantified by element-level condition state data reported in accordance with AASHTO 2001, 2011, or 2019 procedures) for 200 bridges; and superstructure condition ratings of 10,000 UWS bridges in 48 states, the District of Columbia, and Puerto Rico. These three data types have different amounts of refinement to the data and, consequently, the number of bridges evaluated by those methods. This results in a dataset that is well balanced in terms of the depth of the data analysis as well as its breadth, allowing comprehensive conclusions to be developed.

A key aspect of the field work and review of owners' reporting on UWS condition was based on methodical selection of the bridges to be evaluated. The organizational structure for these selections was based on forming groups of bridges in geographic proximity to one another, which were termed "bridge clusters," that targeted the macro- and micro-environments of greatest interest. Specifically, the two environments that were clearly of most widespread concern based on an owner survey (McConnell et al., 2024) were highway overpasses over roadways treated with deicing agents and bridges in coastal environments. The intersection of these two effects for bridges along the northern coastlines was also evaluated. As summarized by Table 1, two condition-related categories were examined in each of these environments: "inferior" and "good" performing. These categories captured the most extreme performance situations by sampling the worst-performing bridges as well as not only good-performing bridges, but bridges that were performing well despite being located in a harsh environment at an advanced age. Table 1 shows the states representing these environments and conditions in the field work and review of owners' reporting. The geographic range of each cluster was generally within a 50-mi radius, which typically resulted in all of the bridges for a given cluster being located within a single state, but included bridges in two states in some situations, as shown in Table 1.

Within each cluster, the bridges were systematically selected for review of owners' reporting based on statistical analysis of key parameters influencing corrosion (e.g., site-specific humidity, distance to the coast, etc.). A subset of these were selected for field work based on capturing the range of performance within a cluster. By structuring the bridge selections in this way, a full range of the effects of many of the most severe macro-environments in the United States can be evaluated, and by including multiple bridges within each cluster (10 to 28 based on the number of influential parameters and the diversity of the environments within the clusters), the effects of different micro-environments within these macro-environments were also quantified. Full details on the cluster bridge selections and associated data can be found in McConnell et al. (2024).

## Sample Field Data

One data type resulting from the field evaluations was ultrasonic thickness measurements, which is the metric that is most readily correlated with structural performance. Field

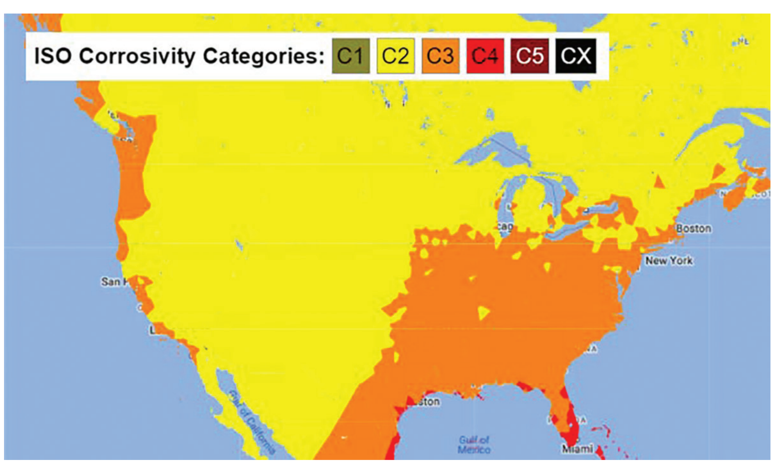


*Fig. 4. International Standards Organization corrosivity categories for locations in continental United States (NIBS, 2023).*

| Table 1. Overview of Cluster Categories and Locations | | | |
|---|---|---|---|
| Condition | Environment | | |
| | Deicing | Coastal | Deicing + Coastal |
| **Inferior** | MD/VA | LA/MS | CT |
| | MN | NC | — |
| | IA | — | — |
| **Good** | NY | TX | NH |
| | CO | NC | — |
| | OH | — | — |

measurements of plate thicknesses obtained from a handheld ultrasonic thickness meter (after minor surface preparation) can be compared to the nominal thickness of the corresponding plate indicated on the structural plans. This comparison can be used to provide an estimate of thickness loss. While this is considered a minimum estimate because the original actual thickness may have exceeded the nominal specified thickness due to plate rolling tolerances, these estimates can be used to update structural capacity calculations (e.g., for load-rating purposes) if significant losses are found that warrant such an evaluation.

