ACCELERATED CORROSION TESTING OF ASTM A1010 STAINLESS STEEL

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BIOGRAPHY

Isaac Groshek is a Structural Engineer with the Middleton, WI Office of AECOM. His current work involves the design of steel and prestressed concrete girder highway bridges, retaining walls, and sign structures. Prior to working at AECOM, Isaac received a bachelor's in civil engineering from the University of Wisconsin-Madison and a master's degree in civil engineering from Virginia Tech. His graduate research focused on the corrosion behavior of stainless steels with applications in the bridge industry.

Matthew is an assistant professor in the Charles E. Via, Jr. Department of Civil & Environmental Engineering at Virginia Tech. He received his doctorate in Civil Engineering in 2015 from Purdue University. Prior to this he worked as a design engineer at Sargent Engineers, Inc. from 2005 until 2010. He earned both a master's and a bachelor's degree in civil and environmental engineering from Utah State University. His research experience includes redundant behavior of steel bridges, fatigue and fracture evaluation of steel structures, bridge monitoring and testing, historical fabrication methods and materials, and large scale testing of structures. He is a member of the TRB AFH70 - Fabrication and Inspection of Metal Structures committee, and the AREMA Committee 15 – Steel Structures.

SUMMARY

ASTM A1010 (recently adopted as ASTM A709 Gr50CR) is a material which has advantageous corrosion properties. It is a low-grade stainless steel which forms a protective patina and has been marketed as an alternative to other bridge steels and corrosion protection methods due to its corrosion resistance in highly corrosive environments. However, the material is currently available in plate form only, and several of the applications in the United States were required to use alternative materials when constructing and connecting secondary members to the A1010 plate girders.

This paper addresses the corrosion behavior of A1010 in several different details relating to recent applications in the US. An accelerated corrosion study was performed which simulated a highly corrosive environment typical of the environment justifying the use of A1010. The research investigated the resulting galvanic corrosion and its effect on the corrosion rate of A1010 plates, several different common bridge steels, and typical fastener materials. In addition, common surface preparation methods were evaluated for their aesthetic effect during patina formation.

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Introduction

The steel bridge industry has been combating the issue of corrosion ever since the first use of structural steel in bridges in the 19th century. Early efforts to reduce the magnitude of corrosion focused on the application of protective coatings, such as paint systems, to the steel surface. The durability of these systems varied widely based on the corrosivity of the environment and the breakdown of the systems in corrosive environments.

Later efforts focused on improving the corrosion resistance of uncoated structural steel; in the 1970s, weathering steel was introduced with hopes of providing a material that could resist corrosion without requiring a coating and subsequent maintenance. While weathering steel performed well in many applications, high corrosion rates in highly-corrosive environments, such as locations with high exposure to deicing chemicals and marine environments, has resulted in recommendations to avoid these types of environments (1)(2). Similar recommendations apply to hot-dip galvanizing and thermal-spray metalizing. While these systems have proven to provide corrosion protection in low to mildly-corrosive environments, coating breakdown may occur in less than 40 years in highly corrosive environments, and these coatings provide challenges for in-situ repairs (1). As such, a cost-efficient structural material which requires little to no maintenance over its service life in corrosive environments has wide potential in the steel bridge industry.

In recent decades, a new stainless steel option, under the ASTM A1010 specification, has been introduced for use in primary bridge members. Originally developed as a lower-cost alternative to higher chromium-content stainless steels, A1010 stainless steel has been estimated to exhibit corrosion resistance approximately 4 to 10 times that of weathering steels (3).

A1010, similar to all other stainless steels, provides corrosion resistance through the natural formation of a protective chromium oxide surface layer in the presence of oxygen. Testing of A1010 has proven its ability to satisfy the mechanical requirements of ASTM A709 GR50 steel, and as such, A1010 has been used for primary members on six bridges within the United States (3). Recently, A1010 has been added to the ASTM A709 specification as ASTM A709 GR50CR. In specific bridge applications, three characteristics of the corrosion behavior remained relatively unknown:

1. **Galvanic corrosion.** When dissimilar metals share an electrical connection and are connected through an electrolyte medium, accelerated corrosion of the more reactive metal will occur. Also known as bimetallic corrosion (4).
2. **Crevice corrosion**. When crevice-like conditions occur on the surface of a stainless steel such that a corrosive substance may infiltrate and reside, the resulting acidity of the trapped solution and lack of oxygen often results in accelerated rates of corrosion (5).
3. **Effect of surface preparation.** After fabrication, steel bridge members commonly receive blasting or grinding on their surface for aesthetic purposes and/or to prepare for painting. This process ultimately changes the surface profile of the steel and may affect the corrosion behavior of the steel.

Given that no structural bolts or shear connectors closely match the chemical composition specified in ASTM A1010, any realistic use of A1010 with bolted connections in primary bridge members will result in a bimetallic connection. Additionally, hybrid girders, which use A1010 plate members only in the most vulnerable locations while combining them with traditional structural steel components, have been considered. The magnitude of galvanic corrosion and the effect on both metals in the connection is of interest. The rate of galvanic corrosion in such detailing may also be dependent upon the surface area ratio of the anode (more reactive metal) to cathode (less reactive metal, likely A1010) within the electrolyte facilitating the reaction (4).

