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Corrosion-Resistant Steel Fastener Assemblies for ASTM A709 Grade 50CR Steel Bridges

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JASON T. PROVINES, P.E.
Research Scientist

AUDREY K. MORUZA
Senior Research Scientist

STEPHEN R. SHARP, Ph.D., P.E.
Associate Principal Research Scientist

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VIRGINIA TRANSPORTATION RESEARCH COUNCIL
530 Edgemont Road, Charlottesville, VA 22903-2454
vtrc.virginiadot.org

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Jason T. Provines, P.E., Audrey K. Moruza, and Stephen R. Sharp, Ph.D., P.E.

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The purpose of this study was to evaluate three types of corrosion-resistant steel fastener assemblies for use on ASTM A709 Grade 50CR (hereinafter "50CR") steel bridges. The three types were ASTM A193 Grade B8 Class 2 (hereinafter "A193 B8-2"); Type 2205 duplex stainless steel (hereinafter "2205"); and bolts made from a martensitic chromium alloy (MCA). The evaluation of the corrosion-resistant steel fasteners included mechanical tests on individual elements of the fastener assembly, such as proof loading and wedge tests on bolts; proof tests on nuts; and hardness tests on bolts, nuts, and washers. Five types of lubricants were also evaluated in terms of chemistry and their effectiveness in reducing galling. Fastener assemblies were also subject to torqued tension and relaxation tests to evaluate their assembly performance. Long-term corrosion test samples of the bolts with 50CR steel were also placed at an exposure site to monitor over time. A cost analysis was also conducted to evaluate the cost of corrosion-resistant steel fastener assemblies relative to standard fastener assemblies.

Test results showed that corrosion-resistant fastener assemblies exist for use with 50CR steel. Specified minimum bolt pretension values and installation parameters, such as the nut rotation for turn-of-nut installation, were determined for these corrosion-resistant fastener assemblies. The study showed that A193 B8-2 and 2205 bolts can be pretensioned to 30 kip whereas MCA bolts can be pretensioned to 49 kip. All corrosion-resistant nuts used in this study met their required specifications for proof and cone proof load tests. Testing confirmed that washer hardness is critical to a bolt's installation performance. The 2205 and MCA washers performed well, but the 303 washers used in this study were insufficiently hardened, leading to poor performance of some A193 B8-2 bolts. A comparison to the findings of previous studies on A193 B8-2 bolts confirmed that harder 303 washers can lead to successful performance of A193 B8-2 bolts. Testing showed that one lubricant was much more effective in reducing galling than the other lubricants. The study also showed that corrosion-resistant bolts lack dimensional standards and their commercial and domestic availability needs to continue to be evaluated. A cost evaluation showed that A193 B8-2 and 2205 fastener assemblies can be expected to cost approximately 8 to 10 times more than galvanized A325 fastener assemblies.

The study recommends that the Virginia Transportation Research Council continue evaluating corrosion-resistant steel fasteners, especially in terms of minimum hardness values for washers, dimensional standards, and domestic and commercial availability, and develop a research needs statement to propose accelerated corrosion testing on standard and corrosion-resistant steel fastener assemblies to determine their relative corrosion resistance. The Virginia Department of Transportation should develop a special provision for using corrosion-resistant steel fastener assemblies on its projects, including their use with 50CR steel and in corrosive environments. This special provision should consider allowable bolt/nut/washer combinations, dimensional requirements, acceptable hardness limits, allowable lubricants, acceptance testing, installation procedures, and specified minimum bolt pretension.

17 Key Words:
ASTM A709 Grade 50CR, 50CR, ASTM A193 Grade B8 Class 2, 2205, duplex stainless steel, corrosion-resistant, fastener assembly, washer hardness, lubrication, galling, bolt installation, RCSC, slip-critical bolted connection

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Jason T. Provines, P.E.
Research Scientist

Audrey K. Moruza
Senior Research Scientist

Stephen R. Sharp, Ph.D., P.E.
Associate Principal Research Scientist

In Cooperation with the U.S. Department of Transportation
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ABSTRACT

The purpose of this study was to evaluate three types of corrosion-resistant steel fastener assemblies for use on ASTM A709 Grade 50CR (hereinafter "50CR") steel bridges. The three types were ASTM A193 Grade B8 Class 2 (hereinafter "A193 B8-2"); Type 2205 duplex stainless steel (hereinafter "2205"); and bolts made from a martensitic chromium alloy (MCA). The evaluation of the corrosion-resistant steel fasteners included mechanical tests on individual elements of the fastener assembly, such as proof loading and wedge tests on bolts; proof tests on nuts; and hardness tests on bolts, nuts, and washers. Five types of lubricants were also evaluated in terms of chemistry and their effectiveness in reducing galling. Fastener assemblies were also subject to torqued tension and relaxation tests to evaluate their assembly performance. Long-term corrosion test samples of the bolts with 50CR steel were also placed at an exposure site to monitor over time. A cost analysis was also conducted to evaluate the cost of corrosion-resistant steel fastener assemblies relative to standard fastener assemblies.

Test results showed that corrosion-resistant fastener assemblies exist for use with 50CR steel. Specified minimum bolt pretension values and installation parameters, such as the nut rotation for turn-of-nut installation, were determined for these corrosion-resistant fastener assemblies. The study showed that A193 B8-2 and 2205 bolts can be pretensioned to 30 kip whereas MCA bolts can be pretensioned to 49 kip. All corrosion-resistant nuts used in this study met their required specifications for proof and cone proof load tests. Testing confirmed that washer hardness is critical to a bolt's installation performance. The 2205 and MCA washers performed well, but the 303 washers used in this study were insufficiently hardened, leading to poor performance of some A193 B8-2 bolts. A comparison to the findings of previous studies on A193 B8-2 bolts confirmed that harder 303 washers can lead to successful performance of A193 B8-2 bolts. Testing showed that one lubricant was much more effective in reducing galling than the other lubricants. The study also showed that corrosion-resistant bolts lack dimensional standards and their commercial and domestic availability needs to continue to be evaluated. A cost evaluation showed that A193 B8-2 and 2205 fastener assemblies can be expected to cost approximately 8 to 10 times more than galvanized A325 fastener assemblies.

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INTRODUCTION

In Virginia and other U.S. states, corrosion is a common cause of bridge deterioration, leading to expensive repairs and maintenance actions. One way to make steel bridges more corrosion resistant is to use ASTM A709 (hereinafter "A709") Grade 50CR (hereinafter "50CR") steel, which is a cost-effective stainless steel (ASTM International [ASTM], 2017). By the use of 50CR steel, a bridge can have inherent corrosion resistance in even aggressive environments. To date, 50CR steel, which was formerly specified as ASTM A1010 steel (ASTM, 2013a), has been used in six bridges in the United States, including the Route 340 Bridge in Waynesboro, Virginia, constructed by the Virginia Department of Transportation (VDOT) (Sharp et al., 2019).

Currently, only one grade of bolt may be used on steel bridges in Virginia in accordance with VDOT's specifications: ASTM F3125 Grade A325 (hereinafter "A325") (ASTM, 2015). In some other states, another grade of bolt can also be specified, i.e., ASTM F3125 Grade A490 (hereinafter "A490") (ASTM, 2015). The main difference between the two types of bolts is the ultimate tensile strength; A325 bolts have a design tensile strength of 120 ksi, and A490 bolts have a design tensile strength of 150 ksi. For most applications, both grades of bolts are specified as Type 1, which gives them improved corrosion resistance effectively equivalent to that of unpainted carbon steel. Type 3 bolts have additional alloying to give them more atmospheric corrosion resistance and are intended to be used with uncoated weathering steel bridges. A325 bolts can also be specified as galvanized, which also provides additional corrosion protection. All types of bolts are typically used in a diameter of 7/8 in.

The six 50CR steel bridges in the United States have a variety of bolt types including A325 Type 3, A325 galvanized, and ASTM A193 Grade B8 Class 2 (hereinafter "A193 B8-2") (ASTM, 2020a). A193 B8-2 bolts are austenitic stainless steel, American Iron and Steel Institute (AISI) Type 304. These bolts are treated with carbide solution for better corrosion resistance and strain hardened to improve desirable mechanical properties, which ensures the bolts have a nominal ultimate tensile strength of 115 ksi for 7/8-in-diameter bolts. Other types of ASTM A193 bolts can have different mechanical properties and fabrication requirements, but all have significantly more inherent corrosion resistance compared to both A325 Type 3 and galvanized bolts.

For VDOT, it is beneficial to understand some of these differences for several reasons. VDOT office practices might need to be revised to address deviations from traditional practices. In addition, if fasteners are received that do not meet the requirements, understanding differences is helpful in determining what changes must be made. For example, the mechanical properties for an austenitic stainless steel can be altered through strain hardening. By deforming the metal, perhaps through cold working, the microstructure can be altered, thus requiring greater force to continue deforming the material. This is observed as a change in the mechanical properties, such as hardness. Therefore, a difference in the mechanical property requirements would be expected when ASTM A193 Grade B8 Class 1 and Class 2 bolts are compared, since Class 1 bolts require only carbide solution treatment and Class 2 bolts require carbide solution treatment and strain hardening. Moreover, the difference in hardness can sometimes be observed when the same material is used for different components, with each component having a different hardness value because of the manner in which it was produced. Finally, different types of austenitic stainless steels can exhibit different types of strain hardening behavior depending on whether the austenitic microstructure is stable or metastable at a given temperature; therefore, it is important not to expect that all austenitic stainless steels will have the same mechanical properties. Because of this, testing is required to determine the limits of each one under certain conditions so that decisions can be made regarding the required parameters for accepting and using these materials.

The choice of fastener assembly, including bolt, nut, and washer, to use with 50CR steel is important because of galvanic corrosion, which can occur when two metals with different corrosion potentials are placed in contact. Currently, there is not a fastener assembly made with 50CR steel on the market. If fastener assemblies made of materials less noble than 50CR steel are selected, they could undergo accelerated corrosion, but this accelerated rate of corrosion is not yet known. As for the bolts that have previously been used with 50CR steel, both A325 Type 3 and A325 galvanized bolts, they have been and continue to be expected to perform reasonably well in less extreme corrosive environments. A193 B8-2 bolts are made of materials that are more noble than 50CR steel, so accelerated corrosion of the fastener is not expected, but they are more expensive and have less strength than A325 bolts, meaning more bolts are required to develop the same amount of force in a bolted connection.

