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Documentation and Evaluation of ASTM A709 Grade 50CR Steel Bridges on Virginia's Eastern Shore

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Final Report VTRC 24-R2

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Supplementary Notes:

Abstract:

Corrosion is a common deterioration mechanism leading to costly maintenance of steel bridges. Although this is the case all over Virginia, it is especially true on Virginia's Eastern Shore, a 70-mile-long peninsula located between the Atlantic Ocean and Chesapeake Bay saltwater bodies. This was especially evident by corrosion damage and the subsequent need for replacement of the Holdens Creek Bridge and repairs on the Onancock Bridge on the Eastern Shore. ASTM A709 Grade 50CR (50CR) steel, a utility grade stainless steel, was selected for the replacement girders of the Holdens Creek Bridge and the bolted repairs of the Onancock Bridge. Since 50CR steel has a greater initial cost compared to traditional corrosion protection systems, design alterations were implemented to reduce the initial cost.

The purpose of this study was to document and evaluate both Eastern Shore bridges, including the condition of each bridge prior to replacement/repair, the design processes with cost-saving alterations, and the condition of each bridge after replacement/repair. Cost-saving design alterations included limiting the amount of 50CR steel used, limiting the number of 50CR steel plate thicknesses, using simpler weld details, using galvanized secondary members, and using galvanized fastener assemblies. For the Holdens Creek Bridge, nonstructural galvanized and metallized/sealed beams were added to the bridge, and for the Onancock Bridge, uncoated weathering steel repairs were implemented, both of which were done to allow for a long-term corrosion performance comparison. A cost analysis was also conducted to determine the future economic potential of 50CR steel. This included examining the recent macroeconomic environment and legislation for highway construction, alloy composition and supply of alloys for 50CR steel, and macroeconomic trends in U.S. steel production that affect the near-future supply of 50CR steel.

Inspection of the Holdens Creek Bridge 1 year after replacement showed that the 50CR steel girders and nonstructural galvanized and metallized/sealed beams were performing well. Inspection of the Onancock Bridge 5 years after repair showed some zinc product migrating between the galvanized fastener assemblies and 50CR steel repair plates. The uncoated weathering steel repairs were not exhibiting pitting or laminar corrosion but did exhibit some loosely adherent small flakes. Both bridges will be monitored over time. The cost analysis showed that the unit cost of 50CR steel for bridge girders on Virginia Department of Transportation (VDOT) projects decreased from $5.84/lb in 2015 to $3.10/lb in 2020, a 47% decrease, an achievement of economic significance. This cost falls in line with prices VDOT has paid for other bridge repairs in recent years. The macroeconomic environment of the last 3 years has been unprecedented and has caused costs for transportation agencies to spike by 50%; however, data suggest that U.S. steel markets are recovering. Alloys in 50CR steel except nickel have also showed marked price and supply stability over this period.

The study recommends that VDOT continue to investigate corrosion-resistant steels, such as 50CR steel, to provide a long service life for steel bridges in corrosive environments. Further, VDOT should update its 50CR steel design guidelines to incorporate the cost-saving design alterations discussed in this report. Finally, VDOT should improve its specifications for metallized steel for potential expanded use in corrosive environments.

Supplemental files can be found at: https://library.virginiadot.org/vtrc/supplements

FINAL REPORT

DOCUMENTATION AND EVALUATION OF ASTM A709 GRADE 50CR STEEL BRIDGES ON VIRGINIA'S EASTERN SHORE

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Virginia Transportation Research Council
(A partnership of the Virginia Department of Transportation
and the University of Virginia since 1948)

Charlottesville, Virginia

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VTRC 24-R2

DISCLAIMER

ABSTRACT

Corrosion is a common deterioration mechanism leading to costly maintenance of steel bridges. Although this is the case all over Virginia, it is especially true on Virginia's Eastern Shore, a 70-mile-long peninsula located between the Atlantic Ocean and Chesapeake Bay saltwater bodies. This was especially evident by corrosion damage and the subsequent need for replacement of the Holdens Creek Bridge and repairs on the Onancock Bridge on the Eastern Shore. ASTM A709 Grade 50CR (50CR) steel, a utility grade stainless steel, was selected for the replacement girders of the Holdens Creek Bridge and the bolted repairs of the Onancock Bridge. Since 50CR steel has a greater initial cost compared to traditional corrosion protection systems, design alterations were implemented to reduce the initial cost.

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INTRODUCTION

Corrosion of steel bridges is a common deterioration mechanism that can lead to costly maintenance. Although this is the case all over Virginia, it is especially true on Virginia's Eastern Shore. The Eastern Shore, as shown in Figure 1, is a 70-mile-long peninsula located north of Virginia Beach, south of Maryland, and along the Atlantic Ocean coastline. It is separated from the rest of Virginia by the Chesapeake Bay. Due to its location between the Atlantic Ocean and Chesapeake Bay saltwater bodies, the Eastern Shore is a highly corrosive environment. This was especially evident by corrosion damage and the subsequent need for replacement or repair of two specific bridges on the Eastern Shore: the Holdens Creek Bridge and the Onancock Bridge.

The Holdens Creek Bridge (Federal ID 23598) is in Accomack County, Virginia, near the Maryland border on the northern portion of the Eastern Shore and carries Jenkins Bridge Road over Holdens Creek. According to traffic data from the Virginia Department of Transportation (VDOT), in 2021, the bridge had an average daily traffic of 840 (VDOT, 2023). An approximate location of the bridge is shown in Figure 1.

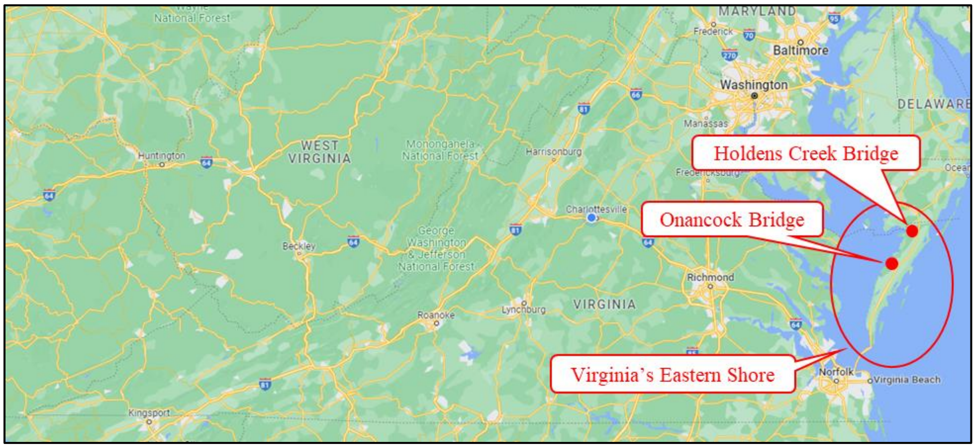


Figure 1. Map of Virginia Showing Eastern Shore. Taken From Google Maps.

The existing bridge, constructed with painted girders and a timber deck with asphalt topping, had been completed in 1993 and had a low water clearance to the brackish water below. For the remainder of this report, this previous bridge is referred to as the "1993 Holdens Creek Bridge," denoted by the year in which it was constructed.

By 1999, the bridge inspection report indicated that the coating had "popped off at several randomly located areas with rust occurring at same" locations. By 2018, VDOT's Hampton Roads District had installed three sister beams in Span 1, and timber blocks had been installed at the abutments on several beams due to the extensive corrosion damage; at this point, a replacement structure was needed. Figure 2 shows photographs of the 1993 Holdens Creek Bridge's low water clearance and section loss due to corrosion as of 2016.

The Onancock Bridge (Federal ID 392) is also located in Accomack County near the middle of the Eastern Shore, as shown on the map in Figure 1. It carries Mount Prospect Avenue over Onancock Creek in the town of Onancock, Virginia. According to VDOT traffic data, in 2017, the bridge had an average daily traffic of 270 (VDOT, 2023).

Like the 1993 Holdens Creek Bridge, the Onancock Bridge was a coated beam bridge. It was built in 1977 with a timber deck and asphalt wearing surface. It also had a low water clearance to the brackish water below, but its clearance was much greater than for the 1993 Holdens Creek Bridge. By 2018, the bridge had minor coating failures throughout but also had a few locations where section loss had occurred and affected the structural capacity of the bridge. The Hampton Roads District decided that bolted repairs were warranted at these locations of increased section loss. Figure 3 shows photographs of the Onancock Bridge's low water clearance and corrosion damage as of 2018.

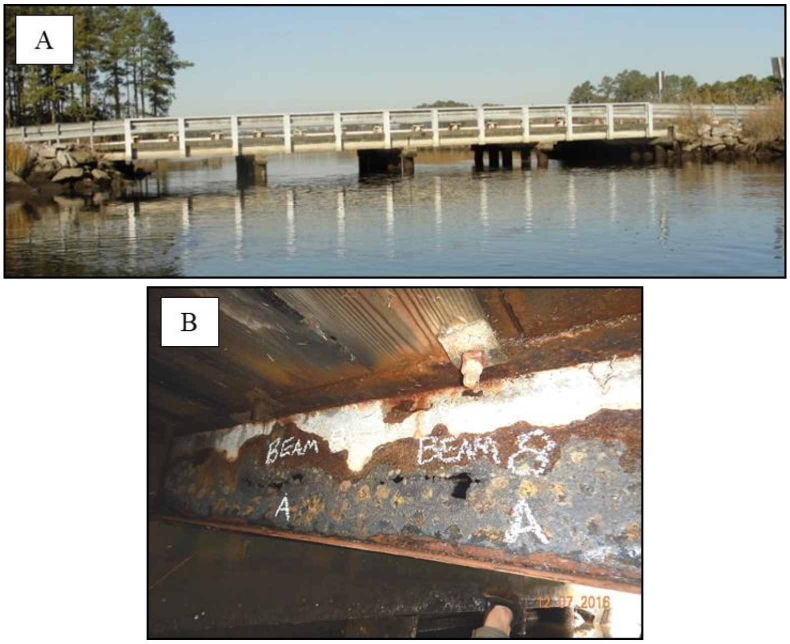


Figure 2. Photographs of the 1993 Holdens Creek Bridge in 2016: (A) low water clearance; (B) section loss as of 2016.

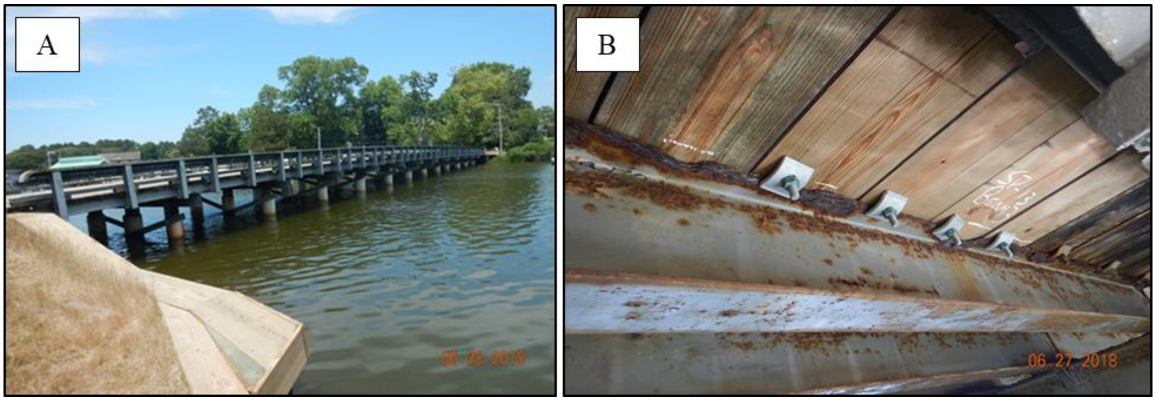


Figure 3. Photographs of the Onancock Bridge: (A) low water clearance; (B) corrosion damage as of 2018.

Over the course of 2017-2019, the Hampton Roads District and the Virginia Transportation Research Council (VTRC) discussed the potential for using ASTM A709 Grade 50CR (50CR) steel for the Holdens Creek Bridge replacement structure and the Onancock Bridge bolted repairs. 50CR steel is a utility grade stainless steel, which has similar mechanical properties to other steel grades in ASTM A709 (nominal yield strength of 50 ksi and nominal ultimate strength of 70 ksi) and approximately 4 to 10 times the corrosion resistance of uncoated weathering steel based on short-term accelerated corrosion testing (ASTM, 2017b; Fletcher, 2011; Groshek and Hebdon, 2020; Provines et al., 2019). All of these properties made it an attractive option for both bridges.

In addition, VDOT had previously used 50CR steel on the Route 340 Bridge (Federal ID 29421) over the South River in Waynesboro, Virginia, in 2015 (Sharp et al., 2019). Although the use of 50CR steel on that project was successful and it was expected to provide life-cycle cost benefits, it did have a higher initial cost of approximately $5.84/lb (including material, fabrication, erection, and shipping). That initial cost was approximately 2 to 3 times that of traditional corrosion protection systems, including uncoated weathering, coated, or galvanized steel. For the Route 340 Bridge, much of the high initial cost was attributed to having a large range of 50CR steel plate thicknesses, 50CR steel bent plate cross frames and diaphragms fabricated with partial joint penetration welds, stainless steel bolts, a long preparation time for the complete joint penetration welds (CJP), and blast cleaning with aluminum oxide.

For the Holdens Creek and Onancock Bridges, 50CR steel was selected as the material for the replacement structure and repairs, respectively, due to its inherent corrosion resistance and the fact that both bridges were in highly corrosive environments. For the remainder of this report, the replacement Holdens Creek Bridge is referred to as the 2022 Holdens Creek Bridge, denoting the replacement year. Since factors that had increased the cost of 50CR steel on the Route 340 Bridge had been identified, the Hampton Roads District and VTRC agreed to devise and implement cost-saving design alterations. In addition, since both the Holdens Creek and Onancock bridges were in environments that were much more aggressive than that of the Route 340 Bridge, it offered an opportunity to evaluate the corrosion performance of 50CR steel in a highly corrosive environment.

PURPOSE AND SCOPE

The purpose of this study was to document and evaluate the use of 50CR steel on the 2022 Holdens Creek Bridge and for the bolted repairs on the Onancock Bridge. This included documenting and evaluating the alterations to the way in which VDOT implements the use of 50CR steel for potential cost savings and collecting the baseline data to aid in the future corrosion performance of 50CR steel in aggressive environments. An additional objective of the study was to evaluate the future economic potential of 50CR steel.

The scope of this study included collaborations with the Hampton Roads District on the designs of the 2022 Holdens Creek Bridge and the Onancock Bridge; discussions with VDOT's Materials Division and fabricator of the 2022 Holdens Creek Bridge; field visits to both bridges; and a cost analysis of the future economic potential of 50CR steel.

METHODS

Three tasks were conducted to achieve the study objectives:

1. Document and evaluate the Holdens Creek Bridge, including the 1993 bridge and the design, fabrication, erection, and corrosion of the 2022 bridge.

2. Document and evaluate the Onancock Bridge, including its condition prior to repairs, the design process for the repairs, and the corrosion of the repairs after approximately 5 years.

3. Conduct a cost analysis of the future economic potential of 50CR steel.

Task 1: Documentation and Evaluation of the Holdens Creek Bridge

The documentation and evaluation of the Holdens Creek Bridge was divided into four subtasks. The first subtask was to document the condition and design of the 1993 Holdens Creek Bridge. The condition was evaluated to illustrate the need for selecting 50CR steel for the new bridge, and the design was documented to provide a comparison with the new bridge designed with alterations to provide 50CR steel cost savings. This subtask was conducted by reviewing inspection reports and drawings of the 1993 Holdens Creek Bridge provided to VTRC by the Hampton Roads District.

The second subtask was to document the design alterations made to the 2022 Holdens Creek Bridge to provide 50CR steel cost savings. The design alterations were developed through discussions with the Hampton Roads District and VDOT's Structure and Bridge Division and were based on VTRC's cost analysis of the Route 340 Bridge (Sharp et al., 2019).

The third subtask was to document the fabrication and erection of the 2022 Holdens Creek Bridge. Fabrication was documented through communications with VDOT's Materials

Division, who relayed information from the bridge fabricator and third-party inspectors. VTRC also assisted in the development of VDOT's Special Provision for Corrosion Resistant Plate Girders, which is used for fabricating 50CR steel girders and was a part of the bid specifications for the 2022 Holdens Creek Bridge. The erection was documented through communications with the Hampton Roads District and by VTRC personnel visiting the bridge site during erection.

The fourth subtask was to perform a corrosion evaluation of the 2022 Holdens Creek Bridge. The intent of this evaluation was to collect initial corrosion data to be compared with future data to determine the bridge's corrosion performance over time. In addition, the initial corrosion data for the 2022 Holdens Creek Bridge were compared to the corrosion performance of the 1993 Holdens Creek Bridge. The corrosion performance of the 50CR steel girders was of particular interest, but other bridge elements were also considered in this evaluation. Initial data included photographs and thickness and chloride measurements on the new bridge. X-ray fluorescence measurements were also taken on the coating from the steel beams from the 1993 Holdens Creek Bridge.

Task 2: Documentation and Evaluation of Onancock Bridge Repairs

The documentation and evaluation of the Onancock Bridge repairs was divided into three subtasks. The first subtask was to document the corrosion performance of the Onancock Bridge prior to the repairs to illustrate the reason for selecting 50CR steel for the repairs. To accomplish this, previous inspection reports of the bridge were reviewed.

The second subtask was to document the design process for selecting the types of repairs to be used on the bridge. The initial design of the bolted repairs on the Onancock Bridge, prior to the decision to use 50CR steel, was sent to VTRC in May 2017. VTRC then had discussions with the Hampton Roads District, VDOT's Structure and Bridge Division, and VDOT's Materials Division to determine revisions to the repair designs to incorporate 50CR steel and other steel bridge corrosion protection systems as points of comparison.

The third subtask was to perform a corrosion evaluation of the bolted repairs. The bolted repairs on the Onancock Bridge were installed in February 2018, and VTRC researchers visited the bridge in May 2023, more than 5 years after the repairs were installed, to evaluate their performance.

Task 3: Cost Analysis of the Future Economic Potential of 50CR Steel

The cost analysis for this study focused on future cost trends of 50CR steel as implied by the recent macroeconomic environment for highway construction and the rising costs agencies have endured since 2020; recent legislation directly affecting highway construction costs; alloy composition and supply of alloys for 50CR steel relative to other grades of stainless steel; and trends in the macroeconomic environment for U.S. steel production that would affect the near-future supply of a specialty material such as 50CR steel.

RESULTS AND DISCUSSION

Task 1: Documentation and Evaluation of the Holdens Creek Bridge

Design and Condition of 1993 Holdens Creek Bridge

The 1993 Holdens Creek Bridge was constructed in 1993 and was made of coated rolled steel beams, a timber bridge, and an asphalt wearing surface. The bridge had four 15-ft spans, continuous from Spans 1 to 2 and from Spans 3 to 4, and had a total length of 60 ft. The rolled steel beams consisted of 11 W12x26 beams spaced at 2-ft intervals. The timber deck and asphalt wearing surface had a thickness of 4¾ in and ¼ in, respectively. The bridge also contained two timber abutments and three timber bents. A typical cross section of the previous bridge is shown in Figure 4.

Based on previous bridge inspection reports, the 1993 Holdens Creek Bridge had a water clearance of 4 to 8 ft at the time of the bridge inspections. However, staff from the Hampton Roads District indicated that the bridge is overtopped with water multiple times per year during flood events. The water in Holdens Creek below the bridge is brackish (i.e., contains a mixture of river water and seawater) because Holdens Creek is an estuary to and is approximately 2 miles from the Chesapeake Bay.

Upon completion of construction of the bridge in 1993, the coating system on the beams was rated “Good” in the 1993 inspection report. Six years later, in 1999, the coating rating was downgraded to “Fair,” and the inspection report noted that the coating had “popped off at several randomly located areas with rust occurring at same” locations. Figure 5 shows a photograph of the condition of the coating system on the girders in 1999. This indicates that portions of the coating began to reach the end of their service life in 1999 since some areas of the steel beams were no longer protected from the corrosive environment. Other portions of the coating still provided corrosion protection but continued to degrade slowly.

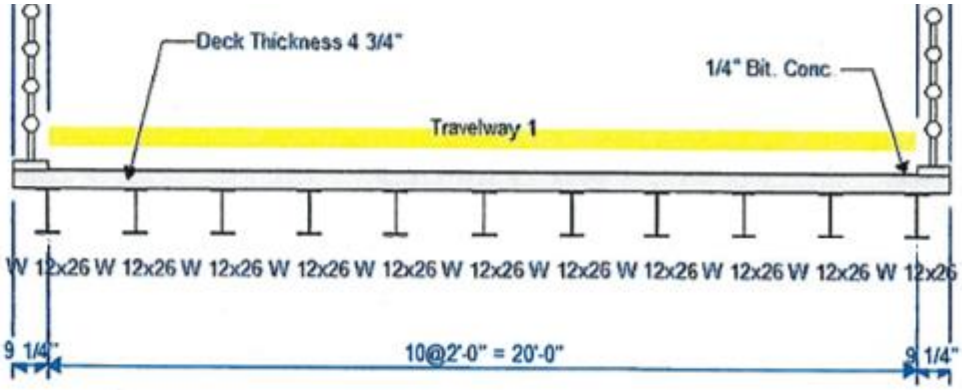


Figure 4. Typical Cross Section of the 1993 Holdens Creek Bridge

Figure 5. Photograph Showing Coating Breakdown for the 1993 Holdens Creek Bridge in 1999, Indicating Loss of Complete Coating Protection After 6 Years

By 2005, the coating was rated “Poor,” and the inspection report indicated there was no significant section loss to the beams. The 2011 inspection report noted that the superstructure condition was rated “6” but also indicated the presence of pitted and stratified rust on beams, shown in Figure 6a. No significant section loss to the beams was reported at that time. The 2014 inspection report indicated a measurable section loss of up to 1/16 in on the steel beams. An example photograph from this inspection report showing this condition is shown in Figure 6b. One year later, the 2015 inspection report noted perforations in beam webs, shown in Figure 6c. Thus, the underlying steel had reached the end of its service life in 2015.

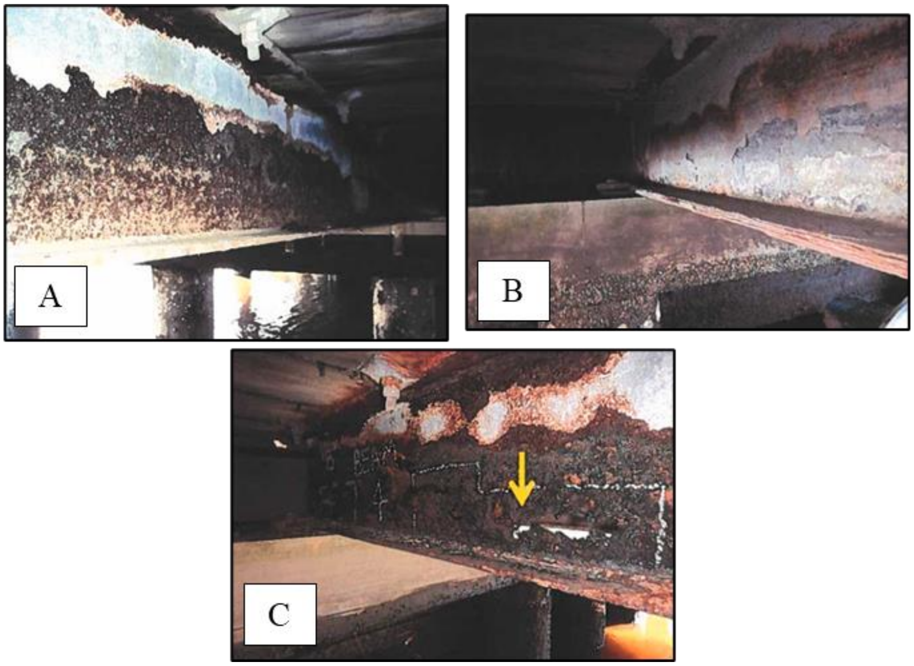


Figure 6. Photographs Showing the 1993 Holdens Creek Bridge: (A) pitted and stratified rust on steel beams in 2011; (B) up to 1/16-in section loss on beams in 2014; (C) perforations in beam webs first reported in 2015.