While the corrosion resistance of A1010 has been found to significantly exceed that of weathering steel for isolated corrosion specimens, it is hypothesized that this resistance may be notably decreased with A1010 use in connections containing crevice-like details. The lack of oxygen in these microenvironments stifles the ability of stainless steels to adequately form a chromium oxide passive surface layer. Common details in steel bridge girders, such as bolted field splice connections, create opportunities for such conditions to occur, and are of interest for applications with A1010.

Abrasive blasting of steel bridge members has been widely automated with the use of wheel abrasive blasting machines which can accommodate full-size plate girders in a single pass. The most common blasting media is rounded steel shot which is more easily recollected and creates less damage on the blasting chamber compared to jagged grit blasting media such as Aluminum Oxide or Garnett. For the majority of structural stainless steels, the use of carbon steels in cleaning procedures is avoided to prohibit excess loose iron from being transferred to the stainless steel and consequent corrosion products to form on the surface. The type of abrasive media used in blasting may have a notable effect on the surface profile of A1010 and the resulting corrosion behavior.

Experimental Setup

Corrosion research has been traditionally conducted by three methods: 1) investigation of historical data on bridge corrosion performance, 2) in-situ corrosion testing of specimens, and 3) accelerated corrosion testing of specimens. Due to time constraints and lack of historical corrosion data for ASTM A1010 stainless steel, the research team selected the third option, accelerated corrosion testing. The objective was to implement an accelerated procedure which would produce corrosion behavior representative of previously performed in-situ testing and one which is already generally accepted within the bridge industry.

While several different procedures exist, the modified SAE J2334 Surface Vehicle Standard was chosen (6). This procedure had been implemented in two independent FHWA corrosion studies and was found to be useful for comparing corrosion behavior of specimens in identical cyclical testing environments (3)(7).

The modified SAE J2334 procedure consists of a repeated 3-stage cycle: 1) humid stage at 50°C and 100% relative humidity (RH) for 6.00 hours, 2) salt application stage with full immersion in salt solution at ambient temperatures for 0.25 hours, and 3) dry stage at 60°C and 50% relative humidity (RH) for 17.75 hours (3)(6)(8). The humid and dry stage environments were created through the use of an automated environmental chamber, while the salt application stage was implemented by manually placing the specimens in soaking tubs filled with the solution. The salt solution was modified from the original SAE J2334 specification to have 5.0 percentage weight of sodium chloride instead of 0.5 percentage weight, based on previous FHWA findings (3). Plastic racks and shelving were used to orient specimens during testing and facilitate movement between environmental chamber and soaking tub, as shown in Figure 1.

Figure 1: Test specimen configuration in environmental chamber and salt solution

The specimen orientation was selected to produce conditions suitable for each type of corrosion of interest. Corrosion is known to accelerate with increasing time of wetness (TOW), or exposure of the metal to the electrolyte. This was controlled by orienting the specimens at position which allowed electrolytes to remain on the specimen surface for a longer time prior to drying.

Five specimen and specimen assembly types were included in the corrosion testing. In general, the term “specimen” refers to an individual plate or fastener component (bolt, nut, or washer) while “specimen assembly” refers to a combination of plates or fasteners connected together during testing. The testing setup types were as follows:

1. **Control Plate Specimens.** Control plate specimens were included to provide baseline data and means of comparison with past corrosion

studies. The four steel types included were ASTM A1010 GR50 (A709 GR50CR), A709 GR50, A709 GR50W, and A709 GR50 with hot-dip zinc galvanized (HDG) coating per ASTM A123. Triplicates were provided for each steel type to reduce sampling error and placed in a near-vertical orientation, at 15° from vertical, typical of the SAE J2334 Standard (6). All plates were 4 in. squares with a thickness of 3/8 in. These plates are shown in Figure 2.

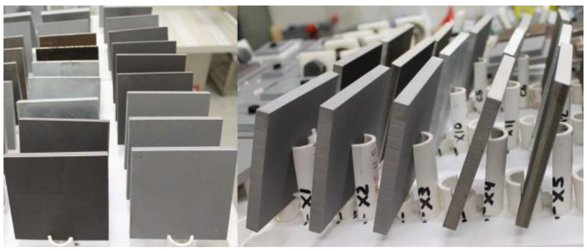

Figure 2: Control plate specimens in plastic racks prior to the initiation of testing

2. **Galvanic Corrosion Plate Assemblies.** A1010 (A709 GR50CR) base plates were directly connected to conventional structural steel top plates to investigate the galvanic corrosion behavior resulting from the bimetallic connection. Top plate steel types included the same three A709 types from the control plates: GR50, G50W, and GR50 HDG. Three different top plate sizes were used in "direct connect" specimen assemblies in an attempt to investigate the surface area of the anode to cathode involved in the galvanic corrosion reaction. Base plate sizes were 4 in. by 6 in., and top plate sizes were 1.75 in. squares, 2.50 in. squares, and 4 in. by 3 in. rectangles. All plates had thicknesses of 3/8 in.