Figure 5 shows the estimated thickness losses based on measurements from two locations indicative of representative performance (i.e., away from improperly designed or maintained areas) on each of 21 bridges relative to the corresponding age of the structure. This data is plotted relative to the upper bounds of section loss (represented by solid lines) that are expected to occur in the ISO environmental corrosivity categories discussed previously [based on an earlier ISO draft (1988) reported by Albrecht et al. (1989)]. In particular, the upper bound to the "high" corrosivity category is of interest because discussions with stakeholders (as part of the research summarized herein) reached a consensus that this is a reasonable threshold for the upper limit of corrosion that is considered acceptable. This decision was made in part because extrapolating this threshold line results in less than 1⁄16 in. of thickness loss after a 75-yr service life, which is viewed as a reasonable compromise between economy and safety relative to plate rolling and inspection tolerances.

Comparing the field data shown in Figure 5 to the high corrosivity category threshold, approximately half of the data points fall above this threshold. In other words, approximately half of the dataset exhibited worse performance than desirable, suggesting that the environment in which these bridges are located should be identified and

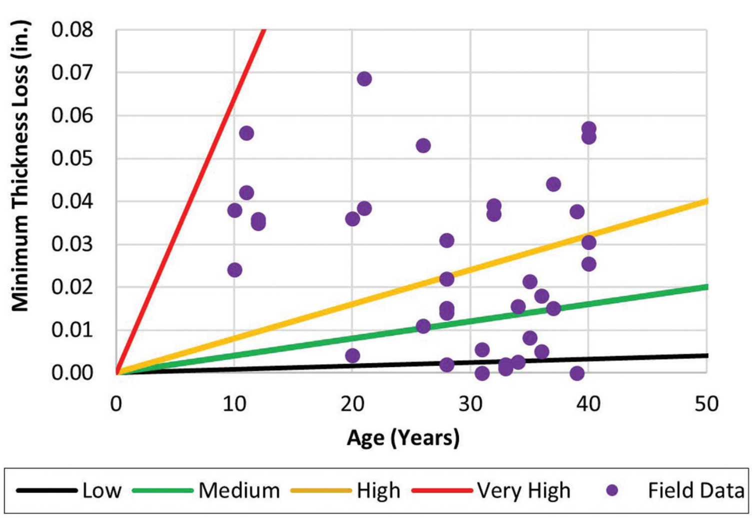


*Fig. 5. Section loss of bottom flanges versus age of bridge for UWS field bridges, plotted relative to corrosivity categories.*

that designs in these environments need more consideration. This data is a key finding supporting the recommendations contained in the following subsection.

Another data type resulting from the field evaluations was soluble chloride concentrations absorbed within UWS samples. This was measured by scraping the outer layer of corrosion by-products from representative locations of the girders (as described with respect to the Figure 5 data), collecting this material, then performing laboratory analysis of it using ion chromatography. This data can be thought of as representing a primary cause of corrosion because it is measuring chloride concentrations, a key factor in the corrosion process. Figure 6 shows this data for two representative subsets of bridges—those in coastal environments and those serving as highway overpasses in environments where deicing agents are used. This shows that the chloride concentrations caused by road spray containing dissolved deicing agents (from underpassing roadways) reaching the superstructure can be significantly higher than the chloride concentrations experienced by bridges in coastal environments. In fact, on average, the chloride concentrations for the bridges serving as overpasses to roadways treated with deicing agents was 10 times higher than the corresponding chloride concentrations on coastal bridges that were not in regions where deicing agents are regularly used. This data is another key finding supporting the recommendations contained in the following subsection.