A193 B8-2 bolts were selected for use on VDOT's Route 340 Bridge and one of the two Oregon Department of Transportation's 50CR steel bridges (Provines et al., 2018). The A193 B8-2 bolts were selected for use on the Route 340 Bridge based on VDOT's desire for the bolts to have greater corrosion resistance than the 50CR steel and the results of a bolt evaluation study (Williams et al., 2017). The bolt evaluation included Grades B6, B8 Class 2 (B8-2), and B8M Class 2 from ASTM A193. All three stainless steel grades, as well as typical A325 bolts, were assessed in terms of their mechanical properties, corrosion resistance, shipping time, cost, and material availability in accordance with Buy America requirements (Federal Highway Administration [FHWA], 2017).

Based on results from the bolt evaluation, the authors concluded that the A193 B8-2 bolts were the most suitable for use on the Route 340 Bridge. Since the 7/8-in-diameter A193 B8-2 fasteners were not able to achieve the standard 39-kip tensile clamping force, a modified tightening procedure was developed in order to develop a consistent tension force of 30 kip. Because of this decrease in tensile force, approximately 40% more A193 B8-2 fasteners were required in the bolted splice of the Route 340 Bridge than if the bridge had been designed using standard Grade A325 bolts (Provines et al., 2018). In terms of cost, the A193 B8-2 fasteners were approximately 8 times more expensive than the A325 bolts when ordered in a small quantity and were approximately 20% more expensive when ordered in a large quantity (Provines et al., 2018).

Although the A193 B8-2 fasteners performed adequately in the evaluation for the Route 340 Bridge, there is a need to investigate other potential stainless steel fastener options for use in stainless steel bridges. Although there are recommended guidelines for stainless steel fasteners for bearing-type connections in the building community, these guidelines do not include slip-critical connections, which are commonly used on steel bridges (Baddoo, 2013). There are also limited test data for stainless steel fasteners that can be used to evaluate their suitability for use on 50CR or other stainless steel bridges.

Another potential option for corrosion-resistant steel fasteners is duplex stainless steel. There are many types of duplex stainless steel, ranging from lean duplex Type 2101 (UNS S32101) to super duplex Type 2507 (UNS 32750). One of the most commonly used duplex stainless steels in the U.S. construction industry is duplex stainless steel Type 2205 (hereinafter "2205") (Provines et al., 2019); 2205 steel has approximately 22% chromium and 5% nickel by weight, which gives it excellent corrosion resistance, i.e., far better than that of 50CR steel. It also has good strength, ductility, and fracture toughness (Provines et al., 2019); 2205 structural fastener assemblies can be purchased from a bolt supplier.

Yet another potential option is a martensitic chromium alloy (MCA) steel that is currently being used to produce reinforcing steel meeting the requirements of ASTM A1035 CS (ASTM, 2020b). This steel has a chromium content of 8% to 10.9% by weight and a martensitic microstructure, both of which might make it a good option for bolting to 50CR steel. Having such similar characteristics could lead to good galvanic corrosion performance if the two steel types were used in conjunction with each other. The MCA steel also has a nominal ultimate tensile strength of 150 ksi, which is more than that of A325 bolts and the same as that of A490 bolts. The company producing MCA steel makes reinforcing steel, allowing for an easy transition to production of round bolts. After discussions with the Virginia Transportation Research Council (VTRC) and VDOT's Structure and Bridge Division about this project, the company that produces MCA steel decided to produce a trial batch of bolts, nuts, and washers of MCA steel to be evaluated as a potential corrosion-resistant steel fastener for stainless steel bridges.

Lubrication selection is especially important for stainless steel fasteners to prevent galling during bolt installation. Galling is when two parts become cold welded to each other. For stainless steel fasteners, common areas for galling to occur are between the bolt threads and the nut threads and in the bearing area between the nut face and washer. When galling occurs during the bolt installation process, the additional friction increases the torque in the fastener while minimizing the tension, neither of which is beneficial. Proper lubrication designed specifically for stainless steel fasteners can minimize the potential for galling to occur. However, not all lubricants designed for stainless steel fasteners offer the same effectiveness. During the acceptance testing for the A193 B8-2 bolts on the Route 340 Bridge, two types of lubricants were assessed. With one of the lubricants, the bolts surpassed their maximum allowable torque prior to reaching their specified tensile clamping force. With the other lubricant, the bolts were able to reach their specified tensile clamping force (Provines et al., 2018).

Another challenge with using corrosion-resistant fasteners is that no published installation parameters or specified minimum bolt pretension values exist for corrosion-resistant bolts. Further, there is no published method for determining these installation parameters. Typical A325 and A490 bolts have specified minimum bolt pretension values and installation parameters (such as the nut rotation for the turn-of-nut installation method) already defined by the American Association of State Highway and Transportation Officials (AASHTO) (AASHTO, 2017) and the Research Council on Structural Connections (RCSC) (RCSC, 2014). These values do not exist for corrosion-resistant bolts because corrosion-resistant bolts have not traditionally been used in slip-critical conditions. A method for determining both the specified minimum bolt pretension and the installation parameters, such as nut rotation for turn-of-nut installation, is needed.

PURPOSE AND SCOPE

The purpose of this study was to evaluate three types of corrosion-resistant steel bolts and their accompanying nuts and washers for use on 50CR and other stainless steel bridges. The three corrosion-resistant steel bolt types selected for evaluation were A193 B8-2, 2205, and MCA steel. Results from the evaluation were compared to test results on industry-standard bolts used on bridges, including A325 and A490 bolts. Although VDOT specifications do not allow A490 bolts to be used on any bridges, they were included in this study for comparison purposes. The accompanying nuts and washers from the corrosion-resistant bolt types were also compared to their industry-standard counterparts. Based on these evaluations, recommendations were made to guide the selection of corrosion-resistant fastener assemblies.

The scope of the study included a literature review, numerous laboratory mechanical tests, long-term field exposure tests, and a cost evaluation. A large portion of the tests were conducted on bolts, but some tests were conducted on nuts and washers.

All bolts tested in this study were 7/8-in-diameter bolts except for some 3/4-in-diameter bolts included in the torqued tension tests. All bolts and nuts used in this study were heavy hex except for hex head MCA bolts used in the lubrication friction tests because of the limited number of heavy hex MCA bolts available. Table 1 shows the bolt, nut, and washer of each fastener assembly tested in this study. The table also includes whether the fastener assembly was a standard or corrosion-resistant type. Although the focus of this study was on the corrosion-resistant fasteners, standard-type fasteners such as A325 and A490 bolts were also included to use as a baseline for comparison to the corrosion-resistant fasteners.

Table 1. Fastener Assemblies Tested

Fastener Assembly Type: Standard or Corrosion-resistant	Bolt Type	Nut Type	Washer Type
Standard	ASTM F3125 Grade A325	ASTM A563 Grade DH	ASTM F436
Corrosion-resistant	ASTM A193 Grade B8 Class 2	ASTM A194 Grade 8	303[a]
Corrosion-resistant	2205[b]	2205[c]	2205
Standard	ASTM F3125 Grade A490	ASTM A563 Grade DH	ASTM F436
Corrosion-resistant	MCA[d]	MCA[c]	MCA[c]

MCA = martensitic chromium alloy.
[a] Denotes 303 washers were not strain hardened.
[b] Denotes 2205 bolts were specified to meet the mechanical requirements of A325 bolts.
[c] Denotes 2205 nuts were specified to meet the mechanical requirements of A563 nuts.
[d] Denotes MCA bolts, nuts, and washers were provided to the Virginia Transportation Research Council without specific ordering requirements.

In this study, 303 washers were used with the A193 B8-2 bolts. The recommended washer type to be used with A193 B8-2 fastener assemblies is 304 stainless steel since it mimics the 304 stainless steel used to manufacture the A193 B8-2 bolts. However, when the fastener assemblies were purchased for this study, multiple bolt suppliers did not have 304 washers available. Therefore, 303 washers were substituted. This was a reasonable substitution since the 304 and 303 alloys are relatively similar. A similar substitution of washer type was also used in the Route 340 Bridge (Provines et al., 2018).

The 2205 bolts used in this study were specified to be made of 2205 material specified to meet the mechanical requirements of A325 bolts. Similarly, the nuts were specified to be made of 2205 material and to meet the mechanical requirements of A563 nuts. The MCA bolt producer provided VTRC with the MCA bolts to assess the viability of using these bolts for future VDOT bridge projects, so no ordering specifications were used. The MCA bolts were manufactured out of two heats of MCA steel to determine if there was any difference in performance between different heats. The two heats are identified in this report as either "HC" or "WF," noted by the markings on the bolt head of each heat. All nuts and washers were produced out of the HC heat. In general, there were no notable differences in performance between the two MCA heats. However, for completeness, distinctions between the two heats of bolts are included in this report.

METHODS

To achieve the study's objectives, the following tasks were performed:

1. review of the literature
2. initial evaluation of bolts
3. proof loading of bolts
4. shear testing of bolts
5. wedge testing of bolts
6. proof testing of nuts
7. cone proof testing of nuts
8. hardness testing of fasteners

9. energy dispersive spectroscopy (EDS) of lubricants
10. friction testing of lubricants
11. torqued tension testing of fasteners
12. relaxation testing of bolts
13. long-term corrosion testing of bolts
14. cost evaluation of fasteners.

In general, the bolt mechanical test results were compared to the test requirements for either A325 or A490 bolts, which are the standard and higher strength bolts, respectively, used in the bridge community. A193 B8-2 and 2205 bolts were compared to A325 mechanical requirements, and MCA bolts were compared to A490 mechanical requirements. These comparisons were selected because bolts within these groups had similar expected strengths. For example, the MCA bolts were expected to perform more similarly to A490 bolts than to A325 bolts, because of their higher strength. A193 B8-2 bolts also have their own mechanical requirements specified in ASTM A193. These requirements in A193 are presented in this report and are generally less restrictive than the A325 requirements.

Similar comparisons were made for the nuts. Since A325 and A490 bolts use an ASTM A563 (hereinafter "A563") nut, all nuts tested in this study (i.e., A194, 2205, and MCA) were compared to the A563 mechanical requirements. Similar to the A193 B8-2 bolts, the A194 nuts already have their own standard, so their test results were compared to ASTM A194 (hereinafter "A194") too.

Similar to nuts, A325 and A490 bolts require the use of ASTM F436 (hereinafter "F436") washers. Therefore, all washers tested in this study (i.e., 303, 2205, and MCA) were compared to the F436 mechanical requirements.