   For each type of steel, additional specimens were included which inhibited galvanic corrosion via a nylon plate barrier between the metals. This provided a comparison between "direct connect" and "nylon barrier" specimens to estimate the magnitude of galvanic corrosion on the direct connect specimens. Specimen assemblies were placed in a near-horizontal orientation, at 85° from vertical, to provide an environment representative of a steel girder bottom flange and provide a higher TOW. Duplicates were provided for each assembly type to reduce sampling error. Galvanic corrosion plate assemblies are shown in Figure 3.

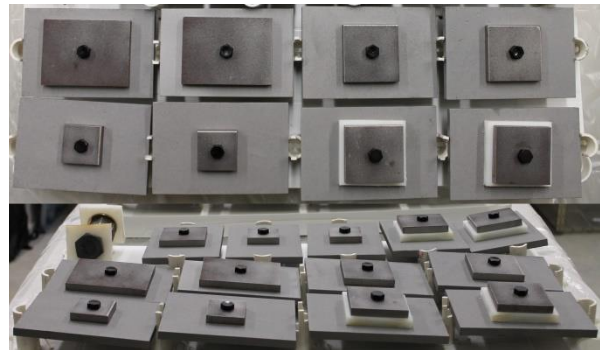

Figure 3: Galvanic corrosion plate assemblies in plastic racks prior to the initiation of testing

3. **Galvanic Corrosion Fastener Assemblies.** In a similar concept to the plate assemblies, the fastener assemblies included A1010 plates connected to conventional fastener assemblies. The fastener types were also connected to separate nylon plates to provide a comparison of assemblies allowing galvanic corrosion and those that do not allow galvanic corrosion. Six fasteners types were included from three categories: uncoated carbon and weathering steel, HDG carbon steel, and stainless steel. For a complete list, see Table 1. A1010 plates were 4 in. squares with a thickness of 3/8 in. and bolts were 3/4 in. in diameter and 2 in. long. Triplicates were provided for each assembly type to reduce sampling error. The plates were placed in a near-vertical orientation, at 15° from vertical, as shown in Figure 4.

Table 1: Fastener combinations for galvanic corrosion fastener assemblies

Bolt Type	Nut Type	Washer Type
A325 Type 1	A563 C	F436 Type 1
A325 Type 3	A563 C3	F436 Type 3
A325 Type 1 HDG	A563 DH HDG	F436 Type 1 HDG
A490 Type 1	A563 DH	F436 Type 1
A193 B8 Class2	A194 Gr8 Class2	410SS
A193 B6	A194 Gr6	410SS

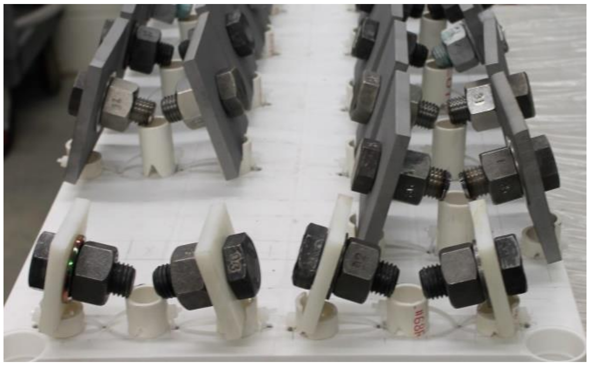

Figure 4: Galvanic corrosion fastener assemblies in plastic racks prior to the initiation of testing

4. **Crevice Corrosion Plate Assemblies.** A1010 base plates were directly connected to A1010 top plates in order to investigate the crevice corrosion behavior of A1010 stainless steel when not involved in bimetallic connections. Base plates were 4 in. squares and top plates were 3 in. squares, with both types of plates having a thickness of 3/8 in. It was hypothesized that the surface preparation which the specimens received may have a significant impact on crevice corrosion. Therefore, specimen assemblies were included in which both the top and bottom plates received aluminum oxide abrasive blasting, in addition to assemblies in which neither the top nor bottom plate received any abrasive blasting. The two types of assemblies are shown in Figure 5. Specimen assemblies were placed in a near-horizontal orientation, at 85° from vertical.

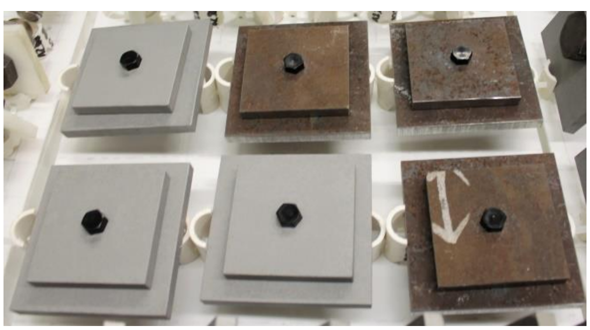

Figure 5: Crevice corrosion fastener assemblies in plastic racks prior to the initiation of testing

5. **Surface Preparation Plate Specimens.** Three different abrasive media were used in order to evaluate the effect of surface preparation on the corrosion behavior of A1010: #280 steel shot, #80 aluminum oxide grit, and #80 garnet grit. Additional control specimens received no blasting. Specimen assemblies were placed in a near-horizontal orientation, at 85° from vertical, as shown in Figure 6. Triplicates were provided for each specimen type to reduce sampling error.

