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Virginia's First Corrosion-Resistant ASTM A1010 Steel Plate Girder Bridge

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16. Abstract:

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The study determined that A1010 steel plate could be bent to form corrosion-resistant secondary members. During the fabrication process, a new supplier of welding electrodes compliant with Buy America regulations was identified. It was also demonstrated that stainless steel fasteners could be used for the splice connections if modifications to the design were adopted. A greater understanding of the rustic patina formation was gained, and possible cost savings were identified, as future A1010 steel plate girders would not require the removal of the mill scale.

Although the weighted unit cost of VDOT's initial use of A1010 steel plate was greater than historic weighted unit costs of traditional steel girder alternatives, the higher costs of A1010 steel plate girders must be weighed against the expected benefit of minimal maintenance over a long service life in corrosive environments. Moreover, their unit costs at construction may reasonably be expected to decrease if they are widely adopted by VDOT for new or replacement structures or structure repairs in appropriate environments. Therefore, the study recommended that VDOT make revisions to the VDOT Manual of the Structure and Bridge Division that will encourage the use of A1010 (now known as ASTM A709 Grade 50CR) steel plate girders. Guidance is provided regarding where in Virginia the use of this type of steel plate girder will benefit VDOT.

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FINAL REPORT

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ABSTRACT

This study documented the construction of the Route 340 Bridge in Waynesboro, Virginia, with maintenance-free corrosion-resistant steel girders, secondary members, and stainless steel fastener assemblies. This included documenting the material properties of ASTM A1010 (hereinafter "A1010") steel plate; girder and secondary member fabrication; erection of the girders with stainless steel fasteners; and completion of the construction process. The types of materials used to fabricate the girders were compared to traditional materials. Information on the material properties, as well as several other innovative bridge features, was also documented. The cost of girders fabricated of A1010 steel plate in the Virginia Department of Transportation's (VDOT's) first application of the material was compared with that of conventional steel girders that VDOT has previously used in corrosive environments, and possible cost drivers for the A1010 steel plate girders were identified.

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INTRODUCTION

Corrosion of carbon steel is a concern for the Virginia Department of Transportation (VDOT) because this material often functions as a critical component in a structure. Most of the steel traditionally used by VDOT has not been alloyed specifically for corrosion resistance, so it can exhibit significant section loss when the protective barrier, usually a polymer coating, breaks down and allows the steel to be exposed to the atmosphere. For many years, uncoated weathering steel was the only alloyed steel used for plate girders to resist corrosion, but its corrosion resistance has had mixed performance in the United States and in Virginia, where it needs to be coated to perform satisfactorily.

The regional environment and the need to keep vehicles moving during colder months result in several sources for salt exposure. Both along the coast and inland, steel is exposed to chloride-containing salts, which cause corrosion of the steel. Along the coast, structures are subjected to both brackish waters and seawater. Moving inland, structures are exposed to salt that is used for deicing roadways. The use of uncoated weathering steel can be limited by the proximity of this steel to water or industrial environments, both of which can prevent the steel's protective patina from performing properly. Given the difficulty of maintaining protective barriers on the steel and the continuing use of deicing salt treatment on roads, another option for mitigating corrosion is to use materials that inherently exhibit greater resistance to salt-induced corrosion, thus providing longer maintenance-free service lives.

Because of the increases in the cost of transportation system maintenance in recent years, VDOT and other departments of transportation (DOTs) have started to investigate and use materials with much greater corrosion resistance but higher initial cost. For example, VDOT has used stainless steel in bridge decks and prestressed concrete piles and has used carbon fiber reinforced polymer (CFRP) strand in prestressed concrete piles and beams (Sharp and Moruza, 2009; Sharp et al., 2019). These materials have higher initial construction costs but have been approved with the expectation of better corrosion performance and greatly reduced maintenance expenditures over the structure's service life. The cost premium of such materials can actually be relatively small when compared with the total cost for replacement of or capacity improvements to a heavily traveled, signature structure in an aggressively corrosive environment. In these instances, weighed against avoided costs of future maintenance and traffic control operations over the relatively long desired service life of the structure, the higher initial cost of a premium construction material may seem to be self-evidently justified. For less-traveled structures also located in high-corrosion zones, judicious use can be guided by comparative analysis of construction costs of premium materials against traditional materials, as provided in this report for ASTM A1010 (hereinafter "A1010") steel.

Polymeric coatings are commonly applied to minimize structural steel corrosion and prevent section loss when the steel is exposed to atmospheric impacts. This corrosion mitigation technique can provide additional life to the steel but will require coating condition checks and additional maintenance of the coating over time. It is estimated that VDOT spends approximately $105 million per year on bridge maintenance statewide, with approximately 10% of this annual cost accounted for by bridge coating maintenance (Sharp et al., 2013). These costs are associated with mobilization, traffic control, environmental protection, painting, and the disposal of waste.

The nature of bridge coating systems can be more complex than is sometimes realized. The composition of coating liquids can differ depending on the type of solvent, resin, and pigment used. Further, bridge coating systems are typically composed of different layers, each serving a particular function. Therefore, care must be taken in the selection of the appropriate coating for a new structure. For existing structures, however, determining the protection mechanism for the structural steel and maintaining the coating system become even more complex and costly. For example, ensuring that the surface is prepared properly and determining if the coating will adhere to the substrate are both critical to corrosion mitigation. Further, coating maintenance in the field requires compliance with environmental and worker safety rules.

Alternatives to this potentially costly coating maintenance should be investigated for their suitability and cost-effectiveness for applications in Virginia since corrosion of steel structures is a concern. One innovative material for mitigation of corrosion and subsequent maintenance costs of plate girder bridges is ASTM A1010 steel plate. This dual grade (ferrite and tempered martensite) stainless steel is produced as a plate product and has great potential for corrosion-resistant plate girders. Several years ago, Fletcher (2011) conducted a study titled *Improved Corrosion-Resistant Steel for Highway Bridge Construction*. In this study, the corrosion resistance of several steel plate products of different compositions was compared, illustrating the superior cost-effectiveness of A1010 steel plate over the service life of the project subject to certain assumptions in the economic analysis (Fletcher, 2011). Because of its increased inherent corrosion resistance, A1010 steel plate has been used on bridges in Pennsylvania (ArcelorMittal, 2013), California (ArcelorMittal, 2013; Seradj, 2012), and Oregon (ArcelorMittal, 2013; Seradj, 2012; Seradj, 2015).

The original Route 340 Bridge, located in Waynesboro, Virginia, and built in 1934 with steel girders, had undergone significant corrosion and deterioration such that the bridge was posted for a weight limit of 15 tons. Originally, uncoated weathering steel was considered for the replacement bridge girders but was not selected because of two conditions of the bridge environment. First, the bridge was located downstream of a chemical plant. Second, the bridge had a low water clearance; the low chord of the bridge was typically about 9 ft above the South River and would be reached by water during a 10-year storm event. These conditions were in areas in which uncoated weathering steel had not performed well historically and its use was not recommended in FHWA's Technical Advisory 5140.22 (FHWA, 1989). Figure 1 shows the original Route 340 Bridge with high water and the chemical plant in the background.

Since uncoated weathering steel was not recommended for this application and a corrosion-resistant material was necessary, VDOT developed a special provision (Special Provision for Corrosion Resistant Steel Plate Girders) that identified changes to its current design, fabrication, and construction practices that would make the bridge more corrosion resistant, including the use of A1010 steel plate girders on the replacement structure. Figure 2 shows a drawing of the elevation and plan views of the new Route 340 Bridge.

Figure 1. Photograph of Original Route 340 Bridge With High Water and Chemical Plant in Background

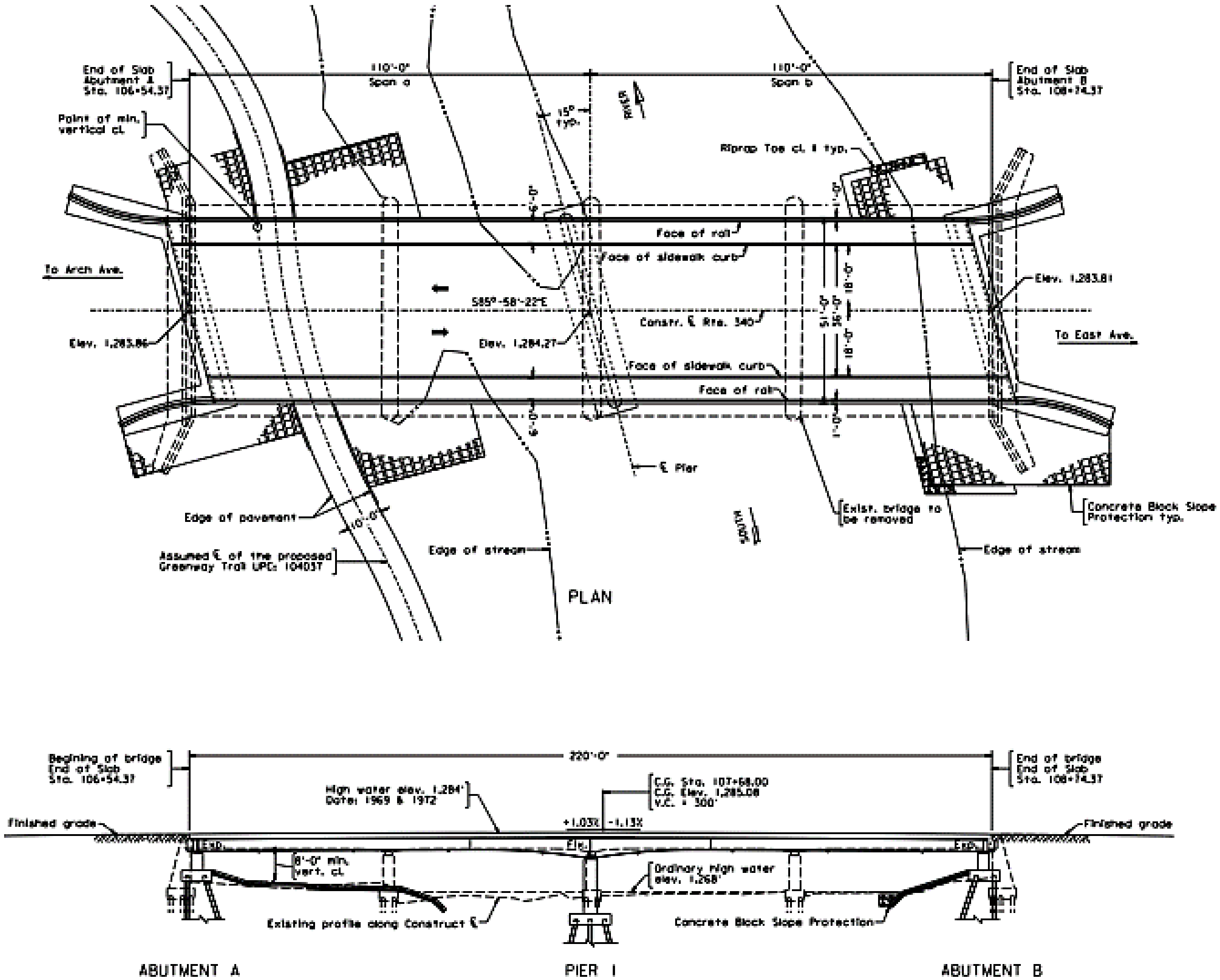


Figure 2. Plan View and Elevation View of the New Route 340 Bridge

An additional benefit of using A1010 steel plate was that although a stainless steel, it still develops a “rustic”-looking patina, which fit the desired aesthetics of the bridge location, which included crossing a downtown park and shared use path, as well as providing access to the historic district of Waynesboro. VDOT made the award recommendation on January 5, 2016, for the $8.4 million replacement of the Route 340 Bridge. The project specifications included VDOT’s initial application of A1010 steel plate for not only the plate girders but also the cross frames and diaphragms. Stainless steel bolts, nuts, and washers were also specified to provide the entire superstructure with sufficient corrosion resistance to yield a 100-year service life with minimal maintenance cost.

PURPOSE AND SCOPE

The purpose of this study was to demonstrate that A1010 steel plate girders can be designed, fabricated, and cost-effectively employed on the Route 340 Bridge. This involved documenting the acceptance and handling of A1010 steel plate by a steel fabricator, noting fabrication issues compared to traditional methods and materials. It also included observing the girders during erection, including installation of the bolted splices with stainless steel fastener assemblies. Finally, since A1010 steel plate has higher material and fabrication costs, the bridge girder cost data were compared to the costs of alternatives including the CFRP prestressed concrete beams used in a Halifax County bridge.

The study included both field and laboratory components. The field component included gathering data at both the fabricator and construction sites, and the laboratory component included testing the bolts and evaluating the surface finish.

METHODS

Five tasks were performed to evaluate the use of A1010 steel plate on the Route 340 Bridge:

1. The material selection rationale was determined.

2. The fabrication feasibility was evaluated.

3. The construction feasibility was evaluated.

4. The weighted unit cost of the A1010 steel plate girders was compared with the cost of conventional steel girders used by VDOT in corrosive environments over the period 2008-2019.

5. Future applications of A1010 steel plate girders were identified.

Task 1: Determination of Material Selection Rationale

Material Selection

Material selection for the Route 340 Bridge was driven by several factors that are discussed in this report. Two of the main reasons for selecting A1010 steel plate were that (1) the bridge was located near an industrial plant, and (2) the bridge had a low water clearance. The use of uncoated weathering steel is not recommended for either condition in FHWA's 1989 Technical Advisory (ArcelorMittal, 2013; FHWA, 1989). Previous research on A1010 steel plate by other states also influenced material selection for the Route 340 Bridge.

Material Properties

The material properties of A1010 steel plate, such as yield strength, tensile strength, elongation, Charpy V-notch (CVN), and hardness values were obtained from the mill test reports provided by the steel supplier. Although values for these mechanical properties have been published elsewhere, the information from the mill test reports comprises a large database that can provide additional confidence with regard to the values reported in the literature. All properties were tested at the top and bottom of each steel plate provided by the steel supplier to the fabricator. In addition, CVN tests were conducted on three samples from the top and bottom of each plate. The material properties were examined to determine how they changed with differing plate thicknesses. For CVN values, the average of the three-sample dataset was used for comparison. The values were also compared to their corresponding specified limits in ASTM A709 (ASTM, Inc. [ASTM], 2017).

As noted on the mill test reports, the yield strength, tensile strength, and elongation values were obtained from samples with a 2-in gauge length that were oriented transverse to the rolling direction of the plate. The rolling direction indicates the direction in which the steel was rolled at the mill when the billets were formed into plates. The samples were tested in accordance with ASTM E8 (ASTM, 2016b). The CVN samples were full-size samples, oriented longitudinal to the plate rolling direction, and were tested at a temperature of 40°F; this test temperature corresponds to Temperature Zone 2 in both the *AASHTO LRFD Bridge Design Specifications* (American Association of State Highway and Transportation Officials [AASHTO], 2017) and ASTM A709 (ASTM, 2017) for a minimum service temperature between 0°F and -30°F. Hardness values were obtained using the Brinell hardness scale in accordance with ASTM E110 (ASTM, 2014a).

Task 2: Evaluation of Fabrication Feasibility

Fastener Assembly Selection and Splice Design

VDOT's special provision for the Route 340 Bridge required the use of 7/8-in-diameter stainless steel bolts, nuts, and washers. These fastener assemblies were used at the bolted field splices of the girders, cross frames, diaphragms, and any other utility attachments. All fastener assemblies used on the bridge were required to meet the specifications listed in Table 1.

Table 1. Specifications for Stainless Steel Fastener Assemblies

Fastener Assembly Part	Specification
Bolt	ASTM A193 Grade B8 Class 2[a]
Nut	ASTM A194 Grade 8[b]
Washer	Type 303

[a] ASTM, 2014b.
[b] ASTM, 2016a.

The specified fastener assemblies were selected to replace the ASTM A325 Type 1 bolts (ASTM, 2014c); ASTM A563 Grade DH nuts (ASTM, 2015); and ASTM F436 washers (ASTM, 2004) that are typically used on VDOT bridges.