Based on the notes and photographs from the inspection reports over the life of the 1993 Holdens Creek Bridge, portions of the coating reached the end of their service life in 1999, after approximately 6 years. This resulted in these steel areas being directly exposed to the corrosive environment at Holdens Creek. By 2015, the inspection report noted the original ¼-in-thick web had perforations, 16 years after the coating had reached the end of its service life. Thus, the underlying steel of the beams was able to provide a service life of approximately 16 years.

Design of 2022 Holdens Creek Bridge

For most steel beam and timber deck bridges for which the superstructure is being replaced and placed on top of the existing substructure, their new superstructure is an in-kind replacement. This means that the new superstructure and deck will have a cross section nearly identical to that of the previous bridge, thereby ensuring that the existing substructure can support the new superstructure and deck without additional complex analysis.

However, cost-saving design alterations were made to the 2022 Holdens Creek Bridge to reduce the cost of using 50CR steel. These design alterations were made based on VTRC's cost analysis of the Route 340 Bridge and discussions with the Hampton Roads District Structure and Bridge Division. The design alterations and resulting justifications are presented in Table 1.

Design Alteration 1 (i.e., using less 50CR steel) was implemented on the 2022 Holdens Creek Bridge by using a transverse glulam timber deck on the replacement structure rather than a traditional timber deck. The glulam deck provides transverse stiffness, which allowed the number of girder lines to be reduced from 11 on the previous bridge to 5 on the new bridge. The additional transverse stiffness of the glulam deck also eliminated the need for cross frames on the new bridge. Only diaphragms at the end of each span were required. The glulam deck also provided the potential for additional durability over a traditional timber deck. Figure 7 shows the cross section of the 2022 Holdens Creek Bridge with the glulam timber deck and five 50CR steel plate girder lines. Galvanized deck stringers with galvanized fastener assemblies as part of the glulam deck were also included. The nonstructural galvanized and metallized rolled steel beams on the exterior of the bridge are discussed later.

Design Alteration 2 (i.e., minimizing the number of plate thicknesses) was implemented on the 50CR steel plate girders by using a single plate thickness for all 50CR steel on the project, including both flanges and the web of the plate girders and the sole plates. The thickness used was determined based on the positive and negative moment capacity of the flanges while maintaining the same girder depth as the previous bridge. Based on these calculations, ¾-in-thick plates were selected for the flanges, and the girder depth was set to 12 in. To maintain the same plate thickness for all elements of the plate girders, ¾-in-thick plates were also selected for the girder webs. Typically for a bridge of this span length, the girder webs would be sized for constructability and would be approximately 9/16 in thick. Therefore, the ¾-in-thick webs would seem uneconomical for a traditional design because there is excess material. However, as shown in Table 1, it is more economical to limit the number of 50CR steel plate thicknesses used. The additional thickness of the web also eliminated the need for transverse stiffeners and provided additional thickness where corrosion was most prevalent on the 1993 Holdens Creek ridge (see web corrosion in Figure 6).

Table 1. Description and Justification of Design Alterations on the 2022 Holdens Creek Bridge to Reduce Initial Cost of Using 50CR Steel

Design Alteration No.	Design Alteration	Justification
1	Limit amount of 50CR steel used	50CR steel is more expensive than traditional steels, so limiting its use provides cost savings.
2	Limit number of different 50CR steel plate thicknesses used	Based on feedback from the 50CR steel supplier, 50CR steel is produced on demand. Also, each new plate thickness requires a separate rolling process. Therefore, the 50CR steel for a particular project can be produced faster and for less cost if the number of plate thicknesses is limited. For the 2022 Holdens Creek Bridge, one 50CR plate thickness was used for the entire bridge; however, for longer span bridges, two different 50CR plate thicknesses may provide more economical designs.
3	Minimize or eliminate complete joint penetration (CJP) welds in favor of fillet welds	Based on the Route 340 Bridge cost analysis, fabrication of the 50CR steel plate girders was a large share of the cost increase. Route 340 Bridge project closeout meetings with the fabricator also revealed that CJP weld preparation and welding were more difficult with 50CR steel than with traditional bridge steels. One reason for this difficulty was that 50CR steel cannot be cut using oxy-fuel, which is a traditional approach to cutting typical bridge steels. Instead, much of the bevel preparation had to be done via manual grinding, which was time-consuming. Further, removing the slag on the 50CR steel CJP welds was more difficult, which meant more time was required for chipping and grinding the CJP welds smooth. The austenitic consumables used for welding 50CR steel also produce approximately twice the amount of distortion compared to traditional steel bridge consumables. This required the fabricator to adjust the welding parameters to minimize distortion. Fillet welds are much less challenging than CJP welds because bevels do not need to be prepared, less slag is produced, and much less potential distortion could occur because fillet welds typically require only a single pass.
4	Use galvanized secondary members	Rolled shapes, such as wide flange beams, angles, and channels, are not currently being produced in 50CR steel. On the Route 340 Bridge, secondary members, such as diaphragms and cross frames, were produced by bending 50CR steel plates into shapes. Since secondary members can be more easily replaced, if necessary, they may be designed for shorter term durability compared to primary members. Galvanized rolled shapes for secondary members can still provide adequate durability in most bridge environments and can reduce cost and construction time.
5	Use galvanized fastener assemblies for all bolted connections to secondary members	Based on the cost analysis for the Route 340 Bridge, stainless steel bolts contributed to the cost increase in multiple ways. First, stainless steel bolts are more expensive than traditional bridge bolts due to their inherent corrosion resistance. Second, stainless steel bolts have lower yield and tensile strengths than traditional bridge bolts, so more stainless steel bolts are required for the strength limit state. Third, typical bridge bolting installation parameters (such as the required nut rotation for the turn-of-nut method) do not yet exist for stainless steel bolts, which can add complexity and time to a project to determine pretensioning practices. Since galvanized secondary members are recommended (see Design Alteration 4), it is recommended that galvanized fastener assemblies be used to match the lesser corrosion resistance of these connections.

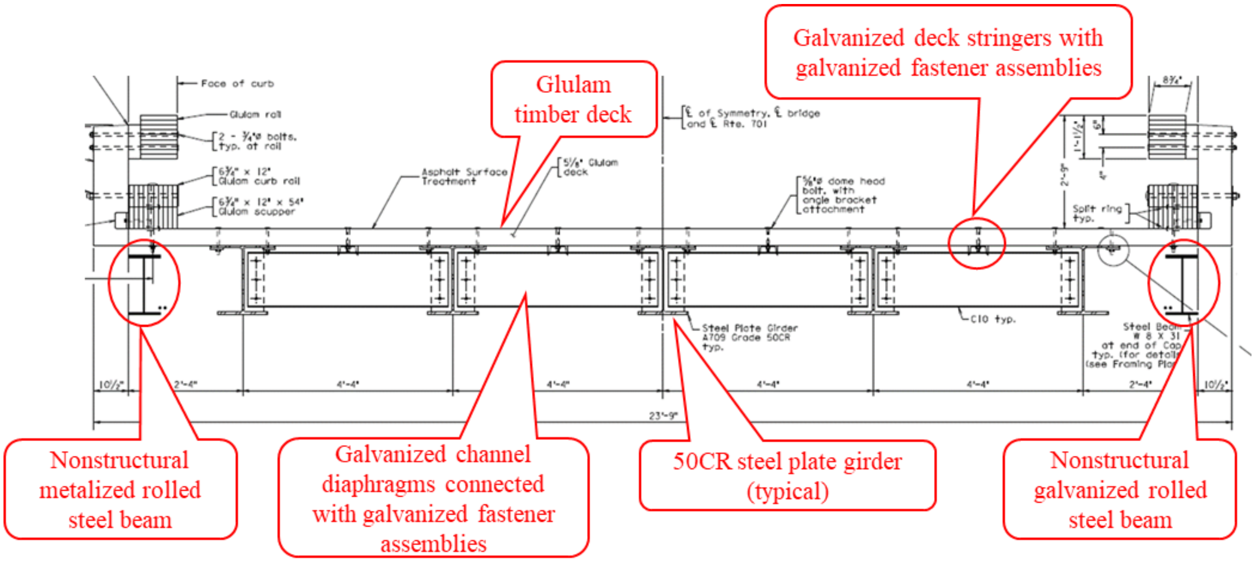


Figure 7. Typical Cross Section of the 2022 Holdens Creek Bridge

Figure 8 shows a cross section of the plate girders constructed with ¾-in-thick plates.

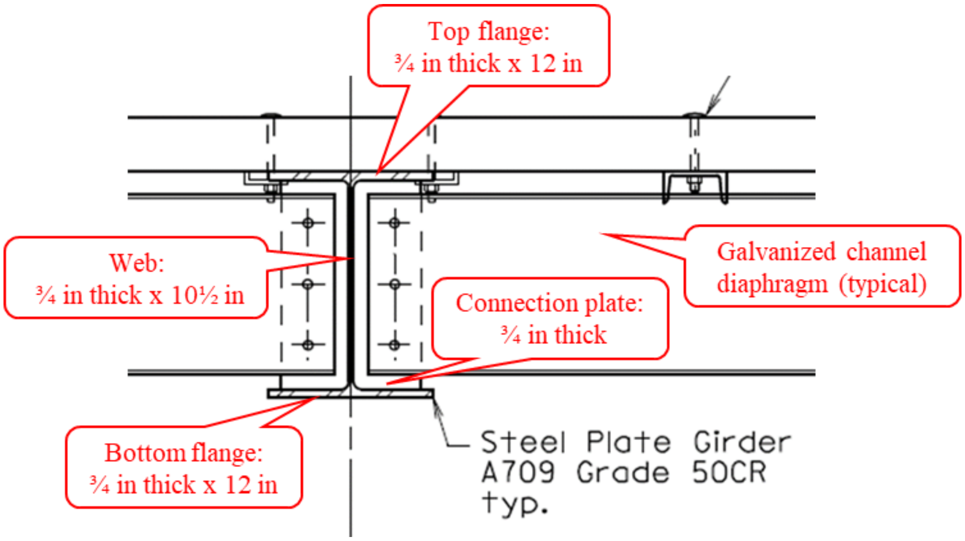


Figure 8. Typical Cross Section of the 50CR Steel Plate Girders Fabricated With ¾-In-Thick Plates

Design Alteration 3 (i.e., simpler welds) was implemented rather easily on the 2022 Holdens Creek Bridge due to its relatively short spans. The span arrangement of the new bridge was selected to match the old bridge, with continuous plate girders from Spans 1 to 2 and from Spans 3 to 4. Since the spans were all 15 ft long, this meant the girders were 30 ft long. Since the girders were relatively short, the flange and web plates could be cut from single steel plates; thus, no CJP welds were required. In addition, no partial joint penetration welds were required since there were no bent plate diaphragms or cross frames on the bridge. This meant that only fillet welds were required on the 2022 Holdens Creek Bridge, including the web to flange welds and the connection plates welded to the girders for the diaphragms. All fillet welds on the bridge were 5/16 in. As mentioned previously, there were no transverse stiffeners required due to the web thickness.

Design Alteration 4 (i.e., galvanized secondary members) was implemented by using galvanized channels for the diaphragms on the bridge. As mentioned in the discussion on Design Alteration 1, no cross frames were required on the bridge due to the glulam timber deck; therefore, diaphragms were required only at the supports.

Design Alteration 5 (i.e., galvanized bolts on secondary member connections) was implemented by using galvanized fastener assemblies to connect the galvanized channel secondary members to the 50CR steel connection plates. Figure 9 shows a framing plan of the 2022 Holdens Creek Bridge, indicating the location of the galvanized diaphragms.

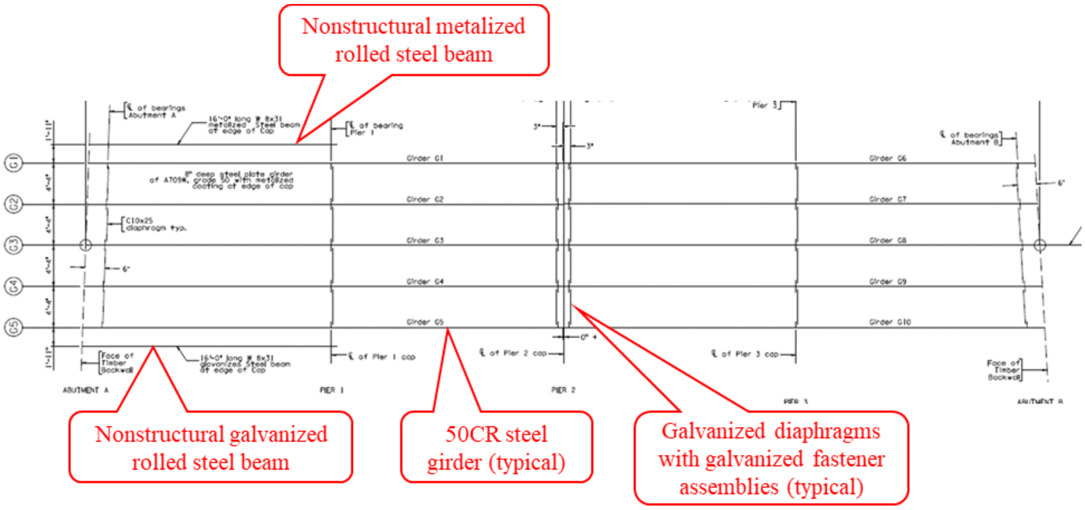


Figure 9. Framing Plan of the 2022 Holdens Creek Bridge

Fabrication and Erection of the 2022 Holdens Creek Bridge

The solicitation for the fabrication of the 2022 Holdens Creek Bridge was issued in May 2020. The solicitation included a much-updated version of VDOT's Special Provision for Corrosion Resistant Plate Girders (used for fabricating 50CR steel girders) as compared to the version used for the Route 340 Bridge. By this time, an AASHTO / American Welding Society (AWS) task group had been created and was tasked with developing a supplemental clause to the AASHTO/AWS D1.5 Bridge Welding Code (D1.5) containing specifications for welding and fabricating 50CR steel. Since this supplemental clause had been reviewed by numerous national experts and was in the balloting stage prior to the solicitation for the 2022 Holdens Creek Bridge, many portions of the D1.5 supplemental clause on 50CR steel were incorporated into VDOT's 50CR steel special provision for the 2022 Holdens Creek Bridge. Doing so allowed for a more thorough VDOT special provision and allowed for a "trial run" of the D1.5 supplemental clause on 50CR steel.

Some of the updates to VDOT's 50CR steel special provision based on the D1.5 supplemental clause for 50CR steel included the following:

- revision of filler metal and consumable certification requirements to include 316L, 316LSi, and 309L cored wire filler metals (this was also based on VDOT's previous research on 50CR steel welding [Fitz-Gerald et al., 2020])

- increase of maximum interpass temperature limitation from 300°F to 450°F

- revision of welding procedure qualification requirements on base metal, filler metal, mechanical testing, and welding personnel

- addition of magnetic particle and penetrant testing frequency requirements

- addition of ultrasonic testing (UT) requirements for calibration, scanning patterns, and acceptance criteria

- addition of requirements for fracture critical members, including consumable storage, ferrite number on deposited weld metal, weld metal toughness, and preheat and interpass temperature.

Additional updates were also made to VDOT's 50CR steel special provision based on VDOT's experience with using 50CR steel on the Route 340 Bridge and additional knowledge gained through discussions with the 50CR steel supplier and other welding experts. Some of these updates included the following:

- allowance of the use of galvanized high strength fastener assemblies (based on Design Alteration 5)

- revision of final blasting requirements, including elimination of garnet blast media and the allowance of standard steel shot, depending on contract document requirements

- addition of mock-up qualification test for the fabricator, requiring UT and radiographic testing of CJP welds.

Since the 2022 Holdens Creek Bridge did not have any CJP welds, the requirements for UT and radiographic testing of CJP welds would not be applicable to this bridge. However, they were included in VDOT's 50CR steel special provision for the case of future bridges containing CJP welds. VDOT's 50CR steel special provision has continued to be revised since the 2022 Holdens Creek Bridge project, and its latest version is provided as a supplementary document to this report.

After two bids were received and evaluated, the winning fabricator for the 2022 Holdens Creek Bridge was awarded the contract in July 2020. By November 2020, the fabricator had submitted shop drawings of the 50CR steel girders for review that were approved by VDOT. Soon after, the fabricator received the 50CR steel plate from the steel supplier and began to conduct in-house tests to evaluate two potential consumables from different manufacturers. Both consumables were 309L all-position wires to be used with the flux cored arc welding process. Using an all-position wire allowed the fabricator to use the same consumable and welding procedure for both the web-to-flange and diaphragm connection plate welds.

Based on in-house test results, the fabricator selected one of the two consumables to proceed with procedure qualification record (PQR) testing. After the initial PQR test failed due to the presence of a weld root crack, tests were re-run with passing results in March 2021. It is believed that the initial failing results were due to the welder, not the welding parameters. The approved welding procedure with the selected consumable consisted of the flux cored arc welding process with 100% CO_2 shielding gas, a calculated heat input ranging from 30.3 to 38.6 kJ/in, a minimum preheat of 70°F, and interpass temperature limits ranging from 70°F to 450°F. Using the qualified welding procedure, mock-up qualification testing was performed in the summer of 2021, with passing results. After successful mock-up qualification testing, the fabricator commenced welding the 50CR steel plate girders.

During production welding of the 50CR steel plate girders, the fabricator noted that 50CR steel was harder than typical bridge steels, which resulted in increased effort required to grind surfaces prior to welding. This same challenge was also noted on the Route 340 Bridge (Sharp et al., 2019). Another challenge for the fabricator was identifying tools and equipment that had not been contaminated by carbon for use on surfaces to be welded. The fabricator accomplished this by using a designated equipment locker and orange paint to identify tools for use on this project. Figure 10 shows photographs taken during fabrication of the 2022 Holdens Creek Bridge.

Overall, welding and fabrication of the 2022 Holdens Creek Bridge steel plate girders were achieved with only the previously mentioned minor challenges. There did seem to be a learning curve associated with welding 50CR steel, but VDOT's Materials Division and VTRC worked with the fabricator to meet all challenges successfully. The fabricated 50CR steel plate girders were shipped and delivered to the Hampton Roads District in October 2021.

Due to limited workforce availability, the 2022 Holdens Creek Bridge was not constructed until the summer of 2022. VTRC researchers were on-site during removal of the 1993 Holdens Creek Bridge and visited the 2022 Holdens Creek Bridge after it had been completed.

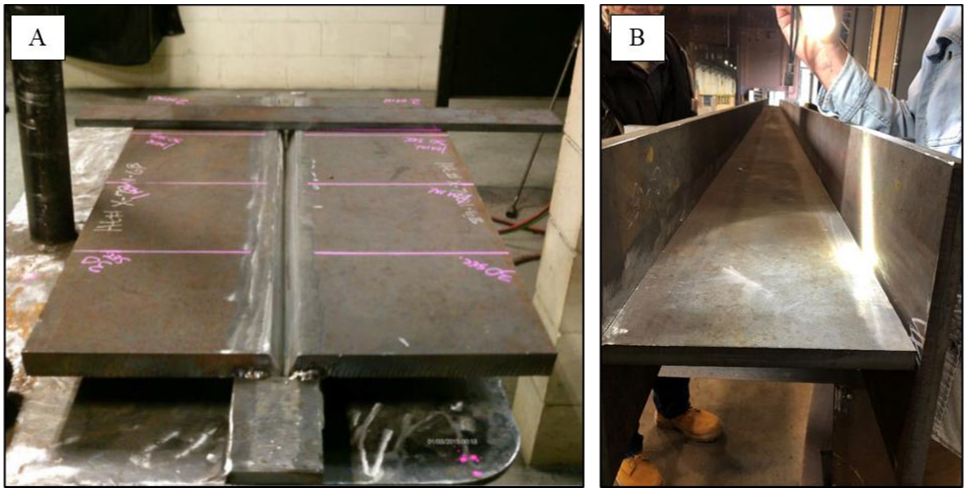


Figure 10. Photographs Taken During Fabrication of the 2022 Holdens Creek Bridge: (A) PQR testing; (B) fit-up of girders. PQR = procedure qualification record.

Figure 11 shows photographs of the 1993 bridge being removed, the 50CR steel girders on-site, and the completed 2022 bridge. Overall, erection of the 2022 Holdens Creek Bridge was the same as erection of a bridge made of a typical bridge steel and corrosion protection system.

Figure 11. Photographs of Erection of the 2022 Holdens Creek Bridge: (A) demolition of old bridge; (B) 50CR steel girders of new bridge on-site prior to installation; (C) completed new bridge from roadway; (D) completed new bridge from underneath showing low water clearance.

Condition Assessment of the Holdens Creek Bridge

As mentioned previously, past inspection reports showed that the coating system on the 1993 Holdens Creek Bridge had a service life of approximately 6 years and that the bare steel had a service life of approximately 16 years. Further, future evaluations of the 2022 Holdens Creek Bridge will eventually be able to be used in determining the service life of 50CR steel.

In order to study the corrosion performance of other traditional steel bridge corrosion protection systems, two nonstructural beams, one with galvanized steel and the other with metallized steel, were added to the 2022 Holdens Creek Bridge. Both nonstructural W8x31 rolled steel beams were designed to be 16 ft long to traverse one of the spans at the bridge. One beam was placed on each exterior of the bridge, as shown in drawings in Figures 7 and 9. These two beams will be monitored over time to determine the service life of both the galvanized and metallized steel at the bridge site. Full-length nonstructural beams, rather than small-scale coupons, were chosen so that their corrosion performance at the site would be representative of actual bridge girders.

The nonstructural galvanized and metallized beams were included in the contract for the fabrication of the 2022 Holdens Creek Bridge and therefore fell under the responsibility of the fabricator of the 50CR steel girders. Both galvanizing and metallizing were performed in accordance with VDOT specifications (VDOT, 2020). To fulfil these requirements, galvanization was performed in accordance with ASTM A123 (ASTM, 2017) and metallization was performed in accordance with S8.2-2017/SSPC-PA 18 (S8.2) (AASHTO/NSBA Steel Bridge Collaboration, 2017). The VDOT and S8.2 specifications do not provide specific requirements on items such as the alloy used, thickness applied, presence of seal coat, etc.; therefore, VDOT's Materials Division worked with the metallizing subcontractor to develop additional specific metallization requirements to be used for this project. These additions are summarized as follows:

- Prior to metallization, steel components shall be abrasive blast cleaned in accordance with SSPC-SP5 (i.e., white metal blast cleaning).