Figure 6: Surface preparation plate specimens in plastic racks prior to the initiation of testing

Evaluation of the corrosion testing was primarily completed through mass loss measurements at 20 day cleaning intervals per procedures outlined in ASTM G1 (9). Equivalent thickness loss calculations were then completed based on mass loss measurements. HDG coating thickness measurements were also taken directly with a coating thickness gage throughout the duration of testing for plates and fasteners with HDG coating.

In order to investigate trends and compare data, ordinary least squares (OLS) linear regression analysis was completed for data sets, and when appropriate, comparison was made between sets using statistical hypothesis testing. When comparing data sets, caution was taken to determine whether apparent differences in trends between data sets were significant, or whether the differences could be reasonably attributed to random sampling errors. Linear regression coefficients and corresponding coefficients of determination, R^2, were calculated using the average thickness loss values of duplicate or triplicate specimens. When hypothesis testing was conducted, all data points were considered in order to properly investigate the deviation or spread of values away from the average mean values.

Experimental Results

1. **Control Plate Specimens.**

Control plates, which were in the near-vertical orientation, for each steel type were shown to exhibit linear thickness loss behavior over the full duration of testing. As a result, linear regression coefficients were calculated using the average thickness losses at the 20 day measurement intervals for each steel type. The results are shown in Table 2.

Table 2: Average thickness loss rates (linear regression coefficients) of control plate specimens.

Steel Type	Coefficient (mils/cycle)	R^2
A1010 GR50	0.021	0.990
A709 GR50	0.237	0.999
A709 GR50W	0.214	0.999
A709 GR50 HDG	0.022	0.983

For control plate specimens, the thickness loss rate of the A1010 plates was approximately 12 times less than that of the A709 GR50, 10 times less than the A709 GR50W, and similar to the A709 GR50 HDG plates.

Corrosion behavior of control specimens corresponded to whether each steel type was able to form a passive surface layer in the highly-corrosive testing environment. Thickness loss data and visual observations confirmed that all three A709 control specimen types were unable to properly form passive surface layers and experienced unstable corrosion. Conversely, the A1010 (A709 GR50CR) plates experienced stable corrosion, with a passive surface layer being able to properly form. This is depicted in Figure 7.

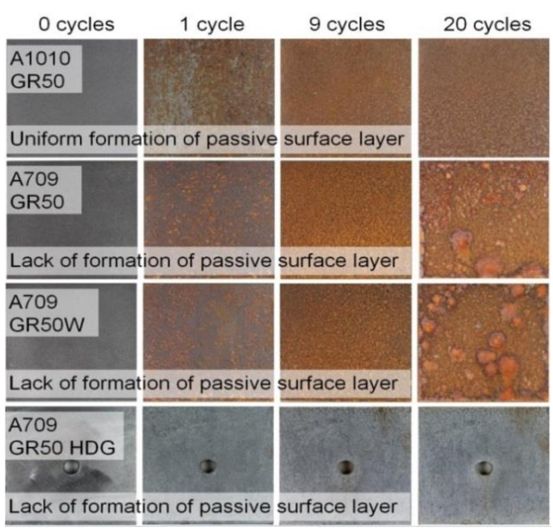

Figure 7: Control plate specimens through 20 testing cycles

A comparison of the current Virginia Tech (VT) study thickness loss rates with loss rates from a recent FHWA study was made, as listed in Table 3. Within both studies, the A1010 stainless steel was shown to experience approximately 10 times less corrosion loss compared to the weathering steel specimens. However, the relative corrosion rates varied between the studies; specimens within the VT study experienced thickness loss rates approximately 20% less than the FHWA study. This difference may be attributed, at least in part, to the different methods for the salt application stage, corrosion chambers used, and abrasive blasting media used for cleaning.

Table 3: Comparison of thickness loss rates of control plates from VT and FHWA corrosion studies.

Steel Type	Coefficient (mils/cycle) [thickness loss - two sides]	
	FHWA	VT
A1010 GR50	0.050	0.042
A588/A709GR50W	0.519	0.428

2. Galvanic Corrosion Plate Assemblies.

- **A1010 (A709 GR50CR) base plates.** Base plates connected to the uncoated A709 GR50 & GR50W top plates experienced thickness loss rates which were between 3 to 8 times greater than the A1010 control plates and increased with time.

  In general, the increase in magnitude was attributed to the near-horizontal orientation of the specimens which caused a higher TOW and longer exposure to corrosive substances. Unstable corrosion was observed, as the plates were unable to properly form a passive surface layer, as seen in Figure 8. This behavior was nearly equivalent for assemblies with each of the three sizes of top plate.