Cutting/Tools/Drilling

To fabricate plate girders, the plate must be shaped and the plate material removed so that it conforms to the requirements of the design. This study monitored this process and documented whether conventional fabrication equipment and techniques could be used. This included cutting the plates to the required dimensions, preparing the surfaces for welding and cleaning after each welding pass, and making holes in the plates where needed. VDOT's special provision specified that oxy-fuel techniques could not be used for cutting and that dedicated tools were required for use, so the response of the fabricator to these changes was especially closely monitored and documented.

Bending

As is standard practice for carbon steel bridges, all secondary members, including cross frames, diaphragms, and utility supports, on the Route 340 Bridge were designed as structural shapes, such as channels and angles. Since structural shapes are not currently being produced using A1010 steel plate, VDOT specified that A1010 steel plate be used on the secondary members so that they would have a corrosion resistance equivalent to that of the plate girders. VDOT specified that the secondary members could be either bent plates or welded built-up members to form structural shapes. Bending of A1010 steel plate had been successful with 0.16-in-thick plate for a bridge in California (Seradj, 2010). However, there were concerns about bending thicker plate, up to 2 in thick. If plate were to be bent to form secondary members, it was important to make sure that there would be no damage in the radius and that the specified bend radius could be achieved. Several plates of different thicknesses were bent at the fabricator's facility, and the results were documented.

Welding

All welding on the primary and secondary members of the Route 340 Bridge was done at a steel bridge fabrication shop. Welding on the girders included complete joint penetration (CJP) butt splices for the web and flanges, longitudinal welds on the web-to-flange connections, and transverse welds on the connections between the stiffeners and the girders. The cross frames were welded using partial joint penetration (PJP) welds because the plates used to form the cross frames were constructed of bent plates. The A1010 steel plate producer recommended using an austenitic stainless steel welding electrode called a 309L electrode (ArcelorMittel, 2013). As the name implies, the electrode is made from Type 309 stainless steel. The "L" signifies that the electrode has low carbon. This electrode is recommended for welding carbon steel to stainless steel or stainless steel to stainless steel because it exhibits favorable resistance to intergranular attack, a form of corrosion along grain boundaries because of chromium depletion during welding attributable to the electrode's low carbon content (Lincoln Electric Company, 2016). The welding processes and positions used, the manufacturers from which electrodes were purchased, and how the manufacturers related to challenges with Buy America regulations (FHWA, 2016) were documented.

Nondestructive Testing

In addition to visual inspection, several nondestructive testing (NDT) techniques were used to assess the quality of the welds. These techniques are commonly used during steel bridge fabrication. The techniques used for this project, as specified in AASHTO/AWS D1.5, were ultrasonic testing (UT), radiographic testing (RT), and magnetic particle testing (MT) (American Welding Society [AWS], 2015). Penetrant testing (PT) is also commonly used and was required by VDOT's special provision because of the stainless steel welding electrode material.

During PT, a red contrast penetrant was applied to weld areas followed by the application of a white developer, as directed by the penetrant manufacturer. The penetrant could be removed with water, and the developer was a non-aqueous type; both were recommended by the manufacturer for concurrent use.

Shear Studs

For this project, conventional carbon steel shear studs were required and necessary to provide composite action between the steel plate girders and concrete deck. It was also required that the studs be applied in the fabrication shop. The stud welding process was documented.

Beam Finish

A nonmetallic blast-cleaning medium, such as aluminum oxide, was required for use on A1010 steel plate as part of this project. The requirement was based on the belief that using a metallic blast medium would create a "polka dot" pattern from the iron particles becoming embedded in the A1010 steel plate surface. Since the aesthetics of the bridge were important, aluminum oxide blast medium was specified as the blast medium to be used by the fabricator. The intent of this was to have the appearance of the new girders match that of the uncoated weathering steel girders on a nearby bridge. However, the fabricator suggested an alternative to using aluminum oxide, and VTRC performed corrosion testing to evaluate the aged appearance of the girders cleaned using the newly proposed blast medium.

Task 3: Evaluation of Construction Feasibility

Bolting

The stainless steel bolts used for bolted connections on the bridge had a smaller clamping force than required by traditionally used bolts. Because of this, a modified bolt tightening procedure had to be developed. This modified tightening procedure was used, and acceptance testing of the bolts was performed. Observations from the field installation were documented.

Bridge Completion Observations

The aesthetics of the Route 340 Bridge were important from the start of the project. A rustic patina was desired by the community so it would match a neighboring structure with uncoated weathering steel girders. The surface finish of the Route 340 Bridge was assessed and documented. Other innovative concepts used with regard to the bridge were documented.

Task 4: Cost Comparison of A1010 Steel Plate Girders and Conventional Steel Girders Used in Corrosive Environments

Because bridge girders made of A1010 steel plate are a fairly new innovation in the United States, their maintenance cost over a lengthy service life is reasonably presumed rather than empirically proven to be low when compared with girders fabricated from conventional materials. Two life-cycle cost studies have been performed on the basis of an assumption of regular maintenance of coating on steel girders (Daghash et al., 2019; Okasha et al., 2012) that show favorable life-cycle cost results for A1010 steel plate girders compared to coated steel girders in corrosive environments. By contrast, in the current study a construction phase comparison was made between the cost of the Route 340 Bridge A1010 steel plate girders and the cost of conventional steel girders suitable for or actually used by VDOT in corrosive environments over the period 2008-2019. In addition, cost drivers for the A1010 steel plate girders in the Route 340 Bridge project were examined to identify those that were not likely to be repeated in subsequent projects as the learning curve for steel bridge fabricators matures and bridge elements of A1010 steel plate are fabricated more commonly.

The unit cost of the A1010 steel plate girders in the Route 340 Bridge was evaluated in two phases. First, the A1010 steel plate girder unit cost was estimated by allocations to contractor and subcontractor marginal shares in order to exclude the material that was purchased in excess of the girder requirements. Second, the estimated unit cost was compared with inflation-adjusted historic unit costs of structural steel girders that would have been conventional options for a VDOT bridge in a corrosive environment. In the second phase, the unit cost of the A1010 steel plate girders was contrasted with (1) the hypothetical costs of weathering steel girders with additional surface treatments to inhibit corrosion, and (2) VDOT's actual costs of coated steel plate girders over the period 2008-2019, adjusted for inflation. The unit costs of the latter group were identified through inspection of VDOT bridge plans.

The discussion of cost drivers reflected information gathered from several sources: A1010 steel plate projects that preceded VDOT's project, a literature review, discussions with stakeholders during site visits to the girder fabrication facility, the post-construction project review meeting of bridge owners and parties involved in girder fabrication and erection, and consensus formed within VDOT since project completion.

Although other state transportation agencies had constructed bridges with A1010 steel plate girders several years before the Route 340 Bridge, the contracts were significantly different with respect to girder procurement. Unlike the contracts of other DOTs, the VDOT contract provided design requirements for the girders but otherwise allowed line item lump sum bidding for installed girders. Further, VDOT does not include steel or concrete bridge element fabricators as delineated subcontractors in its electronic construction cost database, so fabrication costs are not visible within VDOT records. For these reasons, records of open discussions and inspector reports were a major resource in the cost analysis of A1010 steel plate.

Task 5: Identification of Future Applications of A1010 Steel Plate Girders

Based on lessons learned and the results of the cost analysis, VDOT's special provision and office practices were revised and new opportunities for the use of A1010 steel plate were identified.

RESULTS AND DISCUSSION

Material Selection Rationale

Material Selection

ASTM A1010 steel plate (Figure 3) was specified for the Route 340 Bridge. ASTM A1010 stipulates the properties required for martensitic stainless steels that are used in structural applications (ASTM, 2013) with a maximum plate thickness of 2 in. At the time of fabricating the Route 340 Bridge, A1010 steel plate was produced using the normalizing and tempering heat treatment. The steel producer determined that using this heat treating approach resulted in the consistent mechanical properties. Normalizing and tempering, with a maximum tempering temperature of 1400^{o}F, was a requirement of ASTM A1010 at the time (ASTM, 2013).

Material Properties

The data from the steel supplier mill test reports were analyzed and compared for differing plate thicknesses for the following mechanical properties: yield strength, tensile strength, elongation, CVN, and Brinell hardness. Figure 4 shows a plot of yield strength vs. plate thickness. As shown in the figure, all test values met the minimum yield strength requirement of 50 ksi. There were no obvious trends between the test specimens taken from the top or the bottom of the plate. Overall, the yield strength appeared more consistent with thicker plates, aside from one data point with a lower relative yield strength at a thickness of 1⅜ in.

Figure 3. A1010 Steel Plate (½ in) Waiting to Be Moved to Cutting Table to Be Plasma Cut on Down Draft Table

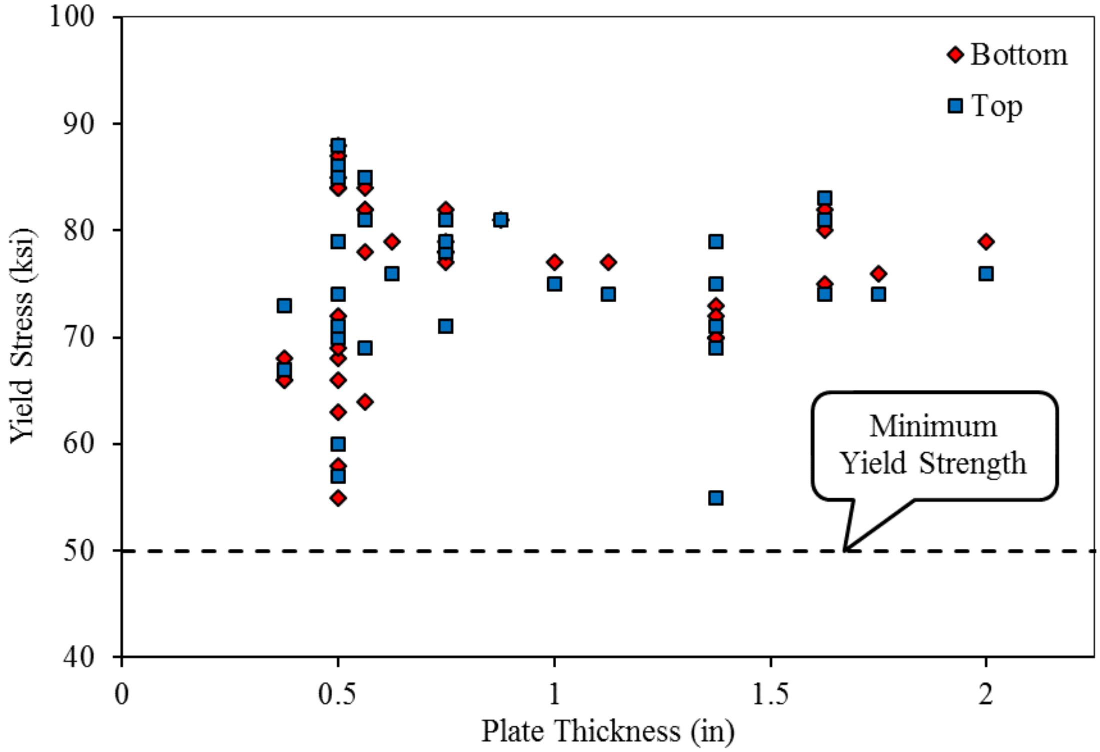


Figure 4. Plot of Yield Stress vs. Plate Thickness From Mill Test Reports

Figure 5 shows a plot of tensile strength vs. plate thickness. Trends appeared to be similar for the tensile strength data compared to the yield strength. All values met the required tensile strength of 70 ksi. There did not appear to be any obvious trends between the data from the top or from the bottom of the plate.

Figure 6 shows a plot of the elongation vs. plate thickness. All test values met the minimum elongation requirement of 21%. There did not appear to be any trends in the results for the top or the bottom of the plates; however, there were clear differences between the elongations of differing plate thicknesses. For plates with a thickness of less than 1 in, the elongation was quite variable, ranging from approximately 23% to 47%. For plates thicker than 1 in, the variation was smaller, ranging from approximately 21% to 28%. From these values, it is also clear that plates thicker than 1 in had lower elongation values.

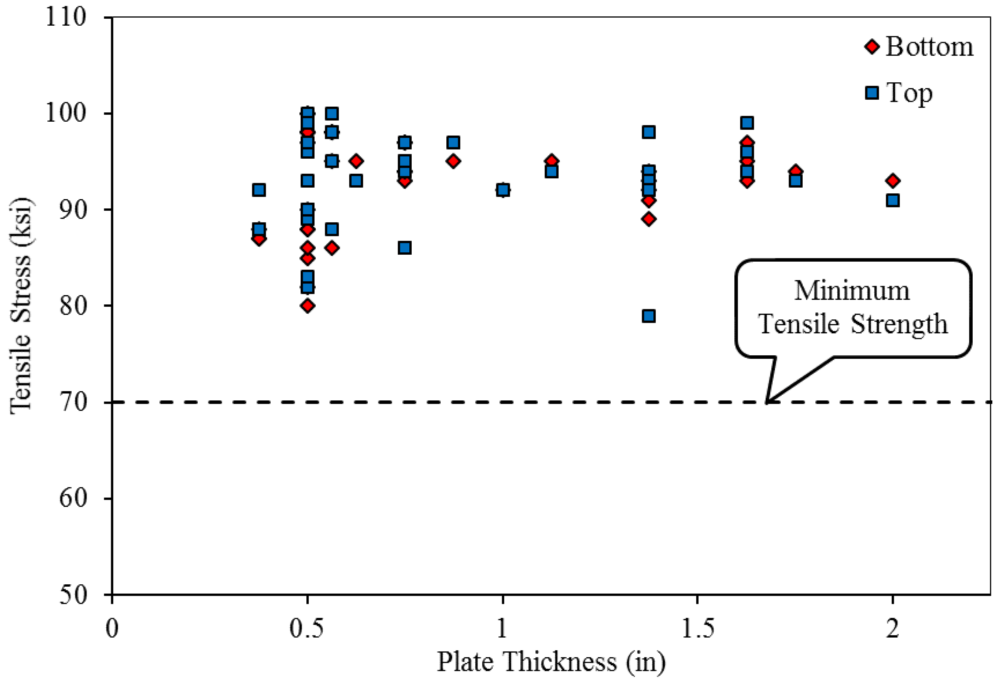


Figure 5. Plot of Tensile Stress vs. Plate Thickness From Mill Test Reports

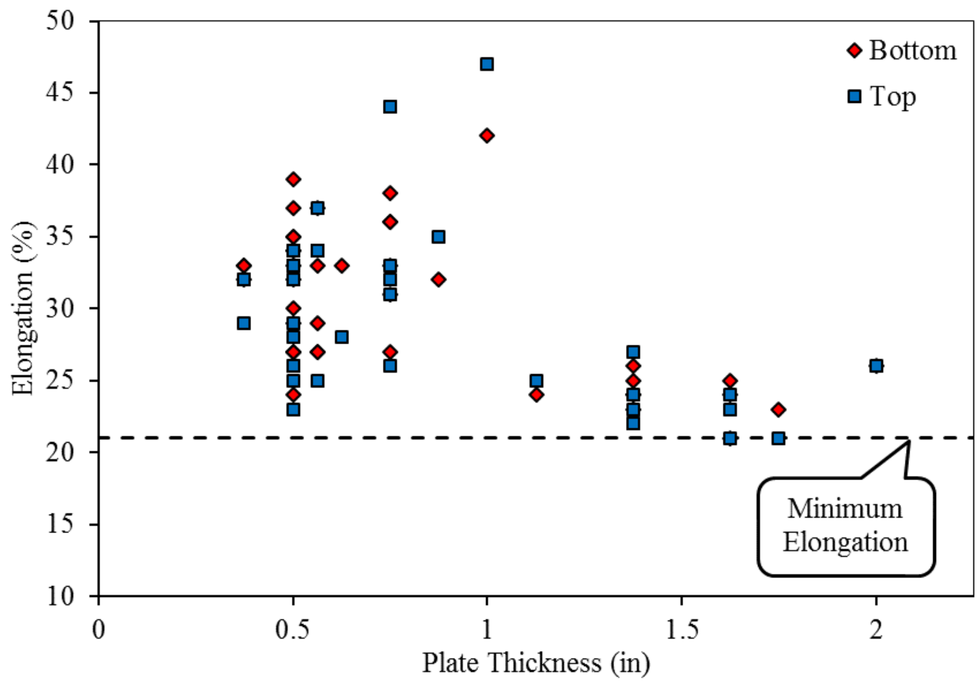


Figure 6. Plot of Elongation vs. Plate Thickness From Mill Test Reports

Figure 7 shows a plot of CVN vs. plate thickness. The CVN values are averages from three samples taken at each test location at the top and at the bottom of the plate that were tested at 40°F. All CVN values exceeded the requirements of 15 ft-lb for non-fracture critical members and 25 ft-lb for fracture critical members by a substantial amount, displaying the good fracture toughness exhibited by A1010 steel plate. There did not appear to be a large difference in CVN between the top and the bottom test locations, though the CVN values became more consistent as the plate thickness increased past approximately 1.5 in.

