CORROSION PREVENTION FOR EXTENDING STEEL BRIDGE SERVICE LIFE

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BIOGRAPHY

Mr. Ault is currently President of Elzly Technology Corporation. Mr. Ault has over 30 years of experience working with a wide variety of corrosion control technologies. His expertise centers on the evaluation, testing, demonstration, and implementation of new technologies. During his career, Mr. Ault has worked with all manner of concrete and steel infrastructure including bridges, piping, buildings, military equipment, offshore platforms and petrochemical plants.

Mr. Ault is actively involved with bridge industry organizations (AASHTO, TRB, and NTPEP) as well as coatings and corrosion standards organizations (SSPC, ASTM, and NACE). He is a member of TRB Standing Committee on Structures Maintenance (AHD30) and chairs the Bridge Steel Coatings Subcommittee (AHD30(2)). He currently chairs an SSPC technical committee and has participated in several interlaboratory studies to establish precision and bias statements for ASTM coatings standards.

SUMMARY

Corrosion is one of the most often-cited problems with steel bridges. To varying degrees, it affects both the appearance and structural integrity of a bridge.

According to the 2015 National Bridge Inventory there are over 180,000 steel bridge structures in the United States, which is nearly 30% of the bridge inventory. A 2001 FHWA study identified the annual direct cost of corrosion for highway bridges in the United States to be \$6.43 to \$10.15 billion.

This paper presents a broad review of practices to extend steel bridge service life by protecting them from corrosion during design and maintenance. The paper will cover standard practices and recent innovations in corrosion control during design and maintenance of both coated and uncoated steel bridges.

This paper is based on NCHRP Synthesis 517, *Corrosion Prevention for Extending the Service Life of Steel Bridges*. The complete report is available at http://nap.edu/25195.

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Keywords

Corrosion, Coatings, Steel Bridges, Weathering Steel, Stainless Steel, Metallizing, Galvanizing, Duplex Coatings

Abstract

To optimize steel bridge structure design, industry offers various options for corrosion control of steel bridges which offer varying combinations of durability, cost, aesthetics, service life, and other characteristics. The technical literature generally addresses "coated steels" and "uncoated steels" separately, and coated steel bridges can be further divided between liquid coatings and metallic coatings (e.g., galvanizing, metallizing).

The current state of the practice for steel bridge design is to use either weathering steel or steel with a three-coat, zinc-based coating system. Weathering steel has some environmental limitations; there are federal and state guidelines to help designers identify unsuitable locations. For either material, the structure should be designed to minimize locations where corrosion is more likely to initiate. For example, geometries should not be designed that will trap water or debris, joints should be minimized, and water should drain away from the steel.

Innovative approaches to provide better corrosion prevention include A1010 and UNS 32205 structural stainless steels and high-durability coatings, such as galvanizing, metallizing, or duplex coatings. Stainless steel bridges are relatively new, whereas the advanced coatings have been around for decades. These more robust corrosion-prevention technologies are more expensive than the current state of the practice. However, LCC analysis shows that these materials can be attractive for structures in severe environments, with long life expectancies, or with limited access for future maintenance.

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Introduction

According to the 2015 National Bridge Inventory there are over 180,000 steel bridge structures in the United States – nearly 30% of the bridge inventory. Corrosion is one of the most often-cited problems with steel bridges. A 2001 FHWA study identified the annual direct cost of corrosion for highway bridges in the United States to be \$6.43 to \$10.15 billion (FHWA 2001). That cost includes \$3.79 billion per year to replace structurally deficient steel bridges and \$0.50 billion per year for the maintenance painting of steel bridges. Several studies have shown that the indirect user costs (e.g., traffic delays and lost productivity) are an order of magnitude higher than the direct maintenance costs.