## Results

The overall objective of the field work described earlier was to establish quantifications for environments where UWS does not perform satisfactorily. The quantifications of the combinations of parameters that create such severe conditions for the two general environments where this occurs that were of greatest concern to bridge owners—coastal environments and overpasses over roadways treated with deicing agents—are summarized later. In addition, quantifications are also provided for high time of wetness environments, which was an environment of concern qualitatively described in prior work (FHWA, 1989). These quantifications of environments presume reasonable design, detailing, and maintenance practices in accordance with FHWA's (1989) long-standing guidance on UWS and should, therefore, be considered as a supplement to these recommendations. The practical translation of this approach is that these results are not a means to avoid poor performance associated with known problematic details, such as leaking joints and details that trap moisture. Rather, these guidelines focus on the "overall performance" of bridges, which is a term meant to represent performance independent of the effects of poor detailing or maintenance, as these issues are better addressed through appropriate design and maintenance practices, as discussed in the next section. Fuller details on the analysis of these environments can be found in McConnell et al. (2024).

### *Coastal Environment*

Table 2 provides the quantitative definition of coastal environments for UWS. This definition is a combination of a distance to the coast less than 1 mi, a humidity score of at least 0.65 [which corresponds to average monthly relative humidity exceeding >65% for each month of the year and

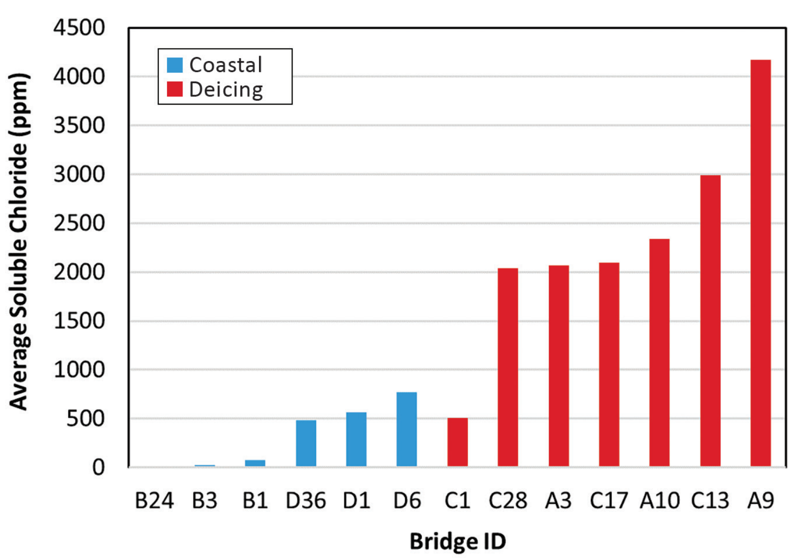


*Fig. 6. Average soluble chloride concentrations for representative coastal bridges and highway overpasses in environments where deicing agents are used.*

| Table 2. Quantitative Definition of Coastal Environment for UWS<br>*(Note: All four criteria must be simultaneously satisfied)* | | |
|---|---|---|
| **Parameter** | **Value** | **Context** |
| Distance to coast | ≤1 mi | Small |
| Humidity score | ≥0.65 | Average monthly relative humidity exceeding >65% for each month and >75% for at least 2 mo per year |
| Atmospheric $Cl^-$ | ≥0.565 ppm | 90th percentile value |
| Crossing type | Waterway | — |

>75% for at least 2 mo per year (see McConnell et al., 2024, for additional details)], and a 90th percentile value (relative to the national UWS inventory) of atmospheric chloride concentration for a bridge that also serves as a waterway crossing (due to the greater severity of this micro-environment in coastal locations). There were no observed instances of UWS bridges with unsatisfactory overall performance in coastal environments that were not waterway crossings. Figure 7 provides a map of the locations where the three quantified variables defining a coastal environment simultaneously occur. Table 2 and Figure 7 demonstrate that the coastal environment for UWS is a relatively limited geographic region. While this definition of a coastal macro-environment shares some similarities with the C4 macro-environment in Figure 4, given that they are both dependent on chloride exposure and humidity, more northern locations are included because it is not dependent upon temperature and is limited to a smaller distance to the coast since this is an explicit consideration in only the definition of a coastal environment for UWS waterway crossings.