Figure 8 shows a plot of Brinell hardness vs. plate thickness. The most current (2017) version of ASTM A709 (ASTM, 2017) does not have any hardness requirements for steel plates. However, the 2009 historical standard ASTM A1010 (ASTM, 2009), which was superseded by the current 2018 version (ASTM, 2018), had a maximum limit of 250 Brinell hardness. Although this value is not a current requirement, all test results from the mill test reports met this requirement. There did not appear to be any obvious trends in the hardness values when either the test location or the plate thickness was considered. All Brinell hardness values were within a range of approximately 160 to 225.

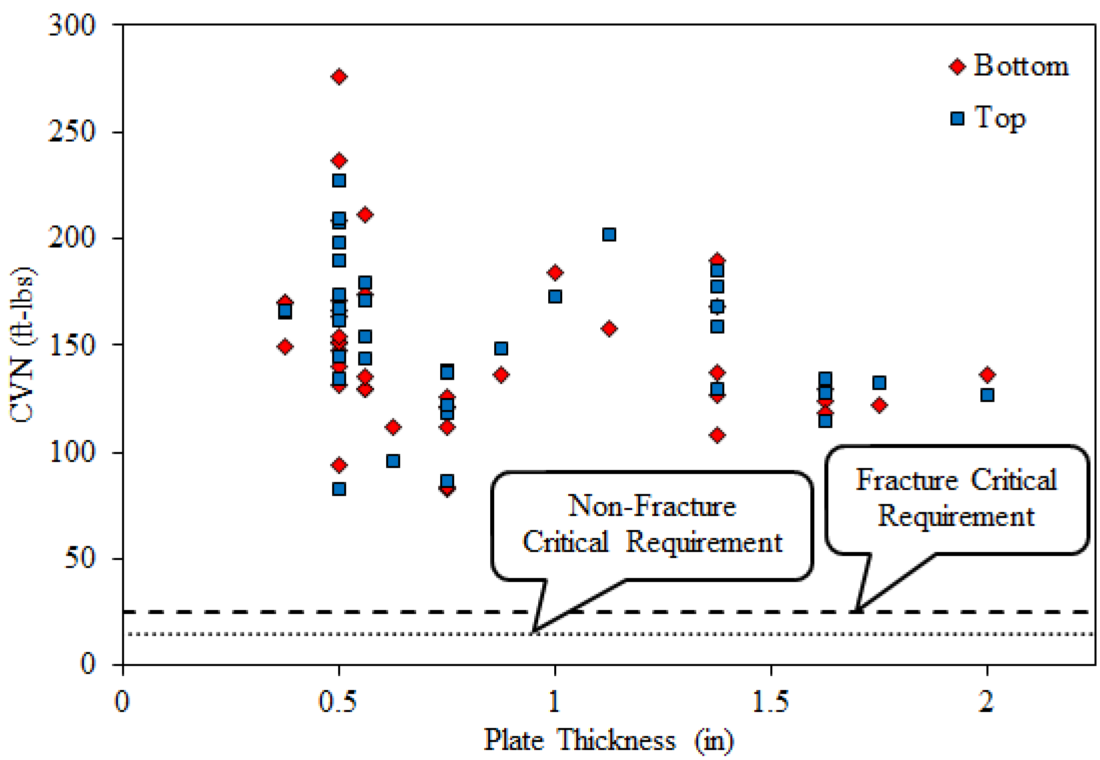


Figure 7. Plot of Average CVN Tested at 40°F vs. Plate Thickness From Mill Test Reports. CVN = Charpy V-notch.

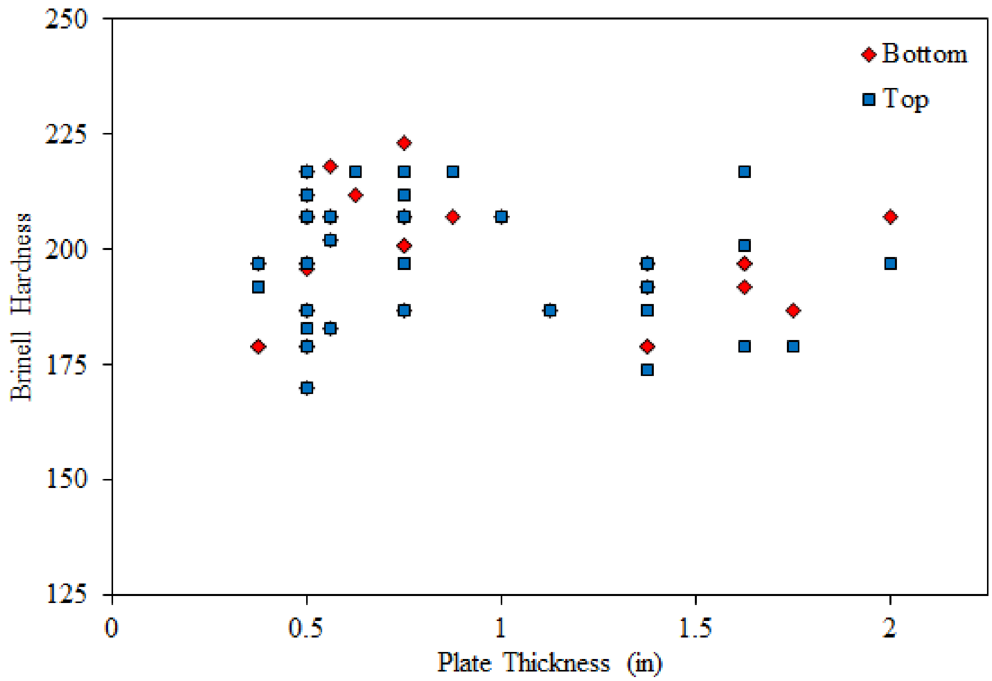


Figure 8. Plot of Brinell Hardness vs. Plate Thickness From Mill Test Reports

Fabrication Feasibility

Fastener Assembly Selection and Splice Design

Although details regarding this portion of the study have been published (Provines et al., 2018; Sharp et al., 2018; Williams et al., 2017), key results are highlighted in this report.

Prior to the construction of the Route 340 Bridge, Williams et al. (2017a) conducted a VTRC study of stainless steel fastener assemblies to determine which types and grades would be best suited for use on the bridge. The study included experimental testing, such as uniaxial tension tests, modified rotational capacity tests, hardness tests, optical and scanning electron microscopy, and sensitization tests, on multiple types of stainless steel bolts, nuts, and washers. The study required confirmation that all hardware met Buy America regulations. The study concluded that ASTM A193 Grade B8 Class 2 (Grade B8-2) bolts, ASTM A194 nuts, and Type 304 washers should be specified for the Route 340 Bridge. All of these fasteners are fabricated from austenitic stainless steel and are more commonly known by the SAE designation of Type 304.

The VDOT specifications required that the Grade B8-2 bolts have a minimum tensile strength of 100 ksi and a minimum clamping force of 30 kip per bolt. This clamping force specification was a result of the modified rotational capacity tests of the previous bolting study, which revealed that Grade B8-2 bolts could consistently develop a clamping force of only 30 kip, which is less than the specified 39 kip for a typical ASTM A325 bolt of the same diameter (Williams et al., 2017). In most cases, the development of a smaller clamping force was due to galling between the threads of the bolt and nut; galling is a known phenomenon in which stainless steel parts become essentially cold-welded together by large amounts of friction. Galling was minimized by using a proprietary lubricant specific to stainless steel, i.e., Never-Seez High Temperature Lubricating Compound. The Oregon DOT had also noted success with using this lubricant. Additional information from this study is provided in Williams et al. (2017).

In addition to the material difference in the bolts, the difference in the plate material had to be accounted for in the splice design (Provines et al., 2018). Since most bolted connections on bridges are designed as slip-critical, the surface condition factor, which is dependent on the plate material and surface condition, must be known during the design of the splice. These factors are provided in the *AASHTO LRFD Bridge Design Specifications* (AASHTO, 2017), but they do not contain values for A1010 steel plate, either unblasted or blast cleaned with garnet media. VDOT elected to assume a Class B surface condition for the splices on the Route 340 Bridge, which corresponded to a blast-cleaned surface and was the most applicable of the existing AASHTO surface conditions. A study is currently underway at VTRC to classify the slip coefficient of unblasted and blast-cleaned uniform and dissimilar metal A1010 steel plate connections.

Although Type 304 hardened washers were required by VDOT's special provision for use on the Route 340 Bridge, the high cost and limited availability of these washers resulted in the use of Type 303 washers on the bridge. Type 303 stainless steel has a slightly reduced corrosion resistance when compared to Type 304 but is nonetheless excellent compared to the traditionally used weathering steel or galvanized steel fasteners.

Overall, the Route 340 Bridge bolted splice design process was similar to that of a typical bolted splice design, aside from the aforementioned reduction in clamping force from 39 kip to 30 kip for the stainless steel bolts. Figure 9 shows a drawing of the final design of the splice.

In each splice half shown in Figure 9, there were 20 bolts in the top flange, 27 bolts in the web, and 40 bolts in the bottom flange. This comprises a total of 87 bolts per splice half, or 174 bolts in each splice of the bridge. The splice was overdesigned for conservatism because it was the first time that stainless steel fastener assemblies had been used in a bolted field splice for a vehicular bridge in the United States. Additional analyses of the bolted splice can be found in Provines et al. (2018).

Cutting/Tools/Drilling

When handling traditional carbon steel, an electromagnetic hoist can be used to move steel plate, but initially there were some concerns about using this type of hoist to move a stainless steel plate. Although A1010 steel plate is a stainless steel, the microstructure contains ferrite and martensite, rather than austenite, which is found in austenitic stainless steels, which allows it to be lifted using an electromagnetic hoist.

Based on the fabrication of A1010 steel bridges for other states, it was known that the steel could not be cut with traditional oxy-fuel techniques. Instead, plasma cutting was recommended by the steel supplier and was accordingly indicated in VDOT's special provision for A1010 steel plate.

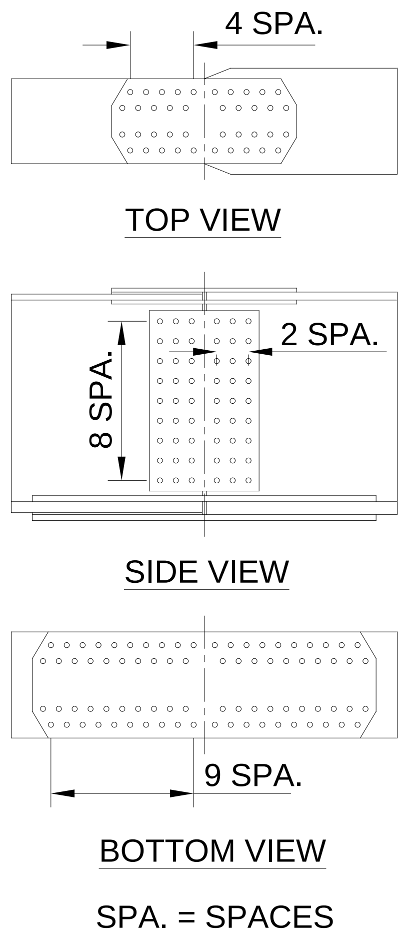


Figure 9. Drawing of Route 340 Bridge Bolted Splice

Initially there were some challenges since the fabricator had to determine the best mixture of compressed gasses that would be used during plasma cutting. After several attempts, the best mixture was determined to be 35% hydrogen and 65% argon; using this mixture, the A1010 steel plate could be cut with an acceptable surface profile (Figure 10).

Another change to VDOT practice covered in VDOT's special provision required the fabricator to use "new tools (grinding and sanding disk, weld cleaning tool) or tools dedicated for ASTM A1010," and carbon steel tools had to be approved by the engineer. For example, new bits were used for drilling, and common hand tools were marked to ensure that only dedicated tools were used (Figure 11). The purpose of this requirement was to reduce the chance of contaminating the weld regions with carbon, and the fabricator achieved this goal.

Earlier work by the Oregon DOT indicated that the machinability and marking of A1010 steel plate were similar to those of ASTM A709 Grade 50 steel (Seradj, 2012). Although dedicated bits were used on the Route 340 Bridge to meet the requirements in VDOT's special provision, it can be seen in Figure 12 that standard bridge components were fabricated with conventional equipment. For future projects, dedicated stainless steel tools will likely be required only for weld regions.

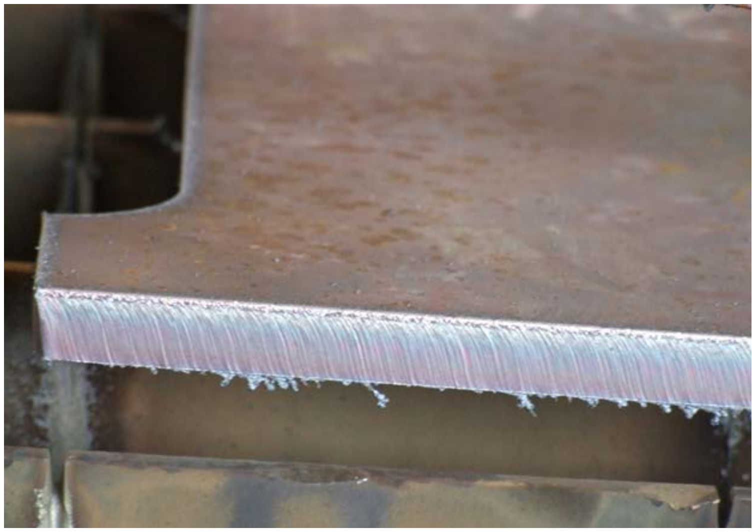


Figure 10. Cut Face After Plasma Cutting A1010 Steel Plate Using a 35% Hydrogen and 65% Argon Mixture

Figure 11. Hand Tools Marked With Green Paint to Indicate They Are Dedicated for Use on ASTM A1010 Steel Plate

Figure 12. Identification Marking and Machining of A1010 Steel Plates Using Conventional Equipment

Bending

In early 2016, the fabricator proposed bending A1010 steel plate into secondary members, rather than welding it into built-up members. The fabricator demonstrated to VDOT that the plate could be successfully bent to the specified radius. The bends were then inspected using visual inspection and UT to confirm that no indications were present in the bends. MT was also used to inspect 10% of the bent members; it also showed no indications along the bends. Successful bending of A1010 steel plate allowed the bent plates to be used in place of traditional structural shapes, thereby providing alloyed corrosion resistance to these secondary members. Examples of the bent plate cross frames, diaphragms, and water line supports are shown in Figures 13 through 15.