- The metallization alloy used shall be 85/15 zinc/aluminum (i.e., 85% zinc, 15% aluminum).

- Metallizing shall be completed within 8 hours of blast acceptance.

- Metallizing shall be applied in multiple passes of 3 to 4 mils to achieve an average thickness of 8.0 to 12.0 mils.

- Metallization shall be applied and checked in accordance with SSPS CS-23. Quality control testing includes the following:

    - tensile bond measurements on companion test plates with a minimum bond strength of 700 psi
    - performance by the metallization applicator of five bend test coupons at the start of each shift, bent around a 0.625-in mandrel.
    - surface profile replica tape measurements in accordance with ASTM D4417.

- Upon final acceptance of metallizing, sealer shall be applied in accordance with the manufacturer's recommendations.

A representative from VDOT's Materials Division was on-site to observe the metallization and sealing processes for the nonstructural beam. Figure 12 shows photographs from that visit.

The nonstructural galvanized and metallized/sealed steel beams were delivered to the Hampton Roads District at the same time as the 50CR steel girders and glulam timber deck. Figure 13 shows a photograph of both beams at the 2022 Holdens Creek Bridge site prior to installation.

In June 2022, measurements were taken on some of the individual components of the 2022 Holdens Creek Bridge before erection of the bridge began. These measurements will serve as the baseline with which future measurements can be compared. The measurement types and results are described in the following sections.

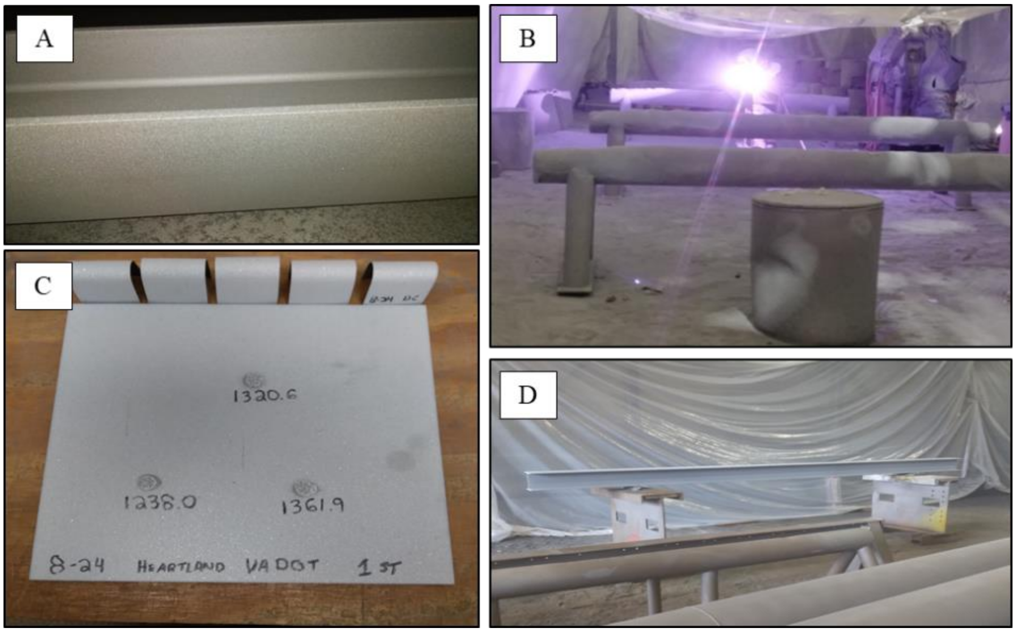


Figure 12. Photographs From Metallizing and Sealing of Nonstructural Beam for the 2022 Holdens Creek Bridge: (A) close-up of beam after blast cleaning, ready to be metallized; (B) beam being metallized; (C) quality control tests, including tensile bond and bend coupons; (D) beam after application of seal coat.

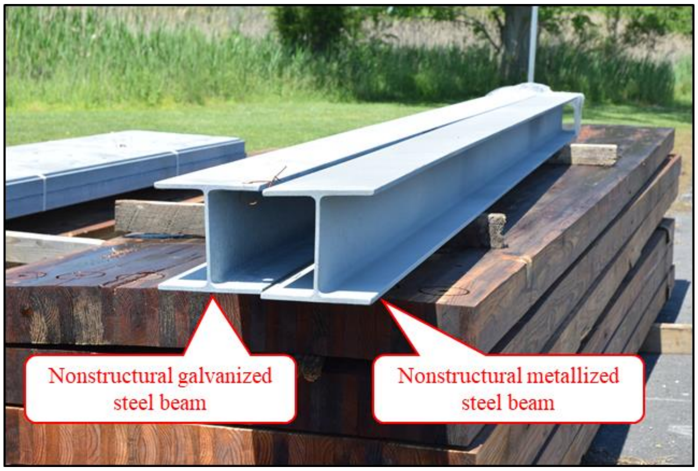


Figure 13. Photograph of Nonstructural Galvanized and Metallized/Sealed Steel Beam at the 2022 Holdens Creek Bridge Site Prior to Installation

The thickness of the steel on the 50CR steel girders was recorded with a UT thickness gauge. As mentioned previously, the nominal thickness of both the web and flange was ¾ in. Ten thickness measurements were made on two different girders. Measurements on each girder were taken from both flanges and the web. The measured thickness of the steel on the 50CR steel girders ranged from 0.83 to 0.86 in.

The thickness of the galvanizing and metallizing/sealing on the nonstructural beams was also recorded. For both beams, 15 thickness measurements were taken along the length of both beams, with measurements being taken on both flanges and the web. These measurements are shown in a box and whisker plot in Figure 14. The figure also includes an example dataset to provide descriptions of the parts of a box and whisker plot.

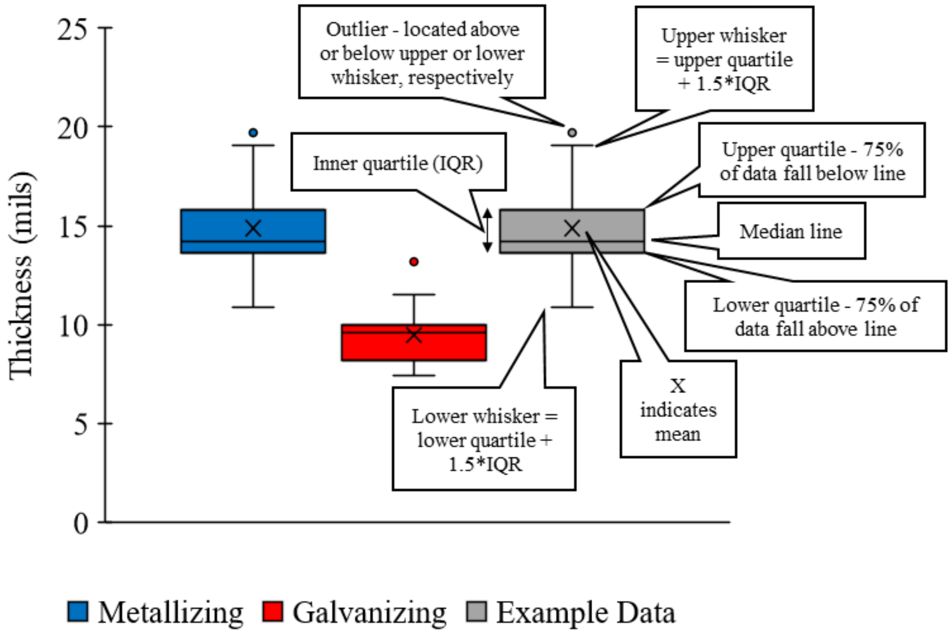


Figure 14. Box and Whisker Plot of Galvanizing and Metallizing/Sealing Thickness Measurements From Nonstructural Beams on the 2022 Holdens Creek Bridge

As shown in the plot, the metallizing/sealing thickness measurements had an approximate mean value of 15 mils and a median value of 14 mils; the lower and upper quartile values ranged from 13.5 to 16 mils. Based on these results, most of the thickness values were relatively consistent, even though the minimum and maximum values ranged from approximately 11 to 21 mils. As discussed previously, the average specified metallizing thickness was 8 to 12 mils, so the additional thickness on the nonstructural beam could be due to the seal coat applied after the metallization process. Also shown in Figure 14 is the galvanizing thickness of the nonstructural beam. The galvanizing thickness measurements had an approximate mean and median value of 9.7 mils, and the upper and lower quartile values ranged from 8 to 10 mils, indicating relatively consistent values.

The thickness of the galvanizing was also measured on secondary elements, such as the diaphragms, deck stringers, and tee plate connectors between the timber piers and pier caps. These elements were shown in the bridge cross section in Figure 7. Figure 15 shows a photograph of one of these tee plate connectors after installation. Fifteen galvanizing thickness measurements were taken on the deck stringers, 12 measurements were taken on the diaphragms, and 12 measurements were taken on the tee plates. These measurements were recorded from random locations on each galvanized secondary element type. The measurements are shown in a box and whisker plot in Figure 16.

Galvanized tee plate (typical) connecting timber piles to timber pier cap

Figure 15. Photograph Showing Galvanized Tee Plates Connecting Timber Piles to Timber Pier Cap

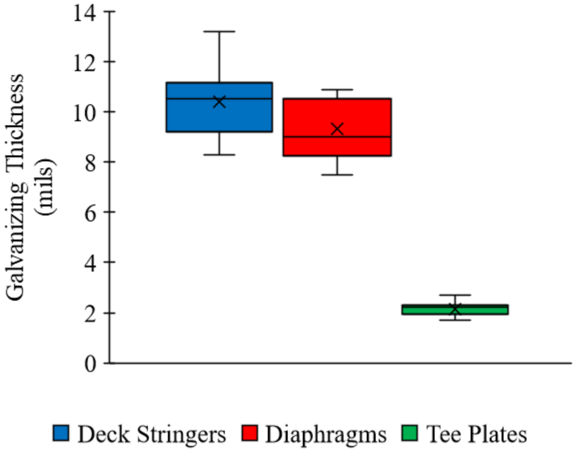


Figure 16. Box and Whisker Plot of Galvanizing Thickness Measurements From Deck Stringers, Diaphragms, and Tee Plates From the 2022 Holdens Creek Bridge

As seen in the plot, the galvanizing thickness on the deck stringers and diaphragms appeared to be similar, with mean values of approximately 10.4 mils and 9.3 mils, respectively. The tee plates, however, had much thinner galvanizing on them, with a mean value of approximately 2.1 mils. With such a thin layer of initial galvanizing, the tee plates should be a focus for monitoring over time, especially since they are located at a lower elevation than the bridge girders and will therefore be submerged in the brackish water more frequently.

In addition to thickness measurements, surface chloride content measurements were made in accordance with International Organization for Standardization (ISO) 8502-6 and were recorded from the 50CR steel girders and galvanized diaphragms. Two measurements on each component type were taken. A limited number of these measurements were taken because it was assumed that they would be similar and relatively small since none of the components had been installed and were all being stored outdoors near the bridge site. These surface chloride content measurements are shown in Table 2.

Table 2. Surface Chloride Content Measurements From 2022 Holdens Creek Bridge

Measurement Location	Surface Chloride Content (mg/m^2)
50CR steel girder, measurement 1	8
50CR steel girder, measurement 2	16
Galvanized diaphragm, measurement 1	10
Galvanized diaphragm, measurement 2	11

Table 3, which shows the chloride deposition rates for different corrosivity categories, taken from ISO 9223 (ISO, 2012), is shown for reference. In Table 3, corrosivity category S0 is representative of a background concentration of chlorides, and category S3 is representative of chloride levels near saltwater.

As shown in Table 2, all four chloride content measurements from the 2022 Holdens Creek Bridge ranged from 8 to 16 mg/m^2. When these measurements were taken, the components from the 2022 Holdens Creek Bridge had been stored on-site for 1 or 2 months, though the exact amount of time is unknown. Regardless, when the chloride content measurements were compared to the chloride deposition rates and corrosivity categories in Table 3, the initial chloride measurements were low, as expected.

X-ray fluorescence measurements were also recorded from the coating on the steel beams removed from the 1993 Holdens Creek Bridge. Six such measurements were taken on a random sampling of the steel beams. These measurements are shown in Table 4.

Based on the measurements in Table 4, the coating on the steel beams of the 1993 Holdens Creek Bridge contained a large percentage of zinc, with the percentage ranging from approximately 98% to 100%. This indicates that the coating system on the steel beams from the 1993 bridge had a zinc-rich primer for its main source of corrosion protection. This would have been a standard type of coating applied when the beams from the 1993 bridge were fabricated and is still a typical coating system used today. When coupled with the inspection reports for the 1993 bridge, the data suggest that the zinc-rich primer coating system had a service life of approximately 6 years in the Holdens Creek Bridge environment.

Table 3. Chloride Deposition Rates and Corrosivity Categories

Chloride Deposition Rate (mg/m^2/day)	Corrosivity Category
Rate ≤ 3	S0
3 < Rate ≤ 60	S1
60 < Rate ≤ 300	S2
300 < Rate ≤ 1500	S3

Source: Taken from ISO 9223.

Table 4. Element Composition, by Weight %, From X-ray Fluorescence Measurements on Coating From Steel Beams Removed From the 1993 Holdens Creek Bridge

Element	Sample No.					
	1	2	3	4	5	6
Zinc (Zn)	99.862	98.055	98.927	98.264	98.025	98.033
Vanadium (V)	0.066	0.109	0.068		0.095	0.09
Titanium (Ti)	0.035	0.226	0.151		0.255	0.215
Iron (Fe)	0.028	1.343	0.845	1.691	1.597	1.655
Copper (Cu)		0.146				
Chromium (Cr)		0.103				
Zirconium (Zr)		0.019				

In May 2023, a little less than 1 year after the 2022 Holdens Creek Bridge was erected, VTRC researchers visited the bridge to collect photographs of the bridge and its components to document its condition. VTRC researchers inspected the bridge deck and railing on foot and inspected the girders, substructure, and nonstructural beams using a jon boat for access.

The glulam deck on the 2022 Holdens Creek Bridge was treated with an asphalt overlay. This was because other VDOT districts had seen premature deterioration of glulam decks due to ultraviolet exposure. For the 2022 Holdens Creek Bridge, and other VDOT bridges with glulam decks, the asphalt overlay serves as a barrier to shield the glulam deck from ultraviolet exposure. Figure 17 shows photographs of the 2022 Holdens Creek Bridge deck before and after the asphalt overlay was placed and photographs of reflective cracking in the asphalt at both abutments. The asphalt overlay thickness was unknown to VTRC researchers.

The guardrail system on the approach roadways to the north and south of the bridge and the railing system on the bridge also provided opportunities to monitor corrosion performance over time. Near the middle of the bridge, the glulam railing system on both sides of the bridge was spliced together using galvanized steel plates. These galvanized steel splice plates are shown in Figure 18. These splice plates were present on both the water side and the traffic side of both the east and west railings. Thickness measurements on the galvanizing of all these splice plates were recorded. Overall, the top splice plates had a galvanizing thickness of 4 to 6 mils, and the thickness of the galvanizing on the bottom splice plates ranged from 7 to 9 mils.

Figure 17. Photographs of the 2022 Holdens Creek Bridge Deck: (A) before asphalt overlay; (B) after asphalt overlay; (c) view of asphalt reflective cracking at north abutment; (D) view of asphalt reflective cracking at south abutment.

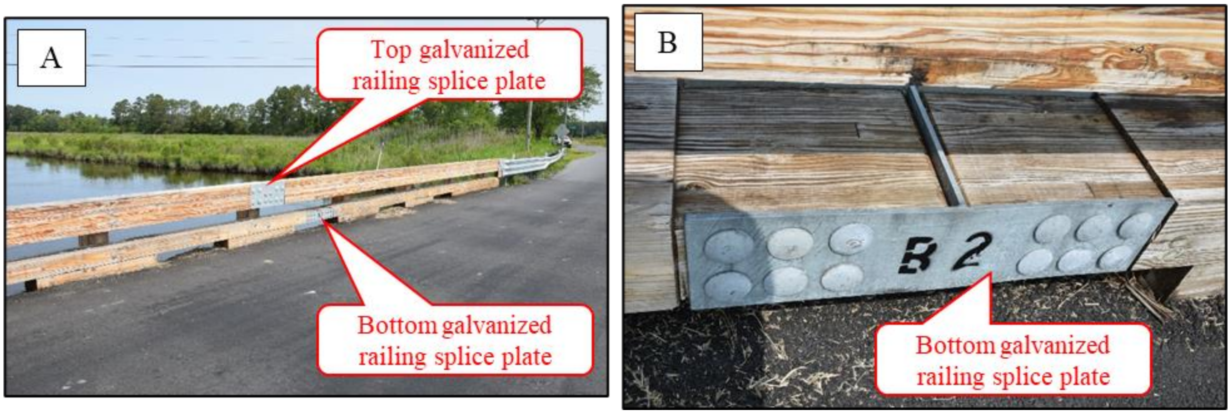


Figure 18. Photographs of Galvanized Splice Plates for Glulam Railing on the 2022 Holdens Creek Bridge: (A) overall view; (B) close-up of bottom splice plate.

The connections from the metal guardrail on the roadway to the glulam railing on the bridge also offered an opportunity to monitor corrosion performance over time with different types of corrosion protection systems. Figure 19 shows photographs of this connection at the southwest corner of the bridge. It can be seen that the metal guardrail connection bolts have steel plate washers, which are not galvanized, between the nuts and galvanized splice plate. It is expected that these steel plate washers are likely made of ASTM A36 steel. Because these steel plate washers were not galvanized and were made from typical carbon steel, they are expected to have much less corrosion resistance than the rest of the surrounding hardware. As for the glulam railing connection bolts, the nuts were galvanized with two different methods: the gray/silver nuts were hot dipped galvanized, and the green nuts were mechanically galvanized. This difference was noted so that any difference in corrosion performance between the two different galvanization methods can be monitored in the future.

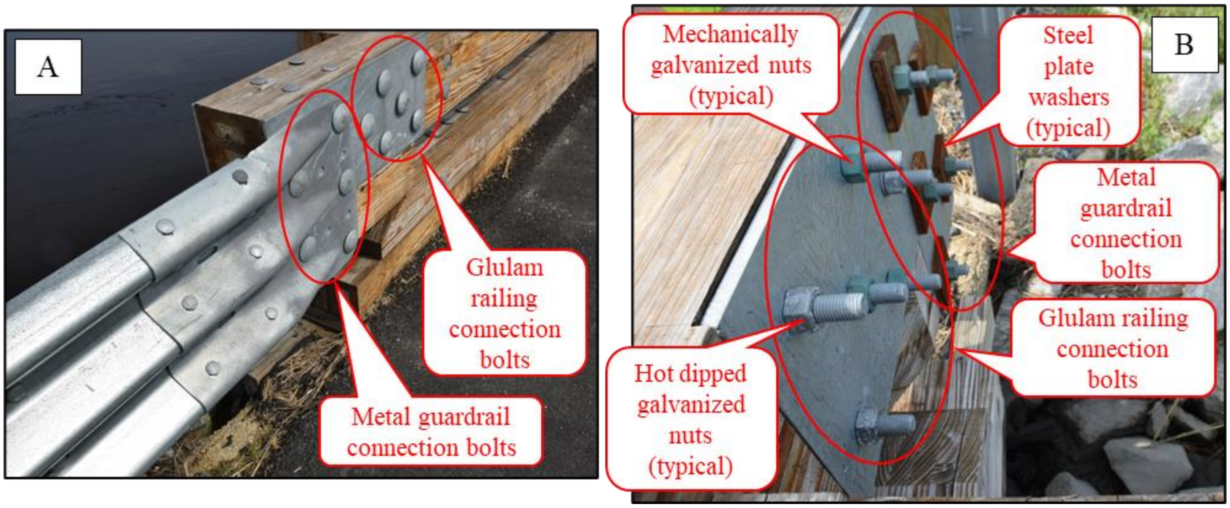


Figure 19. Photographs of Metal Guardrail to Glulam Railing Guardrail Connection on Southwest Corner of Bridge Showing Connection: (A) traffic side; (B) water side.

Figure 20 shows photographs of the underneath side of the bridge. Figure 20a presents a general view showing the 50CR steel girders; a galvanized diaphragm with galvanized fastener connections; a galvanized deck stringer; and the substructure, including a galvanized tee plate connecting the timber piles to a timber pile cap. Figure 20b shows a close-up of one of the 50CR steel girders with a galvanized deck connection clip. Overall, the 50CR steel girders showed the rustic patina that was expected. Water lines were also present on the girders where the water from Holdens Creek below had partially submerged the girders for periods of time. There did not appear to be any zinc product migrating from the galvanized deck connection clips to the 50CR steel girders at this time.

Figure 21 shows additional photographs of the 2022 Holdens Creek Bridge. Figures 21a and 21b show close-up views of the bolted connection between the 50CR steel girders and the galvanized diaphragms. The welds connecting the girder to the diaphragm connection plate all remain shiny. This was the case for all the welds on this connection, including the welds on the bottom flange, web, and top flange. Figure 21c shows that some portions of the web-to-flange welds have a shiny appearance and others are more similar in color to the 50CR steel. Since all these welds are in the same environment at the bridge, this difference in appearance is likely due to differences in welding that occurred during fabrication. Figure 21b also shows an accumulation of built-up debris at one of the piers due to previous high water.

Figure 22 shows photographs taken around the galvanized nonstructural beam, which is located on the Chesapeake Bay side of the bridge. Figure 22a shows the close elevation between the nonstructural beam and the boat sitting on the water below the bridge. Figure 22a also shows additional debris buildup on top of the nonstructural beam, and the close-up photograph in Figure 22b shows a light accumulation of debris on the galvanized nonstructural beam. Figure 22a also shows some vertical railing connection bolts above the galvanized nonstructural beam.

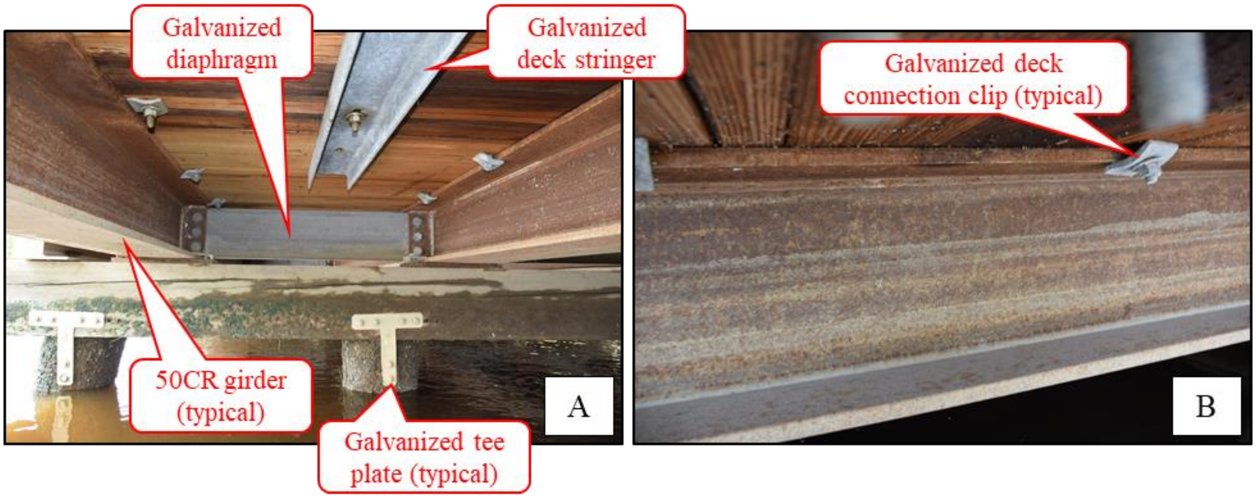


Figure 20. Photographs of Underneath Side of the 2022 Holdens Creek Bridge: (A) general view; (B) close-up of 50CR steel girder.