Literature Review

The literature review included a recent study on stainless steel fastener assemblies and a review of stainless steel bolting specifications. The details of each were reviewed and summarized.

Initial Evaluation of Bolts

Dimensional measurements were taken on the bolt, nuts, and washers from the corrosion-resistant fastener assemblies to compare them to the dimensional requirements for A325 and A490 bolts in ASME B18.2.6, Fasteners for Use in Structural Applications (American Society of Mechanical Engineers [ASME], 2010). It should be noted that the corrosion-resistant bolts were not ordered to meet the requirements of ASME B18.2.6. The comparison was done as a means of identifying any differences in dimensions between corrosion-resistant and standard bolts. Figure 1 shows a drawing indicating the measurements that were recorded for the corrosion-resistant fastener assemblies. Two bolts, nuts, and washers of each corrosion-resistant type were selected at random for measurements. Three duplicate measurements of each measurement type shown in Figure 1 were then taken on the bolt, nut, or washer selected.

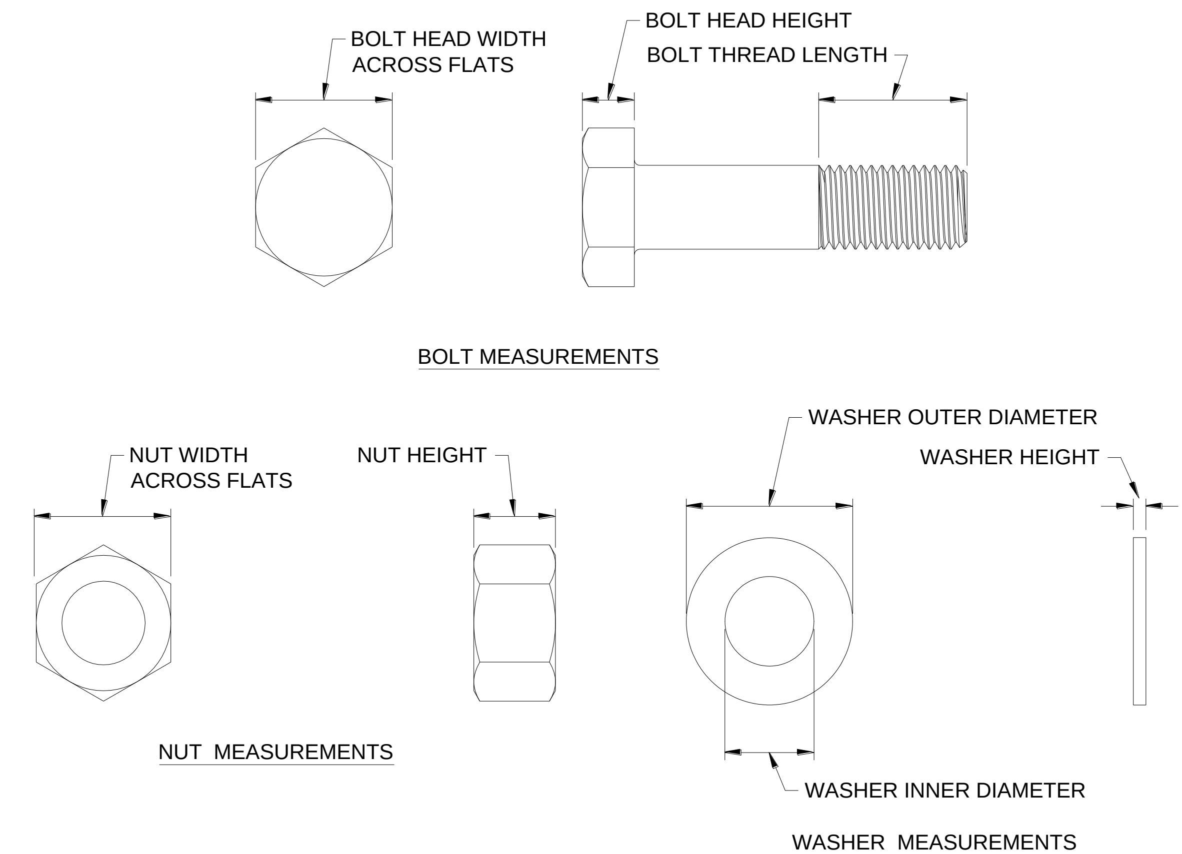


Figure 1. Drawing of Dimensions Recorded on Corrosion-Resistant Bolts, Nuts, and Washers

The mill test reports for the corrosion-resistant bolt types were also examined, and the chemistry for each bolt type was reported.

Proof Loading of Bolts

Proof loading of bolts, similar to tension tests except that bolts instead of plates are used, was conducted on 5-in-long, full-size bolts. Five proof tests were conducted on each bolt type except for the MCA bolts. Six MCA bolts, consisting of three bolts made from each heat, were tested. All bolts were subjected to proof loading in uniaxial tension in accordance with ASTM F606 (hereinafter “F606”) (ASTM, 2016).

Tests were conducted in a servo-hydraulic–controlled 220-kip-capacity load frame. The yield strengths of the bolts were measured using Method 2 and Method 2A in the F606 specification. Method 2A was used for the A193 B8-2 bolts since they are an austenitic stainless steel, and Method 2 was used for the remaining bolts. Figure 2 shows a drawing of the setup for proof loading. Included in the figure are the gauge lengths over which strain was measured during testing to determine the yield strength in accordance with the F606 specification. One gauge length is used for the austenitic stainless steel A193 B8-2 bolts, and another gauge length is used for the remaining bolts.

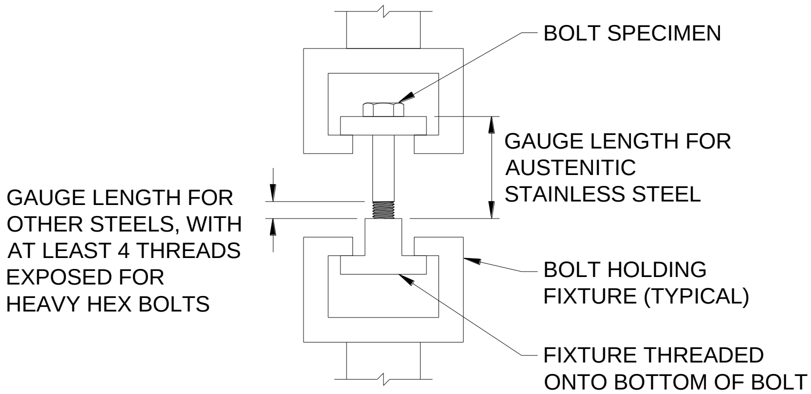


Figure 2. Drawing Showing Bolt Proof Loading Test Setup

Load and displacement from the load frame were also recorded during testing. All test fixtures met the requirements of the F606 specification. All bolts were tested until failure. Figure 3 shows a photograph of the bolt testing fixture.

Figure 3. Photograph Showing Bolt Testing Fixture

Shear Testing of Bolts

Single shear tests were conducted on all bolts in accordance with the F606 specification. Shear tests were conducted on 3.5-in-long, full-size bolts. Similar to the proof loading, shear tests were performed on five bolts of each type except for the MCA bolts. Six MCA bolts, consisting of three of each heat, were tested.

All single shear tests were conducted in tension in a test fixture, as shown in Figure 4. Tests were conducted in a servo-hydraulic–controlled 220-kip-capacity load frame. All test fixtures met the requirements of the F606 specification. Load and displacement from the load frame were recorded during testing. Nuts and washers matching the bolt type were used during testing. All bolts were tested until failure.

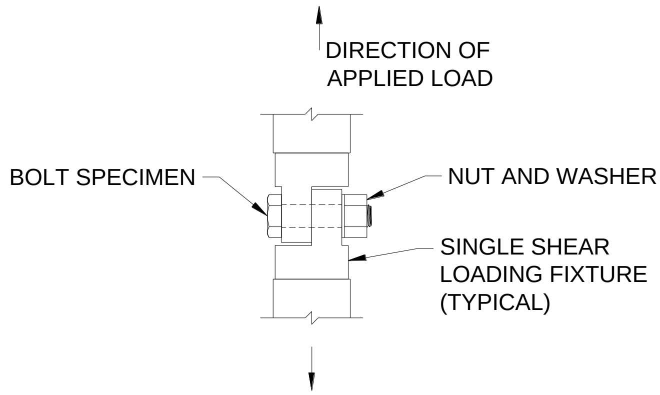


Figure 4. Drawing Showing Bolt Single Shear Test Setup

Wedge Testing of Bolts

Wedge tests were conducted on 5-in-long, full-size bolts in accordance with the F606 specification. Wedge tests involve pulling a bolt in tension with a 10-degree wedge-shaped washer located under the bolt head. The purpose of this test is to evaluate the quality of the bolt head after the shaping process during bolt manufacturing. Similar to the tension and shear tests, wedge tests were performed on five bolts of each type except for the MCA bolts. Six MCA bolts, consisting of three of each heat, were tested. A drawing of the wedge testing setup is shown in Figure 5.

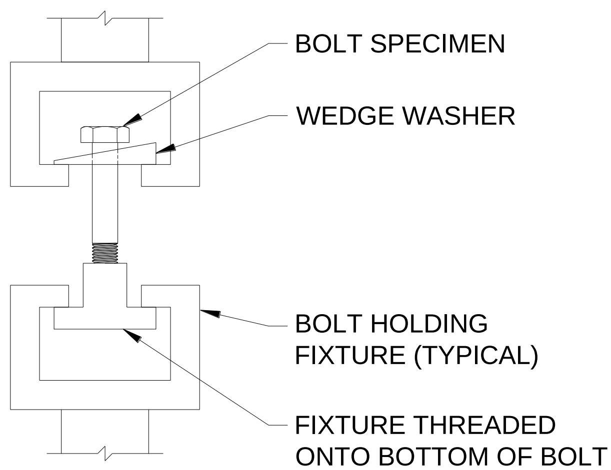


Figure 5. Drawing Showing Bolt Wedge Test Setup

Tests were conducted in a servo-hydraulic–controlled 220-kip-capacity load frame. All test fixtures and wedge washer met the requirements of the F606 specification. Load and displacement from the load frame were recorded during testing. All bolts were tested until failure.

Proof Testing of Nuts

Aside from the bolts, mechanical tests were also conducted on the nuts to evaluate their suitability for use on bridges. One type of test performed was proof testing, as defined in the F606 specification. This test is performed by threading a mandrel into the nut and then pulling it to a defined load to evaluate the strength of the threads within the nuts. To pass this test, the nut should resist the applied load without stripping or rupture and must be removed from the mandrel by finger loosening. Five proof tests were conducted on all nut types.