To varying degrees, it affects both the appearance and structural integrity of a bridge. In some instances, the appearance of a corroded bridge may not be an issue, but in others, it can cause significant public concern. Similarly, the structural effects of corrosion can range from limited weakening of a structure to sudden bridge collapse depending on a variety of details. A 1990 report provides guidelines for evaluating the structural effects of corrosion in steel bridges (Kulicki 1990). Maintainers consider corrosion to be a more significant limiting factor for steel bridge service life than designers. Designers are less likely than maintainers to feel corrosion is the limiting factor for design service life of steel bridges (Figure 1).

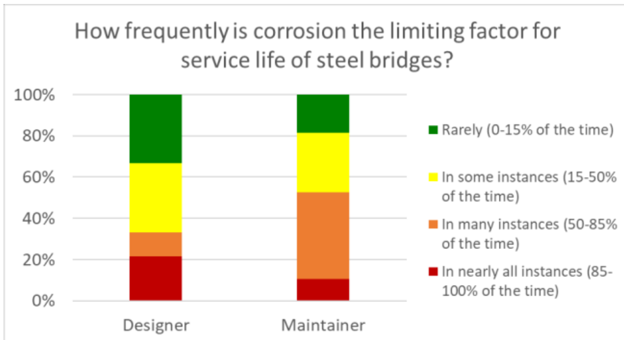

Figure 1. Survey results regarding corrosion as a life limiting factor for steel bridges.[1]

Until the late 1970's, most steel bridges were protected from corrosion by applying three coats of a lead or chromate-based coating system directly over the mill scale that had formed on the steel. Additional coats of the same paint were applied as necessary when corrosion had progressed to an unacceptable level. As the direct and indirect costs of painting increased, the industry looked to alternative corrosion control practices. These alternatives primarily fell into two categories – corrosion resistant steels for uncoated use and cost-effective coating systems for structural steel.

Although there has been much research performed to develop corrosion-resistant steels and cost-effective coatings, it has generally been done in a somewhat isolated and uncoordinated fashion. Furthermore, the considerations for corrosion control vary based on geography; the optimum approach will likely be different in areas of significant deicing salt usage, coastal areas, or the arid regions of the southwestern United States. Some states encounter more than one of these situations, potentially complicating their approach to corrosion control.

The National Cooperative Highway Research Program (NCHRP) Synthesis Topic 48-03 gathered information on practices to extend steel bridge service life by protecting such bridges from corrosion.[1] A synthesis of current practices and existing knowledge on this problem provides a better understanding of how to help combat the problem and extend the service life of aging and newly designed steel bridges. The primary approaches for gathering information were through a literature review and a survey of transportation agencies. Forty-six states and three agencies responded to the survey. This paper is excerpted from the NCHRP Synthesis.

Corrosion Prevention and Control Strategies

When considering corrosion prevention options for bridge structural steel, it is helpful to recognize the corrosion prevention mechanism, degradation of that protection, and eventual repair or maintenance needs. Table 1 provides an overview of six primary corrosion prevention strategies.

Figure 2 shows weighted average frequency of corrosion protection technology use based on the survey results. The data show that zinc-based coating systems and weathering steel are the most common corrosion prevention schemes used by state DOT's. The data suggest that roughly 10% of all steel bridges are designed with some galvanized or metallized structural steel, perhaps limited to secondary members or sections.

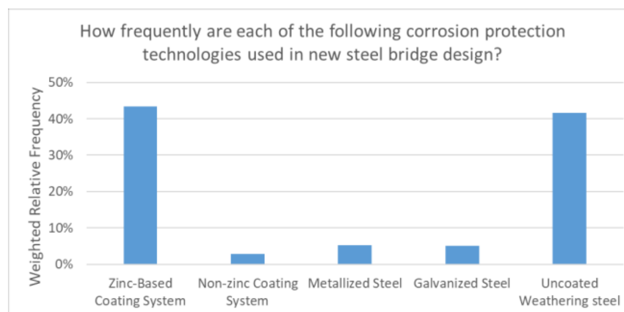

Figure 2. Relative popularity of steel bridge corrosion protection technologies.[1]

Coated Steel

The industry has developed improved coating systems for corrosion control of structural steel. Currently, the most common coating system for new construction and existing coating replacement is a 3-coat system with a zinc-based primer applied over abrasive blasted steel.