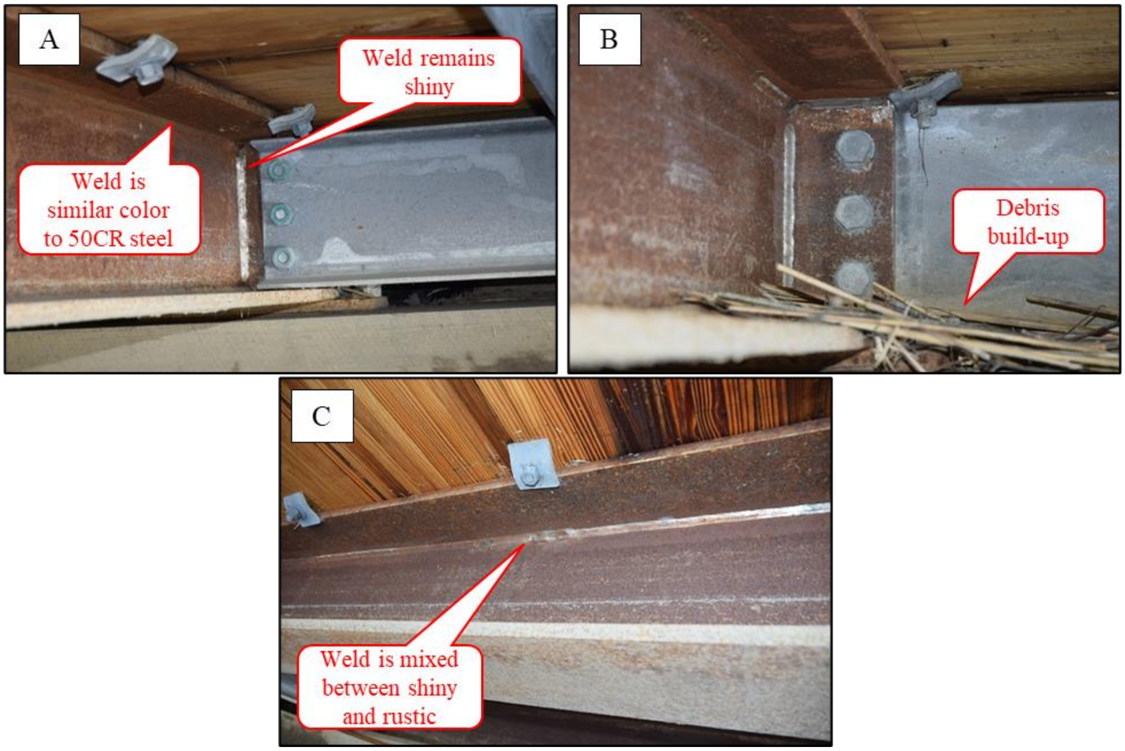


Figure 21. Photographs Showing Differences in Weld Coloration: (A) at diaphragm connection; (B) at diaphragm connection with debris buildup; (C) along length of girder.

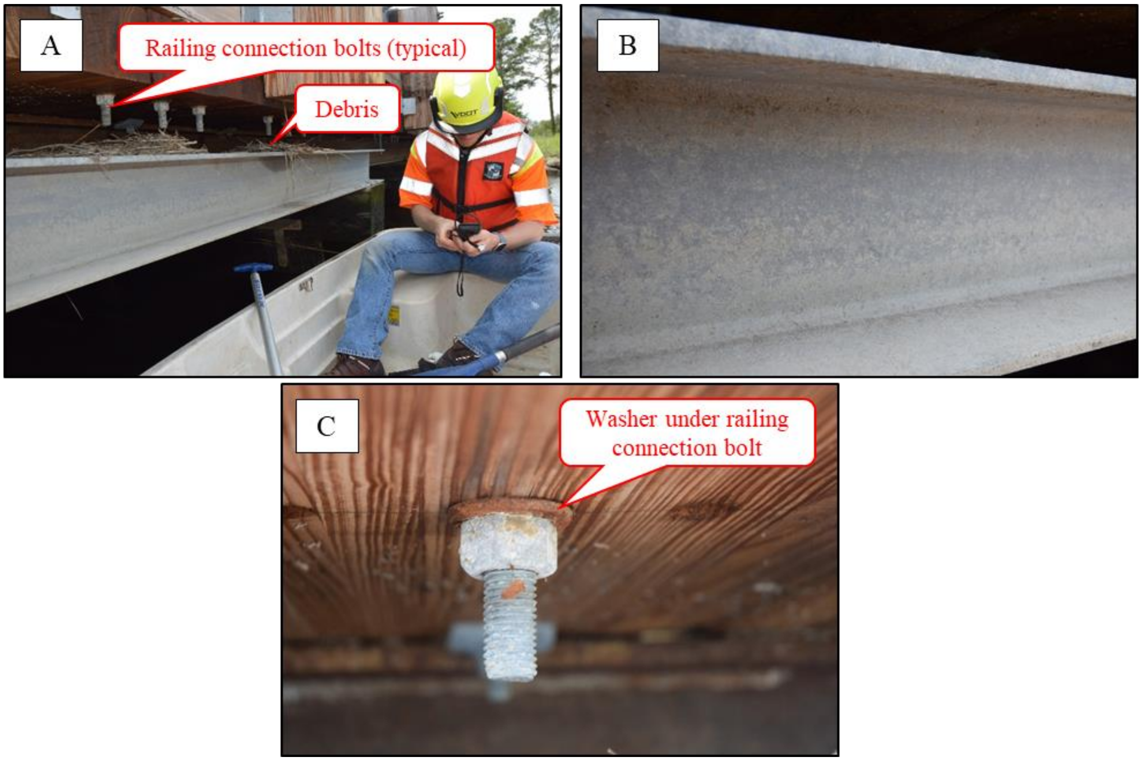


Figure 22. Photographs of Galvanized Nonstructural Beam on Chesapeake Bay Side of the 2022 Holdens Creek Bridge: (A) general view; (B) close-up of beam; (C) close-up of railing connection bolt above beam.

A closer inspection of this connection revealed that the washers between the nuts and glulam deck (close-up shown in Figure 22c) showed more corrosion than the bolts or nuts. This is likely because the washers were not galvanized to begin with. Additional corrosion could also potentially be attributed to timber preservatives in the glulam deck. The galvanizing thickness on these nuts was measured to be 3 to 4 mils and will be monitored over time.

Figure 23 shows photographs of the nonstructural metallized/sealed beam on the Atlantic Ocean side of the 2022 Holdens Creek Bridge. In contrast to the galvanized nonstructural beam, there was no debris accumulation on top of the nonstructural metallized/sealed beam. However, there was more debris accumulation on the ocean side of the bottom flange. These differing levels of debris accumulation are likely due to differences in the ebb and flow of the tide in Holdens Creek. Since debris accumulation can lead to increased corrosion, it will be interesting to watch how it affects both the nonstructural galvanized and metallized/sealed beams.

Figure 24 shows a photograph of one of the galvanized tee plate connections on the substructure. The tee plate connection in this photograph was bent both longitudinal and transverse to the bridge. Since these tee plates were not bent when originally installed (see Figure 15), this is likely to have been caused by movement of the bridge due to traffic and flooding forces.

Elements of the 2022 Holdens Creek Bridge, including its 50CR steel girders, galvanized diaphragms, nonstructural galvanized and metallized/sealed beams, miscellaneous galvanized hardware, and glulam deck, will continue to be monitored and measured over time to document their corrosion performance.

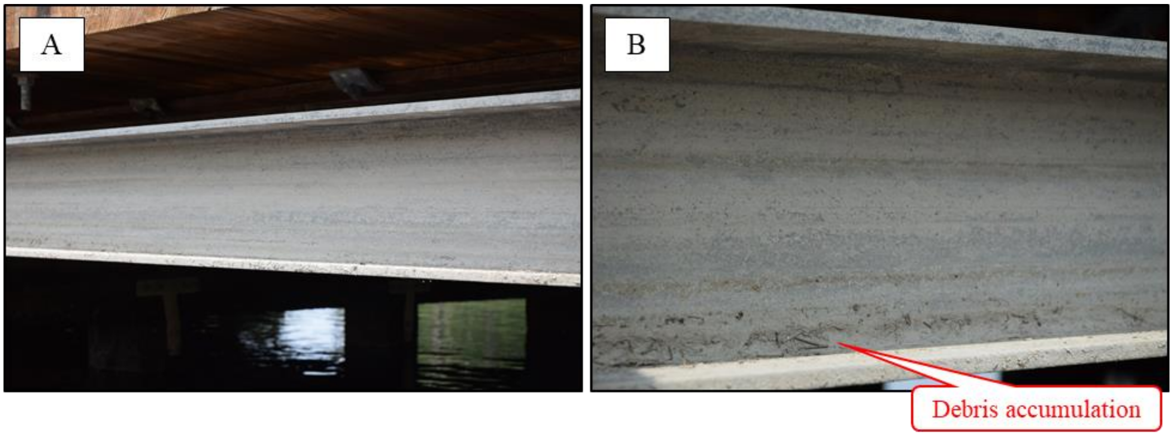


Figure 23. Photographs of Metallized/Sealed Nonstructural Beam on Atlantic Ocean Side of the 2022 Holdens Creek Bridge: (A) general view of beam; (B) close-up of beam.

Figure 24. Photograph of Galvanized Tee Plate Connection Between Piles and Pile Cap on the 2022 Holdens Creek Bridge

Task 2: Documentation and Evaluation of the Onancock Bridge Repairs

Corrosion of the Onancock Bridge Prior to the 2018 Repairs

The Onancock Bridge steel beams are coated to provide corrosion protection. Before the more recent repairs in 2018, VDOT records indicate that the structural steel was coated in 1978. Therefore, a review of the inspection report prior to the repairs in 2018 provides insight into the condition of the bridge before the 2018 repairs. This information is provided in the 2017 VDOT bridge inspection report.

In 2017, the VDOT inspection report indicated that reflective cracking of the wearing surface on top of the deck with crack widths of up to ½ in was observed between all decking timbers. The coating on the beams supporting the timbers was considered “Poor,” so when rain or snow was present, the coating no longer protected the steel and moisture could readily reach the steel. The degree of rusting along these beams is shown in Figure 25. Photographs taken during the 2017 inspection of these beams are provided in Figure 26.

The 2017 inspection report indicated that surface rust and rust scale with section loss were evident along the top flange of all beams, with the section loss primarily at deck clip locations. Surface rust and rust scale were noted in the bottom flanges and webs of all beams, with measurable section loss up to 1/16 in also being observed in the bottom flanges. The inspection report also noted rust perforation in the webs and up to 1/8 in of section loss in the bottom flanges of multiple beams, shown in Figure 27.

The 2017 inspection report recommended that multiple deficient beams receive special attention and be made a priority over routine and preventative maintenance work. It also recommended that a contract be scheduled to clean and paint all structural steel, 6,576 ft^2, which included the steel beams and steel caps.

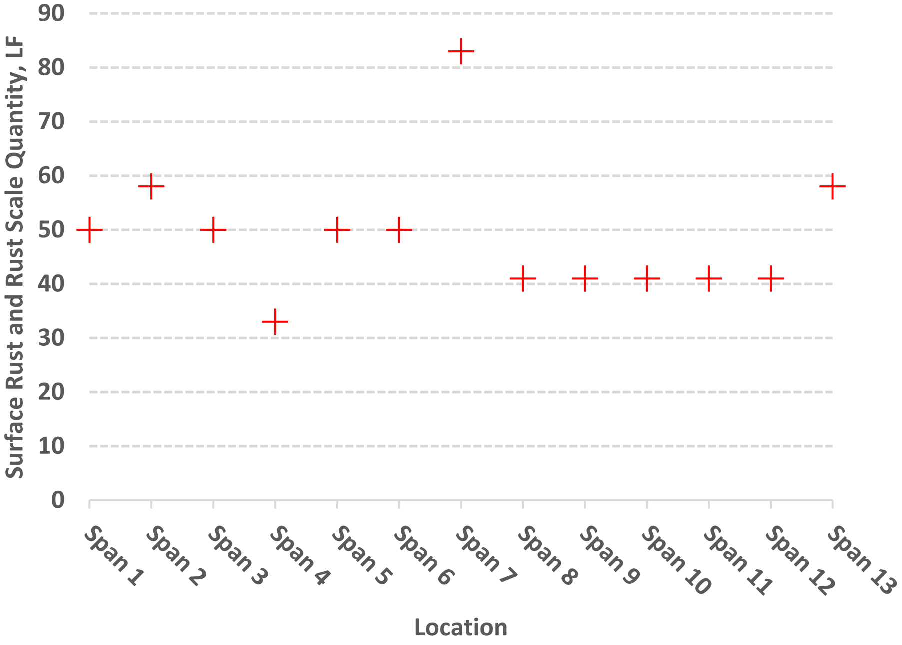


Figure 25. Lineal Feet of Surface Rust and Rust Scale on Beams Within Each Span of the Onancock Bridge

Figure 26. Photographs Showing Coating on Beams of the Onancock Bridge in 2017: (A) loss of coating and surface rusting along beams; (B) section loss on top flange of beams.

Based on these recommendations, VDOT initiated a project to perform repairs on the Onancock Bridge. The project scope of work included four items: (1) repair five steel beams with bottom flange and/or web cover plates; (2) replace seven railing connection rods; (3) remove existing abutment A and replace with new sheet pile wall, steel piles, and steel cap beam; and (4) remove existing abutment B and replace with new sheet pile wall, steel piles, and steel cap beam. Item 1 in the scope of work is the focus of the design and corrosion performance monitoring discussion in this report.

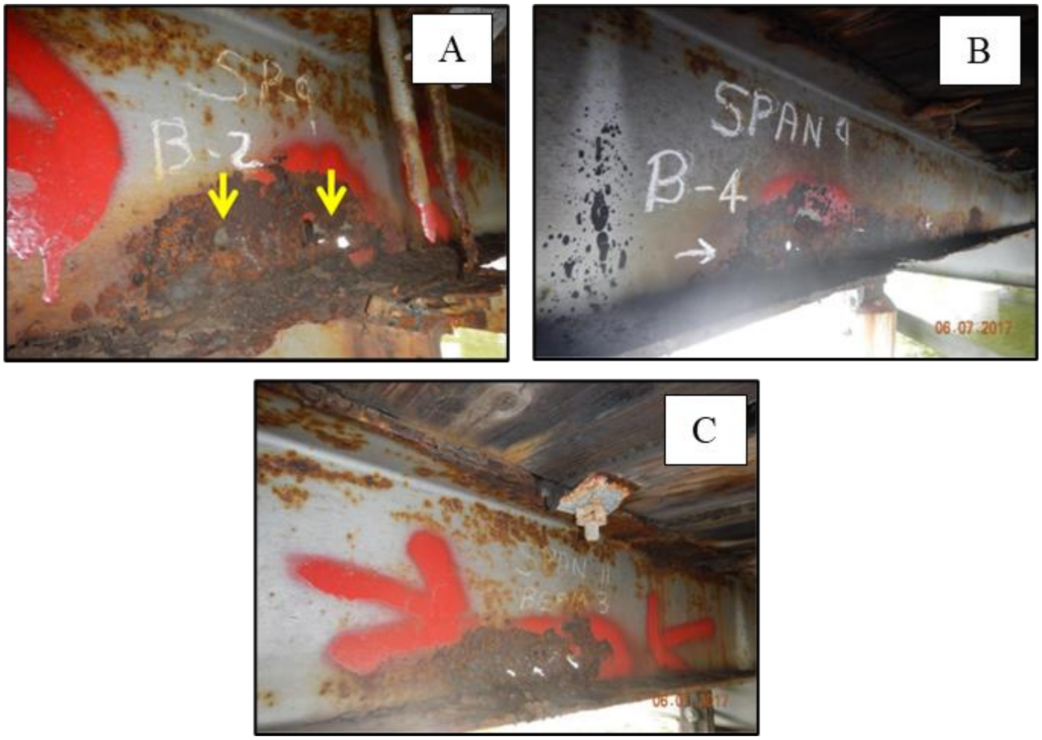


Figure 27. Photographs of the Onancock Bridge in 2017: (A) rust perforation and section loss of bottom flange; (B) rust scale with section loss transitioning from 1/8 in to becoming a knife edge along bottom flange; (C) rust perforation of web at midspan and up to 1/8-in section loss of bottom flange.

Design of Onancock Bridge Repairs

Based on the corrosion evaluation of the Onancock Bridge prior to repairs, 50CR steel was selected for use on the bolted repairs. However, other steel bridge corrosion protection systems were also included in the repairs to compare the relative corrosion performance of 50CR steel to that of weathering and galvanized steel. The initial cost for the fabrication of the Onancock Bridge repair plates was estimated as a lump sum price, no tax, to be $3,350.00. The price included the fabrication of 20 repair plates using the 50CR steel plate material owned by VDOT. The fabricator would provide the ASTM A588 (A588) steel and ship the fabricated plates to Onancock, Virginia. The fabricator was not responsible for providing hardware (bolts, nuts, or washers) or blast cleaning and/or painting the fabricated plates.

Based on the repair plan scope of work, five bolted repairs were required at the Onancock Bridge. Figure 28 shows a framing plan of the Onancock Bridge with the locations of the five bolted repairs indicated by red circles. Among the five locations, there were four different repair types. This is noted by Repair Type 2 being indicated in two locations on the framing plan. The repair types differed by steel type; fastener assembly type; geometry; and whether the repair included a bottom flange splice, web splice, or both.

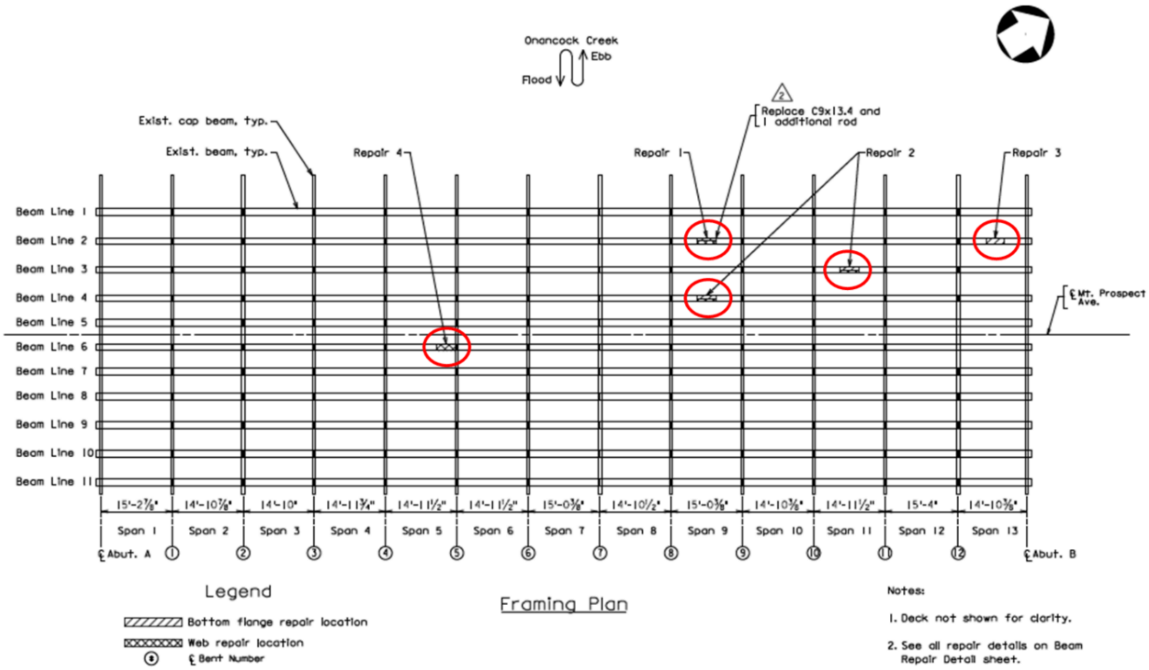
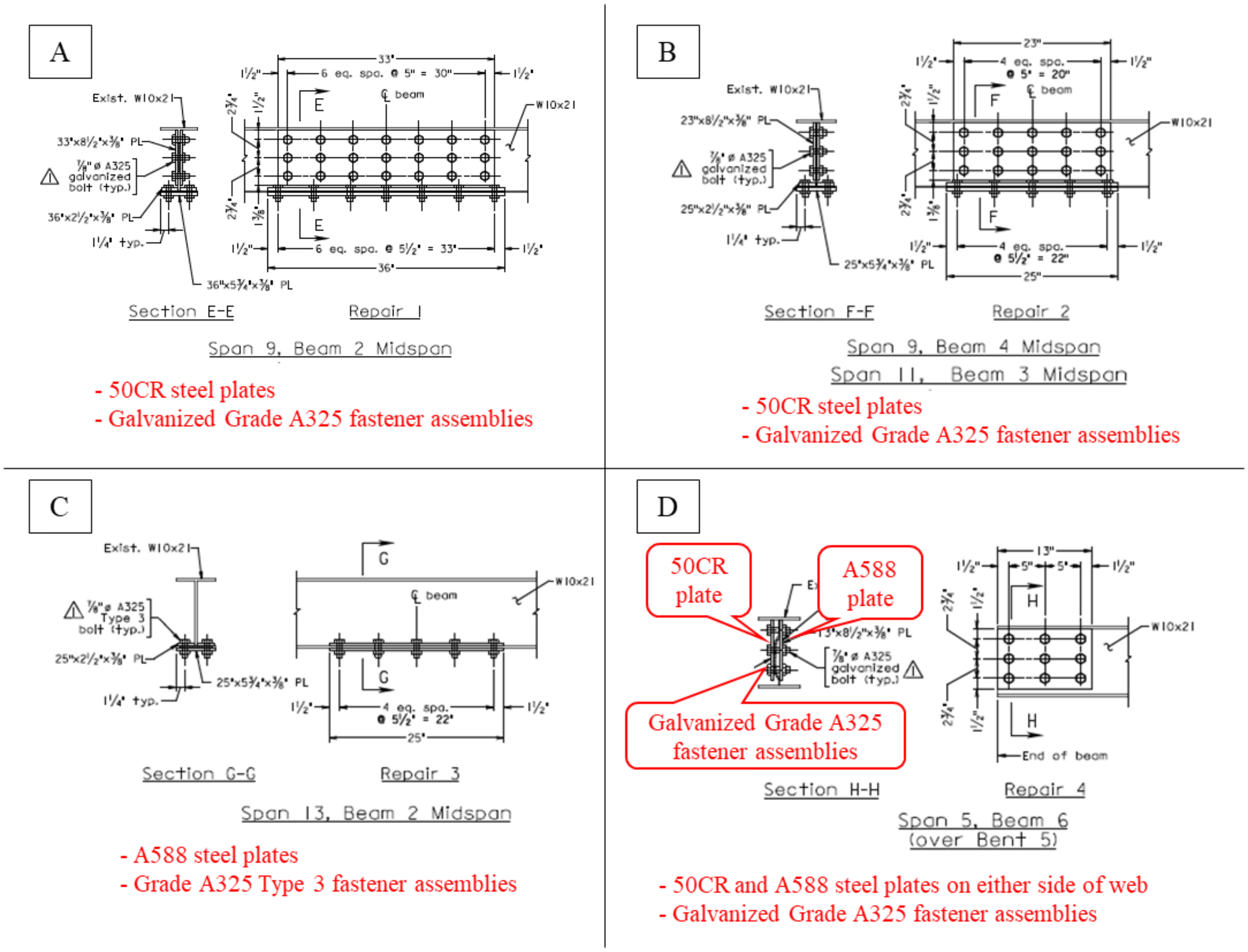


Figure 28. Framing Plan of the Onancock Bridge Showing Bolted Repair Locations. The locations of the five bolted repairs are indicated by red circles.