Figure 13. A1010 Steel Plate After Bending But Prior to Assembly

Figure 14. Close-up of A1010 Steel Bent Plate Cross Frame With Welded Connection


Figure 15. Water Line Support Brackets and Partially Fabricated Diaphragm After Bending

Welding

Originally, all of the 309L welding electrodes used on the Route 340 Bridge were to be produced by the Lincoln Electric Company. However, early in 2016 and after the project had been awarded, VDOT and the bridge fabricator learned that the Lincolnweld 309/309L (LW 309L) electrodes manufactured by the company were no longer being produced in the United States and thus would not comply with Buy America regulations. The same electrodes had been used on the Oregon DOT’s A1010 steel plate bridges, but since their fabrication, the electrode production had moved out of the United States. Fortunately, a domestic producer and supplier of 309L electrodes was discovered; this company, Select Arc, Inc., produced an electrode called SelectAlloy 309L-C (SA 309L-C) that could serve as a replacement of the LW 309L electrode. This electrode was similar except that it was a cored wire, designated by the “C” in the name. Table 2 shows where each of these different electrodes was used in the bridge. It should be noted that both welding electrodes and the flux used for the submerged arc welding process are proprietary. It is recognized that future research work could be conducted to determine equivalent materials for future projects.

A limited amount of the LW 309L electrode was used on the Route 340 Bridge because of the Buy America requirements for imported steel in a construction project. VDOT decided to use the LW 309L electrodes for all CJP butt splices since the fabricator already had acceptable prequalification record results using these consumables. All original fillet welds were made using either the LW 309L or SA 309L-C electrodes. All weld repairs were conducted using the SA 309L-C electrode. There was one difference between the wires, which was noted during fabrication. The LW 309L wire was much stiffer than the SA 309L-C wire, which caused some difficulty in moving through some of the fabricator’s wire feeders. Other than that, the performance of the wires was relatively similar.

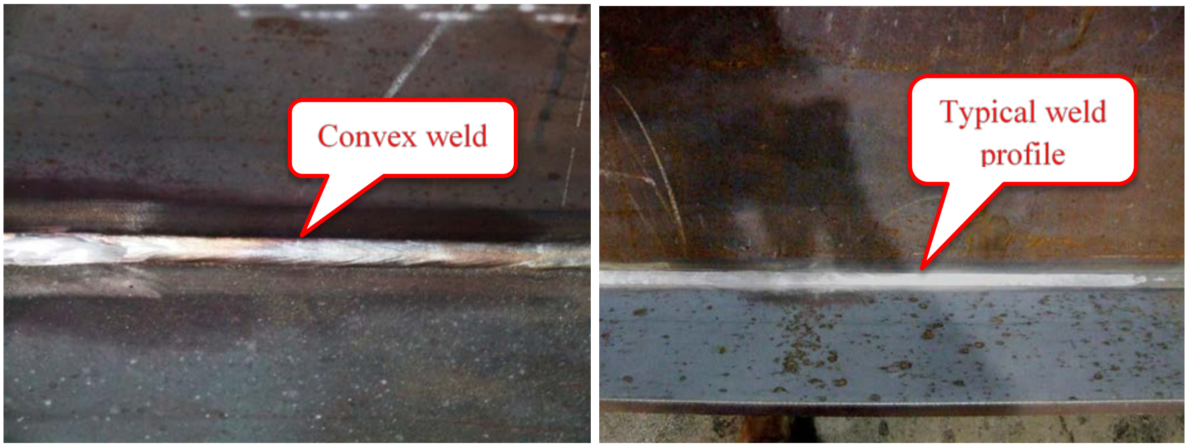
The flux cored arc welding process was used for all repair welds, and the submerged arc welding process was used for all other welds.

Table 2. Weld Description, Location, Technique, Electrode, and Flux/Shielding Used on Route 340 Bridge Girders

Weld Description and Location	Weld Technique	Electrode Wire, Wire Diameter	Flux or Shielding Used
All complete joint penetration welds (splice welds) on web and flanges	Submerged arc process	Lincoln Solid Wire 309/309L, 3/32 in	Lincolnweld Flux 880M
All web-to-flange fillet welds except for the locations described in the next row	Submerged arc process	Select Alloy Flux Cored Wire, 309L-C, 3/32 in	Lincolnweld Flux 880M
Web to flange fillet welds 80 in on the right, near side; bottom flange to web 5/16 in fillet weld and 40 in starting on the left, far side; web-to-flange 5/16 in fillet weld on girder G1A	Submerged arc process	Lincoln Solid Wire 309/309L, 3/32 in	Lincolnweld Flux 880M
Stiffener to web fillet welds on girders: G1A and G2A	Submerged arc process	Lincoln Solid Wire 309/309L, 3/32 in	Lincolnweld Flux 880M
All remaining stiffeners welded to web in girders: G3A, G4A, G5A, G6A, all G1B through G6B, and all G1C through G6C stiffeners to web	Submerged arc process	Select Alloy Flux Cored Wire, 309L-C, 3/32 in	Lincolnweld Flux 880M
Stiffener (bearing area) to web fillet welds on girder: G1B near side on approximately 3 1/2 welds; the solid wire (Lincoln 309/309L) was ground out and replaced	Submerged arc process	Select Alloy Flux Cored Wire, 309L-C, 3/32 in	Lincolnweld Flux 880M
All stiffener to flange fillet welds	Semi-automatic submerged arc process	Select Alloy Flux Cored Wire, 309L-C, 3/32 in	Lincolnweld Flux 880M
All repairs performed	Semi-automatic flux cored arc welding	Select Alloy 309L–AP, 0.045 in	100% CO_2 shielding gas

The CJP butt splices proved to be more challenging when compared to traditional bridge steels. The bevels could not be cut with oxy-fuel based on the fabricator's equipment; therefore, much of the bevel preparation had to be done via manual grinding, which was time-consuming. The CJP welds were constructed using a maximum allowable interpass temperature of 300°F. No specific preheating requirements were given, but the fabricator noted that welding was more effective when sufficient preheating was provided to drive out any moisture; this was also the case for the fillet welds. Once the welds were placed, slag removal on the welds was more difficult than for typical carbon steel welds. This meant more chipping and grinding, which was also time-consuming. The CJP butt splices also had approximately twice the amount of distortion when compared to traditional carbon steel welds because of the austenitic electrode thermal properties, but the fabricator was able to make adjustments for distortion successfully.

The fillet welds were less challenging but did show some differences relative to carbon steel. Originally, the fabricator had elected to construct the web-to-flange welds in the 2F (horizontal) position so that both sides of the web could be welded at once. However, with this position, the 309L electrodes had a propensity to form a convex weld profile. In some cases, the welds met profile requirements, but some had to be repaired. To alleviate this issue, the fabricator elected to weld other web-to-flange connections in the 1F (flat) position. With the 1F position, welds with much more consistent profiles without convexity concerns were produced. Figure 16 shows a photograph of a convex weld profile welded in the 2F position and a typical weld profile welded in the 1F position.



(a) **(b)**

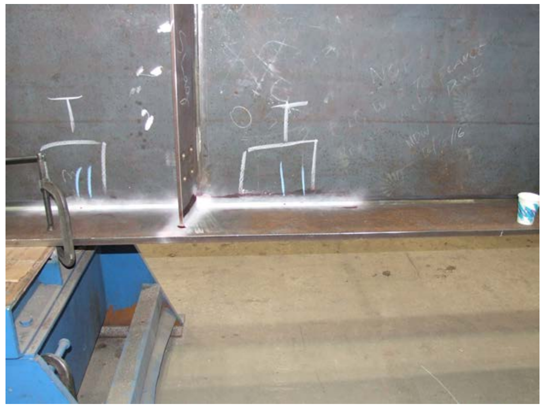
Figure 16. Weld Profiles: (a) convex weld profile produced in the 2F position; (b) typical weld profile produced in the 1F position

NDT

As discussed previously, several NDT techniques were used: UT, RT, PT, and MT. UT provided reasonable results but was sensitive to the difference in density between A1010 steel plate and the electrode metal.

Both film and digital RT were used to inspect the welds. It was quickly evident during the evaluation of the butt welds that when two different plate thicknesses were evaluated with digital RT, the thinner plate would produce an image with artifacts that were not present when the same welds were evaluated using film RT. The manufacturer of the digital RT equipment was consulted, but the cause of the artifacts was not determined. Challenges with digital RT might have been attributable to the difference in microstructure between A1010 steel plate and the electrode metal since A1010 steel plate contains martensite and ferrite and the electrode metal contains austenite. Because of these challenges, the decision was made to use film RT for the remaining portion of the project.

PT was used to inspect both butt and fillet welds for surface indications. As shown in Figure 17a, the contrast between the red penetrant and the white developer allowed for an easy visual identification of areas requiring closer inspection. Figure 17b shows a surface indication that requires repair before the girder is considered acceptable. As expected, PT provided successful results for the fillet welds, although the dye residue was difficult to clean from the welds, which caused it to continue to seep out long after testing took place. MT worked well for evaluating the A1010 steel plate, especially after bending, but it could not be used to inspect the CJP welds because the electrode material is non-magnetic.



(a)

(b)

Figure 17. Penetrant Testing: (a) used to inspect longitudinal web-to-flange weld and transverse stiffener-to-girder weld; (b) close-up of indication found on web-to-flange weld

Shear Studs

Currently, shear studs are not produced in a material similar to A1010 steel plate, meaning that dissimilar metals would be used between the shear studs and plate girder materials. If stainless studs had been used, they likely would have been a Type 304 or Type 316 stainless steel. Instead, carbon steel shear studs were specified for use on the project. This decision was made because the shear studs would be encased in concrete once the bridge deck was cast in the field. This would create an alkaline environment for the shear studs and would prevent them from being exposed to the environment.

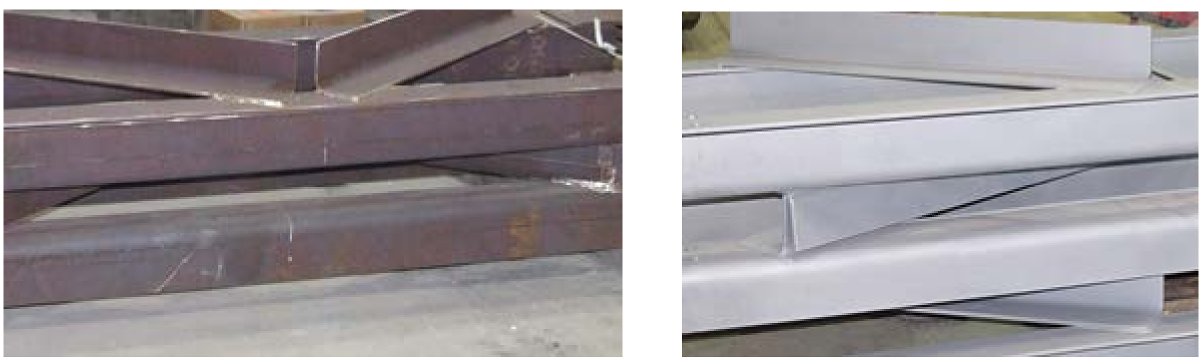
Shear studs can be shop welded for any bridge project, but for this bridge VDOT elected this option because of the better quality control when welding in a shop compared to welding in the field. All of the shear studs were welded to the girders using a stud welding gun. Stud welding locations included the top of the girder top flange (Figure 18a) to provide composite action with the concrete deck and both sides of the girder web to provide a connection with the semi-integral abutments at both ends of the bridge (Figure 18b). In general, attaching the shear studs to the beams went well. However, it was periodically noted that when studs were welded on opposing sides of the web for the semi-integral abutment, some of the studs were not securely attached and had to be re-welded. Although this did not alter the production schedule, it would be beneficial to investigate this issue in greater detail. It is not known if this issue was related to the A1010 steel plate or was simply a result of welding studs to either side of a thin web plate. Overall, welding the shear studs in the shop environment was successful. For future A1010 steel plate bridges, studs could also be welded in the field, depending on Occupational Safety and Health Administration (OSHA) regulations.

(a) **(b)**

Figure 18. Carbon Steel Shear Studs: (a) top flange of beam; (b) top flange and web after mill scale removal

Beam Finish

Early in the fabrication process, the fabricator proposed that VDOT consider using garnet, another nonmetallic blast media, for removing the mill scale rather than the specified aluminum oxide. The fabricator indicated that they had used garnet successfully for other applications. As part of the proposition to change the blast media, the fabricator blast cleaned a welded A1010 steel plate and showed the cleaned plate to VDOT. Figure 19 shows an example of several secondary members before and after cleaning with garnet blast media.

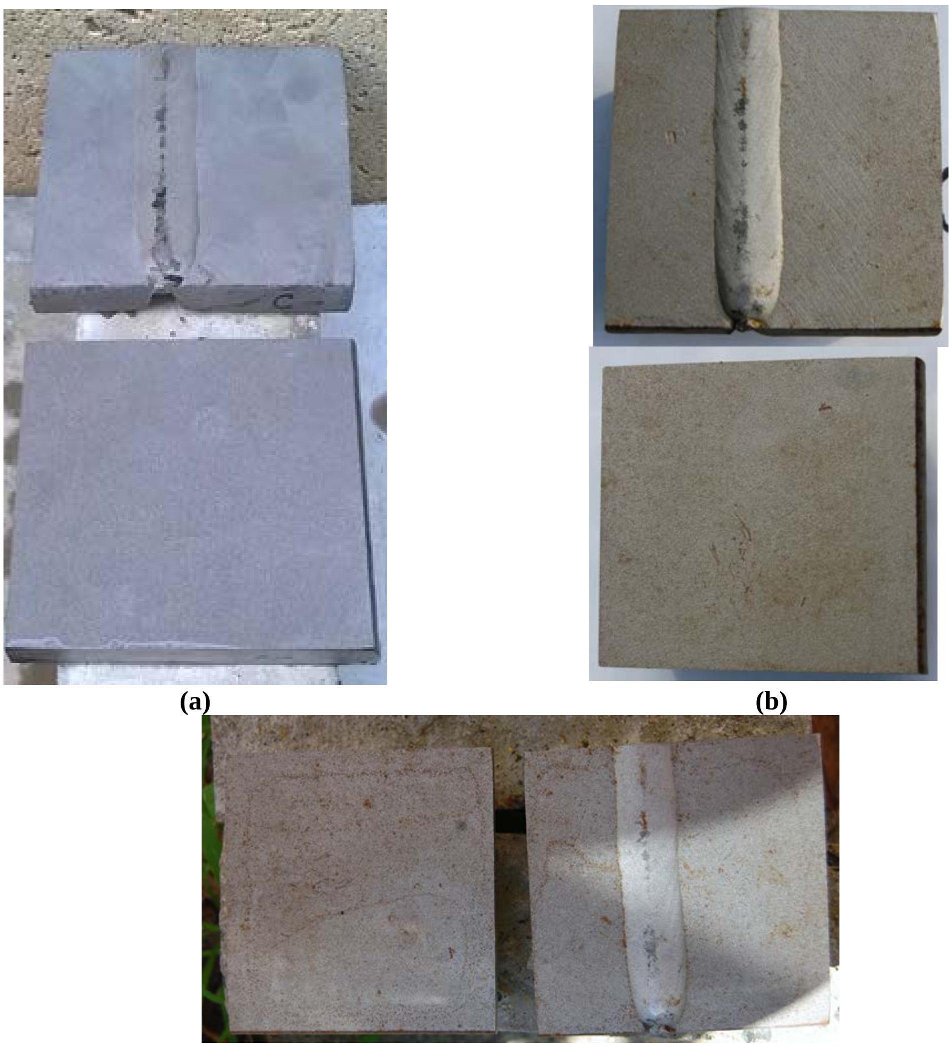


(a) **(b)**

Figure 19. Secondary Members: (a) before being blast cleaned; (b) after being blast cleaned with garnet media to remove mill scale and surface stains

Upon VDOT's observation of the garnet blast-cleaned sample plates, the change in blast media was approved. Since garnet was not originally specified, VDOT wanted to evaluate how the patina on the A1010 steel plate would form with the new blast media. To do this, some small-scale corrosion samples were prepared from the garnet blast-cleaned test plates. The plates were sectioned into specimens and were subjected to two types of corrosion testing: natural environmental exposure, and accelerated corrosion through salt solution exposure.

The natural environmental exposure specimens were placed outside to determine how quickly a rustic patina might form on the surface in the Central Virginia environment. These samples were exposed to moisture from rain and snow events during a 3-year period but were not exposed to salt. As shown in Figure 20, the rustic patina was slow to form.