### *Deicing Environment*

Table 3 provides the quantitative definition of a deicing micro-environment for overpasses over roadways treated with deicing agents where UWS does not consistently perform satisfactorily, or "heavy deicing environments" for brevity. Table 3 illustrates that there are three combinations of vertical under-clearance, average daily traffic (ADT) under the bridge, average annual snowfall, and atmospheric chloride concentration that, when simultaneously satisfied, quantitatively define a heavy deicing environment. It is noted that the combination of vertical under-clearance, ADT under the structure, and average annual snowfall are proxy for quantifying the amount of chlorides from deicing agents that reach UWS superstructures (because site-specific deicing agent data is not widely available) while the atmospheric chloride concentration can further elevate chloride concentrations in marine environments. While the coastal environment was observed as being relatively limited, 11% of the current inventory of UWS bridges

*Fig. 7. Continental U.S. locations meeting definition of coastal environment for UWS waterway crossings.*

| Table 3. Quantitative Definition of Heavy Deicing Environment for UWS *(Note: All five criteria for a given environment must be simultaneously satisfied)* | | | |
|---|---|---|---|
| **Label** | **Inferior Performance Environment 1** | **Inferior Performance Environment 2** | **Inferior Performance Environment 3** |
| Crossing type | Highway | Highway | Highway |
| Vertical under-clearance (ft) | Any | ≤18 | ≤18 |
| ADT under (count) | ≥100,000 | ≥10,000 | ≥4,000 |
| Average annual snowfall (in.) | ≥18 | ≥22 | ≥22 |
| Atmospheric $Cl^-$ (ppm) | NA | NA | ≥0.1 |

falls into one or more of the heavy deicing environments quantified by Table 3. This (combined with the data previously reviewed in Figures 5 and 6) indicates that greater caution is warranted in the use of UWS as highway overpasses in heavy deicing environments.

### *High Time of Wetness Environment*

The third category of environments where inferior overall performance of UWS has been sometimes observed is those with frequent high rainfall, high humidity, and persistent fog. These environments can be concisely quantified by time of wetness, which is the number of hours of year where the combination of temperature and humidity allows condensation to form on metal. ISO (2012) brackets time of wetness into five ranges labeled as T1 to T5, with T5 being the highest time of wetness. Figure 8 indicates the time of wetness categories for various locations throughout the continental United States as compiled by Chase (2012). Comparing this data to the locations where inferior performance of UWS is observed that is not attributed to other factors described in previous sections, it is found that all known instances of these bridges are located in T5, which is limited to very localized areas along the coastline of the Pacific Northwest, while also having significant vegetation. Therefore, time of wetness category T5, representing greater than 5,500 hr/yr, is suggested as being a quantification for this environment of concern.

### *Other Environments*

In addition to the three categories of environments quantitatively discussed previously, two other environments where UWS should be used with caution have been previously identified by FHWA (1989). These are industrial areas and low water crossings. However, industrial areas are a concern that has been mitigated due to Clean Air Act regulations. All known existing standards relating to UWS that quantify a threshold on sulfate (the chemical basis for the concern regarding industrial environments) either directly