Figure 29 shows the details of each repair type. As indicated in the figure, Repair Types 1 and 2 both consisted of 50CR steel repair plates combined with galvanized ASTM F3125, Grade A325 (A325), fastener assemblies. For these repairs, repair plates were installed on the web and bottom flange at each specified location. The repair types differed only by the length of the steel plates required. Galvanized fastener assemblies were selected with these repair types to follow the cost-saving design alterations used for the 2022 Holdens Creek Bridge, discussed previously. Repair Type 3 consisted of weathering steel repair plates and fastener assemblies, i.e., A588 steel plates and A325, Type 3, fastener assemblies. For this repair, plates were added to the bottom flange of the beam. Weathering steel plates and fastener assemblies were selected for this type of repair to serve as the control and to provide a comparison to the 50CR steel plate with galvanized fastener assemblies in Repair Types 1 and 2. Repair Type 4 was somewhat of a combination of Repair Types 1 and 2 and Repair Type 3. Repair Type 4 contained one 50CR steel plate on one side of the beam web, one A588 steel repair plate on the opposite side of the beam web, and galvanized A325 fastener assemblies connecting the repair plates to the existing beam. This combination of steel plates and fastener assemblies was selected to determine the difference in corrosion performance when 50CR steel and A588 steel are connected via galvanized fastener assemblies. The bolted repairs were installed on the Onancock Bridge in February 2018.



- 50CR steel plates
- Galvanized Grade A325 fastener assemblies

- 50CR steel plates
- Galvanized Grade A325 fastener assemblies

- A588 steel plates
- Grade A325 Type 3 fastener assemblies

- 50CR and A588 steel plates on either side of web
- Galvanized Grade A325 fastener assemblies

Figure 29. Bolted Repair Details for the Onancock Bridge Indicating Type of Steel Plates and Fastener Assemblies Used: (A) Repair Type 1; (B) Repair Type 2; (C) Repair Type 3; (D) Repair Type 4.

Corrosion Performance of the Onancock Bridge Repairs

In May 2023, more than 5 years after the bolted repairs had been installed on the Onancock Bridge, VTRC researchers visited the bridge to inspect the repairs and document their corrosion performance. VTRC researchers accessed the underneath side of the Onancock Bridge via a motorized boat owned by the Hampton Roads District to inspect each of the repairs.

Since the Repair Type 1 and both Repair Type 2 repairs consisted of 50CR steel plates with galvanized fasteners and had similar conditions in the field, they are discussed together. Figure 30 shows photographs of Repair Types 1 and 2 from Span 9. Overall, these repairs appeared to be in good condition, and the 50CR steel plates appeared to have a consistent rustic patina. The thickness of the 50CR steel plates was measured with a UT thickness gauge and was consistently 0.40 in. As noted in the design drawings for these repairs, all repair plates had a nominal thickness of 3/8 in.

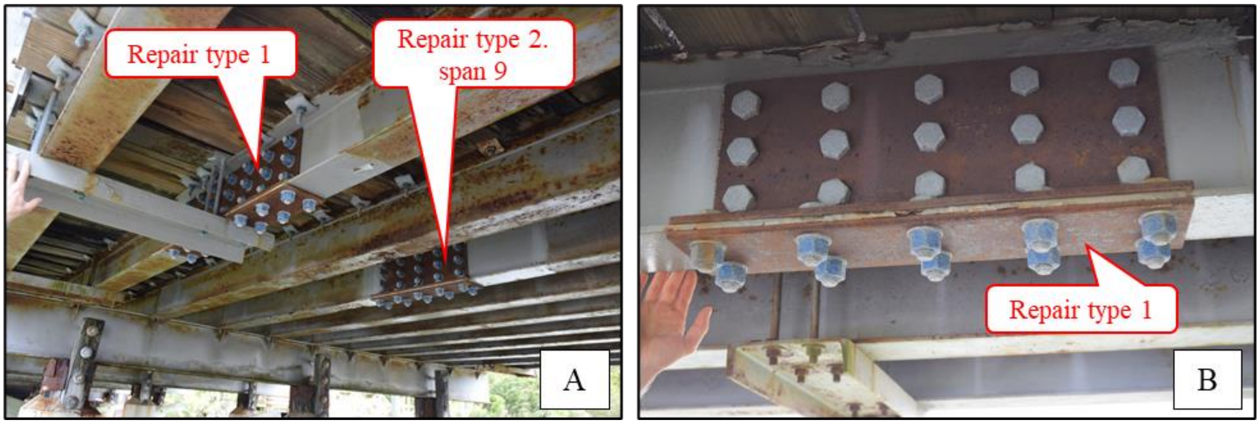


Figure 30. Photographs of Bolted Repair Types 1 and 2 Made of 50CR Steel and Galvanized Fastener Assemblies on the Onancock Bridge: (A) general view of both repairs; (B) close-up of Repair Type 1.

Figure 31 shows close-up photographs of both the nut and washer side of the galvanized fastener assemblies and the bolt head side. In both photographs, there was zinc product migrating from the galvanized fastener assembly to the 50CR steel plate. The migration of the zinc product is caused by galvanic, or dissimilar metal, corrosion between the 50CR and galvanized steels. In this case, the galvanized steel is less corrosion resistant than the 50CR steel, so it is preferentially corroding in the presence of the salt-laden air from the saltwater below the bridge. The migrating zinc product shown in Figure 31 was present on nearly all of the nut and washer sides of the fastener assemblies (as in Figure 31a) but was only partially present on some of the bolt head sides (as in Figure 31b). This is likely because the washer is in full contact with the 50CR steel plate whereas the bolt head is not, due to the forging process used to connect the bolt shank and bolt head. Larger contact areas are expected to have larger galvanic corrosion rates. The zinc thickness on the galvanized nuts and bolt heads was measured with a UT thickness gauge and was found to be 4 to 6 mils.

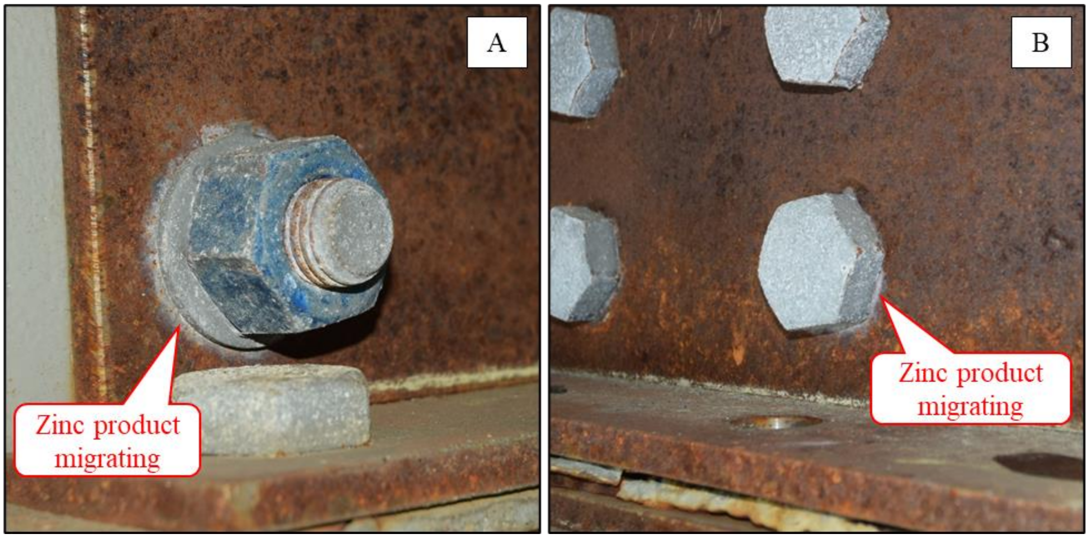


Figure 31. Close-Up Photographs of Bolted Repair Types 1 and 2 Made of 50CR Steel and Galvanized Fastener Assemblies on the Onancock Bridge Showing Zinc Product Migrating From the Galvanized Assembly to the 50CR Steel Plate: (A) nut and washer side of assembly; (b) bolt head side of assembly.

Figure 32 shows photographs of the Repair Type 3, which consisted of A588 steel plates and A325 Type 3 fastener assemblies. Overall, the repair appeared to be in relatively good condition since no advanced corrosion was present, but it did appear to be slightly more corroded compared to the Repair Types 1 and 2. This was expected, since weathering steel is less corrosion resistant than 50CR steel and galvanized steel. The location of these repairs also fall outside the Federal Highway Administration's (FHWA) recommended areas for use of uncoated weathering steel due to the low water clearance and marine environment (FHWA, 1989). The weathering steel plate did not exhibit pitting, crevice, or laminar corrosion, but the steel did appear to have some loosely adherent small flakes. The repair plate on the bottom of the bottom flange and the nut and washer appeared to exhibit these small flakes and were darker than the plate on top of the bottom flange and the bolt head. This is likely because the bottom of the bottom flange is more easily exposed to the salt-laden air compared to the top of the bottom flange. The thickness of the weathering steel plates on the top and bottom of the bottom flange was measured in several locations with a UT thickness gauge and was found to be 0.40 in. As discussed previously, in the design drawings for these repairs, the plates have a nominal thickness of 3/8 in.

Figure 33 shows photographs of Repair Type 4, which consisted of a 50CR steel repair plate on one side of the web, a weathering steel repair plate on the other side, and A325 galvanized fastener assemblies. Figures 33a and 33b show general views of the 50CR steel and weathering steel plates, respectively, and Figures 33c and 33d show close-up views of the same plates. In general, both repair plates appeared to be performing similarly to the other types of repairs inspected.

Figure 32. Photographs of Bolted Repair Type 3 Made of Weathering Steel Plate and Fastener Assemblies on the Onancock Bridge: (A) general view; (B) side view close-up; (C) view of bottom of bottom flange; (D) view of top of bottom flange.

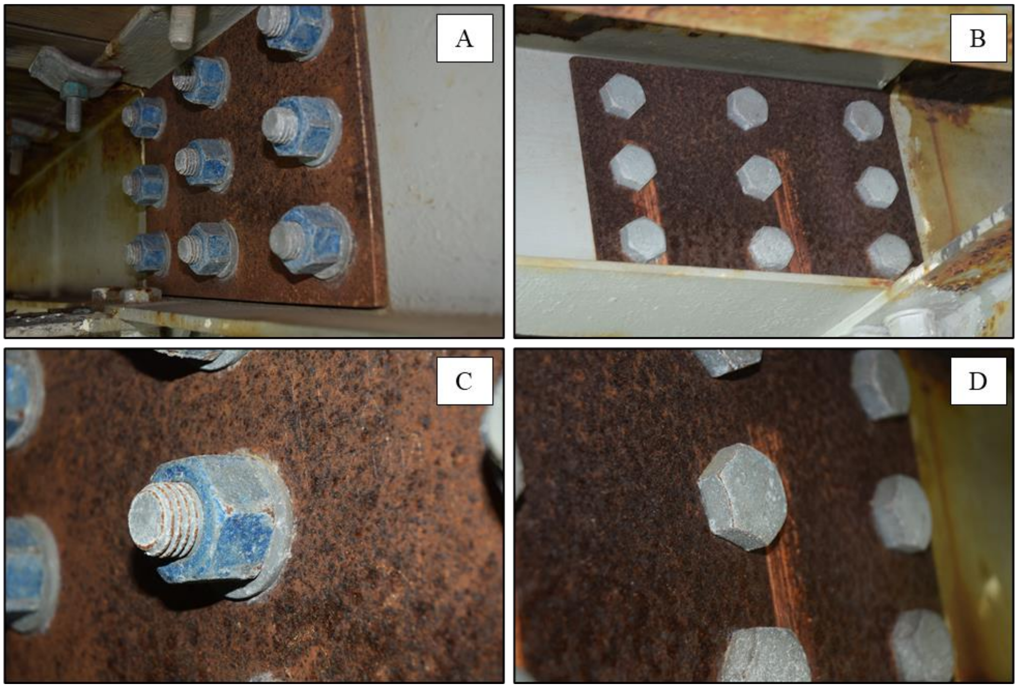


Figure 33. Photographs of Bolted Repair Type 4 Made of 50CR Steel and A588 Steel Plates With A325 Galvanized Fastener Assemblies on the Onancock Bridge: (A) general view of 50CR steel plate; (B) general view of A588 steel plate; (C) close-up of fastener assembly on 50CR steel plate; (D) close-up of fastener assembly on A588 steel plate.

As seen in the photographs, the color of the weathering steel appeared darker than that of the 50CR steel plates. The weathering steel on this repair also appeared to be more tightly adherent when compared with the bottom flange repair plates on Repair Type 3 (shown in Figure 32). This is likely because this repair is located vertically on a beam web, so it is more shielded from the salt-laden air, and is oriented to allow moisture to drain off more than the horizontal bottom flange repair plates on Repair Type 3. There was some zinc product migrating on the 50CR steel repair plates surrounding the galvanized washers, as evident in Figure 33c.

Task 3: Cost Analysis of the Future Economic Potential of 50CR Steel

In terms of unit cost, design, and installation, 50CR steel was generally successful for both the 2022 Holdens Creek Bridge and the Onancock Bridge. However, VDOT experienced delays on its next two 50CR steel bridge projects. Portions of these delays were a result of long lead times for delivery of 50CR steel (in excess of 6 months). The following section describes key factors in the United States and worldwide that are likely to have contributed to restrictions of 50CR steel availability since 2020. The combined impacts of these factors (and others not discussed here) from the fourth quarter of 2020 to the third quarter of 2022 are reflected in the sharp increase in highway construction costs since then. This discussion probes the economic trends and events of the last 2 years in order to gain insights into highway construction cost trends and separately examines commodities linked specifically to 50CR steel.

As a relatively scarce product in irregular use to date, the unit cost of 50CR steel would not be expected to be stable across all projects in which VDOT has used it. In fact, the decline in unit costs for material, fabrication, delivery, installation, and tax from $5.84/lb in 2015 for the Route 340 Bridge, to $5.08/lb for the 2022 Holdens Creek Bridge, and then to $3.10/lb in 2020 for the Featherbed Lane Bridge (a 50CR steel VDOT bridge completed after the 2022 Holdens Creek Bridge) is highly desirable, because it satisfied expectations of unit cost decreasing as tonnage increased and cost-saving design alterations were able to be implemented. In total, the unit cost of 50CR steel decreased by approximately 47% from the Route 340 Bridge in 2015 to the Featherbed Lane Bridge in 2020.

The recent historic spike in national highway construction costs prevents a quantitative life-cycle cost analysis on practical grounds because the future remains unpredictable with respect to both cost inflation and nominal interest rates. Despite great uncertainty about the economic environment in which infrastructure repair and construction must go forward, a strong feature of 50CR steel can be mentioned to summarize part of the following discussion: 50CR steel is not rich in alloys displaying great price swings in recent years. Instead, its alloys have had relatively low and stable prices while the U.S. and global economies have undergone radical market adjustments in a short period of time.

National Cost Trends for Highway Construction

Figure 34 shows the path of the National Highway Construction Cost Index (NHCCI) and the rapid construction cost inflation that began at the end of calendar year 2020 and accelerated in 2021 and 2022. Davis (2023) calculated that price inflation has caused federal highway spending (including advance appropriations from the general fund pursuant to the Infrastructure Investment and Jobs Act [IIJA]) to lose nearly $21.5 billion in value from the first quarter of FY 2021 through the fourth quarter of FY 2022.

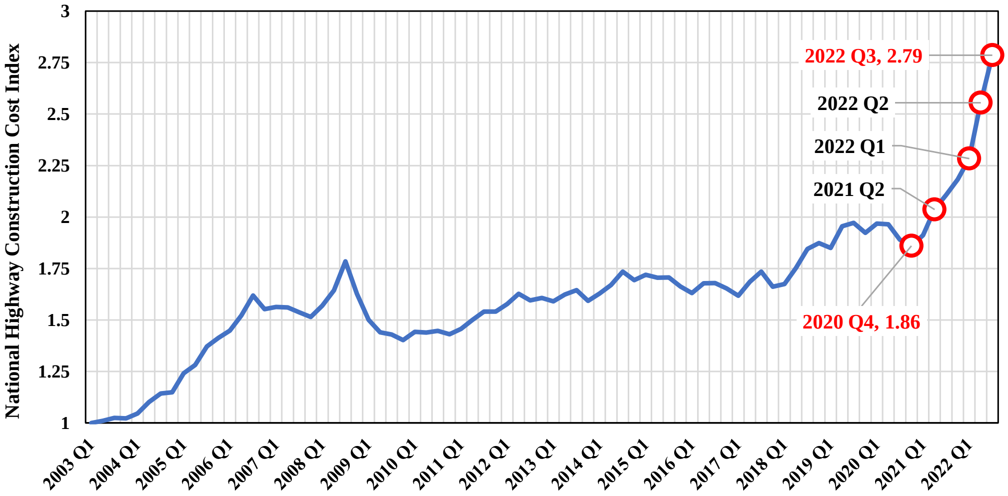


Figure 34. National Highway Construction Cost Index, 2003-2022. Source: Federal Highway Administration, 2023.

Although price inflation in early 2021 was widely considered transitory, since then, inflation has accelerated rather than subsiding, and debate over the causes has been active. Recent research causally linked a reduction in capital expenditure on oil production in 2020 and the consequent reduced supply of oil in 2021 to rising general cost inflation in the United States through 2022 (Gagliardone and Gertler, 2023). Noel (2023) predicted aggravation of cost inflation by "the full force of IIJA funding on material production capacity" and identified fossil fuel costs as the primary cause of cost inflation in the highway construction sector since enactment of the IIJA, noting that asphalt prices are direct derivatives of crude oil prices, just as grading and excavation costs are direct derivatives of diesel fuel costs.

Figure 35 shows that the asphalt and grading/excavation components of the NHCCI have played dominant roles in pushing the highway cost index higher in the last 2 years. The measured contributions to the increase in the NHCCI that are due specifically to asphalt, grading/excavation, and bridge components stand out in Figure 35. Of the 9 percentage point increase in the NHCCI in the third quarter of 2022 over the second quarter of 2022, the components of asphalt, grading/excavation, and bridge accounted for 3.54, 1.80, and 1.57 percentage points, respectively, i.e., altogether nearly 7 percentage points from those three components of the index. Their prominence in driving the NHCCI in turn suggests that the energy costs driving them have played a fundamental role in the NHCCI trend.

Two sectoral shocks directly caused fossil energy prices to spike in 2021 worldwide: the pairing of European gas stores "at their lowest levels for years" after pandemic-related production slowdowns with the natural but unexpected loss of wind in the North Sea in the summer of 2021 (National Wind Watch, 2021; Wallace, 2021).

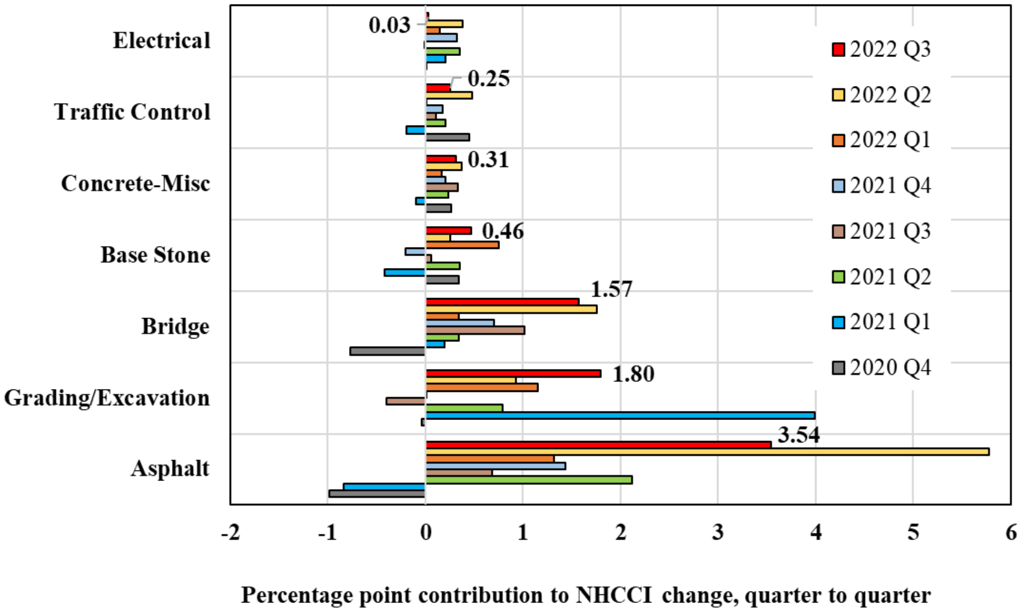


Figure 35. Percentage Point Shares by Components of Quarterly Changes in the NHCCI, 2020 Q4–2022 Q3. NHCCI = National Highway Construction Cost Index. Data source: Federal Highway Administration, n.d.

As energy prices spiked in oil, natural gas, and coal markets in the United States and around the world, recession fears filled the media, accompanied by deliberate calming efforts (such as those cited in Domm [2021]) because of the well-established role of inflation expectations in aggravating actual inflation (Gagliardone and Gertler, 2023).

Exports of U.S. fossil energy in 2021 in response to European demand further stimulated rising energy prices in the United States. Citigroup energy analysts forecast possible winter weather crises in Europe that could send the price of oil to $580/barrel (Domm, 2021). Dissonant pronouncements were common: "Economists say the rise in energy prices would have to be sharper and much more prolonged to cause a recession," but "Bernstein energy analysts looked at past periods where prices rose sharply and found that recessions followed periods where energy costs were at 7% of global GDP, as they reached in October" (Domm, 2021). U.S. energy prices notwithstanding, U.S. natural gas was exported while domestic and foreign supplies were lower than normal due to the pandemic and, in 2022, due to supply chain disruptions caused by international hostilities. Figure 36 shows how producer prices for petroleum and natural gas trended from the beginning of 2021 into early 2023.

Federal legislation that stimulated U.S. infrastructure construction with historic levels of federal funding was enacted in this environment in the IIJA in November 2021. Landers (2022) wrote: "[w]ith $550 billion in new spending over five years, the IIJA affects essentially every infrastructure sector and practically all aspects of civil engineering." Others cited a 10-year spending horizon for the IIJA budget of $550 billion, nearly all through state and local government grants (Salwati and Wessel, 2022). The president of Amtrak observed that "[t]o put the scale of this investment [in passenger rail] in context, the $58 billion the IIJA designates for intercity passenger rail is roughly equivalent to the total federal funding for Amtrak in the 50-plus years since Amtrak's creation" (Gardner, 2021).