Approximately two thirds of the states use the AASHTO National Transportation Product Evaluation Program (NTPEP) program to inform their structural steel coating selection. NTPEP was established to minimize the amount of duplicative testing of transportation materials performed by state

Table 1 - Representative corrosion prevention methods for steel bridges.

		Protection Mechanism	**Functional Mode of Degradation**	**Repair Methods**
Coated Steel	*Painted Steel*	Protective film isolates steel from corrosive elements	Protective coating is breached, typically due to mechanical damage, weaknesses in the applied film (e.g., thin edges), or extreme environmental issues such as UV exposure or mold growth	Maintenance Painting or Coating Removal and Replacement
	Galvanized Steel	Metallurgically bonded zinc protects steel though barrier and sacrificial mechanisms	Galvanizing corrodes, reducing the zinc thickness and eventually allows the steel to corrode	
	Metallized Steel	Sprayed metal coating (zinc, aluminum, or alloys thereof) mechanically bonds to and protects steel through barrier and sacrificial mechanism	Metallizing corrodes or undercuts at weaknesses in the applied film (e.g, blind spots, edges) and eventually allows the steel to corrode	
	Duplex Coating	Organic (liquid) coating applied over metallic coating (metallizing or galvanizing)	Protective organic coating breaks down, exposing the metallic coating which subsequently breaks down as described above	
Uncoated Steel	*Weathering Steel*	Forms corrosion "patina" which reduces steel corrosion rate to a tolerable level	Corrosion patina becomes damaged or disrupted due to local exposure conditions or mechanical damage	Applying a protective coating and/or replacing steel
	Stainless Steel	Form passive chromium-rich oxide film; stability depends on the alloy composition, surface treatments and environment	Lower alloyed stainless steels may rust while higher alloyed stainless steels will tend to pit	Applying a protective coating and/or replacing steel

laboratories. The NTPEP Structural Steel Coatings (SSC) SCC program evaluates protective coating systems intended for use on new and existing structural steel prepared by abrasive blast cleaning.

There are several details to this generic system that vary by state and application. Figure 3 shows the frequency by which various states reported designing steel bridges with a zinc-based coating system. Several states favor coated steel bridges but there doesn't appear to be an obvious trend (e.g., geographic) for this preference. It is most likely based on historical evolution of preferences within each state.

Several states are working to improve the value proposition of coated steel bridges by using different coating systems. Figure 4 shows surveyed states which indicated that they are using coating systems other than zinc-based. With a few exceptions, these states tend to be concentrated in the northeast US. The coating systems include metallizing, galvanizing, and non-zinc-based coating systems. The most common innovative practice reported by bridge designers was the use of metallizing or galvanizing. Florida reported a great interest in coatings with improved gloss and color retention.

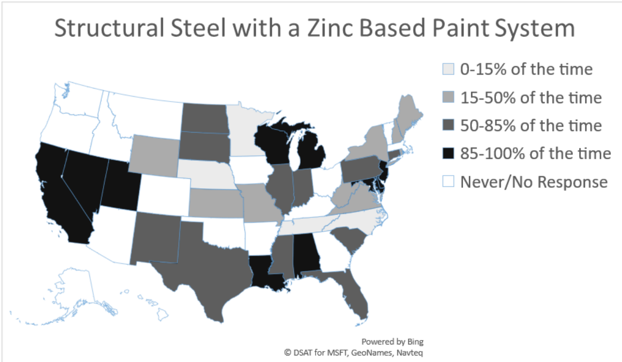

Figure 3. Use of 3-coat, zinc-based coating system for steel bridge corrosion protection.[1]