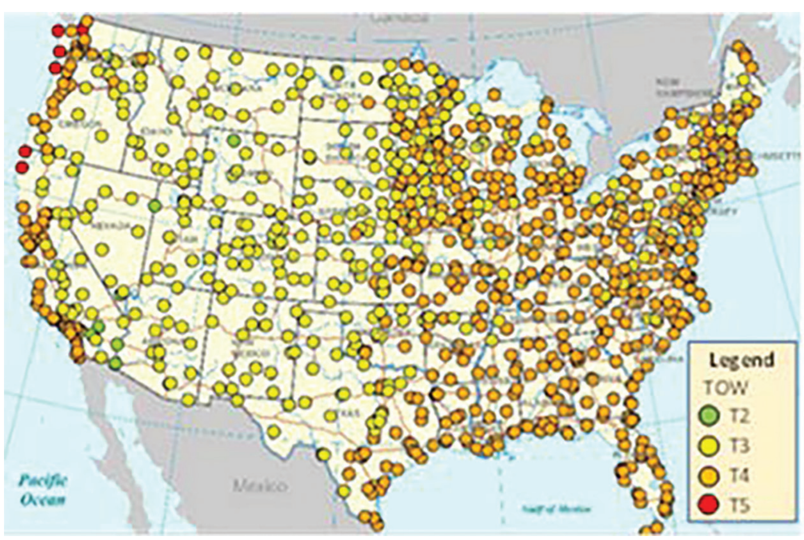


*Fig. 8. Time of wetness categories for continental U.S. locations (Chase, 2012).*

or indirectly refer to sulfate concentrations of 250 μg/m$^3$ or higher. In contrast, the current maximum sulfur dioxide emissions limit by the U.S. EPA is 200 μg/m$^3$. For these reasons, and because UWS bridge owners in the United States have not reported any problems with UWS bridges that are attributed to proximity to industrial sites, industrial environments are suggested as being an obsolete consideration for UWS bridges.

Low-level water crossings are the only environment of concern that has been historically quantified for UWS. Decades of applying the current FHWA guidelines of cautious use of UWS within 10 ft or less of vertical clearance over stagnant, sheltered water or 8 ft or less over moving water suggest that these limits are at least adequate, and most likely conservative, for providing good-performing UWS. It is suggested that a more relevant consideration may be the propensity for flooding at the bridge site that results in the structure being submerged. More significantly, flood events also frequently lead to trapped debris—and, therefore, trapped moisture—on the superstructure. Flooding considerations have the capability to be quantified by metrics such as various intervals of flood stages (e.g., 50-yr, 100-yr) compared to the vertical clearance and the frequency of exceedance of these metrics.

## APPLICATIONS FOR DESIGN AND SERVICE LIFE EXTENSION OF BRIDGES

Considering corrosion as a limit state has implications for both the design and maintenance plans of new bridge designs as well as for the maintenance practices and possible rehabilitation of existing bridges. These considerations allow new and existing bridges to achieve longer service lives. From the perspective of new bridge designs, consideration of corrosion as a limit state may be most readily incorporated into service life design procedures, relative to traditional design procedures largely focused on strength. Service life design is an evolving approach but significant progress on this has been made recently through the publication of the Federal Highway Administration's *Service Life Design Reference Guide* (Hopper et al., 2022). This guide serves as a framework for assessing relevant deterioration mechanisms and then designing corresponding elements accordingly, both through the initial design and determining timelines for anticipated future maintenance needs. As data sets for specific materials in various environments become available, such as the data described earlier, these quantifications can be used to improve the rigor of service life designs by more specifically considering corrosion as a limit state.

While it is uneconomical (and often unnecessary) to design every component or every bridge for a maximum service life, the general goal should be for the structure to be in acceptable condition when it becomes functionally obsolete. Figure 9 conceptually illustrates the goal in terms of the condition of a structure versus time for three alternative scenarios. The dotted line represents a design without careful consideration of degradation mechanisms while the dashed line shows the improvement in performance that results from designs that thoughtfully consider material degradation. Yet, the solid line illustrates that it is only through thoughtful design and maintenance that bridges are generally in acceptable condition when they become functionally obsolete. The following subsections summarize best practices on these topics.