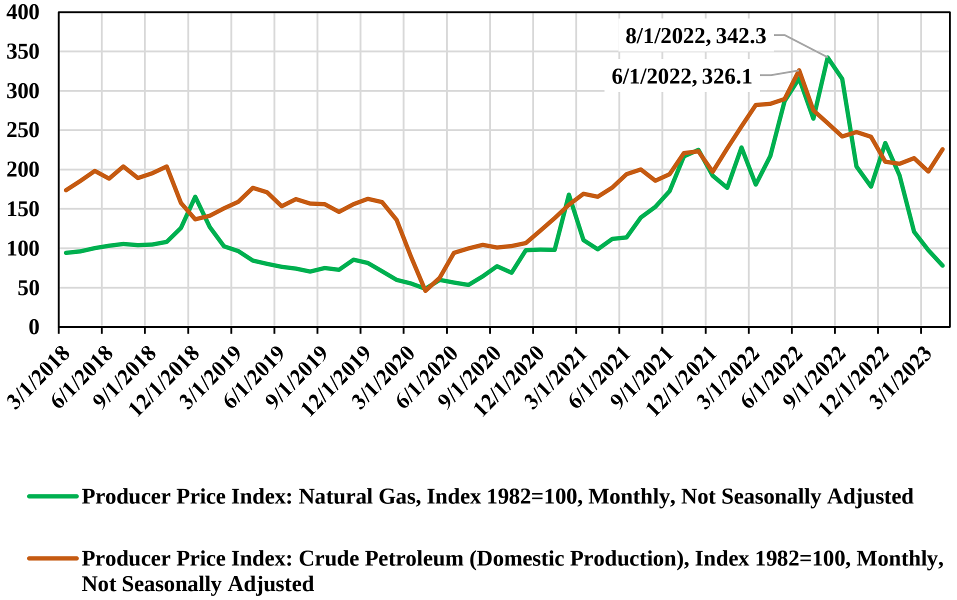


Figure 36. U.S. Bureau of Labor Statistics, Producer Price Index by Commodity: Fuels and Related Products and Power: Natural Gas [WPU0531] and Crude Petroleum (Domestic Production) [WPU0561] (March 2018-March 2023). Source: U.S. Bureau of Labor Statistics, 2023.

In light of the new spending, for purposes of this discussion of economic impacts of price inflation, IIJA funding is accurately understood as significant additional government absorption of goods and services in the U.S. economy.

With the rapid run-up of energy prices in 2021-2022, as indicated previously in Figure 36, some researchers began to question the impact of aggregate demand, i.e., combined private and government expenditures, on general price inflation since 2020. Di Giovanni et al. (2022) found that international trade was less responsive to demand in the COVID era of 2020-2021, partly because of supply chain bottlenecks, and concluded that policies enacted in 2021—e.g., income support programs for Americans—to stimulate aggregate demand produced higher inflation under the prevailing conditions than they would have under normal conditions. In subsequent research, Di Giovanni et al. removed government spending from aggregate demand in a model scenario, allowing their model to measure the impact of fiscal stimulus indirectly (i.e., government expenditures) on inflation under supply chain restrictions. They found that fiscal stimulus over December 2019-June 2022 contributed at least one-half of the total aggregate demand effect on inflation; when government expenditure was excluded, aggregate demand explained one-half or less of the inflation observed in the model (Di Giovanni et al., 2023). They also found that sectoral supply and demand shocks contributed to the total inflation observed in their model.

Some features of the IIJA facilitated money moving out the door swiftly, such as the publishing of only a single funding notice for several programs (thus requiring only one application) and the appointments of state infrastructure coordinators in every state soon after enactment of the legislation (Salwati and Wessel, 2022). Funding related to electric vehicles was deployed quickly: as of the end of March 2022, as much as $7.5 billion was "being invested in the U.S. Electric Vehicle (EV) charging infrastructure . . . through the Bipartisan Infrastructure Law" (National Institute of Standards and Technology, 2022). The National Electric Vehicle Infrastructure Formula Program was provided in both FY 2022 and FY 2023 with $1 billion in advance appropriations from the federal general fund and was not subject to any obligations limitations. The same annual funding is scheduled for each year in FY 2024-2026 (FHWA, 2022).

By 2022, the issue of fiscal stimulus–triggered price inflation was of peak interest to those concerned with the government spending inherent in the IIJA: Speakers at the Brookings Institution 11th Annual Municipal Finance Conference held in July 2022 shared concern about the impacts of anticipated price inflation and its expected stimulation by supply-side disruptions and skilled labor shortages, specifically expecting rising wage levels for workers (Salwati and Wessel, 2022). More telling, the Executive Director of the Colorado DOT reported "nontrivial pressure from parts of the industry" to allow cost overages without thorough justification, in contrast with the agency's need to exercise due diligence for "the best return on taxpayer investments" (Lew, 2022). The federal response was that current inflation would in fact not be exacerbated by the IIJA because most new spending would be in future years (Salwati and Wessel, 2022), but others pointed to short-term negative effects that result from the fact that it takes time to build and that disruptions of infrastructure use during construction cause measurable drag in the economy. To the point, the timing of the infrastructure bill was likened to "leaning forward as the wind blows from behind," i.e., overly stimulating for the U.S.

economy in late 2021, given the cumulative stimulation of pandemic-related income transfers and the American Rescue Plan Act expenditures (Miran, 2021). Finally, further price inflation was expected from manufacturing sector preparations for compliance with the many new mandates of the IIJA that accompany the funding, e.g., for new vehicles (Miran, 2021).

The Inflation Reduction Act (IRA) was enacted 9 months after the IIJA. The utility sector was acutely aware of the combined magnitude of the opportunities in the two new laws: "With IIJA building the underlying physical system capacity and structure to support future change and the IRA serving as the mechanism to catalyze this change, the two investments are somewhat of a complement to each other. Together, nearly 2 trillion federal dollars are allocated towards modernizing infrastructure . . . ." (Monroe, 2022). A study of the effects of the legislation was favorable about its utility in reaching climate goals but stated that the cost could be nearer $1 trillion (Bistline et al., 2023) and that rising interest rates, a labor shortage, and difficulty in procuring critical raw materials could be obstacles to achieving investment on the envisioned scale. In April 2023, the Penn Wharton Budget Model also revised its original estimate of the cost of the IRA from about $385 billion for FY 2022-2031 to $1,045 billion for FY 2023-2032 (Wharton School of Business, 2023). Ironically, it would be the popularity of the production or investment tax credits offered in the IRA that could make the cost of the bill nearly triple.

In summary, it seems reasonable to link the sudden massive funding of expansive infrastructure projects facilitated by the IIJA and IRA with concerns about rapid highway construction cost increases since 2020 and to expect that they will remain linked until a time when general price inflation and the NHCCI return to "normal" pre-COVID trends under the new legislation. The purpose of the two bills, however, is expressly to facilitate a momentous federally managed transition of the U.S. economy away from its current fossil fuel base, and that undertaking should not be forgotten as the economic "shocks" caused by the pandemic per se subside over time.

The impacts of recent pandemic-related sectoral price shocks on the NHCCI are straightforward, and it is to be hoped that those effects will be temporary. Moreover, research has shown that the Ukraine war independently raised oil prices in the United States from winter through early spring of 2022 (Appiah-Otoo, 2022). If energy prices returned to pre-COVID trends in the near future, it would provide welcome assurance that a rapid national energy transition is not a threat to price stability, which would directly threaten U.S. infrastructure construction costs. With that outcome, optimism about the future cost of 50CR steel could be justified. In any case, in this period of high-cost transition out of the COVID era and adjustment to the new legislative landscape, a "wait and see" posture is prudent with respect to irrevocable business decisions.

The latest available data regarding diesel prices and costs per kilowatt-hour of electricity used in the industrial sector suggest that a reversal of the NHCCI trend may be developing. Figures 37 and 38 show for highway diesel and electricity to the industrial sector, respectively, that energy costs have desirable trends in 2023.

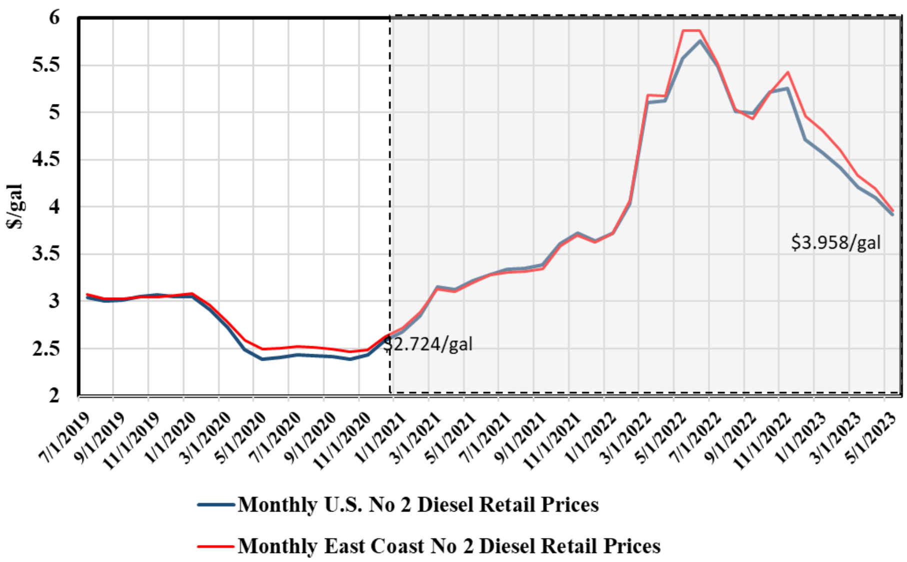


Figure 37. Monthly Diesel Retail Prices (July 2019-May 2023). Data source: Energy Information Administration, 2023.

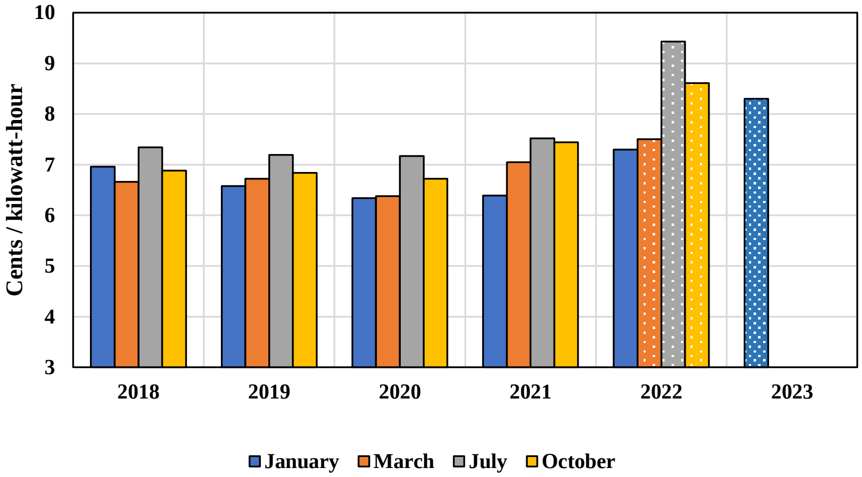


Figure 38. U.S. Total, Average Price of Electricity to Ultimate Customers by End-Use Sector—Industrial (January 2018- January 2023). Pattern fill = preliminary data. Data source: Energy Information Administration, 2023.

Significant Factors in Bridge Costs

Federal Legislation

The NHCCI bridge component consists of all pay items in successfully bid contracts let in the United States for the purpose of bridge work. Clearly, compared to the single item "asphalt," the list of individual pay items in the bridge component could be lengthy, including some items tracked individually in the NHCCI. Nationally, the collection of pay items contained in the bridge component contributed 1.57 percentage points to the 9 percentage point jump in the NHCCI in the third quarter of 2022 from the second quarter of 2022.

In coastal Virginia, the cost of fabricated corrosion-resistant steel is a critical component of the total cost, as well as the design, of bridge projects. However, since 2021, the economics of U.S. steel production have been agitated by confusion over federal rule-making and legislation. Two executive orders in January of 2021 increased the domestic content requirements of the procurement preference rules of the Buy American Act, legislation that applies to federal government procurement and conveys along with federal revenues for projects. For present purposes, the salient change required in the first executive order was to increase the domestic content threshold for end products or construction materials made predominantly of iron or steel (or both) from 50%, as for other materials before the first new order to 95%, with an exception for iron and steel fasteners (Taft Stettinius & Hollister, 2021).

The second executive order, i.e., the second procurement preference rule revision, initially issued only 1 week after the previous rule revision but ultimately comprising the separate Build America, Buy America (BABA) legislation within the IIJA, required that "*all* iron, steel, manufactured products, and construction materials used in infrastructure projects funded at least partly by Federal financial assistance must be produced in the United States" (*Federal Register,* 2022). However, the requirement for "*all*" was to be phased in between 2023 and 2029 starting with a first minimum content of 60% by October 25, 2022, and reaching 75% by 2029 (Taft Stettinius & Hollister, 2021).

The new legislation generated confusion among agencies already subject to Buy America requirements. Existing Buy America requirements impacting state highway agencies date to the transportation budget authorization of 1978 (P.L. 95-599) and are not the same as the requirements on direct federal procurement regulated under the Buy American Act of 1933 (Watson, 2021). For transportation agencies and their suppliers in particular, federal sources clarified the differences between BABA and the familiar Buy America program:

- [T]he BABA requirements apply to financial assistance programs for infrastructure only to the extent that a domestic content procurement preference does not already apply to iron, steel, manufactured products, and construction materials. Thus, the BABA requirement for construction materials supplements the existing DOT Buy America requirements for steel, iron, and manufactured products (*Federal Register,* 2022).

- BABA "provides that the Buy America requirements . . . apply only to the extent that Federal agencies do not already apply a Buy America preference to steel, iron, manufactured products, and construction materials" (Okonkwo, 2022).

The new impact of BABA for highway agencies, then, falls mainly on their purchases of "construction materials" rather than on iron and steel products, as long as Buy America requirements under 23 U.S.C. 313 meet or exceed BABA requirements for iron and steel products. Confusion about "construction material" compliance still led to a 180-day "transitional" waiver that expired on November 10, 2022, during which state and industry compliance procedures for "construction materials" were to be developed. In fact, so far as the newly BABA-regulated "construction materials" in federal projects are included in the bridge component of the NHCCI, it seems very likely that the enactment of BABA in 2022 was a driver of higher prices for the bridge component of the cost index through the third quarter of 2022.

One domestic stakeholder, Texas Iron & Metal, anticipated a "strain to supply chain" from the additional requirements, exacerbated by the war in Ukraine:

> Without any chance to get caught up on projects that languished during the pandemic due to long wait times, builders and fabricators again face weeks and even months of wait times for steel. This has already elevated the pressure on American steel mills to produce more product, and the increase in material requirements from the Buy American Act will only exacerbate the issue. Next, as expected, is an increase in price, which will directly affect builders and fabricators as they work to meet budgets. With high demand and low supply, prices naturally increase, and we're facing new historic highs on U.S. steel prices in the very near future. Due to the Buy American Act, fabricators will be forced to pay the higher prices in order to meet the new thresholds (Texas Iron & Metal, 2022).

In summary, this legislation will require several years of enforcement—without market disturbances—for its success to be determined at stimulating increased domestic output of iron, steel, and steel alloys, not to mention achieving the demand-side goal of lower steel prices generated by a stronger domestic steel sector.

Impacts of Alloys on Domestic Steel Costs

50CR steel contains a maximum of 10.5% to 12.5% chromium; 1.5% nickel; 1.5% manganese; 1.0% silicon; and carbon, phosphorous, sulfur, and nitrogen in smaller concentrations. According to the U.S. Geological Survey, the average price of chromium metal in March 2023 was 19% lower than in March 2022 and the average March 2023 price of ferrochromium was lower than in March 2022. Imports of all grades of chromium ferroalloys in March 2023 were 38% higher than in March 2022. Leading import sources for ferrochromium coming to the United States in March 2023 were South Africa, India, Kazakhstan, and Germany (Schulte, 2023), i.e., nations relatively friendly to the United States. Overall, the chromium markets appear to be relatively stable, at least for the present.

By contrast, the demand for nickel has risen sharply in recent years due to the rising demand for electric vehicle batteries, and in March 2022, a single speculator's crisis in nickel market exposure to losses was threatening enough to cause the London Metal Exchange to take the rare move of closing for several days (Financial Conduct Authority, 2022). Fortunately, stainless steel can use a mixture of Class 1 and 2 nickel whereas electric vehicle batteries can use only Class 1 (Azevedo et al., 2020). Since then, nickel markets have gradually settled down, if not to price levels preceding the crisis.

Steel production accounts for most manganese demand in the United States. Manganese imports of ore, dioxide, ferroalloy, and metal to the United States over January-March 2023 were 30% lower than in 2022, and exports were 50% higher (Kim, 2023). Average spot prices charged in China for U.S. product in March 2023 were 11% to 16% lower than in March 2022, depending on the grade. U.S. silicon stocks at the end of March 2023 were 10% higher than in March 2022, and the average U.S. spot price was 51% less than in March 2022 (Schnebele, 2023). In addition to alloy surcharge information discussed later, the ample supplies and good price trends of these materials in the United States appear to support expectations of market stability, at least in the short term.

The price fluctuations of these alloys will be reflected by varying surcharges on the price of 50CR steel, although those specific surcharges are not published as of this writing. However, North American Stainless (NAS), reportedly the largest fully integrated stainless steel producer in the United States, publishes surcharges for other product lines that provide orders of magnitude.

Figure 39 shows the last 12 months of NAS surcharges on alloy content for two duplex grades and two austenitic grades in long products, flat products, or both. Surcharges vary with percentage content in products and with market forces. Although newly added in recent years, silicon and energy surcharges are low and uniform across grades.

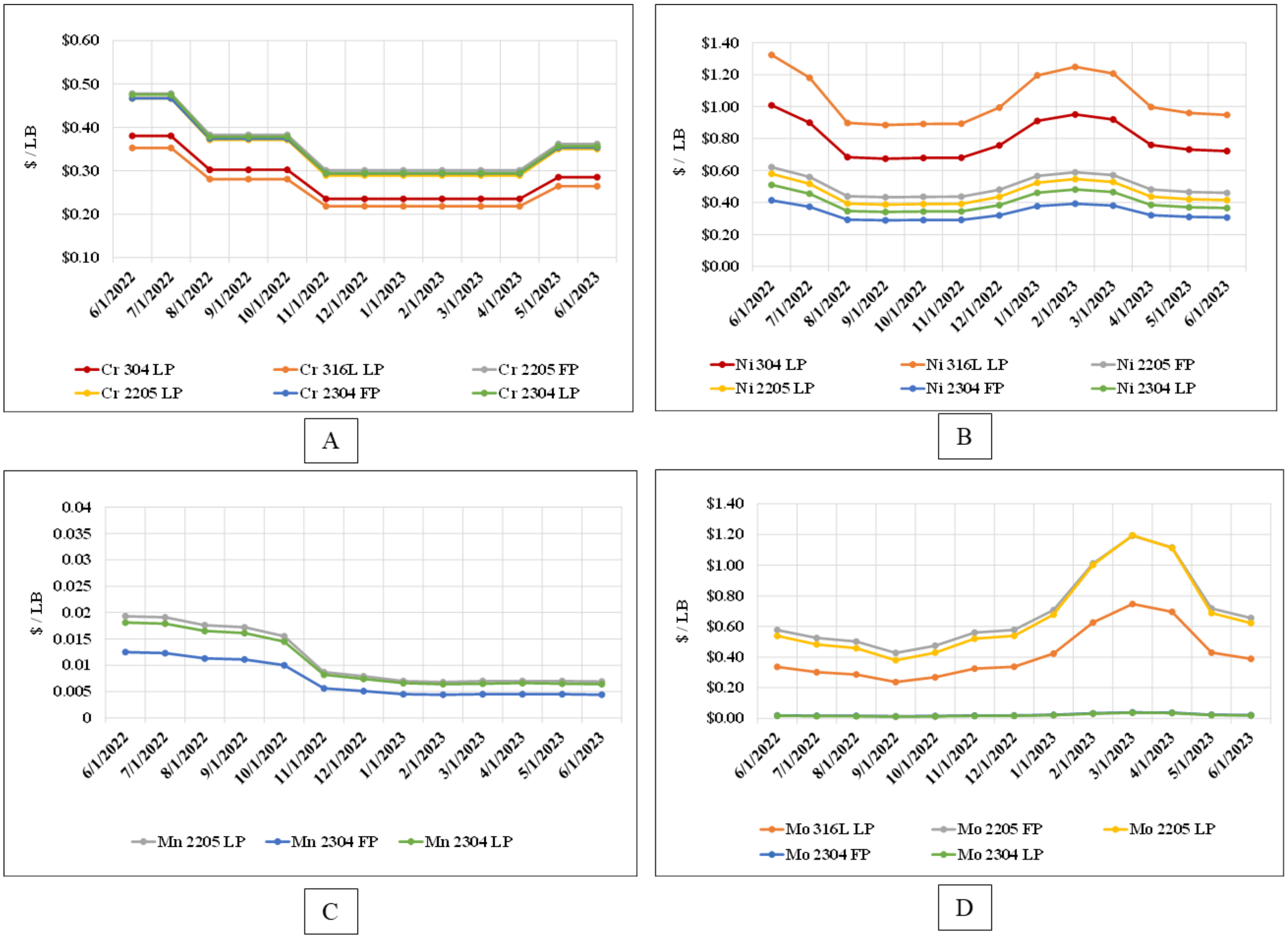


Figure 39. North American Stainless Surcharges for June 2022 – June 2023: (A) Chromium (Cr); (B) Nickel (Ni); (C) Manganese (Mn); (D) Molybdenum (Mo) Alloy Content, Various Grades. 316L contains 10.5% nickel. LP = long products; FP = flat products. Source: North American Stainless, 2023.

50CR steel does not contain molybdenum, but molybdenum is shown here because, like nickel, it has been discovered recently to have an emerging competitor for supplies: increased demand for offshore drilling rigs due to elevated oil prices in 2022 and 2023 (Greenfield and Steven, 2023). Prices for molybdenum surged early in 2023 in the absence of a "black swan event"—i.e., an unpredictable event with potentially large consequences—and might go higher for a while because, in addition to new demand, major primary molybdenum mines have been out of production since about 2015; a secondary production mine in Peru has been stopped by political disruptions; and no new molybdenum mines are coming into production anytime soon (Greenfield and Steven, 2023). Fortunately, the supply of molybdenum does not directly impact 50CR steel.

Figure 40 shows the recent 12- or 18-month history of total surcharges on the grades of steel in Figure 39 in long products and similar grades that come in flat products.