Figure 8: Unstable corrosion occurring on A1010 base plate connected to uncoated A709 top plate

The increase in thickness loss rates over time was attributed to crevice and pitting corrosion occurring in between the faying surfaces of the connected plates; as the depth of the crevices increased, the crevice corrosion rate also increased.

A1010 (A709 GR50CR) base plates connected to coated A709 GR50 HDG plates experienced thickness loss rates between 1.5 to 3 times greater than the A1010 control plates. The base plates experienced near-linear thickness loss rates up to 60 cycles of testing, at which point the HDG sacrificial surface layer on the top plates was fully depleted.

The decrease in thickness loss, compared to the uncoated carbon and weathering steel assemblies, was attributed to the sacrificial protection provided by the top plate zinc coating. The coating provided immediate protection on the faying surface between the plates within approximately 1 inch from the top plate connection, as seen in Figure 9. This protection was evident when comparing base plates connected to the varying top plate sizes; A1010 base plates connected to the largest A709 GR50 HDG top plates received the greatest protection and experienced the lowest thickness lost rates, while the assemblies with the smallest top plates received the least protection and experienced the greatest thickness loss rates.

Figure 9: Galvanic protection occurring on A1010 base plate connected to HDG coated A709 top plate

The sacrificial protection resulted in the prevention of crevice corrosion on the faying surface of the A1010 base plate in direct connect specimens, but did not for the nylon barrier assemblies. As a result, A1010 base plates in nylon barrier assemblies experienced approximately 50% increase in thickness loss rates. However, protection on direct connect assemblies did not cover the full surface of the base plate, but was localized adjacent to the top HDG plate. A comparison of A1010 plates after the full 80 cycles of testing after having been cleaned is shown in Figure 10.

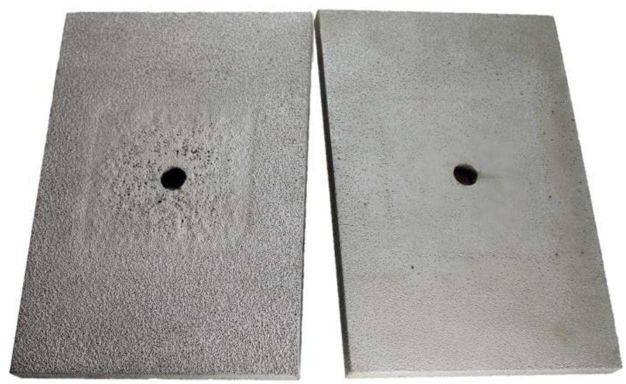

Figure 10: A1010 base plates from direct connect A709 assemblies, GR50 (left) & GR50 HDG (right)

- **Uncoated A709 GR50 & GR50W top plates.** Uncoated top plates connected to the A1010 (A709 GR50CR) base plates experienced linear thickness loss rates which were approximately 1.5 times greater than the uncoated A709 control plates. The overall increase in thickness loss rates was attributed to the change in the assembly testing orientation to a near-horizontal setup. This increased the TOW of the plates and provided longer exposure of the plates to corrosive substances. Unstable corrosion was observed, as the plates were unable to properly form a passive surface layer, as seen in Figure 11.

Figure 11: A709 GR50W top plates after 20 cycles of corrosion testing

A709 GR50 & GR50W top plates in nylon barrier assemblies experienced an approximate 10% decrease in thickness loss rates compared to direct connect assemblies. This indicated that the effect of galvanic corrosion for these top plates was minor, which may be attributed to the minor difference in the electric potentials of the A1010 and A709 GR50 and GR50W metals.

The variation in size for these top plates appeared to have little effect on their thickness loss rates. Based on these results, it is believed that the main electrolyte participating in galvanic corrosion was located between the faying surfaces of the top and base plates, as seen in Figure 12. This configuration indicates a 1:1 surface area of anode (top plate) to cathode (base plate) for each top plate size. Therefore, a change in top plate would not change the surface area ratio of anode to cathode participating in galvanic corrosion within the assembly.

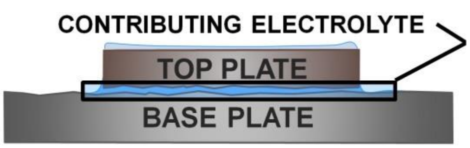

Figure 12: Diagram showing electrolyte permitting galvanic corrosion located primarily between faying surfaces of connected plates

- **Coated A709 GR50 HDG top plates.** Coated top plates connected to the A1010 (A709 GR50CR) base plates experienced thickness loss rates approximately 3 times greater than the coated A709 HDG control plates for nylon barrier assemblies and 5 times greater for direct connect assemblies. Thickness loss rates experienced considerable bilinear behavior, with a noticeable change in slope at 60 cycles, corresponding to the full depletion of the sacrificial HDG coating, as shown in Figure 13. The overall increase in thickness loss rates for both assembly types is attributed to the change in the assembly testing orientation to a near-horizontal setup. Similar to the control A709 GR50 HDG plates, these top plates exhibited unstable corrosion, as the plates were unable to properly form a passive surface layer.