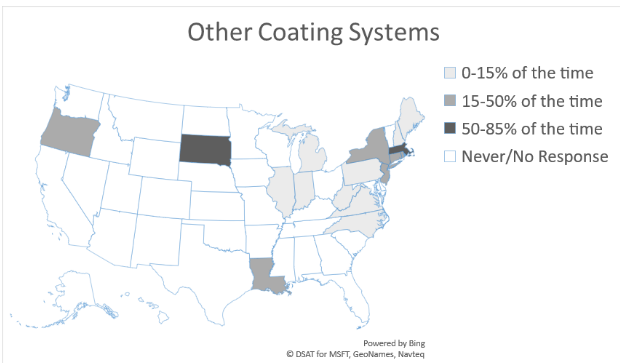

Figure 4. Use of other coating schemes for steel bridge corrosion protection.[1]

While efforts are on-going to improve on the value proposition of traditional paint systems, another approach is to use hot dip galvanized or metallized with a traditional finish coat to provide long-term protection against corrosion. The combination of a metallic coating and a traditional finish coat is often referred to as a "duplex coating." The synergetic life of duplex coatings may be 1.5 to 2.3 times the sum of the individual lives – this means that they may result in service lives in excess of 75 years.[2] Unfortunately, bridge owners have had mixed experience with duplex coatings (including the galvanizing and metalizing process and/or finish coat application). Some DOTs have had success with the approach while others have had issues with galvanizing and metalizing quality, experienced adhesion problems with the finish coating, or have had to perform maintenance painting of the duplex system sooner than anticipated.

For major maintenance of steel bridges, states often will completely remove and replace aged coatings with a 3-coat, zinc-based system. Most states also employ overcoating, spot painting, and/or zone painting strategies for maintaining existing coating systems. The risks and benefits of these strategies vary depending on the specific circumstance and is thus the subject of much discussion.

Corrosion Resistant Steels

As an alternative to protective coatings, the steel industry has developed corrosion resistant steels for uncoated use in bridges and other highway structures. Uncoated steels in current use for bridges include weathering steel grades (ASTM A588, ASTM A709), martensitic stainless steel (ASTM A1010), and lean duplex stainless steel (UNS32205). Uncoated steel bridge designs are considered cost-effective since the maintenance/ replacement of coatings should be eliminated. While it is theoretically possible to build bridges out of other corrosion-resistant steels, other alloys have not yet been accepted as cost effective options.

Weathering Steel

Corrosion resistant steels ("weathering steels") were developed for uncoated use in bridges and other highway structures. The first significant use of uncoated weathering steel on highway bridges in the United States was in the mid-1960's when weathering steel was used in New Jersey and Michigan. Under the right conditions, weathering steel will form a protective oxide (sometimes called a patina) that slows corrosion sufficiently to eliminate the need for painting.

In the 1980's and 1990's there were several research projects investigating weathering steel performance based on perceived problems and agency reservations. This research led to design guidance such as detailing to prevent water accumulation and painting portions of weathering steel structures in zones where the patina may not properly form (e.g., adjacent to expansion joints). Estimates of the current proportion of new steel bridges designed with weathering steel outnumber the proportion of existing weathering steel bridges by a factor of 4, suggesting that many states are becoming comfortable with the material. Figure 5 shows surveyed states which indicated that they are designing bridges with weathering steel for corrosion control.

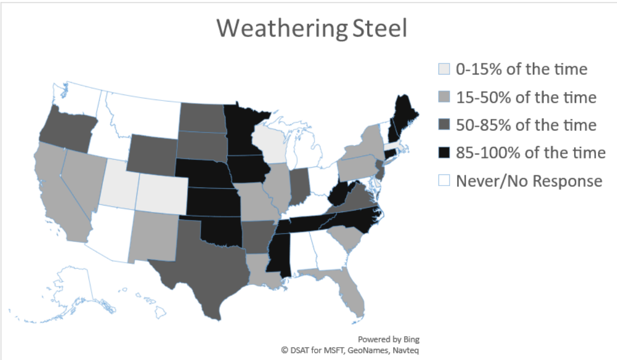

Figure 5. Use of uncoated weathering steel bridge designs.[1]

Stainless Steel

Stainless steel refers to a family of ferrous alloys containing a minimum of 10.5% chromium. Alloys containing this minimum amount of chromium tend to form a passive chromium-rich oxide in oxidizing environments. This passive film provides the stainless steel class of alloys their characteristic high resistance to corrosion. The stability of the oxide layer depends on the alloy composition, surface treatment, and environment. Stability increases with increasing chromium, molybdenum, and nitrogen contents.