The nut proof tests were performed by loading the nut in tension, as shown in Figure 6. Tests were conducted in a servo-hydraulic–controlled 220-kip-capacity load frame. All test fixtures and the threaded mandrel met the requirements of the F606 specification. Load and displacement from the load frame were recorded during testing.

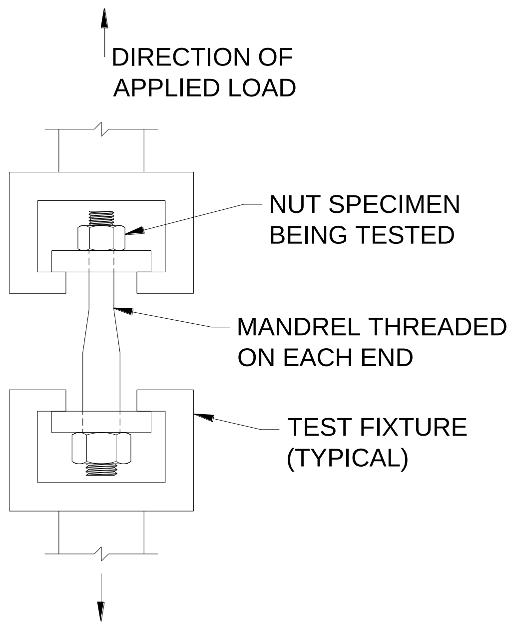


Figure 6. Drawing Showing Nut Proof Test Setup

Cone Proof Testing of Nuts

The second type of mechanical test on nuts was the cone proof test conducted in accordance with the F606 specification. This test is similar to the proof test, but force is applied by placing a conical washer in bearing against the nut. This purpose of this test is to determine if the nut has any surface discontinuities, such as forging cracks or seams, that could reduce its load carrying ability. Five cone proof tests were conducted on all nut types.

The cone proof tests were performed in a fashion similar to that of the proof tests except that load was applied to the nut through a conical washer. This is shown in Figure 7. Tests were conducted in a servo-hydraulic–controlled 220-kip-capacity load frame. All test fixtures, the threaded mandrel, and the conical washer met the requirements of the F606 specification. Load and displacement from the load frame were recorded during testing.

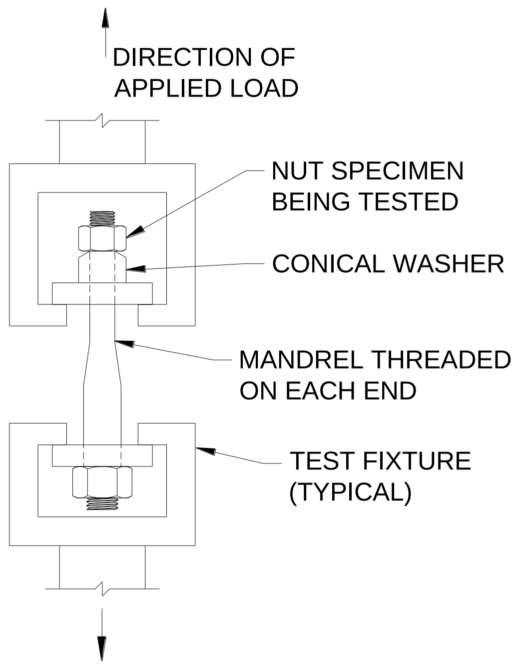


Figure 7. Drawing Showing Nut Cone Proof Test Setup

Hardness Testing of Fasteners

Hardness tests were conducted on bolts, nuts, and washers in accordance with the F606 specification. Hardness tests are conducted because they comprise a simple test to evaluate the strength of the fastener assembly components. The specimen preparation and hardness tests were conducted in accordance with ASTM E18 using the Rockwell C hardness scale (HRC) and Rockwell B hardness scale (HRB). All hardness test locations met the minimum edge distance and adjacent test spacing distance requirements (ASTM, 2017c). The locations for hardness tests were selected in accordance with the F606 specification.

Hardness Tests on Bolts

Tests were conducted on two bolts of each type. For the MCA bolts, hardness tests were conducted on one bolt from each heat. All bolts used for hardness testing were 3.5 in long. Tests were conducted on the top of the head, wrench flats, unthreaded shank, threaded end, and at an arbitration location, which is located one bolt diameter in length (7/8 in) from the threaded end. Exact hardness test locations and test labels for the bolts are shown in Figure 8.

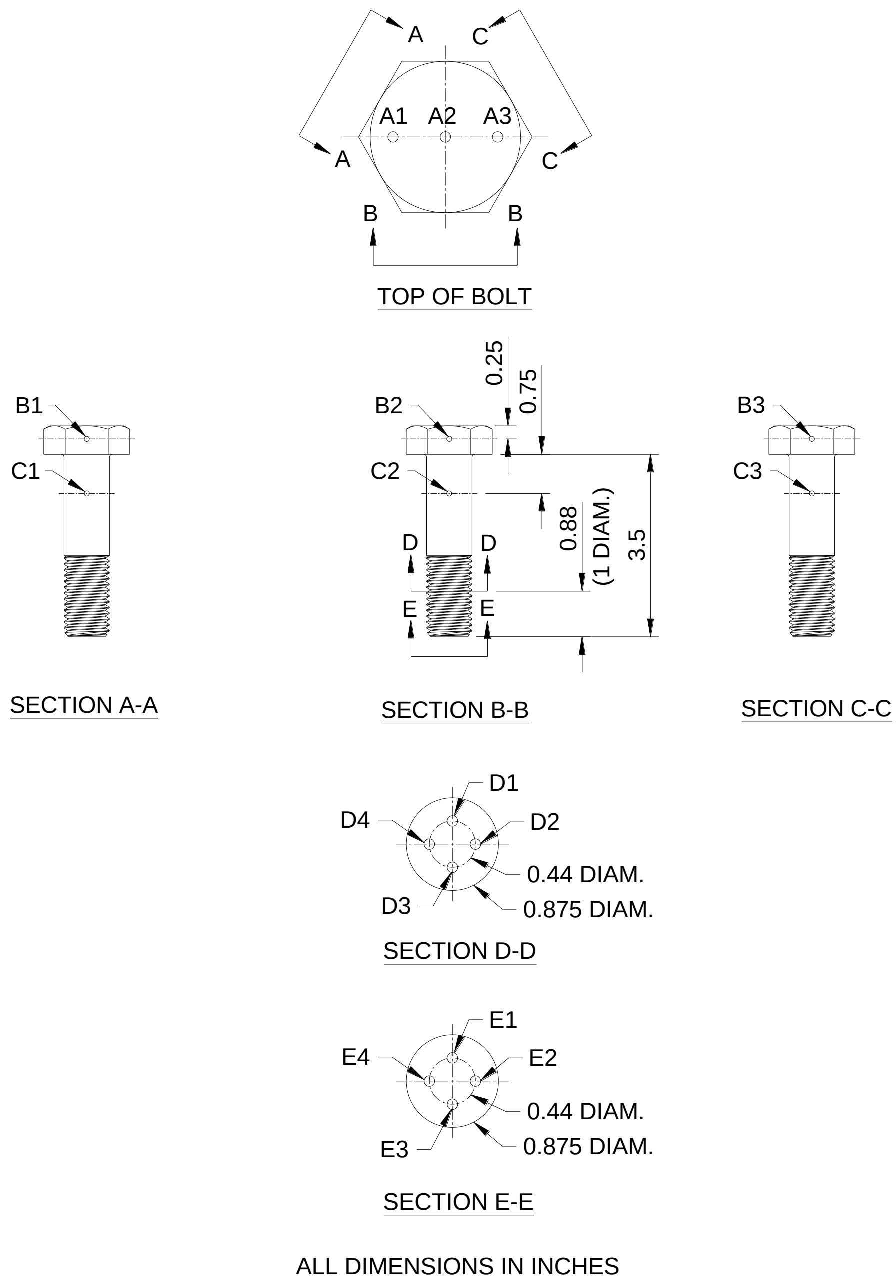
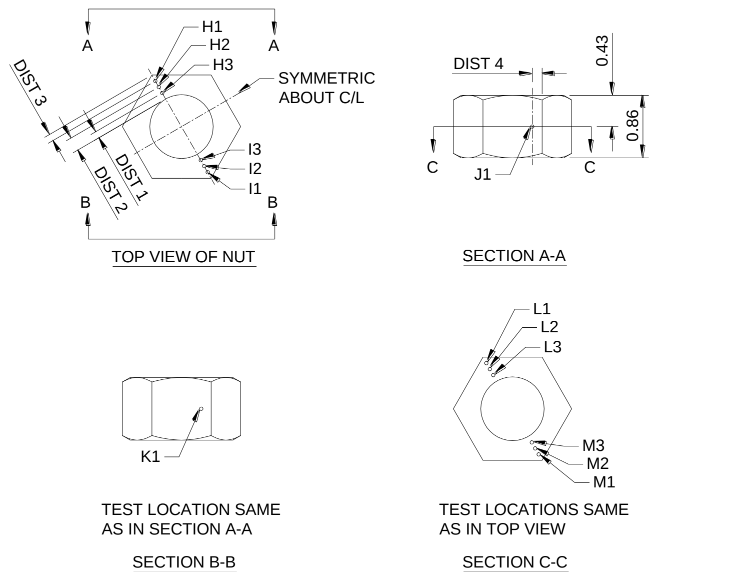


Figure 8. Drawing of Hardness Test Locations on Bolts

Hardness Tests on Nuts

Hardness tests were conducted on two nuts of each type. Nuts were tested on the wrench flats, on a bearing face between the major diameter of a thread and one corner, and on a section through one-half of the nut in the same locations as the bearing face. Exact hardness test locations and test labels for the nuts are shown in Figure 9.



DIST 1 = AS CLOSE TO MAJOR DIAMETER AS POSSIBLE, BUT NOT CLOSER THAN 2.5 TIMES INDENT DIAMETER

DIST 2 = AT THE CORE (HALFWAY BETWEEN MAJOR DIAMETER AND CORNER OF NUT)

DIST 3 = AS CLOSE TO CORNER AS POSSIBLE, BUT NOT CLOSER THAN 2.5 TIMES INDENT DIAMETER

DIST 4 = ONE THIRD OF THE DISTANCE FROM A CORNER TO THE CENTER OF WRENCH FACE (0.14)

DIST = DISTANCE
C/L = CENTERLINE

ALL DIMENSIONS IN INCHES

Figure 9. Drawing of Hardness Test Locations on Nuts

Hardness Tests on Washers

Hardness tests were conducted on two washers of each type. Washers were tested on a surface of the washer and at a minimum depth of 0.015 in into the core of the washer. Exact hardness test locations and test labels for the washers are shown in Figure 10.