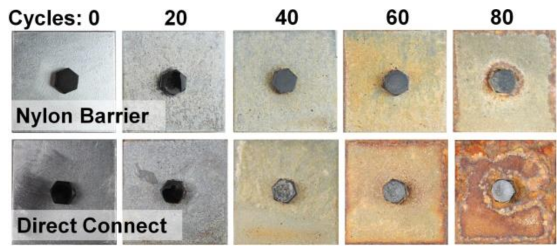

Figure 13: Comparison of direct connect and nylon barrier A709 GR50 HDG top plates

A709 GR50 HDG top plates in nylon barrier assemblies experienced an approximate 40% decrease in thickness loss rates compared to direct connect assemblies. This indicates that the effect of galvanic corrosion for these top plates was significant. Additionally, direct coating measurement thicknesses revealed that HDG top plates in nylon barrier assemblies experienced approximately 25% greater thickness loss rates on the faying surface of the plate compared to the exposed face. For HDG top plates in direct connect assemblies, the loss rates were 50% greater for the faying surface. This reaffirms that while crevice corrosion did cause some disparity between thickness loss rates on front and back faces for both assembly types, a significant amount of galvanic corrosion occurred between the faying surfaces of the A1010 and A709 GR50 HDG top plates for direct connect assemblies.

For these top plates, no clear effect on thickness loss rates was observed for top plates with varying size. This is attributed to the same behavior as the uncoated A709 top plates; the primary contributing electrolyte was located between the faying surfaces of the connected plates.

3. Galvanic Corrosion of Fastener Assemblies.

A1010 plates. Overall, thickness loss rates experienced by the A1010 plates within the galvanic corrosion fastener assemblies were approximately equivalent to the losses exhibited by the A1010 control plate specimens, at 0.02 mils/cycle. A1010 plates connected to all fastener types exhibited nearly linear thickness loss rates over the duration of testing. The A1010 plates in uncoated carbon and weathering steel bolt assemblies experienced thickness loss rates of approximately 0.02 mils/cycle, those connected to HDG bolt assemblies experienced approximately 0.01 mils/cycle, and those connected to B8 Class 2 and B6 stainless steel bolt assemblies experienced approximately 0.03 mils/cycle.

Figure 14: Galvanic corrosion fastener assemblies after 20 cycles of testing.

In general, these differences in thickness loss rates among A1010 plates connected to dissimilar metal bolt assemblies were relatively small in magnitude, even while the percentage increase or decrease appears to be significant. This was due to the passive surface layer formation on the A1010 surface for each of these specimen assemblies and the relatively small portion of surface area on the A1010 plates participating in galvanic corrosion. This behavior would likely increase in an environment in which the electrolyte connecting the plates was thicker or connected the two components for a longer period of time. Given that the use of A1010 in bridge applications would involve atmospheric environments without constant immersion in an electrolyte solution, the effect of galvanic corrosion for the A1010 plates when connected to these fastener types appears to be minimal.

- **General Fastener Data.** Thickness loss values were calculated for fastener specimens under the assumption that all thickness loss occurred on the exposed surfaces, rather than the total surface area. While this assumption proved to be a relatively accurate approximation, as shown in Figure 15, some corrosion loss occurred on surfaces not exposed to the bulk environment due to the salt solution penetrating into the crevices existing in the specimen assemblies. Therefore, fastener thickness loss rates were best used for comparisons for each type of assembly connected to nylon and A1010 plates and also for comparisons between different bolt assembly types rather than comparison to rates from plate specimens.

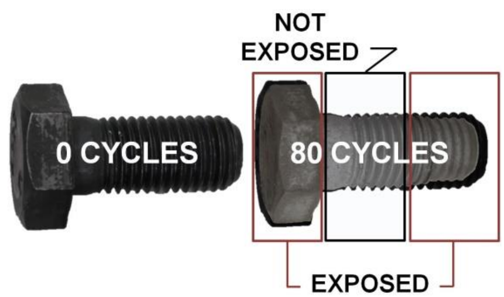

Figure 15: Depiction of relative thickness loss of bolt material based on level of exposure of surface

- **Uncoated carbon and weathering steel fasteners.** The uncoated carbon and weathering steel bolt assemblies, A325 Type 1, A325 Type 3, and A490 Type 1, all exhibited significantly large amounts of thickness loss over the test duration, approximately 0.2 mils/cycle. The thickness loss rates of these three bolt assembly types were over twice the rates experienced by the assembly type with the next closest rates, the B6 ferritic stainless steel bolts. Additionally, similarly to the carbon and weathering steel plate specimens, the A325 Type 1 and Type 3 specimen assemblies experienced negligible increases in thickness loss from galvanic corrosion when connected to A1010 plates as compared to connections with nylon plates.

For these uncoated fastener types, the unstable uniform corrosion resulting from the corrosive environment caused thickness loss rates, as depicted in Figure 16, which were far greater than any increase from galvanic corrosion.