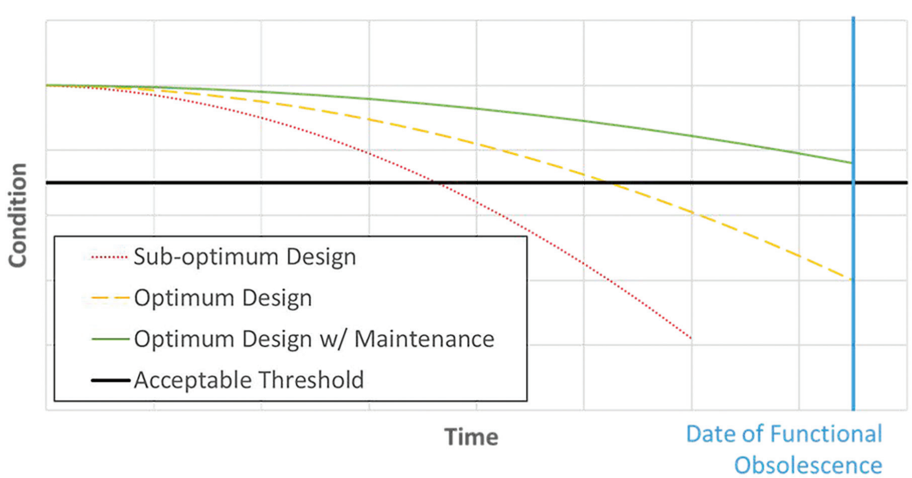


*Fig. 9. Theoretical condition versus time relationship in various scenarios.*

## Design Considerations: Where to Design Using UWS

In considering corrosion as a limit state or when adopting service life design, choosing an appropriate corrosion protection system for the given environment is a critical design consideration. Using UWS as an example because extensive research has been done on whether UWS is an appropriate corrosion protection system for numerous environments, guidelines for the environments in which to use or not use UWS are available. Such guidelines originated with a 1989 technical advisory on the use of UWS from FHWA. Later, FHWA sponsored research to update these guidelines (McConnell et al., 2024), which was summarized in the previous section. This and other research, as well as practical experiences, were used to develop updated guidelines on the use of UWS in different environments (AISC, 2022). A conceptual representation of these guidelines is shown by Figure 10. In this flowchart, the macro-environment is first classified as being either high time of wetness, coastal, or none of the above. The definitions of high time of wetness and coastal were quantified in the previous section. Then, the micro-environment is also evaluated for its potential to increase the chloride concentration or humidity (i.e., exposure to water) relative to the macro-environment. Specific examples of this are waterway crossings in coastal environments, the quantification of a heavy deicing micro-environment that was given in the previous section, low-water crossings susceptible to submersion of the UWS members, and sites with dense vegetation that shelters even the exterior UWS members from sunlight for the majority of the day.

If both the macro-environment and the micro-environment increase the humidity or chlorides, then UWS would not be recommended; instead, a more durable corrosion protection system would be recommended. For example, a paint system could be used, either at the onset or anticipated as future need. While paints may not necessarily perform better than UWS, repainting when paint deteriorates is a relatively common and convenient practice to readily provide continued corrosion protection and an acceptable structural condition with respect to corrosion. If neither the macro-environment nor micro-environment are severe relative to the preceding definitions, then UWS would be the ideal material choice from the perspectives of least first-cost, least life-cycle cost, and proven corrosion performance.

The intermediate recommendation in Figure 10 of "use UWS thoughtfully" results when only the macro-environment or the micro-environment results in increased humidity or chlorides. In these situations, some diminished performance of UWS is likely. However, because of the severity of these environments, it cannot be assured that most other materials or corrosion protection systems would perform ideally either. Therefore, designers and owners may opt for an alternative corrosion protection system or, because of a greater understanding of the behavior of UWS resulting from the extensive long-term studies on this material, use UWS thoughtfully. One example of thoughtful use of UWS is including a sacrificial thickness as a corrosion allowance. Given the data previously shown in Figure 5, a ⅛ in. sacrificial thickness to bottom flanges is a recommended value for most situations because this envelops the expected corrosion losses and results in typical plate thicknesses. Another example of thoughtful use is creating a maintenance plan. While maintenance of all bridges