(a) (b) (c)

Figure 20. Images of Garnet-Blasted A1010 Steel Plate Samples With and Without a 309L Weld Bead: (a) after initial placement outdoors; (b) after 9 months outside; (c) after 3 years of continuous exposure to snow and rain

Since the patina appeared to form extremely slowly under atmospheric conditions, accelerated corrosion tests were performed on the remaining specimens by applying three different solutions to the specimens: tap water, 10% sodium chloride (NaCl), and 10% calcium chloride ($CaCl_2$). The garnet-blasted A1010 steel plate samples were exposed by dipping one-half of each sample in a solution for 30 minutes, removing it, and allowing it to air dry. Photographs were taken the following day before this process was repeated. Samples were not dipped over the weekend but instead remained dry. Samples exposed to tap water showed very little change, but those exposed to either salt solution reacted quickly to form the rustic patina. The response to the different solutions can be seen for tap water in Figure 21, for 10% NaCl in Figure 22, and for 10% $CaCl_2$ in Figure 23. It is interesting and ironic that both saltwater solutions quickly caused the desired rustic patina to form and that solutions traditionally considered detrimental to steel beams could provide a benefit when aesthetics are important.

(a) (b) (c)

Figure 21. Garnet-Blasted A1010 Steel Plate Samples in Tap Water: (a) after 2 days; (b) after 1 week; (c) after 1 month

(a) (b) (c)

Figure 22. Garnet-Blasted A1010 Steel Plate Samples in 10% NaCl: (a) after 1 day, (b) after 2 days; (c) after 9 days

(a) (b) (c)

Figure 23. Garnet-Blasted A1010 Steel Plate Samples in 10% $CaCl_2$: (a) after 1 day; (b) after 2 days; (c) after 9 days

Construction Feasibility

Bolting

Because the Grade B8-2 bolts were able to achieve a clamping force of only 30 kip, rather than the 39 kip of a traditional ASTM A325 bolt, modified acceptance test and tightening methods had to be developed. Results from the previous bolting study (Williams et al., 2017) were used as a starting point, and additional tests were conducted on a Skidmore-Wilhelm bolt tension measuring device to develop these methods.

Both the modified acceptance test and tightening methods were similar to those for ASTM A325 bolts, but they use different values for clamping force, maximum allowable torque, and required nut rotation. In both methods, the turn-of-nut pretensioning method was used for tightening the bolts. The acceptance testing method used for the Grade B8-2 bolts on the Route 340 Bridge is provided in Appendix A. One difference in this method is that for a bolt under a 30-kip tensile load, the maximum allowable torque is 550 ft-lb and for a standard A325 bolt is 710 ft-lb. Another key difference is the required rotation to reach the design clamping force. Table 3 shows the required rotation for the Grade B8-2 bolts and for traditional ASTM A325 bolts for reference.

As shown in the table, the Grade B8-2 bolts required more rotation to reach their design clamping force. The same was true for the ductility check on bolts, which requires a specified rotation to produce 1.15 times the design clamping force in the bolts. Additional information on the acceptance method can be found in Provines et al. (2018).

Table 3. Required Rotation of Bolts to Meet Design Clamping Force

	Bolt Length		
Bolt Type	**$L \leq 4d_b$**	**$4d_b > L \geq d_b$**	**$8d_b > L \geq 12d_b$**
ASTM A193 Grade B8 Class 2	½ turn	⅔ turn	1 turn
ASTM A325	⅓ turn	½ turn	⅔ turn

L = length of bolt; d_b = bolt diameter.

The importance of lubrication was especially apparent during a demonstration acceptance test meeting between the erection contractor and VDOT. The erection contractor compared two types of lubricants on subsequent bolt tests. When the contractor's alternative lubricant was used, the bolt failed to meet the design clamping force and exceeded the maximum allowable torque. When the recommended Never-Seez lubricant was used, the bolt met the required clamping force while remaining below the maximum allowable torque. These results were consistent with those reported by the Oregon DOT, which had used these fastener assemblies for bolted cross-frame connections for one of their A1010 steel plate girder bridges. A photograph taken during the acceptance testing is shown in Figure 24.

Because the Never-Seez lubricant is a proprietary product, additional research is necessary to identify other lubricants that are compatible with stainless steel bolts. Research is currently underway at VTRC to identify additional lubricants, as well as other stainless steel fastener assemblies, that have potential for use in corrosion-resistant bridges.

The bolt installation process went smoothly in the field. Although the rotation and torque requirements were different for the Grade B8-2 bolts than for the standard ASTM A325 bolts, the contractor did not encounter any major issues with the modified tightening procedure. One unexpected challenge that did occur was that the paint from the paint marker used to mark the starting and finishing lines for the nut rotation did not adhere to the stainless steel nuts. Once the nuts began to be tightened, the paint from the marker would rub off such that it was no longer visible. This was resolved by marking the face of the nuts with a center punch tool so that a permanent mark would remain on the nut through tightening. After the nuts were marked with a center punch, the bolt installation process continued without any other challenges. A photograph of the bolted splice installation is shown in Figure 25. Tables of average daily torque values for the bolts during installation are provided in Appendix B.

Figure 24. Acceptance Testing of ASTM A193 Grade B8 Class 2 Bolts


Figure 25. Installation of Stainless Steel Fasteners on Bolted Splice

Bridge Completion Observations

The steel girders were shipped to the jobsite between the end of December 2016 and the beginning of January 2017. An unexpected observation came when the girders were shipped to the jobsite in three shipments over 3 separate days. The first shipment of girders was delivered from Williamsport, Pennsylvania, to the bridge site in Waynesboro on a clear, sunny day. When the girders arrived, they were a distinct gray color. The second shipment of girders was delivered through rain, and the girders appeared mostly gray with some indications of the rustic patina beginning to form. The third and final shipment of girders was delivered through snow showers and, as a consequence, deicing salt that had been applied to the roadway along the delivery route.

When the girders arrived, the patina had already started to form, causing the girders to appear mostly brown. This observation was consistent with accelerated corrosion test results on the garnet-blasted A1010 steel plate specimens: water did not quickly cause a rustic patina to form, but saltwater did. Since the only difference among the shipments of the girders was the environment through which they were delivered, it appears that spray containing deicing salt was kicked up from the roadway onto the girders, which accelerated the formation of the patina.

There were discussions about possibly accelerating the formation of the patina on the girders in the first and second shipment to match those in the third shipment in order to provide a uniform aesthetic on all of the girders; however, the decision was made to allow the patina to form naturally on the girders. It was reasoned that by allowing the patina to form naturally and monitoring it, this would give VDOT a better understanding of how much more slowly the patina forms as the steel corrodes in this environment as compared to uncoated weathering steel beams. Figure 26 shows a photograph of the installation of the stainless steel bolted splice and the various stages of the patina observed during erection.

Overall, the design, fabrication, and construction of the A1010 steel plate members used on the Route 340 Bridge included many successes. The bridge was the first ever to use A1010 steel haunched girders, stainless steel fastener assemblies for a bolted splice, and A1010 steel secondary members. The project showed that a conventional steel bridge fabricator can successfully fabricate a bridge from A1010 steel plate. A second, competitive welding consumable was discovered that complies with Buy America regulations. Other innovative concepts that originated from previous VDOT studies and were used on the Route 340 Bridge include the use of stainless steel mild corrosion-resistant reinforcement in the deck and substructure; a thrust block located near the centerline of the bridge to account for lateral load caused by skew; and high performance concrete with a low permeability concrete mixture and low shrinkage admixture in the bridge deck. The bridge (Figure 27) was opened to traffic in June 2017. The bridge received two awards because of its many innovations: a Prize Bridge Award at the World Steel Bridge Symposium in Baltimore, Maryland, in April 2018, and the VDOT Commissioner's Award for Outstanding Achievement in the Category of Innovation in 2019.

Figure 26. Various Stages of Patina on Steel Girders

Figure 27. Award-Winning Route 340 Bridge in Waynesboro, Virginia

Cost Comparison of A1010 Steel Plate Girders and Conventional Steel Girders Used in Corrosive Environments

The initial estimated unit bid cost for fabrication and erection of the A1010 steel plate girders, derived from the lump sum bid cost for VDOT Item 61800 ["NS (nonstandard) Structural Steel Plate Girder ASTM A1010 Grade 50"] and VTRC estimates of structural steel purchased including waste, was $6.18 per pound. The unit bid cost was subsequently revised using invoice-based fabricated quantities in freight documents, adding about 9.8 tons of A1010 steel plate (as calculated by VTRC researchers) that was purchased for other research, resulting in a total purchased weight of about 384,140 pounds. On this weight basis, a revised unit cost of $5.84 per pound in 2015 dollars was derived from the sum of marginal unit costs attributed to project phases by prime contractor and subcontractor tasks (in 2015 dollars), as given in subcontractor payments (Table 4).

The estimation approach for unit girder cost required that contractor costs be spread over the total weight of the purchased steel whereas the subcontractors' costs were spread over only the weight of A1010 steel plate that was fabricated and erected as the Route 340 Bridge. The result is still an approximation because the weight of A1010 steel plate that was fabricated included both girders and secondary bridge members. Unfortunately, the study was not designed to demonstrate a cost-effective first use of A1010 steel plate but rather to explore the boundaries of feasibility with A1010 steel plate. Nevertheless, the estimated unit costs of the A1010 steel plate girders in this study can be usefully compared with the cost of VDOT's alternative girder options used historically in corrosive environments.

Table 4. Marginal Attributions of Unit Cost of A1010 Steel Plate Girders by Construction Phase (2015 $)

Payee	Contract Bid for Item 61800 ($)	Subcontractor Payments ($)	Value Added ($)	Marginal Cost ($/lb)	Marginal Cost Basis	Share of Unit Cost (%)
Prime contractor	$2,170,000		323,272	0.84	All ASTM A1010 steel	14
Erection subcontractor		1,846,728	121,875	0.33	Fabricated ASTM A1010 steel only	6
Fabrication subcontractor[a]		1,724,853	1,073,117	2.94	Fabricated ASTM A1010 steel only	50
A1010 steel plate manufacturer		497,883	497,883	1.30	All ASTM A1010 steel	22
Freight		39,000	39,000	0.11	Fabricated ASTM A1010 steel only	2
Blast cleaning		30,000	30,000	0.08	Fabricated ASTM A1010 steel only	1
Virginia tax		84,853	84,853	0.23	Fabricated ASTM A1010 steel only	4
Total			$2,170,000	$5.84		100%

[a] Fabrication cost included cost of fastener assemblies.

Project documents provided the detail shown in Table 4 for the allocated marginal costs of the A1010 steel plate girders in the Route 340 Bridge. “Value added” at each construction phase is defined as the net contractor or subcontractor payment, and “marginal cost” is “value added” spread across the relevant marginal cost basis (i.e., relevant pounds of A1010 steel plate) in an effort to disentangle the total quantity of purchased A1010 steel plate from the quantity of A1010 steel plate actually used in the girders. VDOT correctly anticipated that the dominant share of girder unit cost would be for girder fabrication, where fabrication costs were net of freight, blast cleaning, and state tax costs because those costs were itemized in project documents or discussions and could be set apart. Fabrication is estimated here to have accounted for 50% of the estimated unit cost of the girders. At almost $1.30 per pound at the time of the contract award in late 2015, the A1010 steel plate material accounted for about 22% of the estimated unit cost of $5.84 per pound in the winning bid (2015 dollars), as shown in the last column. In other words, girder fabrication, blast cleaning, shipment, erection, and state taxes added $4.54 per pound, or 78% of the unit cost. Adjusted for construction cost inflation since December 2015, the $5.84 per pound bid cost would be $6.58 per pound in 2019 dollars.

Table 5 is a compilation of VDOT’s inventory of steel girders and beams purchased over the period 2008-2019 and gives weighted average costs by category of girder steel and finish. Had the Route 340 Bridge not been a research project, the girders might have been advertised with galvanized ASTM A709 Grade 50W (VDOT Item 61812, galvanized) because of federal guidance recommending against using uncoated weathering steel in proximity to an industrial site or with 8 ft or less of clearance over moving water (FHWA, 1989).

Table 5. Inflation-Adjusted Weighted Average Bid Costs by Girder/Beam Item Code and Surface Treatment, 2008-2019 (2019 $)

Steel Grade[a]	Item Code	Surface Treatment	Minimum ($/lb)	Median ($/lb)	Maximum ($/lb)	No. of Projects	Total Pounds
Structural Steel Plate Girders							
50	61811	Galvanized	1.89	4.31	4.77	1	71,310
		Painted	4.04	4.47	5.08	10	1,863,470
50W	61812	Galvanized	2.90	2.95	3.45	1	100,400
		Partial paint	1.63	2.24	2.79	28	28,422,900
		Unpainted	1.74	2.18	2.73	77	51,716,310
HPS50W	61813	Partial paint	1.59	5.76	9.66	1	105,000
HPS70W	61814	Unpainted	2.00	3.07	7.11	2	965,600
Structural Steel Rolled Beams							
50	61821	Galvanized	2.25	2.87	3.71	72	1,777,205
		Painted	2.17	3.95	7.00	5	177,560
		Plain	0.76	1.14	1.64	1	68,343
50W	61822	Painted	2.69	3.18	3.62	1	69,000
		Partial paint	2.59	2.97	3.79	8	675,430
		Unpainted	1.91	2.11	2.55	6	1,029,900
Structural Steel Plate Girders							
36	68106	Painted	8.95	12.12	20.15	1	13,393
50	68107	Galvanized	3.87	3.87	3.87	1	76,000
		Metalized	2.79	3.15	4.31	1	140,100
		Painted	2.58	3.00	4.13	10	4,025,100
50W	68108	Painted	1.99	2.71	3.32	1	2,548,600
		Partial paint	2.13	2.47	3.18	9	7,367,580
		Unpainted	1.46	1.61	2.44	12	4,094,190
Structural Steel Rolled Beams							
36	68112	Painted	7.27	10.06	11.72	4	78,827
50	68113	Galvanized	2.78	3.35	4.44	23	1,608,470
		Metalized	3.43	3.60	3.95	2	179,500
		Painted	3.55	4.36	5.69	7	287,840
		Plain	4.56	6.53	17.32	1	61,800
50W	68114	Partial paint	2.54	3.02	3.54	6	480,050
		Unpainted	2.27	2.84	4.06	6	585,900

[a] All ASTM A709.

Judging by the inflation-adjusted median cost of Item 61812 (galvanized) in Table 5, these girders could have cost less than 50% of the cost of the A1010 steel plate girders in the construction phase, in 2019 dollars. However, the only VDOT project that used galvanized Grade 50W girders (the Genito Road Bridge) was constructed in 2011 and seems unlikely to represent the 2019 cost of galvanized Grade 50W girders (Provines et al., 2019). In the absence of more data points, empirical conclusions are beyond reach regarding the relative costs of galvanized weathering steel plate girders versus A1010 steel plate girders.

The A1010 steel plate girder cost premium is slightly less unfavorable if compared with that of painted Grade 50 girders, VDOT Item 61811 (painted). Life-cycle costs of A1010 steel plate girders have typically been compared analytically with this alternative, most recently in Daghash et al. (2019). Based on median weighted unit costs in Table 5, painted Grade 50 girders (VDOT Item 61811, painted) could have cost about 68% of the cost of A1010 steel plate girders in the construction phase, in 2019 dollars.

The bridge plans provided details on bridge beams as well as bridge girders in VDOT's inventory. A comparison of the median cost data for Grade 50 steel beams (VDOT Item 61821) in Table 5 suggests that a galvanized or paint coating came at double or triple, respectively, the median cost of a plain Grade 50 beam for VDOT. Judging by Table 5, however, galvanized or painted Grade 50 beams still cost only 44% or 60%, respectively, of the cost of the A1010 steel plate girders in the Route 340 Bridge, in 2019 dollars. It should be noted that nearly 79% of the 1.95 million total pounds of Grade 50 beams, VDOT Item 61821, consisted of SS-8 (steel girder bridge with timber deck) kits procured in eVA, Virginia's electronic advertising and procurement system, and that nearly all of these beams were galvanized.