Figure 16: A325 Type 3 bolt specimens from A1010 plate assembly

In contrast to the A325 Type 1 and Type 3 assemblies, the A490 Type 1 bolt assemblies experienced statistically significant effects of galvanic corrosion for the nuts and bolts connected to A1010 specimens. This behavior is intriguing given that the chemical composition requirements for A325 Type 1 and A490 Type 1 specimens are nearly identical. This behavior may be attributed, in some respect, to the varying heat treatments applied to each bolt type. However, for the end purpose of this study, it is sufficient to note that the use of A490 Type 1 bolt assemblies with A1010 plates would likely result in prohibitive thickness loss rates of the A490 bolt assemblies due to a combination of uniform and galvanic corrosion.

- **HDG coated carbon steel fasteners.** The HDG coating on the fasteners provided an effective means of protecting the steel below throughout the duration of testing, with thickness loss rates of approximately 0.04 mils/cycle. However, the effect of galvanic corrosion occurring on the HDG specimens connected to A1010 plates was proven to be statistically significant and ultimately resulted in an increase in rates of thickness loss of approximately 30% as compared to nylon plate assemblies in which no galvanic corrosion was present. A comparison of the bolts connected to the different plate types is shown in Figure 17.

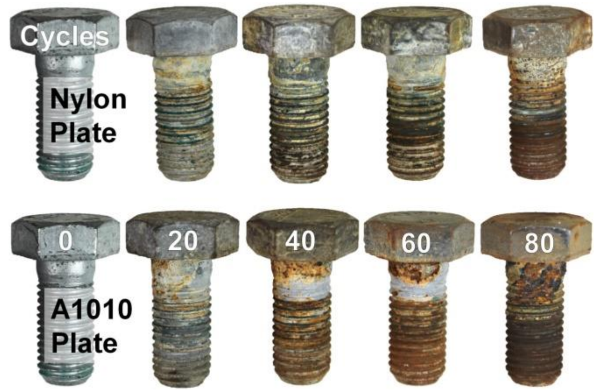

Figure 17: Comparison of A325 Type 1 HDG bolt specimens from nylon and A1010 plate assemblies

In corrosive environments, it is possible that the depletion of the HDG coating on these bolts would occur at rates up to 30% higher when connected to A1010 plates due to the effects of galvanic corrosion. This increase in coating thickness loss rates is also accompanied by staining on the A1010 specimens caused by the shedding of the HDG coating from the bolt assemblies, which may be visually unappealing.

- **B6 (Ferritic) stainless steel fasteners.** B6 bolts exhibited a moderate amount of thickness loss due to corrosion, approximately 1 mil/cycle, and also experienced a statistically significant increase in thickness loss from galvanic corrosion. The B6 bolts experienced approximately a 50% increase in corrosion from galvanic corrosion, and the GR6 nuts experienced roughly a 300% increase.

For both of these specimens, the thickness loss average rate when connected to A1010 plates was approximately 0.2 mils/cycle per exposed surface. This thickness loss rate was roughly half of the rate experienced by the uncoated carbon and weathering steel bolt assemblies when connected to A1010 plates. This thickness loss rate was accompanied by a significant amount of pitting corrosion around the shank of the bolt and around the exposed threads, as shown in Figure 18. The extensive pitting corrosion seen on the B6 bolts connected to an A1010 plate requires further investigation of this behavior if these bolt assemblies are to be specified for use with

A1010 plates in highly-corrosive environments.

Figure 18: A193 B6 bolt specimens from A1010 plate assembly, showing pitting corrosion

- **B8 Class 2 (Austenitic) stainless steel fasteners.** Thickness loss on these austenitic bolts was negligible over the testing duration when attached to both nylon and A1010 plates. In the end, it was determined that galvanic corrosion from these bolt assemblies caused a slight increase in the thickness loss rate of the A1010 plates to which they were connected. However, the magnitudes of these losses were relatively minimal, roughly 0.01 mils/cycle, and did not appear to be prohibitive for the use of this bimetallic connection.

4. **Crevice Corrosion Plate Assemblies.** A1010 base plates and top plates experienced thickness loss rates which were roughly linear over the full duration of testing and approximately 4 times greater than the A1010 control plates. The thickness loss rates were nearly equivalent for specimens having received abrasive blasting and those without blasting, with any apparent differences not being statistically significant.

   The increase in thickness loss for these plates compared to control plates was attributed to the near-horizontal orientation of the specimens which resulted in unstable corrosion was observed, and the plates were unable to properly form a passive surface layer. The increase in thickness loss rates over time was attributed to crevice and pitting corrosion occurring in between the faying surfaces of the connected plates. The relatively significant amount of pitting corrosion shown on A1010 base plate specimens is shown in a comparison with control plates in Figure 19.

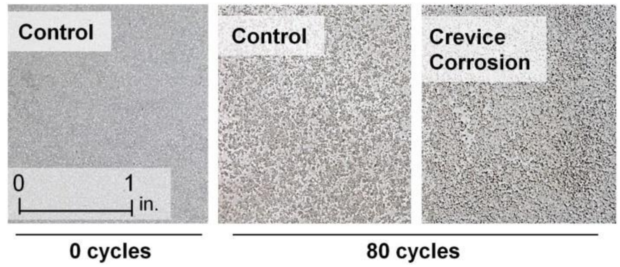

Figure 19: Comparison of A1010 control and crevice corrosion specimens

5. **Surface Preparation Plate Specimens.** For surface preparation specimens, mass loss data was collected only following 80 cycles of testing in order to allow the specimens to experience continuous corrosion over the full duration of testing. Therefore, more focus was given toward the visual appearance of the plates.