Energy Dispersive Spectroscopy of Lubricants

Different types of stainless steel fastener lubricants were selected to evaluate their effectiveness in preventing galling with each type of corrosion-resistant bolt. Five lubricants were selected for use in this study. One of the lubricants selected is typically used for standard-type structural steel fasteners. The other four lubricants were marketed specifically for stainless steel fasteners. Figure 11 shows a photograph of each of the lubricants included in this study, labeled from left to right. Lubricant 1, on the left, is a lubricant typically used for carbon steel fasteners. Lubricant 2 was used on the Route 340 Bridge with the A193 faster assemblies (Provines et al., 2018).

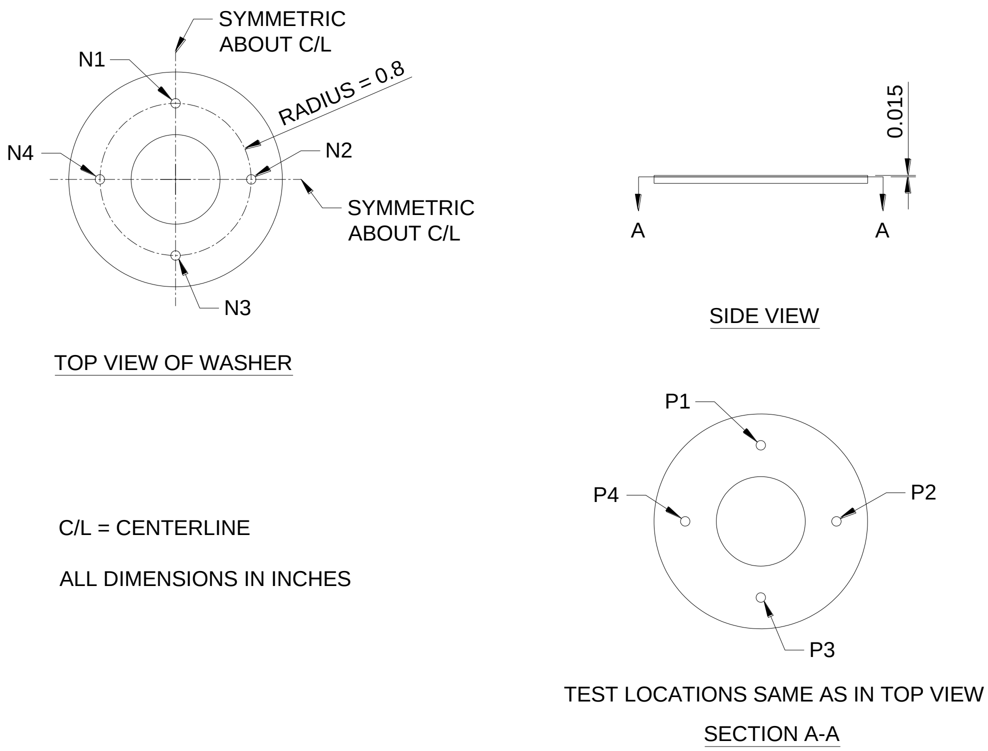


Figure 10. Drawing of Hardness Test Locations on Washers

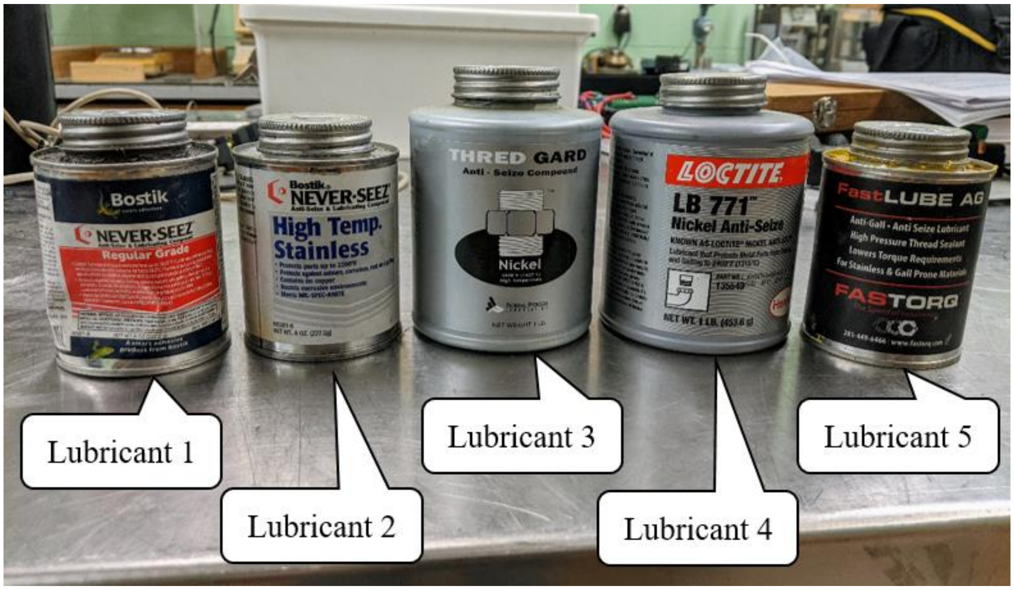


Figure 11. Photograph of Lubricants Used

All five lubricants were evaluated in terms of additions of unique elements and effectiveness. This was done to distinguish the lubricants more by chemistry than by product name. It was anticipated that some lubricants would perform better than others and that it would benefit VDOT to specify those high-performing lubricants for use with stainless steel fasteners. However, it is difficult for VDOT to specify materials by product name because sole source specifications do not allow competition from multiple suppliers. On the other hand, VDOT could easily specify high-performing lubricants based on chemistry requirements. Therefore, EDS was conducted by taking a sample of each lubricant and analyzing it in a scanning electron microscope using the accompanying EDS detection system.

Although it was recognized that EDS is not able to capture all known elements in these lubricants, it is able to identify quickly a number of elements that might be influential in the performance of these lubricants. Further, the technical datasheet for each lubricant confirmed the presence of certain elements that were unique to each product. Therefore, EDS was used to determine the weight percentage of carbon (C), oxygen (O), sodium (Na), magnesium (Mg), aluminum (Al), silicon (Si), phosphorus (P), sulfur (S), potassium (K), calcium (Ca), titanium (Ti), chromium (Cr), manganese (Mn), iron (Fe), nickel (Ni), copper (Cu), and molybdenum (Mo). It was anticipated that this approach would provide a means of distinguishing lubricants and determine if certain elements were associated with improved performance.

Friction Testing of Lubricants

The lubricants were also evaluated in terms of their effectiveness in preventing galling during bolt installation through friction tests. Generally, an effective lubricant should maximize tension and minimize torque in a bolt during installation. This is because tension is required for the pretensioned bolted connections used for steel bridges to develop sufficient clamping force between connected parts. Torque is a byproduct of friction developed when a bolt is tightened by turning a nut.

Friction tests were conducted by pairing each type of fastener assembly with each type of lubricant. For the A325 and A490 bolts, three tests each were conducted with Lubricant 1, since this lubricant is typically used with carbon steel bolts. For all corrosion-resistant bolts, three tests were conducted with each bolt and lubricant pairing. The number of tests conducted with each bolt type and lubricant type is shown in Table 2; 3.5-in-long bolts were used for all friction tests. MCA bolts with hex heads were used because of the limited number of heavy hex head MCA bolts possessed by VTRC.

The lubricant tests were conducted using a bolt tensioning device, a torque wrench, and a torque multiplier. These tests were performed in a manner similar to how a rotational capacity test in ASTM F1325 (ASTM, 2015) begins. Bolt tension was recorded using the bolt tensioning device; torque on the nut was recorded using the torque wrench; and the nut rotation angle was recorded using an angle of turn protractor on the torque multiplier. A plot of the bolt force vs. nut rotation was monitored during testing.

Table 2. Test Matrix for Friction Testing of Lubricants

Bolt Type	No. of Friction Tests				
	Lubricant 1	Lubricant 2	Lubricant 3	Lubricant 4	Lubricant 5
A325	3	0	0	0	0
A193 B8-2	3	3	3	3	3
2205	3	3	3	3	3
A490	3	0	0	0	0
MCA	3	3	3	3	3

MCA = martensitic chromium alloy.

First, a fastener assembly, consisting of a bolt, nut, and washer, and lubricant were selected. Threads of the bolt and nut were inspected to ensure that no damage was present. Second, lubricant was applied to the threads of the nut and bolt and to the turning face of the nut and washer. Third, the bolt, nut, and washer were installed into the bolt tensioning device with three to five threads within the grip length of the bolt. If needed, additional F436 washers were used as spacers between the bolt tensioning device and the washer/nut in the fastener assembly. The nut was then installed finger tight on the bolt.

A torque wrench and torque multiplier were then used to turn the nut until the bolt tension reached 4 kip. At that point, the protractor on the torque multiplier was set to zero to signify the beginning of the test. The torque wrench and torque multiplier were then used to turn the nut 20 degrees, at which point bolt tension, torque, and nut rotation angle were recorded. The process continued in a similar fashion, with tension, torque, and nut rotation recorded every 20-degree increment until it was clear that the plot of bolt force vs. nut rotation had become non-linear. This process was completed for each bolt and lubricant combination shown in Table 2.

Lubricant effectiveness during friction tests was evaluated by the k-factor, calculated in accordance with Equation 1. The values of 12 in the numerator and 1,000 in the denominator of the equation are unit conversions when the units as defined in Equation 1 are used.

$$K = \frac{12\,T}{1{,}000\,Fd} \qquad \text{[Eq. 1]}$$

where

K = k-factor (unitless)
T = bolt torque (ft-lb)
F = bolt tension (kip)
d = nominal bolt diameter (in), taken equal to 7/8 in for all tests in this study.

In Equation 1 it is clear that as torque increases so does the k-factor. This means that a smaller k-factor indicates that a lubricant is more effective in minimizing torque while maximizing tension. The maximum k-factor allowed for A325 and A490 bolts is 0.25, according to ASTM F3125 Annex A.2 for rotational capacity testing. This maximum allowable k-factor is given in terms of a maximum torque, i.e., that the maximum torque shall not exceed 0.25 times the tension in the bolt and the bolt diameter (ASTM, 2015).