In the VDOT inventory data underlying Table 5, individual projects with uncoated Grade 50W steel girders (VDOT Item 61812, typically subject to partial paint requirements of Section 407 of the VDOT specifications) can be found with a girder weight comparable to that of the Route 340 Bridge project. In these like-sized projects, uncoated weathering steel girders have median weighted average unit bid costs of about 36% of the unit cost of the A1010 steel plate girders, in 2019 dollars. As noted previously, these girders are not considered acceptable alternatives to more corrosion-resistant girders in aggressively corrosive environments, but their actual costs may be adjusted for additional (corrosion-inhibiting) surface treatments as described in the following discussion. These hypothetical adjusted costs can then be compared to the costs of the A1010 steel plate girders in the Route 340 Bridge project.

In a presentation at the 2017 annual meeting of the Transportation Research Board, a fabricator estimated the cost premium for a full paint coating on weathering steel to be 25% (R. Medlock, personal communication), suggesting that the hypothetical weighted median cost of an unpainted Grade 50W girder taken from Table 5 (VDOT Item 61812, unpainted) would increase if the girder had a full paint coating to about $2.73 per pound, or 41% of the A1010 steel plate girder unit cost (2019 dollars). The cost premium for galvanizing a weathering steel girder is about 47% according to the fabricator, resulting in a galvanized Grade 50W girder hypothetical weighted median cost of about $3.08 per pound, or 47% of the A1010 steel plate girder unit cost (2019 dollars). This hypothetical median cost for galvanized weathering steel girders exceeds the actual inflation-adjusted unit bid cost of $2.95 in the only such project in VDOT's experience, but as discussed previously, the 2011 project cannot be assumed to represent such costs accurately in 2019.

The surface treatment premiums provided by the fabricator allowed comparisons by project size (i.e., girder pounds installed) of the cost of the A1010 steel plate girders and the hypothetical costs of painted or galvanized Grade 50W steel girders (VDOT Item 61812), corrosion-resistant finishes that are practically nonexistent in VDOT's actual inventory. Figures 28 through 31 show these results. The A1010 steel plate girder cost can also be compared by project size with the actual unit bid costs of Grade 50 steel girders (VDOT Item 61811) that were painted or galvanized, finishes that are practically ubiquitous for Grade 50 steel girders in VDOT projects. Figure 32 shows these results. All comparisons in Figures 28 through 32 were adjusted for inflation and are therefore in equivalent 2019 dollars.

As a baseline, the scatter plot in Figure 28 shows actual minimum and median unit bid costs for unpainted Grade 50W steel girders (VDOT Item 61812) over 2008-2019; the A1010 steel plate girder unit cost is also shown. The few projects with more than 500,000 pounds of steel were excluded as irrelevant, given the size of the Route 340 Bridge project. In Figures 29 and 30, the baseline unpainted Grade 50W steel girder bid costs in Figure 28 are escalated by the painting or galvanizing cost premiums indicated by the fabricator (24% or 41%, respectively). Figure 30 also shows the unique 2011 Genito Road Bridge galvanized Grade 50W girder unit bid costs (in 2019 dollars). These results show that the actual unit cost of the A1010 steel plate girders in the Route 340 Bridge project was far higher than the hypothetically escalated cost of painted or galvanized Grade 50W steel girders according to the fabricator's cost premiums.

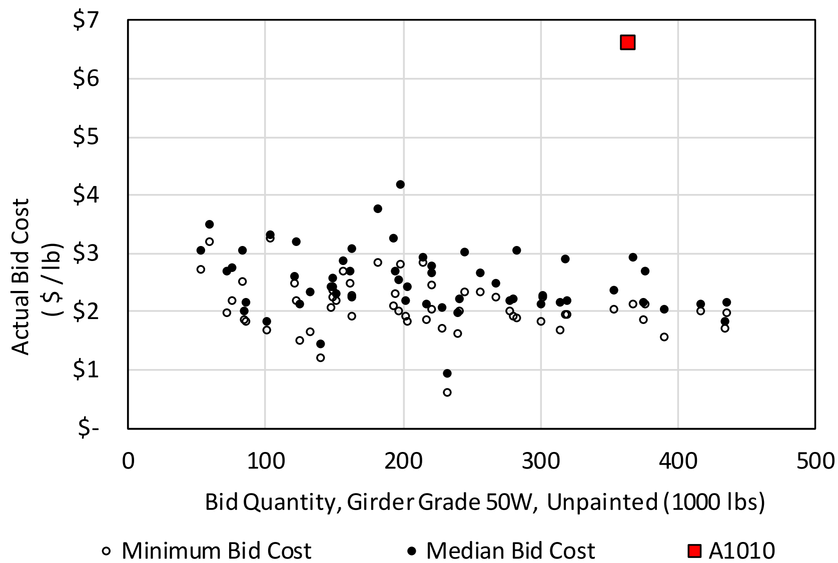


Figure 28. VDOT Project Bid Quantities and Costs, Girders Grade 50W (VDOT Item 61812), Unpainted, 2008-2019 (2019 $)

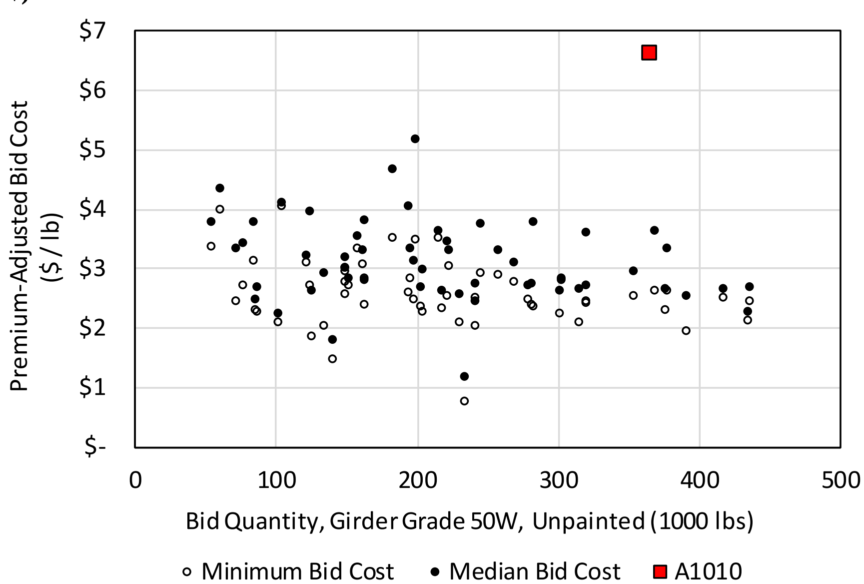


Figure 29. VDOT Project Bid Quantities and Costs, Girders Grade 50W (VDOT Item 61812), Unpainted, With Painting Cost Premium Added, 2008-2019 (2019 $)

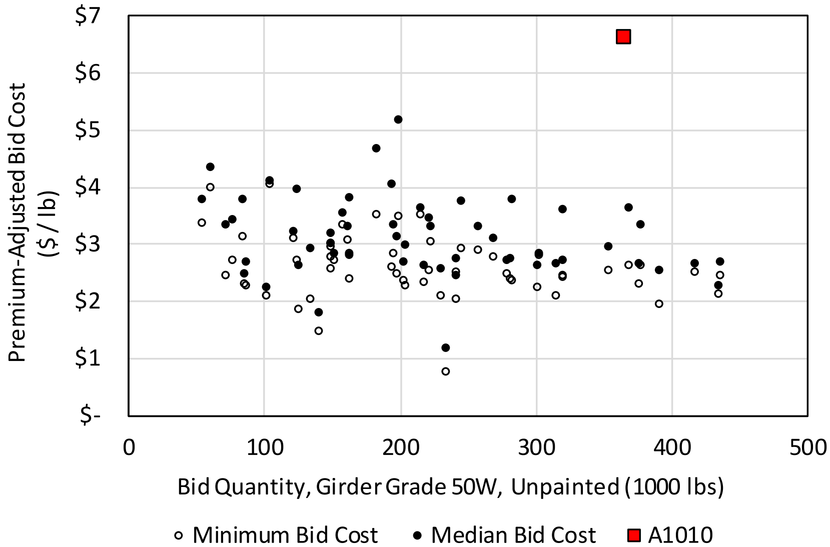


Figure 30. VDOT Project Bid Quantities and Costs, Girders Grade 50W (VDOT Item 61812), Unpainted, With Galvanizing Cost Premium Added, 2008-2019 (2019 $)

Comparing like-sized projects, in Figure 29 the painted Grade 50W steel girder hypothetical median unit cost for installed girders of comparable weight to the Route 340 Bridge girders (around 350,000 pounds) is only about 55% of the unit cost of the A1010 steel plate girders (and the minimum unit cost is a lower percentage). Figure 30 shows that the galvanized Grade 50W steel girder hypothetical median unit cost for a comparable girder line item is about 62% of the unit cost for the A1010 steel plate girders. In other words, in both comparisons the A1010 steel plate girders in the Route 340 Bridge are significantly costlier than the median unit costs of the hypothetically surface-treated comparators.

Figure 31 shows that the costs of the A1010 steel plate girders are more similar to the maximum bid costs for unpainted Grade 50W steel girders with hypothetical painted or galvanized surface finishes. In fact, for only a slightly larger project than the Route 340 Bridge in terms of girder pounds bid, the maximum unit bid costs would have exceeded the A1010 steel plate unit costs had the weathering steel girders been required to be painted or galvanized at the cost premiums quoted by the fabricator. Maximum bids for major conventional contract items are seldom correlated with awarded contracts, but the comparison places the first-use unit costs of the A1010 steel plate girders in a familiar context for VDOT.

It is more interesting to compare the A1010 steel plate girder unit cost with VDOT's actual unit costs of Grade 50 steel girders that were actually bid with protective surface treatments. Figure 32 shows minimum bid cost data for painted Grade 50 steel girders (VDOT Items 61811 and 68107 in Table 5) compared to the unit cost of the A1010 steel plate girders in the Route 340 Bridge, all in 2019 dollars. Each item code featured a single galvanized girder project during the period 2008-2019, and minimum bids for these projects are also shown. Figure 32 suggests that the estimated unit cost of the A1010 steel plate girders is consistent with an upper limit of actual minimum unit bid costs (dotted line) for painted Grade 50 steel girders in VDOT's experience.

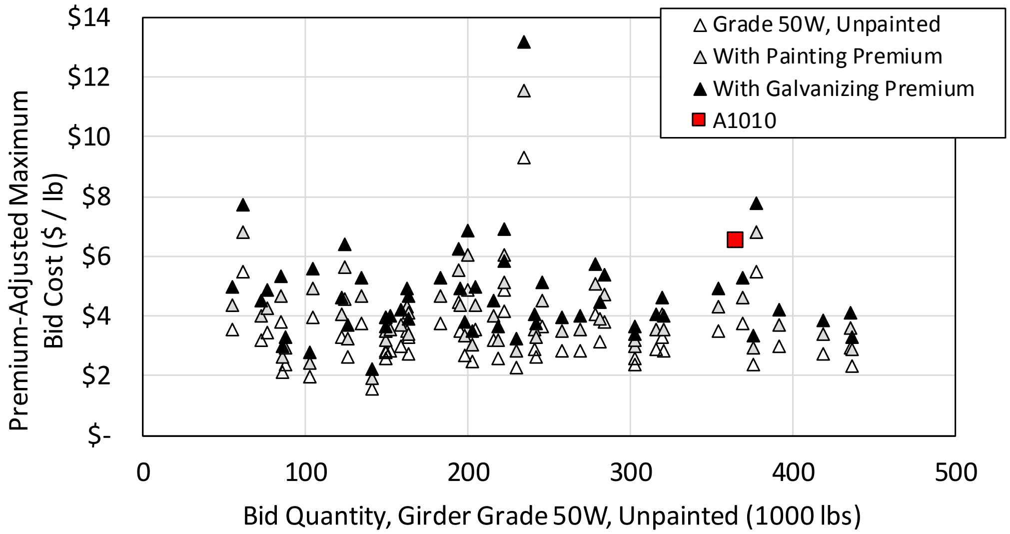


Figure 31. VDOT Project Bid Quantities and Maximum Unit Bid Costs, Girders Grade 50W (VDOT Item 61812), Unpainted, With Galvanizing and Painting Cost Premiums Added, 2008-2019 (2019 $)

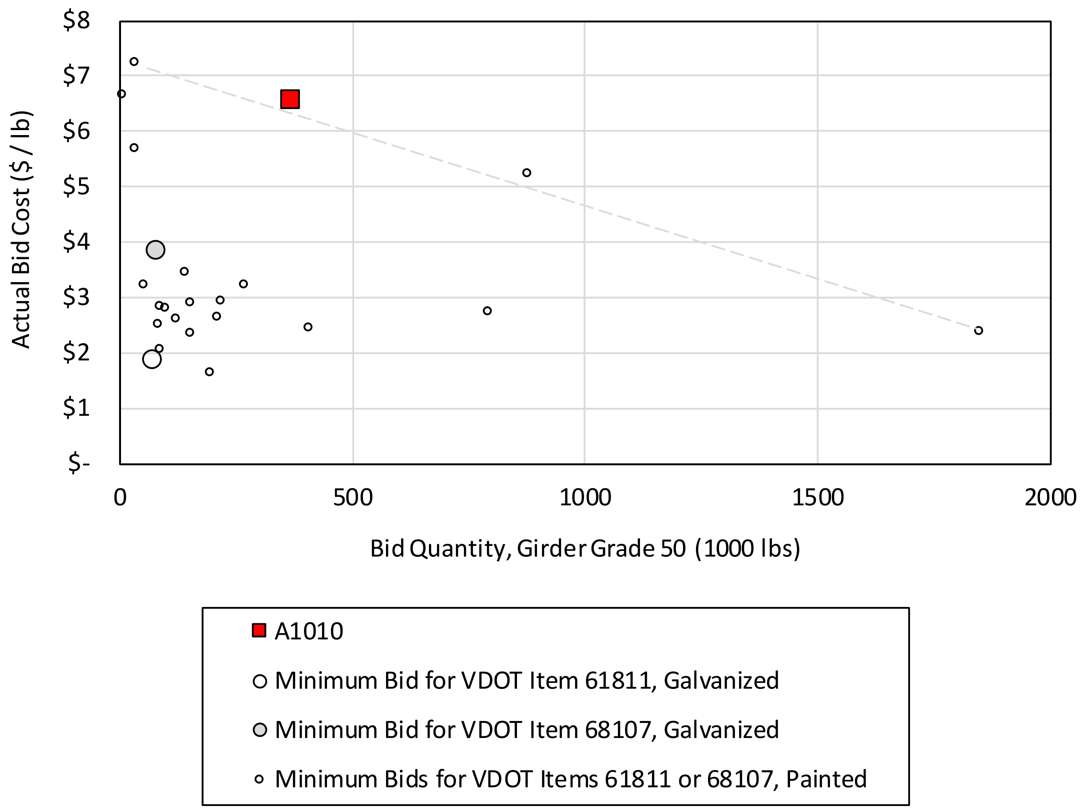


Figure 32. VDOT Project Bid Quantities and Minimum Unit Bid Costs, Girders Grade 50 (VDOT Items 61811 and 68107), Painted or Galvanized, 2008-2019 (2019 $). The dotted line indicates a linear downward trend in upper minimum bid values for VDOT Item 61811, Painted, as bid quantities increase.

The comparison of painted Grade 50 steel girders with A1010 steel plate girders is common in theoretical life-cycle cost analyses that have been performed to encourage market penetration of A1010 steel plate because of its inherent corrosion-resistance over its expected long and low-maintenance service life. The life-cycle cost superiority of A1010 steel plate is invariably demonstrated because of the cumulative impact of lifetime recoating costs for Grade 50 steel girders (Daghash et al., 2019; Okasha et al., 2012). In these analyses, however, A1010 steel plate girders are always costlier than painted Grade 50 steel girders at the construction stage, and cost advantages of the A1010 steel plate girders appear only in the long run. By contrast, Figure 32 suggests that A1010 steel plate girders could be cost-competitive with painted Grade 50 girders at the construction phase, depending on project specifics and bids.