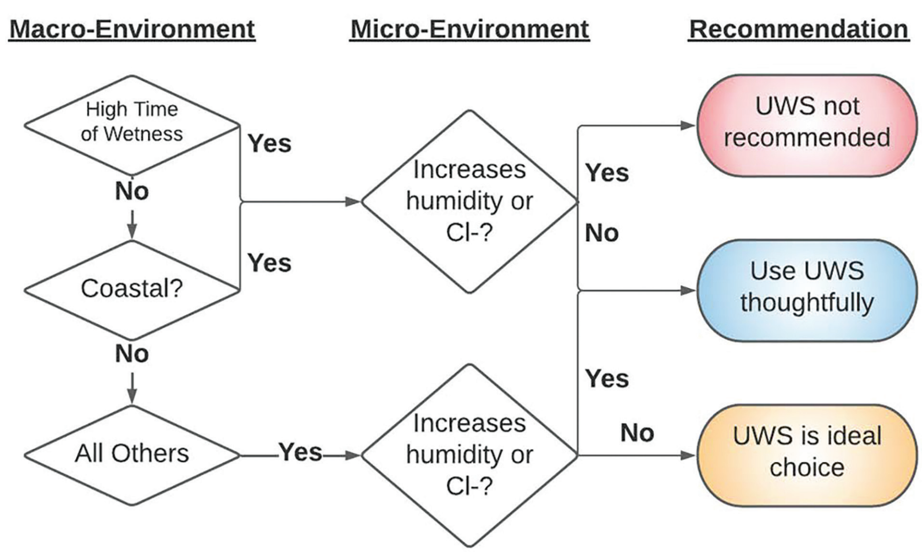


*Fig. 10. General concept for UWS use based on macro- and micro-environment (AISC, 2022).*

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 minimizes deferred maintenance problems and improves bridge performance. Maintenance considerations that may be included in maintenance plans or generally considered for extending the service lives of existing bridges are further discussed in the following section. Both sacrificial thicknesses and maintenance plans are further discussed in AISC (2022).

### Maintenance Considerations

Maintenance considerations can either be preprogrammed in a maintenance plan at the time of original design, implemented into a maintenance plan that is developed during the service life of a bridge, or implemented individually or in combination as the need arises. The most effective maintenance considerations for steel bridges, and possibly other bridge types, include consideration of the drainage of the runoff (that is often salt-laden in winter months) from the bridge deck and other surfaces where water may collect. The overarching concept of these considerations is preventing this runoff from reaching the structural components of the structure, through well-designed and well-maintained drainage systems. Best practices for initial design of drainage systems are readily available in FHWA (1989) and AISC (2022) guidelines. While the implementation of these design practices is widespread, maintaining these drainage systems is not. In particular, leaking bridge joints are a frequent occurrence, which leads to widespread deterioration of structural members beneath these leaking joints. Therefore, it is strongly recommended that these joints be repaired or replaced before they deteriorate or as soon as possible thereafter. Lifespans on typical joint lifespans compiled by Milner and Shenton (2014) are also summarized by AISC (2022), which can be used for maintenance planning purposes. Ideally, joint maintenance should be programmed at internals not to exceed the anticipated life span of the joint.

Alternatively, to prevent leaking joints and the associated structural deterioration, the ideal scenario is to eliminate joints wherever possible. A common means of doing this is by using integral or semi-integral abutments. Additional information on jointless bridges and the practical constraints thereof is summarized by AISC (2022). A newer strategy that achieves the same effect from a drainage standpoint without complicating the structural design is to place the expansion joint beyond the back wall with a drainpipe or trough that collects the runoff and discharges it away from the superstructure. For example, this is a widespread strategy used by the Virginia Department of Transportation, which has a standard detail for this known as a Virginia Abutment (Figure 11) and has been retrofitting numerous bridges throughout their jurisdiction with this design detail.