Equation 1 was used to calculate the k-factor for each fastener assembly and lubricant pairing to determine which combinations were most effective. Results were used to select two lubricants deemed most effective to be used in the torqued tension tests.

Torqued Tension Testing of Fasteners

The torqued tension tests were conducted in a manner similar to that of the friction tests with two modifications. First, only the two most effective lubricants, shown through friction testing, were used with the corrosion-resistant fastener assemblies. Similar to the friction testing, the standard lubricant (i.e., Lubricant 1) was used with the A325 and A490 bolt assemblies. Second, rather than each test being terminated after the plot of bolt force vs. nut rotation had become non-linear, tests were continued until either the bolt tension suddenly decreased, the bolt became noticeably difficult to tighten, or the bolt fractured. In most cases, the bolt tension did not suddenly decrease until after it had already reached a maximum value and was descending on the plot of the bolt force vs. nut rotation curve. Bolt force, torque, and nut rotation were recorded at 20-degree increments until completion of the tests.

K-factors were determined from the torqued tension tests to add to the dataset compiled during the friction tests. Torqued tension test data were evaluated in three plot types: bolt force vs. nut rotation, bolt torque vs. nut rotation, and torque vs. tension.

Data from the torqued tension tests were used to evaluate the pretensioning behavior of the corrosion-resistant bolts. These data were also used to develop installation procedures for using corrosion-resistant bolts on pretensioned bolted connections since none currently exists. The method to determine installation parameters for corrosion-resistant fasteners focused on the turn-of-nut installation method since this method is currently used by VDOT. Although VDOT does use direct tension-indicating washers, these types of washers do not yet exist in corrosion-resistant form. Therefore, the direct tension-indicating washer installation method was not considered.

Relaxation Testing of Bolts

Relaxation is a time-dependent deformation because of sustained load. Since many bolted connections are slip-critical, connected plates transfer load through friction on the faying surfaces between the plates. This friction is maintained through the clamping force of the bolt. Relaxation of bolts is not desirable because deformation of a bolt could lead to a loss of the clamping force and thus loss of friction between faying surfaces. Relaxation is not a concern for A325 bolts because testing has shown that an average 5% reduction in load can be expected over time without other detrimental effects (Chesson and Munse, 1965; Reuther et al., 2014). However, relaxation should be considered for stainless steel bolts since limited test data exist on the topic (Baddoo, 2013).

Therefore, relaxation tests were conducted on all corrosion-resistant bolts and the A325 and A490 bolts for comparison. Relaxation tests were conducted on four 3.5-in-long bolts of each type except for the MCA bolts, for which four tests were conducted on both the HC and WF heats. Two tests were conducted on each type of 5-in-long bolt. A test matrix for the relaxation tests is shown in Table 3.

Table 3. Test Matrix for Relaxation Tests

Bolt Type	Minimum Initial Pretension (kip)	No. of Relaxation Tests on 3.5-in-Long Bolts	No. of Relaxation Tests on 5-in-Long Bolts
A325	39	4	2
A193 B8-2	30	4	2
22055	30	4	2
A490	49	4	2
MCA	49	4 HC and 4 WF	2 HC

MCA = martensitic chromium alloy.

Relaxation tests were conducted by first lubricating a bolt and nut with Lubricant 5. Then, the bolt was inserted through ASTM A36 (hereinafter "A36") steel plate(s) and a center hole load cell with a capacity of 100 kip. A matching washer and nut were then installed onto the end of the bolt. The bolt was then tightened with a torque wrench and torque multiplier. Bolts were tightened to an initial pretension, which was measured by the load cell. The minimum initial pretension values for each bolt type are shown in Table 3. The minimum initial pretension values for A325 and A490 bolts were their design pretension values of 39 kip and 49 kip, respectively. A193 B8-2 bolts were tightened to 30 kip, which was their design pretension value for the Route 340 Bridge (Provines et al., 2018); 2205 bolts were also tightened to this pretension value for consistency. MCA bolts were tightened to 49 kip to match the A490 bolts. Figure 12 shows the test setup for the relaxation tests, and Figure 13 shows a photograph of the same.

Once the bolts were tightened to their initial minimum pretension value, initial loads in each bolt were recorded approximately 1 hour after the bolts were tightened and were then recorded every hour for 1,000 hours, about 42 days, at which point the test was considered complete.

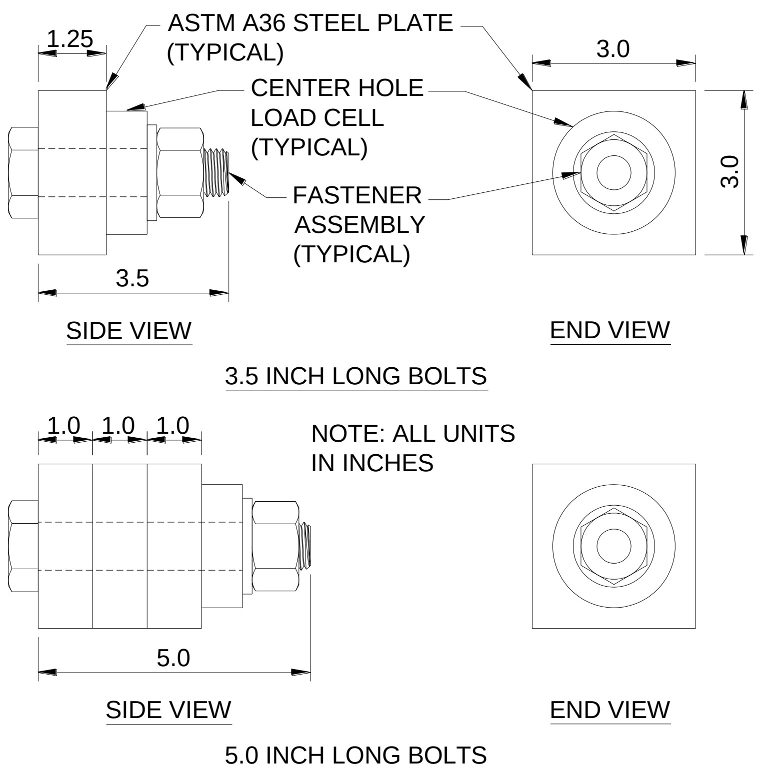


Figure 12. Drawing Showing Relaxation Test Setup

Figure 13. Photograph of Example 5-in-Long Bolt During Relaxation Test Sitting on Plastic Pipe

Long-Term Corrosion Testing of Bolts

The long-term corrosion performance of the corrosion-resistant fasteners was evaluated by placing bolted specimens at one of VTRC's exposure sites to monitor over time by visual assessment. VTRC's exposure site on the north island of the Hampton Roads Bridge-Tunnel was selected since it is in an aggressive environment located only a few feet from the Atlantic Ocean. This site is home to many other long-term corrosion test specimens from other projects. These specimens are all fastened to exposure racks made of corrosion-resistant material and are located on secured, VDOT-owned land.

All long-term corrosion specimens consisted of a corrosion-resistant fastener assembly, a 50CR steel plate, and a dissimilar metal steel plate. A 50CR steel bent plate was used for corrosion specimens; 50CR steel was used because these corrosion-resistant bolts are expected to be used with 50CR steel. A bent plate was used simply for the convenience of being able to attach the specimen to the existing corrosion racks and to provide the desired orientation of the specimen. The horizontal leg of the bent plate was attached to the corrosion rack, and the vertical leg of the bent plate was bolted to the dissimilar metal plate to simulate a bolted connection on a girder web. The dissimilar metal types included ASTM A588 (hereinafter "A588") steel (i.e., weathering steel); A36 hot dipped galvanized steel (HDG); MCA steel; A588 HDG; and 2205 stainless steel plate. The 50CR steel plate was used in all specimens since corrosion-resistant fasteners are expected to be used predominantly with 50CR steel. The dissimilar metal plate was used in the specimens since it is anticipated that dissimilar metal bolted connections will be used with 50CR steel in future applications.

Figure 14 shows a drawing of the long-term corrosion test specimens. All bolts used in these long-term corrosion samples had a diameter of ¾ in.

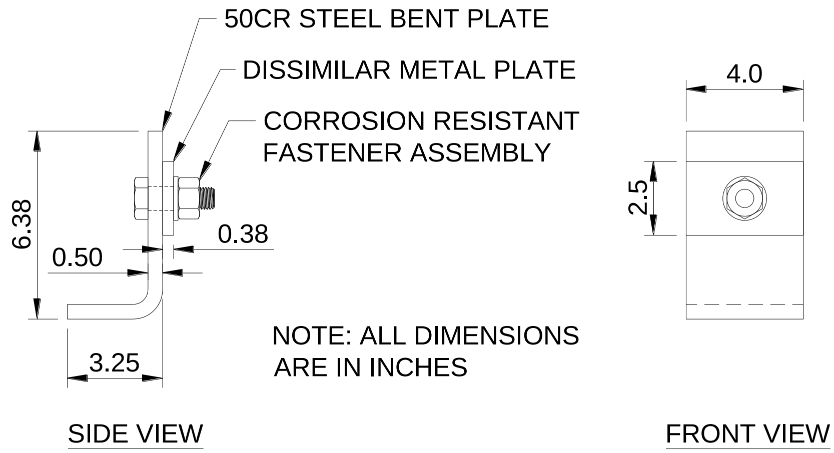


Figure 14. Drawing of Long-Term Corrosion Test Specimens

Table 4 shows a test matrix of the long-term corrosion tests. Although not included in the table, all specimens included a 50CR steel plate, as noted in Figure 14. Specimen 0 did not include a dissimilar metal plate and, instead, consisted only of a 50CR steel plate with an A325 fastener assembly. This specimen was used as a control for comparison with other samples. The remaining specimens were divided into five groups based on the following dissimilar metal plate types: A588, A36 HDG, MCA, A588 HDG, and 2205. There were four specimens in each group, each consisting of a different type of corrosion-resistant fastener assembly.