Table 4 suggests that girder fabrication contributed one-half of the unit cost for the A1010 steel plate girders. In general categories, some degree of fabrication cost premium for these girders was anticipated through material, design, process, and human factors that were flagged in open meetings, discussions and inspector documentation before, during, and after the Route 340 Bridge construction. The factors listed here were identified as potential cost drivers for the project.

Material Factors

1. The purchased volume of A1010 steel plate required for the project was boosted by plate to be used for secondary members, adding as much as 30% to the unit cost of the installed girders by one estimate. The fabrication of these secondary members from A1010 steel plate was a research cost since in other A1010 steel plate bridges, secondary members have been fabricated of galvanized Grade 50 or uncoated Grade 50W steel. The A1010 steel plate had to be bent by the fabricator into structural shapes for the secondary members since they are not available in A1010 steel plate. The plates for the secondary members were bent successfully by the fabricator, however, resulting in the establishment of a low-risk benchmark for the previously unknown process and removal of that source of process uncertainty for other fabricators.

2. VDOT specified stainless steel bolts with reduced clamping force after installation, introducing several cost deltas of unknown magnitude to the superstructure bid cost. Installation requirements needed to be determined; the availability of materials for fastener assemblies that were compliant with Buy America regulations was unknown; turn-of-the-nut requirements added extra labor cost; and the reduced design clamping force led to a greater quantity of bolts needed. At the time the Route 340 Bridge was under construction, stainless fastener assemblies were expected to add 20% above conventional fastener costs to the project, and the choice of fasteners was left to the erection subcontractor. A related 2017 study (Williams et al., 2017), however, established that the ASTM A193 Grade B8 Class 2 bolts were compliant with Buy America regulations, mechanical properties, and cost-effectiveness relative to other stainless steel fasteners for use with A1010 stainless steel plate, reducing both search and risk costs for future projects. Follow-on bolt studies from VTRC will provide further guidance on materials for fastener assemblies in contact with A1010 steel plate girders that may lead to cutting this cost component significantly.

3. Buy America regulations led the fabricator to identify a welding consumable that was superior to the original material in several ways, including availability and workability, two important elements for preserving critical path fabrication plant scheduling.

Design Factors

1. The variable web depth in the haunched girder design created some steel plate "waste" from the standpoint of material usage. However, in this bridge, as in other bridges of uncoated weathering steel, the haunch was the preferred design because it allowed increased web depth only over the pier rather than across the entire span. The haunch at the pier prevented the need for a significant increase in flange thickness or an increase in web depth across the entire span. The former would have caused a significant cost increase for structural steel on the project and the latter was effectively prohibited by the site constraint, i.e., the clearance required above the floodplain and the riverside shared use path (and even if possible would have entailed an increase in A1010 steel plate material and thus total cost as well). In summary, the haunch design may be considered an "extra" cost of the Route 340 Bridge that was more required than truly optional.

2. The A1010 steel plate in the Route 340 Bridge was designed in six thicknesses ranging from 0.2 in to 2 in. Although extra cost associated with variable thickness was not anticipated, reducing the number of different plate thicknesses in a future design is a practical approach to reduce material costs.

Process Factors

1. Blast cleaning with aluminum oxide was originally specified by VDOT but was performed by the fabricator with garnet at a higher cost with VDOT's permission. Future unit costs can be expected to be lower if blast cleaning to remove mill scale is not specified at all, instead allowing the natural surface patina to form. This practice may be preferable since an unanticipated difference in road weather conditions during the second and third girder shipments caused differential impacts on some girders, resulting in an uneven girder patina in the newly erected bridge.

2. Hexavalent chromium is released as a dust, fume, or mist upon welding stainless steel and nonferrous chromium alloys. An OSHA Fact Sheet (OSHA, 2006) states that breathing small amounts of the toxin is not problematic for most people even with prolonged exposure. For greater occupational exposure, OSHA has standards that require employers to limit exposure in the workplace; monitor exposure every 6 months if initial exposure levels reach the specified action level; provide protective equipment (including respiratory) and clothing; implement effective hygiene and housekeeping practices; and provide periodic medical examinations including at employment termination (OSHA, 2006). Employee rotation to limit exposure is expressly forbidden by OSHA, with implications for work hours and labor costs. In the Route 340 Bridge project, a welder reported that the two different sources of

welding consumables that had been used had very different levels of hexavalent chromium emissions, one high enough to require both respirators and fume extractors and the other low enough that a respirator was optional. It seems unlikely that fabricator costs related to mitigation of occupational hexavalent chromium exposure will be subject to a high degree of variability or that competitive contract bidding or fabrication experience will reduce those costs significantly.

3. Welding of A1010 steel plate in the Route 340 Bridge project was considered challenging enough to constitute an embedded, independent research project regarding which more detail is provided elsewhere in this report. One of VDOT's most important goals in the study of A1010 steel plate was to achieve satisfactory welds, requiring additional relatively stringent anti-contamination measures at the fabrication plant. Experience gained in this research project, however, established welding parameters for fabrication of A1010 steel plate bridge elements in the future, including significant labor improvements by means of certifying satisfactory interpass temperatures. As a bonus, if extensive blasting is not required in the future, requirements to minimize carbon contamination will be further reduced.

Human Factors

1. Welders had prequalified for the horizontal welding position, but persistent convexity of these welds eventually required a transition to the flat welding position in which relatively inexperienced welders were not expert. In fact, an inspection report states that final repairs by experienced welders to initial repairs by inexperienced welders "added many additional man hours."

2. The newly blast-cleaned girders required re–blast cleaning (estimated by the inspector at 30 to 40 person-hours) because of accumulation of carbon particles on the girder surfaces during storage in the fabrication bay, causing rapid rusting when the girders were moved outside. If limited blast cleaning becomes the rule for A1010 steel plate, this labor and material cost will be largely avoidable in the future.

3. Because of material cost and limited availability, excessive care may have been a factor in the higher fabrication cost in this project.

A1010 stainless steel plate is literally in a class by itself compared to VDOT's conventional girder materials. Unfortunately, its unit cost in the Route 340 Bridge project was double the unit cost of hypothetical galvanized weathering girders (after a 41% cost premium over unpainted Grade 50W steel for galvanizing was added). Research gains in the cost categories and issues noted seem to offer ready opportunities for cost reductions now that A1010 steel plate fabrication can be moved confidently beyond the "risk"-fraught research phase, particularly if smaller steel fabricators become familiar with the technology and methods required for safe work with stainless steel.

For savings to become nontrivial, Table 5 suggests that the most practical first step might be expansion of the use of A1010 steel plate on a smaller scale, including in projects in which state forces directly provide bridge erection, to eliminate the need for high-share prime contractor project managers. Small projects could also foster supply lines from smaller fabricators and possibly near-specialization, allowing further reductions in unit costs while still being profitable. Finally, since ASTM A709 Grade 50CR steel (which is how A1010 steel is currently being specified) is not proprietary, smaller producers should be encouraged to investigate this line of material. Although these events are far from certain to occur—let alone to occur soon—without VDOT's active facilitation, it is certain that if VDOT does not act to reduce and remove barriers to entrance into both the fabrication and supply of this material, its high cost could easily persist.

Figure 33 shows that most of VDOT's bridge girder and beam material requirements over 2008-2019 consisted of unpainted and partially painted Grade 50W steel, i.e., VDOT Item 61812UP (unpainted) or VDOT Item 61812PP (partially painted). Yet these girders will require a significant maintenance expense to prevent or mitigate corrosion over their full service life and are contraindicated in aggressively corrosive environments.

Notwithstanding the high unit bid cost of the first application of A1010 steel plate in bridge girders, it was nonetheless more cost-effective relative to the estimated cost of the main corrosion-resistant alternative (galvanized Grade 50W steel plate girders) than were the first CFRP-reinforced concrete bulb-T beams installed in a bridge in Halifax County in 2014. In the latter project, the CFRP beams cost more than 200% of the statewide average for the conventional alternative beams and nearly 300% of a fabricator's concurrent quote for the same.

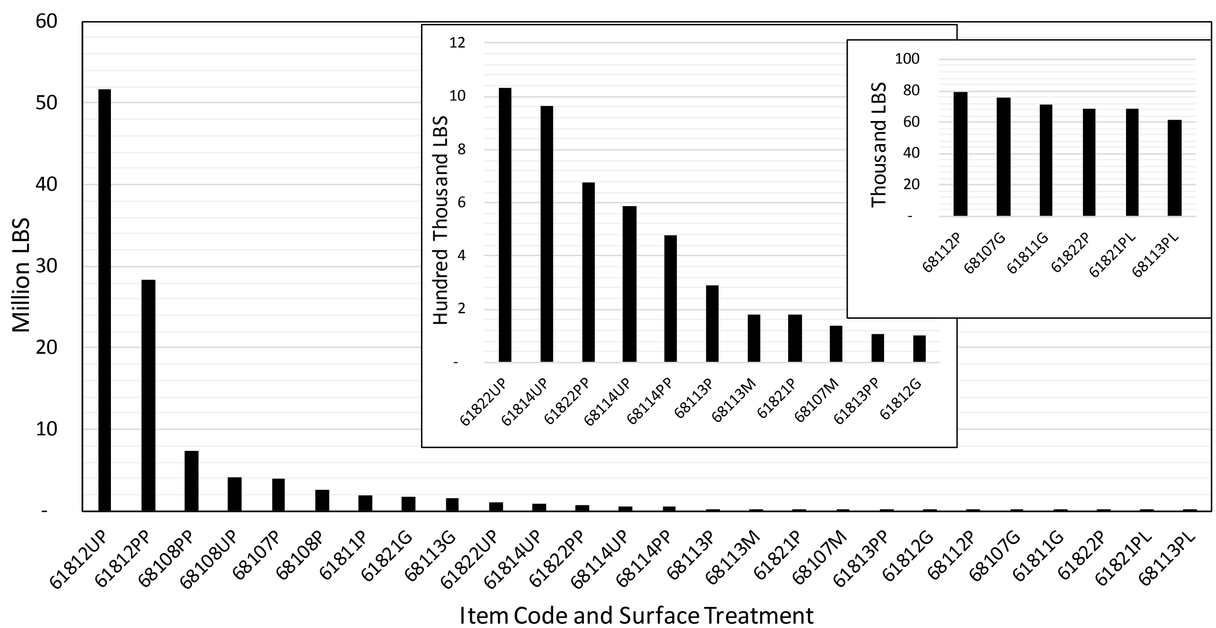


Figure 33. Total Bid Quantities of Girders and Beams in Competitive Bid VDOT Projects by Item Code, 2008-2019. G = galvanized; M = metalized; P = painted; PL = plain; PP = partial paint; UP = unpainted.

In contrast, the estimated median unit cost of a hypothetical galvanized Grade 50W steel girder in a project of a size comparable to that of the Route 340 Bridge was 62% of the cost of the A1010 steel plate girders; thus the A1010 steel plate girder cost was about 160% of the cost of the hypothetical galvanized Grade 50W steel girders. CFRP costs have since fallen to compete with other premium materials in recent VDOT bridge construction projects. Under similar competitive circumstances, the same may be expected of A1010 steel.

Future Applications

Based on VDOT's need, project observations about fabrication, and construction feasibility and cost analyses, VDOT's special provision on the use of A1010 stainless steel plate was revised. The revised special provision incorporated the newly adopted reference, ASTM A709 Grade 50CR, which allows A1010 steel plate to be specified easily as a bridge steel. The revised special provision is provided in Appendix C. It is being used for two current VDOT projects incorporating Grade 50CR steel plate girders in bridges. One project, in the Hampton Roads region, is a low-clearance brackish tidal river crossing located close to the Chesapeake Bay. The other project, in Northern Virginia, comprises a rehabilitation of a historic truss structure. VDOT's Structure and Bridge Division has also incorporated Grade 50CR steel into its office practices, which encourage using the steel in applications where uncoated weathering steel is not expected to perform well.

CONCLUSIONS

- *A1010 steel plate can be bent successfully to a 2.5t radius (where t = plate thickness) without causing damage to the bent regions.*

- *Flanges fabricated from A1010 steel plate can be bent for haunched girders.*

- *Cross frames using bent plates instead of rolled channels and rolled angles can be fabricated.*

- *Stainless steel bolts cannot develop clamping forces equivalent to that of Grade A325 bolts of the same diameter. Modification to bolted splices designed in accordance with the AASHTO LRFD Bridge Design Specifications must be considered because of the lower clamping force in stainless steel bolts.*

- *Removal of mill scale adds to the cost of A1010 plate girder fabrication and does not guarantee uniform patina formation.*

- *Rustic patina formation on garnet-blasted surfaces is relatively slow except in the presence of chloride-containing solutions, when it occurs faster.*

- *Type 309L electrodes that comply with Buy America regulations were readily available at the time of the Route 340 Bridge fabrication.*

- *Shear studs were successfully welded in the fabrication shop, and proof-testing should be conducted on field-welded studs to merit changing from shop to field installation.*

- *Several NDT techniques, i.e., PT, UT, and RT, were successfully used to identify defects within welds, but additional research on UT and RT is warranted.*

- *The estimated unit cost of the A1010 steel plate girders was about 60% more than the estimated median unit cost of the alternative of galvanized weathering steel girders; this is a more favorable comparison than has been found for other premium materials in a first trial for VDOT, such as the 100% cost delta with CFRP-reinforced concrete bulb-T beams over conventional concrete bulb-T beam alternatives.*

RECOMMENDATIONS

1. *VDOT's Structure and Bridge Division should work with VTRC to revise the VDOT Manual of the Structure and Bridge Division, Part 2: Design Aids and Typical Details, Chapter 11 (VDOT, 2018), to provide design guidance for an ASTM A709 Grade 50CR (formerly A1010) steel plate girder equivalent to that provided for a typical carbon steel plate girder.*

2. *VTRC should work with VDOT's Structure and Bridge Division and one or more VDOT districts to prepare a bid (or bids) for a group of bridge replacement structures that are being replaced because of accelerated corrosion, shortening bridge life, to determine if the use of ASTM A709 Grade 50CR steel plate girders could be a cost-effective strategy for reducing the number of VDOT's structurally deficient bridges over a 75-year life cycle.*

3. *VDOT's Structure and Bridge Division should specify ASTM A709 Grade 50CR steel as an alternative design option to prestressed concrete beams reinforced with CFRP in design-build projects and projects under Virginia's Public-Private Transportation Act in highly corrosive environments to increase competition among corrosion-resistant girder options.*

IMPLEMENTATION AND BENEFITS

Implementation

Implementation of Recommendation 1 will include the addition of design and fabrication guidance for using ASTM A709 Grade 50CR steel specifically with regard to differences from other A709 steels (carbon steel) girders. VDOT's Structure and Bridge Division has already incorporated Grade 50CR steel into the VDOT *Manual of the Structure and Bridge Division* (VDOT, 2018). Additional design and fabrication guidance in the manual will come from numerous ongoing VTRC research projects and planned specification updates. First, within 1 year of the publication of this report, another report will be published by VTRC on the characterization of the slip coefficient of slip critical bolted connections constructed of either

Grade 50CR or Grade 50CR and other ASTM A709 steels. Second, within 1 year of the publication of this report, another report will be published by VTRC on welding Grade 50CR with different electrode materials. Third, within 2 years of the publication of this report, yet another report will be published by VTRC on the mechanical and corrosion properties of corrosion-resistant bolts for Grade 50CR steel bridge applications, including guidance and recommendations for their use. Fourth, within 4 years of the publication of this report, AASHTO/AWS will publish an updated version of the D1.5 Bridge Welding Specification that includes guidance for welding Grade 50CR connections. Findings from each of these reports will be incorporated into the VDOT *Manual of the Structure and Bridge Division* (VDOT, 2018), which will provide VDOT districts with the information necessary to design and fabricate Grade 50CR steel plate girders. Implementation of Recommendation 1 will be completed within 5 years of the publication of this report. Upon completion of the aforementioned research and specification updates, revisions to the VDOT *Manual of the Structure and Bridge Division* (VDOT, 2018) should allow district structure and bridge engineers to grant approval for the design waiver needed for use of Grade 50CR steel.