Another aspect of a maintenance plan or other periodic maintenance is bridge washing and cleaning. The clear benefits of these practices for UWS bridges are documented by McConnell et al. (2024), where statistical analyses revealed that for highway crossings specifically, bridge washing was the second most highly correlated variable with bridge performance (as quantified by superstructure condition ratings), second only to age of the structure. Best practices for bridge washing are outlined by AASHTO (2023) and recommended frequencies for washing various bridge components are given by AISC (2022).

Lastly, a final aspect of a maintenance plan or other periodic maintenance can include maintenance painting. This is an essential item for bridges that are initially painted. For uncoated steels used in environments where thoughtful use

*Fig. 11. Virginia Abutment (Hoppe et al., 2016).*

of UWS is recommended based on the guidelines described in the previous section, maintenance painting after decades of service should be anticipated as a potential need. If UWS fails to perform in an acceptable manner in a given situation, AISC (2022) give 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.

## CONCLUSIONS

The content of this paper reviews information that can be used to advance considerations of corrosion, which are presently relatively subjective and qualitative, to a more scientifically grounded and data-driven design process. The ultimate vision is to implement the concept of a limit state [which is ubiquitously used for providing sufficient resistance to physical stresses (Eq. 1)] to designing for corrosion, through limit state equations comparing predicted corrosion resistance to the anticipated corrosive effect of the environment (Eq. 2). In terms of predicted corrosion resistance, two categories of information have resulted from the recent research summarized herein. One of these was binary categories of good and inferior corrosion resistance of UWS based on the environment in which it was located. This detailed analysis of UWS is an important focus because of it being the minimum life-cycle cost option in environments where it performs well. The other category of information related to corrosion resistance was relative rankings of the corrosion resistance of other corrosion protection systems. The datasets used to form both of these conclusions were based on long-term, in-situ field performance of real structures, using large national datasets. Ongoing laboratory research will supplement these findings by providing quantitative assessments for different corrosion protection systems in identical environments, which is not possible to do the field.

With respect to quantifying the corrosive effects of environments, the environments of greatest concern to owners have been quantified for UWS but have not been quantified for other materials or corrosion protection systems beyond the relatively coarse considerations shown in Figure 4. One of these is coastal environments. The coastal environments of concern for UWS are limited to the micro-environment of waterway crossings existing in the macro-environments mapped in Figure 7, which are quantitatively described by Table 2. A second environment of concern is highway overpasses in environments where deicing agents are heavily used. The heavy deicing environment for highway overpasses is governed by micro-environment effects (rendering a map an unsuitable descriptor) that are described by Table 3. These conclusions can be thought of as indirect means of summing a set of environmental variables to begin framing corrosion as a limit state. This same approach could be readily applied to gain a similar level of understanding for other corrosion protection systems and/or materials, which would be highly valuable future research. Such analyses should also consider alternative degradation mechanisms for the corrosion protection system or material under evaluation. While corrosion of steel is governed by the "elements" comprising water and chloride, it should be considered that other corrosion protection systems and materials are vulnerable to effects such as those caused by ultraviolet radiation, freeze-thaw cycles, etc.

Lastly, unlike most other limit states where initial design considerations can be relied upon to achieve the limit state, corrosion limit states can be most effectively met through initial design considerations coupled with maintenance practices. This includes practices that increase corrosion resistance and/or decrease the severity of the environment. To achieve appropriate corrosion resistance when the environment is not exceptionally corrosive, the least-cost option of UWS is recommended. However, when the corrosivity of the environment is high, the corrosion resistance can be increased by choosing alternative corrosion protection systems. Alternatively, designers can also decrease the severity of the environment in various ways, with the most impactful option being, in general, detailing the nano-environment (during the initial design) to limit exposure to water and performing periodic inspections and maintenance as needed to maintain adequate protection from and drainage of water. This is true for both bridges and the exposed elements of buildings. Furthermore, during the service life of highway bridges, data demonstrates there is significant benefit to decreasing the severity of the environment through maintenance actions such as joint maintenance and bridge washing. Thoughtful combinations of these strategies allow structures to reach or exceed their targeted lifespans for minimal cost.

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