Recently, there have been efforts to fabricate plate girder bridges from highly corrosion resistant steels (e.g., ASTM A1010, UNS32205, UNS32316). These alloys exhibit corrosion resistance in environments where weathering steels are susceptible to corrosion such as high time-of-wetness or high levels of chlorides. Ideally, any increased material cost would be offset by the savings associated with longer service life, simpler detailing, or by eliminating the need to paint certain areas (i.e., zone painting).

ASTM A1010 describes a dual phase martensitic stainless steel.[3] This steel is intended to meet the structural performance requirements of grades 50W and/or 70W of ASTM A709 while providing sufficient corrosion resistance for application in uncoated structures in high time of wetness or chloride exposure environments which are too corrosive for weathering steel alloys. In 2004, the Fairview Road Bridge over the Glen-Colusa Canal in Colusa, California was constructed of ASTM A1010 grade 50 steel. The first ASTM A1010 steel plate girder bridge, the Dodge Creek Bridge, was constructed in Oregon in 2012 and another bridge, the Mill Creek Bridge, shortly followed in 2013. To date, bridges have been constructed of ASTM A1010 in Oregon, Iowa, Virginia, and California.

Duplex stainless steels have a mixed microstructure of austenite and ferrite, which is achieved through an appropriate combination of chemical composition and heat treatment. This microstructure gives the duplex stainless steel alloys similar or superior corrosion resistance to austenitic stainless alloys with greater strength than UNS S31600. Duplex stainless steels have been used in bridge structures for a wide range of applications. Several bridges constructed between the years 2000 and 2012 contained duplex stainless steel structural elements.[4,5] Duplex stainless steel is attractive for bridge applications for several reasons, including:

- the bridge can have high profile or high architectural content,
- complex fabrications may have high fabrication and construction cost, which can be offset by the longer lifetimes attainable with duplex stainless steel
- the duplex stainless steel offers a desirable architectural appearance, and
- the duplex stainless steels provide long term corrosion resistance, which leads to reduced maintenance.

Designing for Corrosion Prevention and Control

Of the states responding to the design section of the survey, a slight majority address corrosion differently based on environmental or operating conditions. States with written guidelines include Florida, New York and Missouri. Issues that are typically considered include: average daily traffic, difficulty of access, climatic conditions (humidity), use of deicing salts, proximity to the coast, height above water, “tunnel-like” conditions, ownership (state vs local), and importance of road (e.g., evacuation route). The following specific design guidance for corrosion was reported:

- Galvanize or metallize hard to access structures (e.g., over high ADT road)

- Environment may dictate the selected option (including whether or not deicing salts are used)
- Ownership – higher corrosion prevention used for state vs local bridges
- Weathering steel is used/coated in accordance with FHWA guidelines
- Established zones within the state (e.g., one state had 4 zones – Mild rural/industrial; severe industrial, mild marine, severe marine)

Four respondents (Kansas, New York State, Connecticut, and Maryland) reported using specific corrosion allowances in new bridge design for weathering steel structures; one of those respondents (Maryland) indicated they also use corrosion allowances for painted steel structures. Examples of corrosion allowances included adding 1/16-inch to the webs of exterior girders where drainage is allowed over the edge, 1/8-inch additional thickness on weathering steel structures, and "increasing flange thickness." A 1/16-inch corrosion allowance would accommodate a corrosion rate of slightly less than 0.001-inch per year (1 mil per year) for a 75-year service life.