Table 4. Long-Term Corrosion Test Matrix

Specimen No.	Dissimilar Metal Plate Type	Bolt Type	Nut Type	Washer Type
0	None[a]	A325	A563 DH	F436
1	A588	A325 Type 3	A563 DH3	F436 Type 3
2	A588	A325 HDG	A563 DH HDG	F436 HDG
3	A588	MCA	MCA	MCA
4	A588	A193 B8-2	A194	303
6	A36 HDG	A325 HDG	A563 DH HDG	F436 HDG
7	A36 HDG	MCA	MCA	MCA
8	A36 HDG	MCA Zn/Ni plated	MCA Zn/Ni plated	MCA Zn/Ni plated
9	A36 HDG	A193 B8-2	A194	303
10	MCA	A325 HDG	A563 DH HDG	F436 HDG
11	MCA	MCA	MCA	MCA
12	MCA	MCA Zn/Ni plated	MCA Zn/Ni plated	MCA Zn/Ni plated
13	MCA	A193 B8-2	A194	303
14	A588 HDG	A325 HDG	A563 DH HDG	F436 HDG
15	A588 HDG	MCA	MCA	MCA
16	A588 HDG	MCA Zn/Ni plated	MCA Zn/Ni plated	MCA Zn/Ni plated
17	A588 HDG	A193 B8-2	A194	303
18	2205	MCA	MCA	MCA
19	2205	MCA Zn/Ni plated	MCA Zn/Ni plated	MCA Zn/Ni plated
20	2205	A193 B8-2	A194	303
21	2205	2205	2205	2205

HDG = hot dipped galvanized; MCA = martensitic chromium alloy.
[a] Denotes that Specimen 0 consists only of a 50CR plate and no other dissimilar metal plate.

Some MCA fasteners in the table also have a zinc/nickel (Zn/Ni) plating. These were produced by the MCA manufacturer to offer enhanced corrosion resistance on top of the MCA steel bolts. The structural properties of the MCA Zn/Ni–plated bolts were expected to be the same as those of the standard MCA bolts, so these bolts were included only in the long-term corrosion tests.

The long-term corrosion test specimens were assembled by installing a bolt in each test specimen using the turn-of-nut installation method. Similar to the torqued tension tests, a torque wrench and torque multiplier were used to turn the nut and a wrench was used to prevent the bolt head from rotating. A fixture was also assembled to prevent the specimen from rotating. This fixture is shown in Figure 15.

When the bolt was installed in each specimen, the bolt was first tightened to a snug tight condition, meaning both plates were in firm contact. The angle of turn protractor on the torque multiplier was then zeroed to use this as the reference point from which to measure the nut rotation. Then, the bolt was tightened using the nut rotation value as determined from the torqued tension tests.

Figure 15. Fixture Used for Bolt Installation on Long-Term Corrosion Test Specimens

Cost Evaluation of Fasteners

To evaluate the cost of corrosion-resistant fastener assemblies, comparative prices of the components of selected fastener assemblies were sampled once from five suppliers in February 2020 for quantities of 2,000 units. Fastener assemblies in this evaluation included A325, A325 Type 3 (weathering steel), A325 HDG, A193 B8-2, 2205, and A490 bolted assemblies. For the A193 B8-2 fastener assemblies, Type 304 washers, instead of Type 303, were used in the cost evaluation. Although 303 washers were used in this study for reasons previously described, it was expected that 304 washers would be used for future A193 B8-2 fastener assemblies and thus were included. MCA bolted assemblies were excluded from the cost evaluation since these assemblies comprised a trial batch and were not yet being mass produced.

RESULTS AND DISCUSSION

Literature Review

Since stainless steel fastener assemblies are not commonly used in pretensioned bolted connections in structural applications, literature on the topic is limited. However, since their use is highly desirable in corrosive applications, the University of Duisburg-Essen (UDE) in Germany conducted an investigation from 2014 through 2017 on their use (Stranghöner, 2018). This comprises the only known previous investigation on stainless steel bolts for use in pretensioned bolted connections. Among other topics, the study included evaluation of lubricants, tightening behavior, and relaxation of stainless steel fasteners. These evaluations were conducted on various types of stainless steels, including austenitic and duplex. Further discussion of these evaluations is provided in the following sections. Although not exactly related to the work in this current study, the UDE study also evaluated the slip coefficients of stainless steel faying surfaces (Stranghöner et al., 2017a).

Lubricants for stainless steel fasteners were tested in the UDE study by means of torqued tension tests of different combinations of bolt and lubricant types (Stranghöner, 2018). Individual lubricants were evaluated by their k-factor, which is a quantitative measure of a lubricant's effectiveness. Although all lubricants were deemed suitable for use in stainless steel fasteners by their producer, some performed more effectively by improving both the bolt's ultimate force and ductility. Galling, a form of cold welding between moving parts, was noted in less effective tests as sudden drops in bolt load during torqued tension testing (Stranghöner et al., 2017b).

Tightening behavior in the UDE study was also evaluated using torqued tension tests. These tests also included different combinations of bolts and lubricants (Stranghöner, 2018). A criterion for evaluating a stainless steel fastener's potential for use in a pretensioned bolted connection was developed as part of this process (Stranghöner et al., 2017b) because it was not included in European specifications. The criterion was based on European standards and included requirements for a stainless steel bolt's design installation pretension, ultimate strength, lubricant effectiveness, and ductility. Although a criterion was developed for evaluating a bolt's torqued tension behavior, specific tightening parameters, such as the nut rotation for the turn-of-nut installation method, were not developed as part of the UDE study. Testing showed that the calibrated wrench method of installation was effective under laboratory conditions for stainless steel fasteners (Stranghöner et al., 2017b).

Relaxation tests in the UDE study were conducted by tightening stainless steel bolts to 70% of their ultimate strength and measuring the bolt force for approximately 14 days (Stranghöner, 2018). Multiple bolt diameters and lengths were tested to evaluate the effect of each on bolt relaxation. After 14 days of testing, the stainless steel bolts had a loss of initial pretension ranging from 3.4% to 6.6%. Data from the relaxation tests were extrapolated over a 50-year period to determine that an approximately 5.3% to 10.5% reduction in initial pretension could be expected. Therefore, the UDE researchers concluded that relaxation of stainless steel bolts could be treated similar to that of carbon steel bolts (Afzali et al., 2017).

Stainless steel bolting specifications were also examined in the literature review. The specifications included were ASTM A193 (ASTM, 2020a), ASTM A320 (ASTM, 2018), ASTM A1082 (ASTM, 2019), and ASTM F593 (ASTM, 2013b). ASTM A193 (ASTM, 2020a) covers stainless steel bolts for pressure vessels at high temperatures and was the specification used to order the bolts for the Route 340 Bridge. This specification contains numerous options for ferritic and austenitic stainless steels. With regard to differing steel types and bolt diameters, the specification allows 34 types of bolts. Of all of these bolt types, the A193 B8-2 bolts offer the highest ultimate strength at 115 ksi for 7/8-in-diameter bolts, which is slightly less than the 120-ksi ultimate strength of traditional A325 bolts used for bridges. ASTM A194 (ASTM, 2017a) is the nut specification used for ASTM A193 bolts.

ASTM A320 (ASTM, 2018) covers stainless steel bolts used for pressure vessels at low temperatures and provides requirements for ferritic and austenitic stainless steels. It contains 14 allowable bolt types with regard to steel type and bolt diameter. When 7/8-in-diameter bolts are considered, there are a few bolt options specified in ASTM A320 that have specified ultimate strengths greater than 120 ksi, but they are ferritic stainless steels, which are typically not as corrosion resistant as austenitic or other stainless steel types.

ASTM A1082 (ASTM, 2019) covers stainless steel bolts for special purpose applications such as pressure vessels and provides requirements for duplex and precipitation hardening grades of stainless steel. With regard to steel type and bolt diameter, this specification provides requirements for 31 types of bolts. The precipitation hardening bolts in ASTM A1082 have a specified ultimate strength of 115 to 190 ksi. However, precipitation hardening stainless steels are not as corrosion resistant as other types of stainless steel, including duplex. The duplex stainless steel bolts have ultimate strengths ranging from 90 to 116 ksi, still slightly less than those of traditional A325 bolts. This includes a 2205 option, which has a specified ultimate strength of 95 ksi and sufficient ductility.

ASTM F593 (ASTM, 2013b) covers stainless steel bolts for general use requiring corrosion resistance and includes austenitic, ferritic, martensitic, and precipitation hardening stainless steel bolts. With regard to steel type and bolt diameter, this specification contains 33 bolt types. It also contains bolts with tensile strengths up to 220 ksi for martensitic, 170 ksi for precipitation hardening, 100 ksi for ferritic, and 160 ksi for austenitic stainless steels. Based on their specifications alone, it is possible that other bolt types in ASTM F593 could be used for corrosion-resistant bridges. ASTM F594 (ASTM, 2009) is the corresponding nut specification to be used with ASTM F593 bolts.

Initial Evaluation of Fastener Assemblies

Average dimensional measurements for the corrosion-resistant bolts are shown in Table 5. Measurements for A325 bolts are included for comparison. According to ASME B18.2.6, a 7/8-in-diameter bolt must have a width across the flats of 1.394 to 1.438 in and a head height of 0.531 to 0.563 in (ASME, 2010). When the values in Table 5 were compared to these requirements, all three corrosion-resistant bolt types met the requirements for width across flats and head height.

Table 5. Average Dimensional Measurements for Corrosion-Resistant Bolts

Bolt Type	Width Across Flats (in)	Head Height (in)	Thread Length (in)
A325	1.413	0.553	1.5
A193 B8-2	1.417	0.559	2.0
2205	1.425	0.556	1.5
MCA	1.433	0.561	2.125

MCA = martensitic chromium alloy.

When the thread lengths of the bolts are compared, Table 5 shows that the thread length of the 2205 bolts was the same as that of the A325 bolts whereas the thread lengths of the A193 B8-2 and MCA bolts were different. This was not surprising since the corrosion-resistant bolts were not ordered to meet the dimensional requirements of ASME B18.2.6. However, it does illustrate that there is not a dimensional standard for corrosion-resistant bolts. Thread length is important to consider since having threads in the shear plane of a bolted connection on a bridge is not recommended. Therefore, having consistent dimensional standards for corrosion-resistant bolts would be beneficial.

Average dimensional values for the corrosion-resistant nuts are shown in Table 6. According to ASME B18.2.6, a heavy hex nut for a 7/8-in-diameter bolt must have a width across the flats of 1.394 to 1.438 in and a height of 0.833 to 0.885 in (ASME, 2010). When the values in Table 6 were compared to these requirements, all corrosion-resistant nuts met the nut dimensional specifications.