VTRC is currently working with the Hampton Roads District on a single replacement structure (Jenkins Bridge Road Bridge) constructed with steel girders and a timber deck. The Richmond, Hampton Roads, Fredericksburg, and Culpepper districts have all expressed interest in replacing a group of low-volume, steel beam and timber deck bridges using Grade 50CR steel. These districts have offered to work with VTRC to group approximately five of these bridges within a single bid specification. Implementation of Recommendation 2 appears ready for projects with low traffic volume or a timber deck or where concrete bridge beams are not feasible because of low load capacity abutments, girder weight restrictions, or girder depth constraints. These projects should be erected by VDOT state forces. The VDOT districts could make a single order of steel, potentially at a cost reduction, after determining the structures that will need to be replaced within a fiscal year. The girders can be kept on-site without exposure concerns until a construction opportunity arises. It is possible that bids from multiple districts could be released at the same time, which would increase the quantity of work for a fabricator to bid on. Superstructure replacement of steel beam timber deck structures include road closures and can take approximately 1 week. Using Grade 50CR steel girders would allow future maintenance of these structures to include only a deck replacement, which could limit road closure to approximately 1 day. The improved performance of the superstructure would reduce maintenance over the life of the bridge and since past superstructure replacements have often been preceded by significant load reductions, there would be more uniform access for emergency and other heavy trucks over 75 years.

Implementation of Recommendation 2 will occur within 4 years of the publication of this report.

Implementation of Recommendation 3 will specify that VDOT's Structure and Bridge Division stipulate that acceptable options for highly corrosion-resistant girder materials consist of Grade 50CR steel plate and CFRP-reinforced prestressed concrete. Ideally, the specification of an option of Grade 50CR girders would be implemented gradually from smaller to larger projects. By allowing the use of Grade 50CR on design-build projects and projects under Virginia's Public-Private Partnership Act, competition would be promoted between highly corrosion-resistant premium materials that have been specified for use by VDOT. Implementation of Recommendation 3 should be phased in within 5 years of the publication of this report to allow adequate time for ongoing research to be completed and incorporated into bridge design specifications and welding specifications and for increased experience with Grade 50CR steel among VDOT, fabricators, and consultants.

Benefits

The benefit of implementing Recommendation 1 is that makes it easier for bridge engineers to specify the use of ASTM A709 Grade 50CR steel. This provides VDOT with a more corrosion-resistant material option than uncoated weathering steel for use when the proximity of weathering steel to bodies of water or to industrial or marine environments is a concern. In locations where the use of coated weathering steel is an option, ASTM A709 Grade 50CR steel could also be used. This is especially applicable where future maintenance actions are not desirable because of environmental concerns, poor access, high traffic volume, etc. The longevity of uncoated Grade 50CR steel and low expected maintenance costs will provide long-term cost savings.

The benefit of implementing Recommendation 2 is that VDOT experience is acquired in procurement and construction with Grade 50CR steel, and bulk procurements can potentially result in lower costs from fabricators, including qualified contractors under Disadvantaged Business Enterprise regulations. Implementing the recommendation has a high potential for long-term maintenance and replacement cost savings because of corrosion resistance of the steel in bridges that have required relatively frequent replacement in the past. In the long run, implementing this recommendation will result in reductions in the numbers of deficient structures maintained by VDOT and more reliable access for emergency and commercial vehicles across Virginia.

The benefit of implementing Recommendation 3 is that it fosters cost competition among premium materials on projects, which could favorably influence market availability and cost of Grade 50CR steel. If implemented after implementation of Recommendation 2, the implementation of Recommendation 3 gives fabricators increased experience with Grade 50CR steel fabrication, which should eventually decrease costs of production for corrosion-resistant materials in girders. Implementing Recommendation 3 would also potentially moderate pricing of corrosion-resistant beams in large contracts. Similar to Recommendations 1 and 2, the use of ASTM A709 Grade 50CR steel will provide VDOT with a corrosion-resistant option yielding long-term savings.

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APPENDIX A

DAILY TEST OF ASTM A193 B8 7/8-IN BOLTS WITH A MINIMUM CLAMPING LOAD OF 30 KIP AND ULTIMATE TENSILE STRENGTH OF 100 KSI

EQUIPMENT REQUIRED:

1. Calibrated Skidmore-Wilhelm bolt tension measuring device
2. Spud wrenches and calibrated torque wrench
3. Nominal diameter washers
4. Steel section to mount the Skidmore-Wilhelm device
5. Bolt length measuring device

PROCEDURE:

Skidmore-Wilhelm Bolt Testing for 7/8-in-Diameter Bolts

1. Obtain three nut/bolt/washer assemblies from each lot to be used that day.

2. Measure the length of the bolt (the distance from the end of the bolt to the washer face at the bolt head to shank interface) to determine the required nut rotation.

3. Apply a pea-sized amount of Never-Seez® High Temperature Stainless Lubricating Compound to the threads of the bolt, and disperse evenly using a brush. Use additional lubricant to cover all bolt, nut, and washer contact surfaces.

4. Insert the bolt into the Skidmore-Wilhelm testing frame. Stack the appropriate number of washers on the nut side of the bolt so that no more than three threads of the bolt are exposed after hand tightening of the nut.

5. Tighten the assembly to an initial tension loading of 4 kip by turning of the nut.

6. Define the zero angle of rotation by making collinear marks on the wrench socket and the testing apparatus.

7. Tighten the nut until 30 kip of tension is achieved. The 30 kip of tension shall be achieved before the required rotations in Step 8 are reached. Record the value of the torque and the angle of rotation relative to the initial marking in Step 6. The torque value from the test shall not exceed $T = 0.25\ PD$, where P = tension in pounds and D = bolt diameter in feet. For a 7/8-in bolt diameter at 30 kip, the maximum torque value is 550 ft-lb.

8. Proceed to tighten the nut to the rotation listed below. The rotation is measured from the initial marking in Step 6. Record the torque and tension. The torque value from the test shall not exceed $T = 0.25\ PD$, where P= recorded tension in pounds and D = bolt diameter in feet.

Bolt Length (L)	$L \leq 4 \times$ Bolt Diameter (BD)	$4 \times BD < L \leq 8 \times BD$	$8 \times BD < L$
Required Rotation	1/2	2/3	1

9. Remove the bolt from the Skidmore-Wilhelm test frame. Check the thread condition by rethreading the nut onto the bolt, by hand, to see if it can be tightened to the location at the end of the test.

10. Repeat the test on the other two assemblies. If all three bolts pass, average the torques recorded in Step 7, and record that value as the daily inspection torque for bolts from that lot installed on that day.

11. If the bolts do not all pass, the contractor may elect to lubricate all the bolts in that lot and repeat the test. Otherwise, the bolts are considered rejected.

APPENDIX B

ROUTE 340 BRIDGE DAILY BOLT TEST RESULTS

Results from the three different daily test dates of ASTM A193 B8 7/8-in bolts are provided in Tables B1 and B2.

Table B1. Average Daily Torque Values at 30 kip

Test Date	**Bolt Length, in 4 1/2**	**Bolt Length, in 3 1/2**	**Bolt Length, in 3**	**Bolt Length, in 2 3/4**	**Bolt Length, in 2 1/4**
12/29/2016 Sample No. 1	420	400	460	390	440
12/29/2016 Sample No. 2	320	430	420	300	390
12/29/2016 Sample No. 3	440	420	450	350	430
12/29/2016 Average	*393*	*417*	*443*	*347*	*420*
12/29/2016 Standard Deviation	*64*	*15*	*21*	*45*	*26*
1/5/2017 Sample No. 1	400	320	380	Did not tension this date	
1/5/2017 Sample No. 2	360	370	380	Did not tension this date	
1/5/2017 Sample No. 3	370	320	390	Did not tension this date	
1/5/2017 Average	*377*	*337*	*383*	*Did not tension this date*	
1/5/2017 Standard Deviation	*21*	*29*	*6*	*Did not tension this date*	
1/6/2017 Sample No. 1	Did not tension this date			500	460
1/6/2017 Sample No. 2	Did not tension this date			500	420
1/6/2017 Sample No. 3	Did not tension this date			450	440
1/5/2017 Average	*Did not tension this date*			*483*	*440*
1/5/2017 Standard Deviation	*Did not tension this date*			*29*	*20*

Table B2. Average Daily Torque Values Required Rotation

Test Date	Bolt Length, in									
	4 1/2		**3 1/2**		**3**		**2 3/4**		**2 1/4**	
	2/3 Turn	**kip**	**1/2 Turn**	**kip**	**1/2 Turn**	**kip**	**1/2 Turn**	**kip**	**1/2 Turn**	**kip**
12/29/2016 Sample No. 1	560	41	550	40	590	41	500	48	440	34
12/29/2016 Sample No. 2	440	39	470	42	550	42	440	47	480	35
12/29/2016 Sample No. 3	580	42	490	42	550	43	500	42	450	34
12/29/2016 Average	*284*	*41*	*272*	*41*	*303*	*42*	*263*	*46*	*246*	*34*
1/5/2017 Sample No. 1	570	44	400	41	510	40	Did not tension this date			
1/5/2017 Sample No. 2	480	45	430	42	600	42	Did not tension this date			
1/5/2017 Sample No. 3	500	44	400	40	610	42	Did not tension this date			
1/5/2017 Average	*517*	*44*	*410*	*41*	*573*	*41*	*Did not tension this date*			
1/6/2017 Sample No. 1	Did not tension this date						700	38	590	35
1/6/2017 Sample No. 2	Did not tension this date						670	35	570	33
1/6/2017 Sample No. 3	Did not tension this date						700	36	600	36
1/5/2017 Average	*Did not tension this date*						*690*	*36*	*587*	*35*

APPENDIX C

VDOT SPECIAL PROVISION FOR
CORROSION RESISTANT STEEL PLATE GIRDERS

VIRGINIA DEPARTMENT OF TRANSPORTATION
SPECIAL PROVISION FOR
CORROSION RESISTANT STEEL PLATE GIRDERS

January 31, 2018

DESCRIPTION

This special provision addresses materials, handling requirements, and fabrication requirements specific to ASTM A709 Grade 50CR structural steel, formerly referenced as ASTM A1010 Grade 50. Requirements will follow the standard VDOT Specifications for structural steel except as noted below.

SECTION 105—CONTROL OF WORK of the Specifications is revised as follows:

Section 105.10 Plans and Working Drawings is amended to include the following:

Materials shall conform to the requirements of Section 105 of the Specifications except:

(c) Working Drawings: The spacing and height of stud shear connectors shall be shown on the shop plans (working drawings). Working drawings for A709 Grade 50CR structural steel will be returned to the Contractor after being reviewed. Reviews shall be completed within 60 days from the date of receipt by the Department.

SECTION 107—LEGAL RESPONSIBILITIES of the Specifications is revised as follows:

Section 107.17 (a) Construction Safety and Health Standards is amended to include the following:

a. Since ASTM A709 Grade 50CR is a chromium bearing steel, fabricators shall comply with OSHA standards for safety as part of cutting and welding operations. Each fabrication shop shall perform its own monitoring to determine what conditions require supplemental ventilation and/or air supply.

SECTION 226—STEEL STRUCTURES of the Specifications is revised as follows:

Section 226.02 Detail Requirements is amended to include the following:

Materials shall conform to the requirements of Section 226 of the Specifications except:

(h) High-Strength Bolts, Nuts, Washers, and Direct Tension Indicators shall conform to the following respective ASTM specifications:

High-Strength Bolts	Nuts for Use with High-Strength Bolts, Heavy Hex	Washers (Hardened)	Direct Tension Indicators
ASTM A325, Type 1 galvanized	ASTM A563, Grade DH	ASTM F436	ASTM F959

SECTION 407—STEEL STRUCTURES of the Specifications is revised as follows:

Section 407.02 Materials is amended to include the following:

Materials shall conform to the requirements of Section 407 of the Specifications except:

(b) Plate material shall conform to the requirements of ASTM A709 Grade 50CR steel.

a. Additional time could be required for production and fabrication of plate materials. Contractor shall work with fabricators to determine production schedule requirements to ensure project delivery dates are met. It is estimated that up to a 6-month delay could occur if ASTM Grade 50CR plate material is not in stock.

Section 407.04 (j) Stud Shear Connectors is amended to replace the ninth sentence with the following:

All shear stud connectors shall be shop applied and structural steel shall be erected in accordance with Section 107.17 of the Specifications. The contractor shall take this into account when preparing worker protection plans.

Section 407.04 Fabrication Procedures is amended to include the following:

Submerged arc welding electrode shall be a Lincolnweld ER309L, 3/32 inch diameter electrode with Lincolnweld 880M flux or SelectAlloy EC309L 3/32 inch diameter electrode with Lincolnweld 880M flux.

1. Additional time could be required for production and fabrication of plate materials. Contractor shall work with fabricators to determine production schedule requirements to ensure project delivery dates are met. It is estimated that up to a 6-month delay could occur if consumables that meet the Buy America requirements are not in stock.

(m) Cutting: Oxy-fuel cutting of ASTM A709 Grade 50CR is not allowed, but instead ASTM Grade 50CR shall be plasma cut.

(n) Perform all welded connection to ASTM A709 Grade 50CR in accordance with AWS D1.5 modified as follows:

1. Maximum interpass temperature is limited to 300°F.

2. Inspection of ASTM A709 Grade 50CR complete joint penetration weld is qualified by mock-up testing developed by the fabricator and approved by the engineer. Inspection of full penetration welds will be done by both ultrasonic testing and radiographic testing in accordance with VTM 29 and VTM 30.

3. Perform fillet weld inspection identified in AWS 01.5 section 6.7.7 by ASTM E 165 Standard Test Method for Liquid Penetrate Examination.

4. Perform weld preparation, including repair, of ASTM A709 Grade 50CR with new tools (grinding and sanding disk, weld cleaning tool) or tools dedicated for ASTM A709 Grade 50CR. Do not use carbon steel tools unless approved by the Engineer.

(o) Fabricator Qualification: This bridge uses martensitic/ferritic stainless steel plate welded with an austenitic stainless steel electrode. The fabricator shall have the following experience in order to submit a bid for the project:

1. Fabricator shall be certified to meet the requirements of advanced bridges under AISC certification program for structural steel fabricators.

2. Perform welder qualification test per AWS D1.5 Part B on ASTM A709 Grade 50CR steel plate in presence of the Engineer. Welders must be qualified for groove welds per Section 5.23.1.2 of AWS D1.5. Give four weeks' notice to the Engineer prior to test performance. Welders, Welding Operators and Tack Welders who have not passed the qualification test with ASTM A709 Grade 50CR steel base and filler shall not perform work on ASTM A709 Grade 50CR steel materials.

3. Fabricator shall demonstrate through welder qualification Section 5.1, D1.5 successful welding procedure qualification test on ASTM A709 Grade 50CR steel materials.

4. Proof of acceptable experience performing submerged arc welding of ASTM A709 Grade 50CR plate using Lincolnweld ER309L or SelectAlloy EC309L. Acceptable experience is proven by passing the welder qualification test per AWS D1.5 Part B on ASTM A709 Grade 50CR using Lincolnweld ER309L or SelectAlloy EC309L.

5. Fabricator shall meet one of the following requirements:

    a. Historical proof of successfully welding ASTM A709 Grade 50CR plate using Lincolnweld ER309L or SelectAlloy EC309L or equivalent for actual plate girder structural applications on at least one previous bridge project.

    b. Demonstrate to VDOT the ability to fabricate ASTM A709 Grade 50CR and be approved prior to acceptance of bid.

Section 407.06 (i) Finishing is amended to include the following:

If required in the contract documents, blast media for ASTM A709 Grade 50CR steel materials shall be steel shot.

Girder shipping schedule should consider weather and presence of de-icing salt on the roadway of travel to aid in producing formation of a uniform patina. If possible, girders should not be shipped in snowy weather.

All exposed surfaces of corrosion resistant plate girders shall be washed to remove any alkaline product resulting from concrete placement operations, or other surface films that would alter the formation of a uniform patina.

Section 407.06 (j) Protective Coatings is amended to include the following:

Galvanizing or coating is not required.