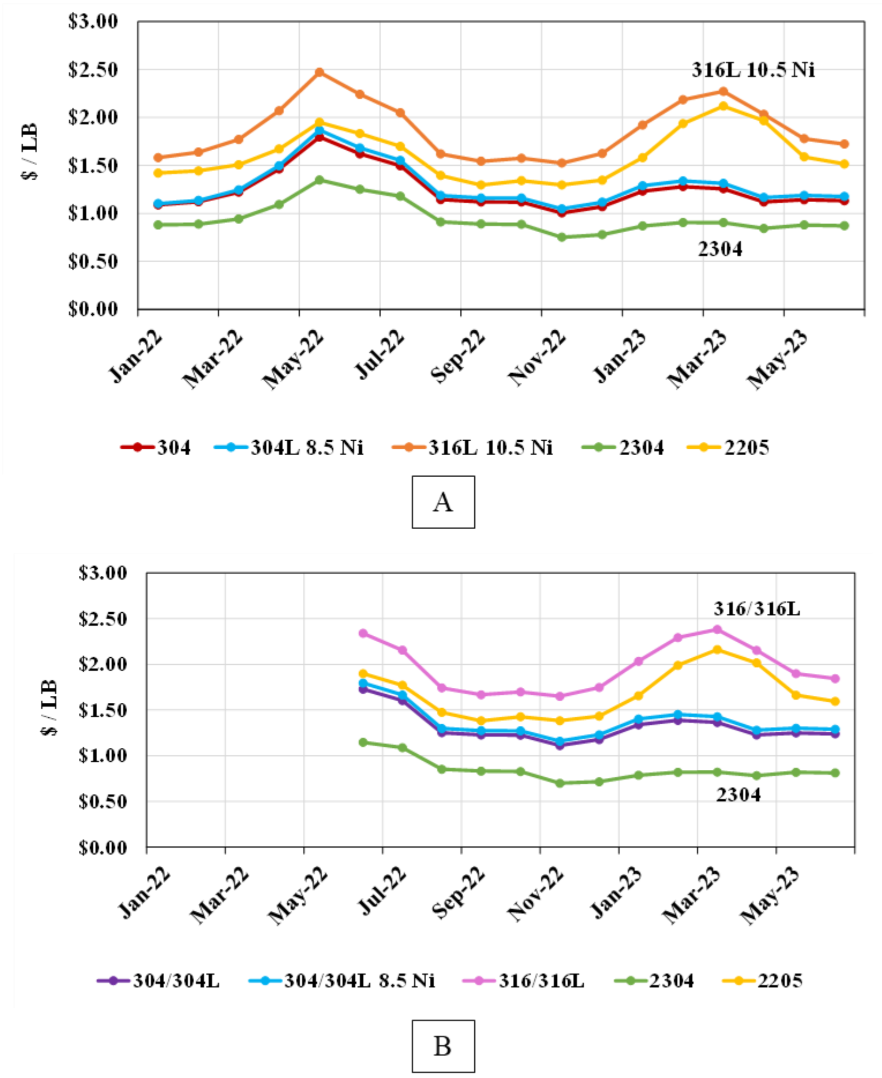


Figure 40. North American Stainless Alloy Surcharges for January 2022 – June 2023: (A) long products angle/rebar/wire rod; (B) flat products. Source: North American Stainless, 2023.

50CR steel has lower chromium and nickel contents and a higher (low-cost) manganese content than the grades shown in Figure 40 (and no molybdenum content). As a result, in theory, 50CR steel ought to carry lower total surcharges than even 2304 duplex stainless steel (shown in Figure 39) on the basis of alloy content.

Iron and energy are costs that all steels carry but the stainless grades will carry other surcharges in proportion to their alloy contents, which steel producers must procure as inputs. Figure 41 shows the past 12 months of alloy costs for NAS. The series history is not long enough to encompass the time period since the fourth quarter of 2020 and the sharp rise in the NHCCI discussed previously, but the input costs for silicon, chromium, and manganese are steadily declining in 2023 and reliably mere fractions of nickel and molybdenum costs over the period shown.

Although 50CR steel nominally contains less than one-half the nickel content of 2304 duplex stainless steel, nickel is likely to be a long-term unit cost vulnerability for any stainless steel. Figure 42 shows an upward cost trend for nickel imports that is supported by the growing worldwide favor for electric vehicles crowding its original dominant use in steel production. In any case, the competition for global nickel supplies between stainless steel production and electric vehicle batteries is not a temporary market condition, and increasing nickel prices should be routinely factored into expectations of future stainless steel prices.

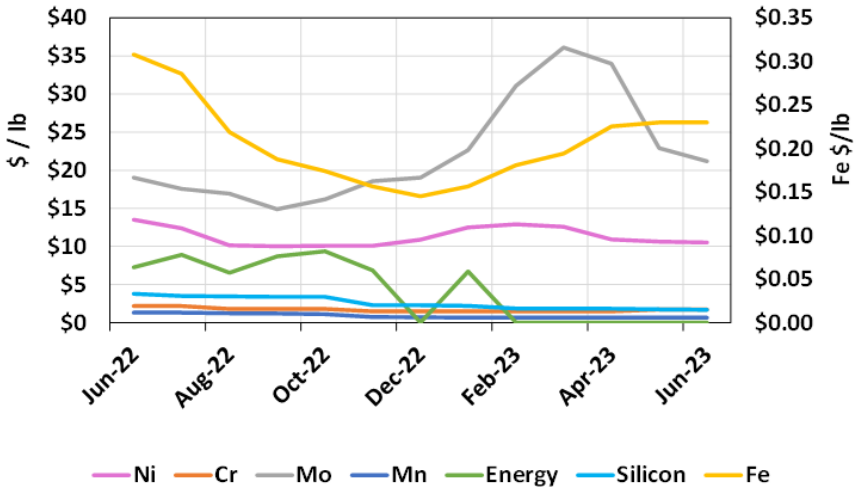


Figure 41. North American Stainless Current Rates on Surcharge Cost Items by Month for June 2022 – June 2023. Source: North American Stainless, 2023.

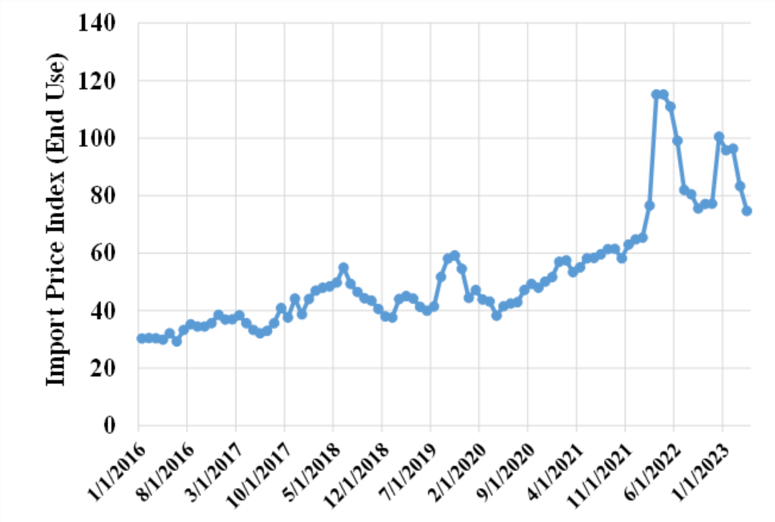


Figure 42. Import Price Index for End Use Nickel for January 2016 – April 2023. 2007=1. Not seasonally adjusted. Source: Federal Reserve Bank of St. Louis, 2023.

U.S. Steel Production

The U.S. government takes an active interest in nurturing the domestic steel industry, as well as in the total supply of steel available domestically, by means of treaties, tariffs, and select tariff exemptions deployed according to need. The U.S. Geological Survey provided the following information about the U.S. iron and steel industry in 2022 (Tuck, 2023):

1. In 2022, the United States was the fourth largest (world) producer of raw steel behind China, India, and Japan, although China produced more than 12 times U.S. production.

2. Imports to the United States were sourced mainly from Canada, Brazil, Mexico, and the Republic of Korea, and the balance (41%) was sourced by other nations.

3. Construction absorbed 46% of total domestic shipments, the automotive sector absorbed 26%, and other major steel-using sectors took in less than 10% each.

It can be noted here that Cleveland-Cliffs Inc. (hereinafter “Cleveland-Cliffs”), the manufacturer of the 50CR steel used in recent VDOT projects, represents itself as a leading supplier of automotive steel, specifically electrical vehicle steel (Cleveland-Cliffs, 2022a).

Three companies operating 11 U.S. mills produced about 29% of raw steel using basic oxygen (blast) furnace (BF) technology in 2022, and 50 companies produced about 72% of raw steel at 101 “mini-mills” using electric-arc furnace (EAF) technology. BF mills have preserved their competitive advantage for higher quality grades of steel, flat-rolled sheet and plate, but since 1969, EAF mills have come to dominate other steel product markets by undercutting BF production costs (Watson, 2022).

Weekly estimates of domestic raw steel production and capacity utilization published by the American Iron and Steel Institute indicated that 2021 cumulative raw steel production exceeded 2022 by 5.5 million net tons, as implied in Figure 43. In fact, 2021 was a relative boom year for domestic steel production and capacity utilization. Watson (2022) reported that profits in 2021 were more than 10 times their level in 2020 whereas domestic production of raw steel was only 18% higher in 2021, noting that profitability in steel production is mainly due to high-capacity utilization. However, Figure 43 shows production and capacity utilization turnarounds as of January 2023. These trends appear to be an industry shift since they have been sustained for several months.

The American Iron and Steel Institute's estimated regional weekly steel production is shown in Figure 44. All regions except the Western region showed a turnaround in weekly production between December 2022 and June 2023: 16% in the Southern region, 10% in the Northeast, 8% in the Midwest, and 3% in the Great Lakes region. Western region production fell by 13%. Further, the Midwest alone had a slightly increasing weekly production trendline even including 2022 data whereas all other regional production trendlines including 2022 data had negative, if small, signs.

Watson (2022) estimated that 8% more domestic steel production capacity will result from investments made in 2022, most of which he expects will be in EAF mills. Watson pointed to the cancellation in 2021 by the United States Steel Corporation of the modernization of its integrated mill in western Pennsylvania and the discontinuation of raw steel production at its mill near Detroit, Michigan. Meanwhile, the company has bought out a mini-mill operator in Arkansas and plans to build an EAF mill there.

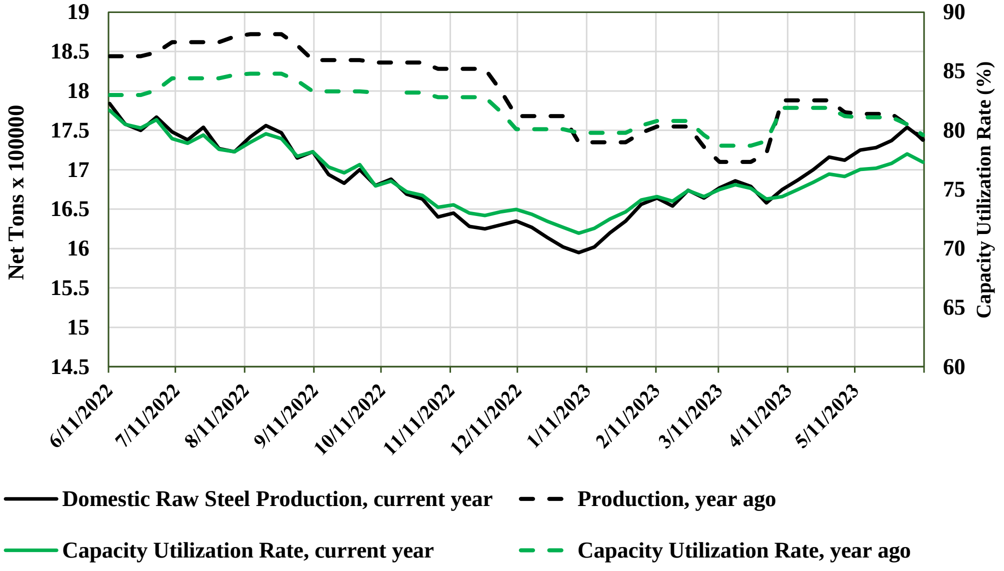


Figure 43. American Iron and Steel Institute Weekly Raw Steel Production for June 2022 – June 2023. Source: American Iron and Steel Institute, 2023.

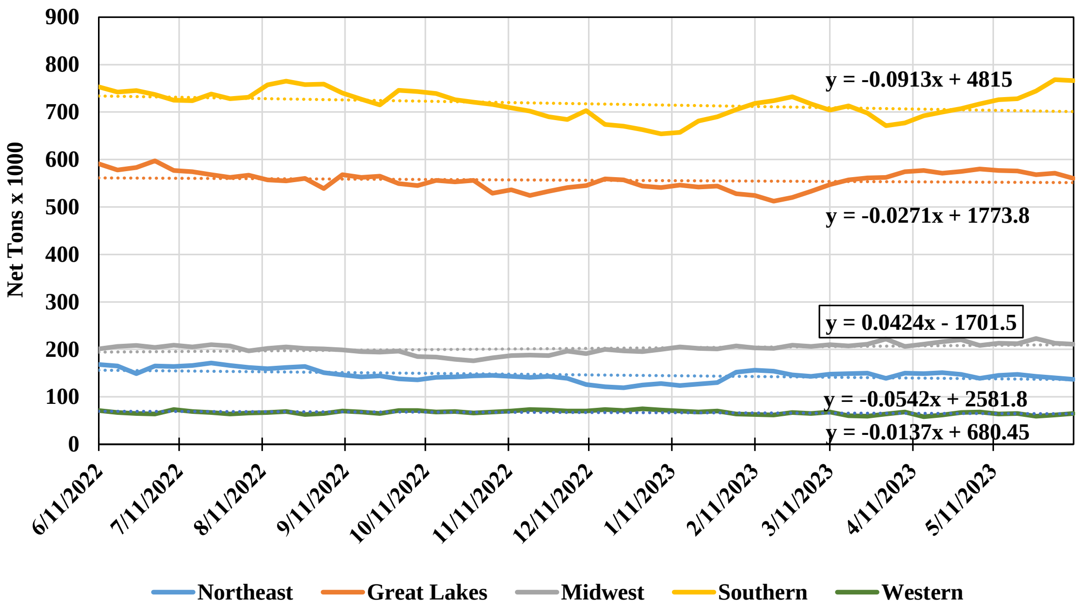


Figure 44. Regional American Iron and Steel Institute Weekly Raw Steel Production for June 2022 – June 2023. Source: American Iron and Steel Institute, 2023.

On the other hand, Cleveland-Cliffs merged with AKSteel in March 2020, keeping it a wholly owned subsidiary, and purchased two ArcelorMittal USA sites in Pennsylvania in December 2020, one being the BF mill that was VDOT's original source for 50CR steel plate (Cleveland-Cliffs, 2022b). Cleveland-Cliffs 2022 annual report stated that these acquisitions facilitated vertical integration of their "legacy iron ore business" with steel production. After entering the scrap business in 2021, they now corporately own their supply chain from mining of raw materials to finished high-value steel products (Cleveland-Cliffs, 2022b). Cleveland-Cliffs is signaling responsiveness to the IIJA and IRA by specializing in steel suitable for the new electric fleet. Watson (2022) observed that "[m]any [U.S.] steel producers have transitioned to harder-to-make steel products, such as advanced high-strength steel or lightweight steel for automotive uses, to better compete in the domestic market and avoid the impact of cheaper steel imports."

Cleveland-Cliffs stated: "Domestic construction activity and the replacement of aging infrastructure directly affects sales of steel to [the infrastructure and manufacturing] market" (Cleveland-Cliffs, 2022a). The former ArcelorMittal plate mill acquired by Cleveland-Cliffs could remain a producer of 50CR steel if Cleveland-Cliffs meets its own goal of serving the construction industry. The rising raw steel output levels projected by Watson (2022) in 2023 (and going forward) would be a more favorable environment for the production of specialty grades such as 50CR steel than the recent years of business uncertainty have been. Further, assuming the new IIJA legislation delivers on its aspirations, the increasingly captive domestic steel market created by BABA provisions might eventually be sufficient to increase domestic demand for 50CR steel to the point of interesting Cleveland-Cliffs in producing it more regularly, which would help to decrease lead times.

The run-up in U.S. domestic steel prices beginning in 2020 is reflected in international plate markets in Figure 45 with a final data point for May 2023. U.S. steel prices were considered unsustainable in 2021 with significant market corrections due when supply chain blockages were alleviated in the future (Watson, 2022). According to Watson (2022), high U.S. prices are in general due not only to tariffs but also to the transition of U.S. steel producers to harder-to-make, high-value steel products for their primary export customers, Canada and Mexico. Further, market corrections of prices will have to include the costs of decarbonization of steel manufacturing for four domestic steel producers (including United States Steel Corporation and Cleveland-Cliffs) that have set corporate objectives for 2030, an undertaking that will require significant research and development of the decarbonization path. Watson (2022) estimated that devoting as little as 1.4% of iron and steel industry operating revenue—the average annual rate spent in the U.S. primary metals subsector over 2013-2020—to decarbonization research and development would have cost approximately $2 billion in 2020.

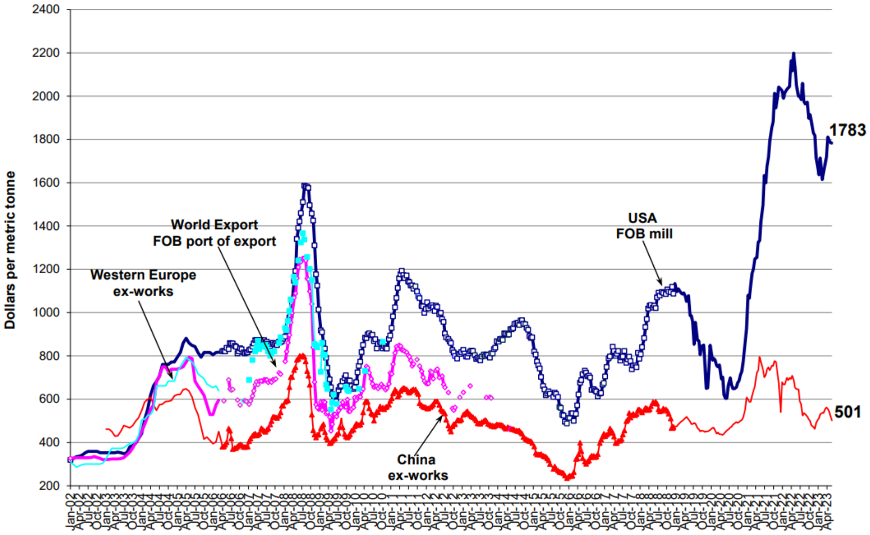


Figure 45. SteelBenchmarker Plate Price: USA, China, Western Europe and World Export. May 22, 2023. Source: World Steel Dynamics, 2023. SteelBenchmarker Price History Tables and Charts. May 22, 2023. Used With permission.

Breakpoint Unit Cost

Two VDOT contracts for bridge repairs over railroad rights of way (i.e., tracks) were let in 2020 under UPC 113839 and 117968, covering two and four structures, respectively. Bid on the basis of linear feet and "each," unit costs were not readily comparable with other contracts for the same kind of work.

All bridge plans indicated that repair steel should be ASTM A709, Grade 50, and repair plates should be A36 steel, all to be coated to reasonably match the existing bridges. Repairs were both bolted and welded. Bolted repairs included standard high-strength fastener assemblies; faying surfaces and steel cut edges were to be prepared in accordance with normal VDOT standards. Jacking and blocking did not appear in the schedule of bid items or change orders for any bridge. Live loads were allowed on all structures during repairs. Table 5 gives calculated unit costs based on pounds of steel as implied by bridge plans and the winning bid costs for the repairs based on bid units of linear feet or location ("each").

Table 5. Calculated Unit Costs in VDOT Winning Bids by Repair Type, UPCs 113839 and 117968

Federal Structure No.	18067	17929	4405	18145	10560	18141
Beam End	$68.93	$74.83	$142.45			
Web-Flange	$24.57	$37.74	$52.74	$58.07	$54.25	
Web	$29.58	$36.85	$64.33	$44.02		$43.38
Flange	$36.46	$81.21			$86.37	$69.51
Diaphragm A	$20.58	$33.08				
Diaphragm B		$35.40				
End Diaphragm				$42.14		$49.42
Full Bearing Stiffener						$110.31
Web-Flange A						$56.00
Web-Flange B						$52.99
Partial Height Bearing Stiffener				$96.45		$42.22
Full Height Bearing Stiffener A				$114.96		
Full Height Bearing Stiffener B				$107.83		
Partial Height Beam End				$88.99		

Both UPCs separately itemized some costs for each bridge: nonstandard (NS) Mobilization, NS Maintenance of Traffic, NS Environmental & Worker Protection, NS Disposal of Material, and Construction Access; thus, they were excluded from unit repair costs. UPC 117968 included an item cost for zone coating of the last 5 ft of the beams.

Highway bridges over railroad rights of way typically have special features adding non-itemized costs to repairs: higher vertical clearance over track(s), concrete rather than riprap slope protection, and management of the necessary access to railroad rights of way in coordination with train schedules. Also, in some locations, qualified welders have been particularly difficult to employ on VDOT projects. Last, these bridges have been in continuous service for nearly 50 years. Some of these factors as well as others may underlie the surprising unit costs in Table 5 for the apparently conventional repairs that were bid for these six structures.

The winning bid for the 50CR steel in the Featherbed Lane Bridge was $3.10/lb, a cost that included material, fabrication, delivery, and tax. Thus, the unit cost of the 50CR steel was the lowest of the three 50CR steel bridge bids for VDOT by that point and was for a rural truss bridge on the National Register of Historic Places. a project with a higher public interest profile than the repairs in UPC 113968 or 117968. Yet, certainly the Featherbed Lane Bridge is also located distant from a population center and necessitated travel to the work site.

In addition to using durable materials such as 50CR steel on projects whose design is intentionally fixed (by the National Register) and that will never be judged obsolete, private industry has adopted 50CR steel for its own heavy-duty, long-duration uses where rapid design obsolescence is not a hazard. In addition to bridge structures, other uses of 50CR steel include railroad cars, electrical transmission towers, and mining equipment (American Alloy Steel, 2022), and numerous others have been recommended by the product developer (ArcelorMittal, 2014). As stewards of their own capital expenditures, private industry interest in maximization of profits sets a standard worthy of investigation.

Increasingly in recent years, VDOT has experienced difficulty finding qualified welders available for its projects; in fact, this problem may be part of a long-term trend. According to the Bureau of Labor Statistics (BLS), the occupational group including welders (and cutters, solders, and brazers) is projected nationally to grow only 2% over the period 2021-2031, and employment growth at the national level will be predominantly in the manufacturing sector, which in Virginia is a fraction of what it was as an employer in 2000 (let alone 1975). Nationally, the construction industry is projected to see 4% growth in the larger occupational group including welders, but the self-employed in that group will shrink by 14.2% by 2031 under the BLS labor projections (BLS, 2023). In 2022, the annual mean wage for the occupational group is highest in water, sewage, and other systems at $141,800 and second highest in nuclear electric power generation at $112,379. The annual mean occupational group wage is $71,500 in "Heavy and Civil Engineering Construction," putting average-income welders working on VDOT projects potentially at a 22nd annual mean wage rank for this occupational group nationally (BLS, 2023), a rank that is likely to be known to welders and unlikely to attract many skilled workers to civil engineering construction. Finally, according to BLS, most new employment will be to fill existing positions as workers retire rather than to increase net growth. Overall, there is no reason to believe that the twin problems of scarcity of welders and base qualifications for VDOT work will be alleviated in the next decade. Rather, applying increasingly hard-to-find welder skills to longer-lasting repairs should be weighed carefully against higher initial costs for durable materials like 50CR.