Of the designers responding to the survey, 40% indicated that life cycle cost considerations are formally considered either qualitatively or quantitatively during the design stage. Nebraska reported using a tool developed by the FHWA called RealCost. Based on this analysis, alternatives with significantly (e.g., 15%) lower life cycle cost are preferred; if all options have comparable life cycle costs then the least initial cost is selected. Generally, if an analysis shows that a strategy is cost effective in one situation then it is presumed to be cost effective in similar situations.

Most of the states did not require corrosion maintenance procedures as part of the design, though one state (Rhode Island) did require designers to provide recommended corrosion maintenance procedures for coated steel structures.

Corrosion Control Maintenance

Corrosion control maintenance primarily involves cleaning and painting bridges. The decision to perform maintenance is most commonly a condition-based decision. For both painted and unpainted steel bridges, users identifying as maintainers reported that inspection recommendations and coating condition code most commonly drive corrosion maintenance. The survey suggests that routine inspections are generally adequate for identifying corrosion maintenance needs on both coated and uncoated steel structures. Seventeen percent of respondents reported that they use supplemental inspections for uncoated steel structures and 11% reported that they use supplemental inspections for coated steel structures. In some cases, the supplemental inspections were used to populate a condition database separate from the NBI database. In other cases, the supplemental inspections were to more thoroughly define maintenance needs for planning and execution.

The most common reported research need by designers included issues related to maintenance decision-making (when to replace coating system, how to cost-effectively maintain, how much corrosion can be tolerated when aesthetics are not a concern). A better understanding of the effects of deicing salts and the need for less corrosive deicing materials was also a reported research need.

Figure 6 shows the various ways that agencies determine budget needs for corrosion maintenance. Most users reported that corrosion maintenance competes with other bridge maintenance needs for funding. "Other" responses include:

- A corrosion control budget is established for in-house paint crew projects. For bridge painting by contract forces, steel bridge corrosion maintenance competes with other bridge maintenance needs
- A yearly defined amount of paining money is allocated.
- Included with other bridge preservation activities
- Preventative maintenance is only budgeted for major bridges

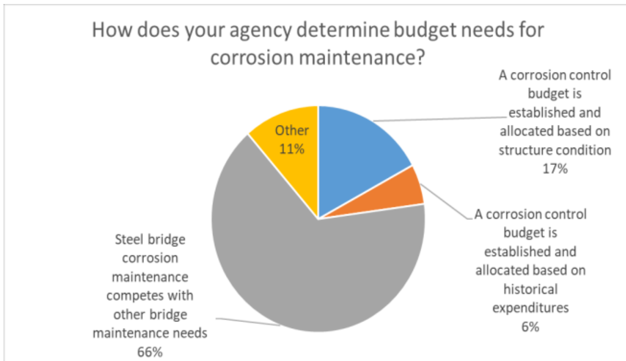

Figure 6. Survey responses regarding budgeting for corrosion maintenance.[1]

Conclusions

Based on the results of this synthesis, several areas of research needs have been identified which could help reduce the cost of steel bridge corrosion. They can be categorized in the following broad categories:

- Optimize current corrosion prevention schemes (e.g., improve weathering steels, improve coating processes). This may include developing standard specifications, design details to reduce corrosion, performing field studies to document the real-world performance of current technologies, and incremental improvements to current practices.
- Develop and demonstrate state-of-the-art approaches to corrosion prevention. These approaches include metallic coatings, duplex coatings, high-durability finish coats, improved corrosion resistant steels, and stainless steels. Research projects would generate specifications and standards, training programs, case studies, etc.
- Improve methodologies for service life design and prediction based on environmental conditions at the location of the structure. This would include projects to move corrosion prevention design from "deemed to satisfy" approaches toward partial probabilistic approaches.
- Improve methodologies for life-cycle planning, risk management, and financial planning for preservation of corrosion prevention systems. These methodologies would help owners justify preservation needs, allow them to demonstrate the value of executing preservation activities, and help them optimize their preservation practices.

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