   Mass loss data from these plate specimens showed that specimens having received aluminum oxide grit and no abrasive blasting experienced slightly greater thickness loss rates, approximately 0.02 mils/cycle. Conversely, specimens having received garnet grit and steel shot abrasive blasting experienced slightly less thickness loss rates, approximately 0.01 mils/cycle. For all specimens, the thickness loss rates were very low, indicating stable corrosion associated with the A1010 plates being able to form a passive surface layer. Thickness loss rates are listed in Table 4.

Table 4: Average thickness loss rates (linear regression coefficients) for surface preparation specimens

Surface Preparation Type	Coefficient (mils/cycle)
Aluminum Oxide Grit	0.025
No Abrasive Blasting	0.017
Garnet Grit	0.008
Steel Shot	0.006

Visual observations of the A1010 specimens indicated that the main difference in corrosion behavior of the various specimens was the appearance of corrosion products on plates blasted with grit media at earlier stages of testing. Conversely, specimens blasted with steel shot specimens did not experience the same appearance of corrosion products at early stages of testing. By later stages of testing, all specimens had uniform distribution of corrosion products and appeared approximately visually equivalent.

The difference in early corrosion behavior is likely the result of the difference in surface profiles produced by the different blasting media; the use of shot media produces a microscopic surface profile which is rounded and wavy, with "hills" and "valleys" randomly spaced on the surface. In addition, the collisions of shot media with the A1010 steel produce minor work hardening of the surface. This profile type is not prone to trap moisture and facilitate localized corrosion. Therefore, the corrosion products do not appear as readily and may appear less uniform. In contrast, the use of grit media produces a microscopic surface profile with jagged peaks which facilitates moisture and traps corrosive substances. This microenvironment produces corrosion products on the A1010 surface at earlier stages of exposure which are likely to be more evenly distributed on the surface. A visual comparison of the specimens is shown in Figure 20.

Figure 20: Comparison of A1010 surface preparation plate specimens at early and late stages of testing

In atmospheric conditions, the difference in early corrosion behavior may be more apparent, as the TOW of the steel will be less than accelerated corrosion testing conditions. Such behavior may be increased further in environments where corrosion products are not evenly applied to the steel surface, such as in bridges exposed to the splashing of deicing salts from a roadway below.

Conclusions

All specimens were subjected to accelerated corrosion tests in a simulated highly corrosive environment. Therefore the following conclusions apply to applications where members and/or components would be exposed to severe corrosive substances, such as marine environments, locations with large amounts of applied deicing salts, and near heavy industrial locations.

On the use of ASTM A1010 plates:

- The orientation of the A1010 plate may have a significant impact on its ability to form a passive surface layer. In horizontal orientations, the plate will experience higher time of wetness and greater exposure to corrosive substances, thereby presenting more difficulty for the natural formation of the protective surface layer.
- A1010 is expected to have 4 times greater resistance in near-horizontal orientations and 10 times greater resistance in near-vertical orientations relative to A709 Gr50W.
- In details which are prone to trapping moisture and condensation, A1010 experienced notable pitting corrosion.
- The use of steel shot blasting media on A1010 may result in a slight reduction in thickness loss rates compared to grit media, and may result in a more uneven aesthetic formation of corrosion products at early exposure of the metal to the environment compared to the grit media. However, long-term aesthetics do not appear to be affected by the shot blast media.

On the use of uncoated carbon and weathering steel plates and fasteners in connections with ASTM A1010:

- Carbon and weathering steel experienced considerable uniform corrosion in highly-corrosive environments. When connected with

A1010 in these environments, the thickness loss from uniform corrosion far exceeded that from additional galvanic corrosion.

On the use of hot-dip galvanized (HDG) plates and fasteners with ASTM A1010:

- HDG specimens experienced significantly less thickness loss from uniform corrosion compared to uncoated carbon and weathering steel while the sacrificial zinc layer had not been fully depleted.
- The current research found galvanic corrosion of HDG specimens connected to A1010 plates may be up to 50% greater than uncoupled specimens.
- When connecting A1010 and HDG specimens, aesthetic staining of the A1010 surface adjacent to the connection may be expected.

On the use of stainless steel fasteners with ASTM A1010:

- ASTM A193 B6 (ferritic) stainless steel bolt assemblies experienced a moderate increase in thickness loss when connected to A1010. This bolt type is also likely to experience significant pitting corrosion when exposed to a highly-corrosive environment and should be investigated further for applications in such locations.
- ASTM A193 B8 Class 2 (austenitic) stainless steel bolt assemblies experienced negligible corrosion loss when connected to A1010. A minor increase in thickness loss from galvanic corrosion was experienced by A1010 when connected to this bolt type.

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