Summary of Cost Analysis

Recent surges in the NHCCI are discussed at length here, as are the following: recent trends in energy costs; recent legislation with potential bearing on energy costs and domestic steel demand due to changes to domestic procurement requirements; the recent histories of alloy surcharges on stainless steel; and the domestic steel production environment including corporate commitments to decarbonize domestic iron and steel production. Of importance, the composition of 50CR steel is distinguished from that of other stainless steels by its low-cost alloys, none of which has been volatile in price or has associated black swan events as have nickel and molybdenum in the last 2 years.

The two UPCs discussed previously for the repair of six bridges over railroad rights of way were low-tonnage projects at about 36,000 and 21,000 lb. Low tonnage might account for their high unit costs, but in any case, the high unit costs in such contracts are justified on the logical premise that the bid process itself affects whatever cost efficiency is attainable. 50CR steel thus falls in line with prices VDOT has paid in recent years, with the difference that it has the advantages of stainless steel in its corrosion resistance and longevity. Two considerations remain: (1) what breakpoint price VDOT can determine is satisfactory to award a contract using 50CR steel, knowing its advantages to VDOT and its value in private industry; and (2) when the economy will again be operating under a rate of cost inflation within historic trends.

With the caveat to expect rising nickel prices, however, the successful identification of a fabricator able to meet a price point of $3.10/lb for 50CR steel in 2020, just prior to a wave of historic macroeconomic disturbances reverberating in both the United States and the global economy, should encourage VDOT to remain agnostic on the topic of 50CR steel until economic conditions return to more normal boundaries.

CONCLUSIONS

- *50CR steel can be successfully designed using cost-saving design alterations for simple bridges in corrosive environments.* The 2022 Holdens Creek Bridge was a relatively simple bridge due to its short overall length and short span lengths. Cost-saving design alterations to simplify the bridge further included limiting the amount of 50CR steel used, limiting the number of different 50CR steel thicknesses on a project to either one or two, using simpler weld details (such as limiting or eliminating CJP welds), using galvanized secondary members, and using galvanized fastener assemblies.

- *50CR steel girders can be successfully fabricated.* There were minor fabrication challenges with PQR testing, increased effort in grinding 50CR steel surfaces to be welded, and identification of carbon-free tools to use on 50CR steel surfaces to be welded; however, all of these challenges were overcome through communications among the fabricator, welding consumable supplier, VDOT's Materials Division, and VTRC.

- *Construction of the 50CR steel girders on the 2022 Holdens Creek Bridge was successful.* The 50CR steel was received by the fabricator within the 6-month lead time requirement in VDOT's special provision on corrosion-resistant steel plate girders. Erection was also simple since the 50CR steel girders were relatively short and did not contain a bolted field splice. Equipment requirements during erection of the 50CR steel girders were the same as for conventional bridge steels.

- *Traditional corrosion protection systems provided a limited service life for the 1993 Holdens Creek Bridge, located on the Eastern Shore of Virginia, with low water clearance.* The zinc-rich coating on the bridge provided a service life of 6 years, and bare steel provided a service life of 16 years.

- *Metallizing was successfully specified and implemented for one of the nonstructural beams on the 2022 Holdens Creek Bridge.* Although the existing VDOT guidance does not provide specifics on metallization surface profile, alloy, thickness, and seal coat, VDOT's Materials Division was able to work with the metallizing subcontractor to establish specific requirements to use on the project.

- *After 1 year of service on the 2022 Holdens Creek Bridge, the 50CR steel girders and the nonstructural galvanized and metallized/sealed beams are performing well.* The 50CR steel girders were expected to perform well due to their inherent corrosion resistance. Galvanized and metallized/sealed girders may provide adequate corrosion resistance in similar corrosive environments.

- *After 5 years of service on the Onancock Bridge, the 50CR steel repairs with galvanized fastener assemblies are performing well.* There was some zinc product migration from the galvanized fasteners to the 50CR due to galvanic corrosion, but it was relatively minor.

- *After 5 years of service on the Onancock Bridge, the uncoated weathering steel with weathering steel fastener assemblies were not exhibiting pitting, crevice, or laminar* *corrosion, but some loosely adherent small flakes were present.* The 50CR steel with galvanized fasteners is not exhibiting any of these forms of corrosion or any small flakes.

- *As a product in infrequent use and production, the unit price for 50CR steel achieved in the Featherbed Lane Bridge winning bid ($3.10/lb) was an economic achievement of significance.* This unit cost from 2020 is approximately 47% less than the unit cost of 50CR steel on VDOT's Route 340 Bridge in 2015. The macroeconomic environment of the last 3 years has been unprecedented for state transportation agencies, as costs since the end of 2020 through the fall of 2022 spiked by 50%, as measured in the FHWA National Highway Construction Cost Index. But some data suggest that U.S. steel markets are recovering in 2023, and alloys in 50CR steel except nickel have shown marked price and supply stability over this period.

RECOMMENDATIONS

1. *VDOT should continue to investigate alloyed corrosion-resistant steel, such as 50CR steel, for its potential to provide a long service life for new construction or repairs in corrosive environments.* 50CR steel has been successfully designed, fabricated, and erected on multiple VDOT bridges, and these bridges have shown good corrosion performance over multiple years of service.

2. *VDOT's Structure and Bridge Division should include the cost-saving design alterations described in this report in its design guidelines for corrosion-resistant steel.* VDOT's current design guidelines for corrosion-resistant steel are contained in File No. 11.11-1 in Chapter 11 of Part 2 of the VDOT *Manual of the Structure and Bridge Division.* The proposed design alterations include limiting the amount of 50CR steel used, limiting the number of different 50CR steel thicknesses on a project, using simpler weld details, using galvanized secondary members, and using galvanized fastener assemblies. It is anticipated that these design alterations can be easily incorporated into new designs.

3. *VDOT's Structure and Bridge Division should improve its specifications for metallizing steel.* The specifications should address requirements for application procedure, surface preparation, surface profile, alloy, thickness, and seal coat.

IMPLEMENTATION AND BENEFITS

Researchers and the technical review panel (listed in the Acknowledgments) for the project collaborate to craft a plan to implement the study recommendations and to determine the benefits of doing so. This is to ensure that the implementation plan is developed and approved with the participation and support of those involved with VDOT operations. The implementation plan and the accompanying benefits are provided here.

Implementation

Regarding Recommendation 1, implementation will consist of continued exploration of the topic by VTRC continuing its work on current research related to 50CR steel; leading the AASHTO/National Steel Bridge Alliance Collaboration Task Group 18 on duplex stainless steel; and coordinating discussions with corrosion-resistant steel plate producers and trade organizations, among other activities. This will also include future monitoring of the 2022 Holdens Creek Bridge and the Onancock Bridge every 5 to 10 years.

Regarding Recommendation 2, after the successful fabrication and erection of the 2022 Holdens Creek Bridge, VDOT has experienced delays on its next two 50CR steel bridge projects. These delays were the result of lead times more than 6 months, resulting in delayed delivery of 50CR steel from the plate producer to the fabricator, and a fabricator's inability to obtain passing PQR tests and an acceptable welding procedure. Based on these recent negative experiences, VDOT does not plan to design more bridges using 50CR steel in the near future. Therefore, VDOT will not implement Recommendation 2 at this time.

Regarding Recommendation 3, to aid in its implementation, VTRC will perform a technical assistance study to review the corrosion performance and metallizing specifications used on the limited number of metallized beams in VDOT's inventory; review relevant published metallizing corrosion test data; review metallizing specifications used by other departments of transportation or other agencies; and coordinate discussions with industry experts. VTRC will prepare a proposal to conduct this technical assistance study and will submit the proposal within 1 year of the publication of this report. Based on the results of this technical assistance study, VDOT will perform a field trial with VTRC's assistance in which VDOT will build a bridge with metallized steel girders to allow VTRC and VDOT's Structure and Bridge Division to become familiarized with the entire process of metallizing steel superstructures. VDOT's Structure and Bridge Division will improve its metallizing specifications after the technical assistance study and the field trial have been completed.

Benefits

The benefit of implementing Recommendation 1 is that it allows VTRC to continue to develop a coating-free steel bridge solution in highly corrosive environments. As demonstrated by the condition of the 1993 Holdens Creek Bridge and the need for repairs on the Onancock Bridge, as well as many other steel bridges in Virginia, there is clearly a need for having corrosion-resistant steel as an alternative to concrete. This will also allow VTRC and VDOT to continue to build upon their nationally recognized expertise in corrosion-resistant steels.

The benefits of implementing Recommendation 2 are that the proposed design alterations can help mitigate construction delays and provide potential cost savings when 50CR steel is used, both of which contribute to VDOT's mission of delivering projects on time and on budget.

The benefits of implementing Recommendation 3 are that having improved specifications for metallizing steel beams provides more direction for fabricators when conducting metallizing on VDOT projects and helps ensure that VDOT obtains quality products that can provide a long service life in corrosive environments.

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REFERENCES

AASHTO/NSBA Steel Bridge Collaboration. *S8.2-2017/SSPC-PA 18: Specification for Application of Thermal Spray Coating Systems to Steel Bridges.* 2017.

American Alloy Steel. Duracorr Overview. 2022. https://www.aasteel.com/duracorr/. Accessed June 2, 2023.

American Iron and Steel Institute. Weekly Raw Steel Production. 2022-2023. https://www.steel.org/industry-data/. Accessed September 1, 2023.

Appiah-Otoo, I. Russia–Ukraine War and US Oil Prices. *Energy Research Letters*, Vol. 4, No. 1, 2023. https://erl.scholasticahq.com/article/37691-russia-ukraine-war-and-us-oil-prices. Accessed August 15, 2023.

ArcelorMittal USA. Plate Duracorr: Life-Cycle Cost-Effective 12% Chromium Stainless Steel. 2014. File:///U:/A_New%20Reports/A_Eastern%20Shore%20bridges%20-

%20Copy_08_10_21/COSTS/ARCELORMITTAL%20DURACORR.pdf. Accessed June 2, 2023.

ASTM International. *ASTM A123/A123M: Standard Specification for Zinc (Hot-Dip Galvanized) Coatings on Iron and Steel Products*. West Conshohocken, PA, 2017a.

ASTM International. *ASTM A709/A709M: Standard Specification for Structural Steel for Bridges.* West Conshohocken, PA, 2017b.

Azevedo, M., Goffaux, N., and Hoffman, K. How Clean Can the Nickel Industry Become? September 11, 2020. https://www.mckinsey.com/industries/metals-and-mining/our-insights/how-clean-can-the-nickel-industry-become#. Accessed May 30, 2023.

Bistline, J., Mehrotra, N., and Wolfram, C. Economic Implications of the Climate Provisions of the Inflation Reduction Act. BPEA Conference Draft, Spring 2023. https://www.brookings.edu/wp-content/uploads/2023/03/BPEA_Spring2023_Bistline-et-al_unembargoedUpdated.pdf. Accessed September 1, 2023.

Bureau of Labor Statistics. Occupation Wages and Employment, May 2022: 51-4121 Welders, Cutters, Solderers, and Brazers. April 25, 2023. https://www.bls.gov/oes/current/oes514121.htm. Accessed June 2, 2023.

Cleveland-Cliffs Inc. A Fully Integrated, High-Quality Steel Producer. December 31, 2022a. https://www.clevelandcliffs.com/about. Accessed June 13, 2023.

Cleveland-Cliffs Inc. 2022 Annual Report. 2022b. https://www.clevelandcliffs.com/investors/sec-filings/annual-reports##document-5340-0000764065-23-000065-2. Accessed June 14, 2023.

Davis, J. Highway Construction Costs Have Risen 50% in Two Years. 2023. https://www.enotrans.org/article/highway-construction-costs-have-risen-50-in-two-years/. Accessed June 11, 2023.

Di Giovanni, J., Kalemli-Ozcan, S., Silva, A., and Yildirim, M. Global Supply Chain Pressures, International Trade, and Inflation. National Bureau of Economic Research Working Paper 30240. July 2022. https://www.nber.org/papers/w30240. Accessed June 9, 2023.

Di Giovanni, J., Kalemli-Ozcam, S., Silva, A., and Yildirim, M. Quantifying the Inflationary Impact of Fiscal Stimulus Under Supply Constraints. National Bureau of Economic Research Working Paper 30892. March 2023. https://www.nber.org/system/files/working_papers/w30892/w30892.pdf#page=12&zoom=100,57,254. Accessed June 11, 2023.

Domm, P. Sharp Surge in Energy Prices Threatens Economic Recovery and Is Already Slowing Growth. October 12, 2021. https://www.cnbc.com/2021/10/12/sharp-surge-in-energy-prices-threatens-economic-recovery-and-is-already-slowing-growth.html. Accessed June 9, 2023.

Energy Information Administration. Gasoline and Diesel Fuel Update. 2023. https://www.eia.gov/petroleum/gasdiesel/. Accessed August 14, 2023.

Energy Information Administration. Electric Power Monthly. U.S. Petroleum Product Exports Set a Record High in 2022. March 20, 2023a. https://www.eia.gov/todayinenergy/detail.php?id=55880. Accessed May 24, 2023.

Energy Information Administration. U.S. Energy Facts Explained. May 3, 2023b. https://www.eia.gov/energyexplained/us-energy-facts/data-and-statistics.php. Accessed May 31, 2023.

Federal Highway Administration. NHCCI Dashboard, Component Contribution. n.d. https://explore.dot.gov/views/NHIInflationDashboard/ComponentContribution?%3Aiid=1&%3Aembed=y&%3AisGuestRedirectFromVizportal=y&%3Adisplay_count=n&%3AshowVizH. Accessed August 14, 2023.

Federal Highway Administration. Technical Advisory: Uncoated Weathering Steel in Structures. Technical Advisory 5140.22. Washington, DC, 1989.

Federal Highway Administration. Bipartisan Infrastructure Law Fact Sheet: National Electric Vehicle Infrastructure Formula Program. February 10, 2022. https://www.fhwa.dot.gov/bipartisan-infrastructure-law/nevi_formula_program.cfm. Accessed June 9, 2023.

Federal Highway Administration. National Highway Construction Cost Index (NHCCI). 2023. https://www.fhwa.dot.gov/policy/otps/nhcci/. Accessed August 14, 2023.

Federal Register. Notice That the Build America, Buy America Requirement for Construction Materials Applies Effective November 10, 2022, and Notice of Proposed Waiver of That Requirement for a Narrow Category of Contracts and Solicitations. November 15, 2022. https://www.federalregister.gov/documents/2022/11/15/2022-24743/notice-that-the-build-america-buy-america-requirement-for-construction-materials-applies-effective. Accessed June 1, 2023.

Federal Reserve Bank of St. Louis. Import Price Index for End Use Nickel. 2023. https://fred.stlouisfed.org/series/IR14240. Accessed September 1, 2023.

Financial Conduct Authority. Joint Statement From UK Financial Regulation Authorities on London Metal Exchange and LME Clear. April 4, 2022. https://www.fca.org.uk/news/statements/uk-financial-regulation-authorities-london-metal-exchange-lme-clear. Accessed May 30, 2023.

Fitz-Gerald, J.M., Sean, R., Agnew, S.R., and Xia, X. *Welding of ASTM A709 Grade 50CR Using Austenitic Filler Wires With Varying Heat Inputs and Maximum Interpass Temperatures.* VTRC 20-R24. Virginia Transportation Research Council, Charlottesville, 2020.

Fletcher, F.B. *Improved Corrosion-Resistant Steel for Highway Bridge Construction.* FHWA-HRT-11-062. Federal Highway Administration, Washington, DC, 2011.

Gagliardone, L., and Gertler, M. Oil Prices, Monetary Policy and Inflation Surges. National Bureau of Economic Research Working Paper 31263. May 2023. https://www.nber.org/papers/w31263. Accessed June 9, 2023.

Gardner, Stephen. Quote from: U.S. Congress. Hearing from the House Committee on Transportation and Infrastructure Subcommittee on Railroads, Pipelines, and Hazardous Materials. “Leveraging IIJA: Plans for Expanding Intercity Passenger Rail.” December 9, 2021. https://www.amtrak.com/content/dam/projects/dotcom/english/public/documents/corporate/testimony/2021/Amtrak-President-Gardner-House-Railroads-Testimony-Leveraging-IIJA-120921.pdf. Accessed August 30, 2023.

Greenfield, M., and Steven, B. 4 Key Factors Driving the ‘Perfect Storm’ in Molybdenum Markets. *S&P Commodity Global Insights,* February 13, 2023.

Groshek, I.G., and Hebdon, M.H. Galvanic Corrosion of ASTM A1010 Steel Connected to Common Bridge Steels. *Journal of Materials in Civil Engineering,* Vol. 32, No. 8, 2020.

International Organization for Standardization. *ISO Standard 9223: Corrosion of Metals and Alloys—Corrosivity of Atmospheres—Classification, Determination, and Estimation*. 2012.

Kim, J. Manganese in March 2023. U.S. Geological Survey, 2023. https://d9-wret.s3.us-west-2.amazonaws.com/assets/palladium/production/s3fs-public/media/files/mis-202303-manga.pdf. Accessed May 30, 2023.

Landers, J. New Infrastructure Law Provides Historic Federal Funding. March 1, 2022. https://www.asce.org/publications-and-news/civil-engineering-source/civil-engineering-magazine/issues/magazine-issue/article/2022/03/new-infrastructure-law-provides-historic-federal-funding. Accessed June 9, 2023.

Lew, S. Outlook for State and Local Infrastructure Spending. In *Eleventh Annual Municipal Finance Conference*, 73. The Brookings Institution, 2022. https://www.brookings.edu/wp-content/uploads/2022/06/20220720_mfc_day3_transcript.pdf. Accessed October 5, 2023.

Miran, S. The Trillion-Dollar Infrastructure Bill Will Fuel Inflation. August 8, 2021. https://www.wsj.com/articles/bipartisan-infrastructure-bill-inflation-stimulus-biden-automobile-regulations-american-rescue-plan-11628447581. Accessed June 9, 2023.

Monroe, W. The Utility of Now: How Utilities Can Maximize IIJA and IRA Benefits. November 7, 2022. https://www.utilitydive.com/spons/the-utility-of-now-how-utilities-can-maximize-iija-and-ira-benefits/635304/. Accessed June 9, 2023.

National Institute of Standards and Technology. The Future Is Charged: National Electric Vehicle Infrastructure (NEVI) Formula Program. March 29, 2022. https://www.nist.gov/news-events/news/2022/03/future-charged-national-electric-vehicle-infrastructure-nevi-formula. Accessed June 9, 2023.

National Wind Watch. Energy Prices in Europe Hit Records After Wind Stops Blowing. September 14, 2021. https://www.wind-watch.org/news/2021/09/14/energy-prices-in-europe-hit-records-after-wind-stops-blowing/. Accessed June 9, 2023.

Noel, B. Highway Construction Costs Up 50% Since Passage of IIJA. April 19, 2023. https://www.forconstructionpros.com/infrastructure/article/22833858/highway-construction-costs-up-50-since-passage-of-infrastructure-investment-and-jobs-act#:~:text=The%20damage%20done%20by%20inflation,of%20the%20IIJA%20into%20law. Accessed June 11, 2023.

North American Stainless. Long Products Bar Alloy Surcharge. 2023. https://www.northamericanstainless.com/NAS_App/Surcharge1?language=E&type=B).

North American Stainless. Flat Products Alloy Surcharge. 2023. https://www.northamericanstainless.com/surcharge/flat-products/.

Okonkwo, E. Buy America Overview. 2022. https://www.fhwa.dot.gov/construction/cqit/buyam/overview20220802.pdf. Accessed May 28, 2023.

Provines, J.T., Sharp, S.R., Osman, O., and Daghash, S. *Maintenance-Free Corrosion-Resistant Steel Plate for Bridges.* VTRC 19-R21. Virginia Transportation Research Council, Charlottesville, 2019.

Salwati, N., and Wessel, D. Four Questions (and Answers) About the Infrastructure Investment and Jobs Act. August 8, 2022. https://www.brookings.edu/blog/up-front/2022/08/08/four-questions-and-answers-about-the-infrastructure-investment-and-jobs-act/. Accessed June 9, 2023.

Schnebele, E. Silicon in March 2023. U.S. Geological Survey, 2023. https://d9-wret.s3.us-west-2.amazonaws.com/assets/palladium/production/s3fs-public/media/files/mis-202303-simet.pdf. Accessed May 30, 2023.

Schulte, R. Chromium in March 2023. U.S. Geological Survey, 2023. https://d9-wret.s3.us-west-2.amazonaws.com/assets/palladium/production/s3fs-public/media/files/mis-202303-chrom.pdf. Accessed May 30, 2023.

Sharp, S.R., Provines, J.T., Moruza, A.K., Via, W.F., Jr., and Harrop, K.N. *Virginia's First Corrosion Resistant ASTM A1010 Plate Girder Bridge.* VTRC 20-R10. Virginia Transportation Research Council, Charlottesville, 2019.

Taft Stettinius & Hollister LLP. Important Changes to the Buy American Act and President Biden's "Made in All of America" Executive Order. *Law Bulletin*, February 18, 2021.

Taft Stettinius & Hollister LLP. Increased Domestic Content Requirements in the Final Buy American Act Rule. *Law Bulletin*, April 12, 2022.

Texas Iron & Metal. The Buy American Act Increases Domestic Iron and Steel Requirements. March 7, 2022. https://www.texasironandmetal.com/the-buy-american-act-increases-domestic-steel-requirements/. Accessed May 25, 2023.

Tuck, C. *Mineral Commodity Summary—Iron and Steel.* January 2023. https://pubs.usgs.gov/periodicals/mcs2023/mcs2023-iron-steel.pdf. Accessed June 10, 2023.

U.S. Bureau of Labor Statistics. Producer Price Index by Commodity: Fuels and Related Products and Power: Natural Gas [WPU0531] and Crude Petroleum (Domestic Production) [WPU0561]. 2023. https://fred.stlouisfed.org/series/WPU0561. Accessed August 14, 2023.

Virginia Department of Transportation. *Approved Materials List*. Richmond, 2017.

Virginia Department of Transportation. *Road and Bridge Specifications.* Richmond, 2020.

Virginia Department of Transportation. Virginia Department of Transportation's ArcGIS Online Site. 2023. https://vdot.maps.arcgis.com/home/index.html.

Wallace, J. Energy Prices in Europe Hit Records After Wind Stops Blowing. *Wall Street Journal*, September 13, 2021. https://www.wsj.com/articles/energy-prices-in-europe-hit-records-after-wind-stops-blowing-11631528258. Accessed June 9, 2023.

Watson, C. Congress Expands Buy America Requirements in the Infrastructure Investment and Jobs Act (P.L. 117-58). December 7, 2021. https://crsreports.congress.gov/product/pdf/IF/IF11989#:~:text=Buy%20America%20requirements%20traditionally%20extend%20to%20public-works%20transportation,utilities%3B%20broadband%20infrastructure%3B%20and%20real%20property%20and%20buildings. Accessed May 25, 2023.

Watson, C. Domestic Steel Manufacturing: Overview and Prospects. May 17, 2022. https://crsreports.congress.gov/product/pdf/R/R47107. Accessed June 13, 2023.

Wharton School of Business, University of Pennsylvania. Update: Budgetary Cost of Climate and Energy Provisions in the Inflation Reduction Act. April 27, 2023. https://budgetmodel.wharton.upenn.edu/estimates/2023/4/27/update-cost-climate-and-energy-inflation-reduction-act. Accessed June 11, 2023.

World Steel Dynamics. Steelbenchmarker Price History Tables and Charts. 2023. http://www.steelbenchmarker.com/. Accessed June 1, 2023.