Table 8 shows the chemical compositions of each of the three corrosion-resistant bolt types, which were taken from the mill test reports from the bolt supplier. Chemistry results for the standard bolt types, including A325, A325 Type 3, and A490, are included in the table for comparison. The chemistry results reported in Table 8 are for the 7/8-in-diameter, 3.5-in-long bolts of each type. Chemistry results were also provided for the other bolt diameters and lengths but were nearly identical to those reported in the table.

Table 6. Average Dimensional Measurements for Corrosion-Resistant Nuts

Nut Type	Width Across Flats (in)	Height (in)
A194	1.400	0.854
2205	1.430	0.858
MCA	1.434	0.873

MCA = martensitic chromium alloy.

Table 7. Average Dimensional Measurements for Corrosion-Resistant Washers

Washer Type	Outer Diameter (in)	Inner Diameter (in)	Thickness (in)
303	2.250	0.944	0.105
2205	2.252	0.941	0.107
MCA	2.094	0.945	0.164

MCA = martensitic chromium alloy.
Red text indicates that the measurement did not meet the specification.

Table 8. Chemical Composition of Corrosion-Resistant Bolts Taken From Mill Test Reports

Bolt Type	Percentage by Weight											
	C	Mn	P	S	Si	Cu	Ni	Cr	Co	Mo	Sn	B
A325	0.38	0.83	0.008	0.022	0.23			0.35				
A325 Type 3	0.35	1.07	0.008	0.006	0.26	0.29	0.28	0.49		0.02	0.007	0.003
A193 B8-2	0.044	1.53	0.026	0.026	0.27	0.32	8.03	18.04	0.23	0.30		
2205	0.022	1.28	0.020	0.001	0.47	0.09	5.59	22.34	0.20	3.30	0.004	0.002
A490	0.36	0.91	0.006	0.024	0.24			1.01		0.16		
MCA-HC	0.12	0.62	0.009	0.014	0.40	0.15	0.09	9.87		0.01	0.008	

MCA = martensitic chromium alloy; HC is an industry designation.

Table 8 shows that there are clear differences between the chemistries of the corrosion-resistant and standard bolt types. The easiest difference to see is the relative amounts of chromium and nickel, both of which provide inherent corrosion resistance. The A193 B8-2 bolts have approximately 18% chromium (Cr) and 8% nickel (Ni); the 2205 bolts have approximately 22% chromium and 5.5% nickel; and the MCA bolts have slightly less than 10% chromium. These values can be compared to the compositions of the standard bolts, which contain approximately 1% chromium or less and no traceable amounts of nickel. Different amounts of chromium and nickel are present in each of the corrosion-resistant bolts, which affect structural properties, corrosion resistance, and cost.

Proof Loading of Bolts

Test data from the uniaxial proof loading of the bolts were converted into stress vs. strain curves. Stress was calculated using the net tensile area of the bolts. Typically, proof loading data for structural bolts would be presented in terms of force vs. elongation curves. However, stress vs. strain curves are presented here since stress and strain are independent of specimen size and thus are more reflective of a material's property. This was done since new types of bolting materials were being investigated. Individual stress vs. strain curves for each bolt tested are provided in Appendix A. A representative sample from each bolt type was selected to be used for comparison between the bolt types. Figure 16 shows these representative curves from each bolt plotted together. Stress vs. strain behavior for the two heats of MCA bolts appeared to be negligible, so both heats were included in the representative curve for the MCA bolt. Also included in the figure are the minimum stress value required for A325 bolts and the minimum and maximum stress values required for A490 bolts.

When the A193 B8-2 and 2205 bolt curves are compared to the A325 curve, it is clear that both corrosion-resistant bolts have lower strengths than the A325 bolts. However, both do meet the minimum stress required for ASTM F3125 Grade A325 bolts. The corrosion-resistant bolts also provide substantially more ductility than the A325 bolts. When the shapes of the curves are compared, the A193 B8-2 bolts demonstrate continuous yielding, which is illustrated by the more rounded curve with no well-defined yield stress. This type of behavior is common for stainless steels (Baddoo, 2013). The 2205 bolt curve shape does not demonstrate this continuous yielding behavior quite as distinctly as that of the A193 B8-2 bolts.

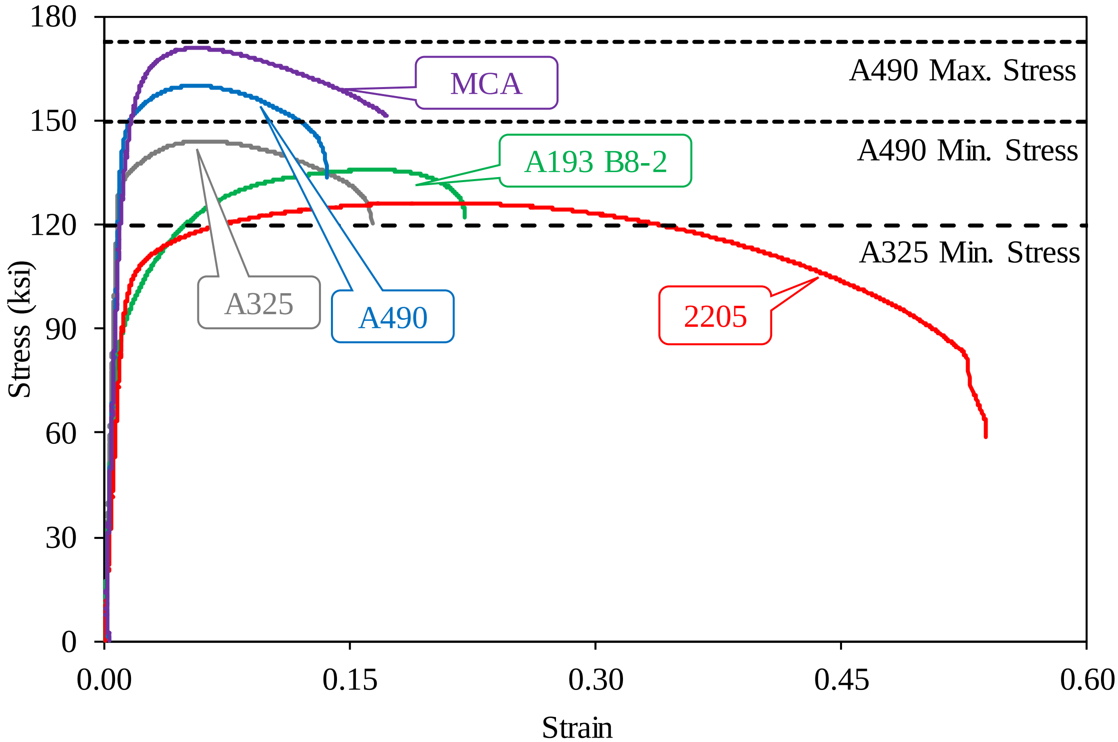


Figure 16. Proof Loading Stress vs. Strain Comparison of Bolts

Table 9 shows the tensile requirements for A325, A193 B8-2, and A490 bolts. Some of the values and headings of the requirements shown in the table were equivalently converted to allow for an easier comparison among the three specifications. Tensile strengths and proof load requirements in the A325 and A490 specifications are given in terms of load but are provided in Table 9 in terms of stress for an easier comparison to Figure 16. Stress values were obtained by dividing the required load values by the net tensile area of the bolt. All three specifications provide a minimum requirement for the yield strength of the bolts, but it is presented differently in the specifications. The A325 and A490 specifications state this requirement as an "Alternative Proof Load Yield Strength Method" measured using a 0.2% offset. The A193 B8-2 specification states this requirement as "Yield Strength" and also uses a 0.2% offset. Therefore, both are deemed equivalent and are listed together in the second column of Table 9.

Table 10 shows the average results from the proof loading tests for each bolt type. When the test results in Table 10 are compared to the requirements in Table 9, it is clear that the average yield strength of the A193 B8-2 bolts (82.3 ksi) meets the requirements of both A193 (80 ksi) and A325 (92 ksi).

Table 9. Proof Loading Requirements for A325, A193 B8-2, and A490 Bolts

Bolt Specification	Minimum Yield Strength Using 0.2% Offset (ksi)	Minimum Tensile Strength (ksi)	Maximum Tensile Strength (ksi)
ASTM F3125 Grade A325	92.0[a]	120	None
ASTM A193 Grade B8 Class 2	80	115	None
ASTM F3125 Grade A490	130.1[a]	150	173

[a] A325 and A490 specifications refer to this requirement as "Alternative Proof Load Yield Strength Method" using a 0.2% offset.

Table 10. Average Results From Proof Loading of Bolts

Bolt Type	Yield Strength, 0.2% Offset[a] (ksi)	Tensile Strength (ksi)
A325	131.2	144.3
A193 B8-2	82.3	136.1
2205	97.1	126.5
A490	145.7	160.3
MCA	134.9	170.8

MCA = martensitic chromium alloy.
[a] Gauge lengths used for yield strength measurements are shown in Figure 2.

The yield strength of the 2205 bolts (97.1 ksi) also exceeds the requirements of A325. The smaller yield strength of the A193 B8-2 bolts compared to the 2205 bolts is due to the continuous yielding behavior present in the A193 B8-2 bolts. The tensile strengths of both the A193 B8-2 (136.1 ksi) and 2205 (126.5 ksi) bolts exceed the minimum tensile strength of the A325 requirements (120 ksi).

Similar comparisons can be made for the MCA bolts. The yield and tensile strengths of the MCA bolts (134.9 ksi and 170.8 ksi, respectively) meet the requirements of A490 (130.1 and 150 ksi, respectively). The tensile strength of the MCA bolts is also less than the maximum allowed tensile strength of A490 bolts (173 ksi).

In summary, all of the corrosion-resistant bolts met the requirements of their comparable specification. That is, the A193 B8-2 and 2205 bolts met the yield and tensile requirements of A325 and the MCA bolts met the yield and tensile requirements of A490.

Shear Testing of Bolts

Shear load vs. actuator displacement data were used to compare the shear behavior of the bolts. Individual shear load vs. actuator displacement curves for each of the bolts tested are provided in Appendix A. Figure 17 shows a representative shear load vs. actuator displacement curve for each of the bolts tested. The plot also includes dashed lines representing the minimum shear loads for A325 and A490 bolts. These values were calculated using the nominal ultimate strength for each bolt type multiplied by the gross area of the bolt and a factor of 0.625 as indicated by the RCSC (RCSC, 2014). The gross area of the bolt was used because the shear plane was located on the shank portion of the bolts during testing. Similar to the proof loading tests, there were minimal differences between the shear loads for the two heats of the MCA bolts, so they were plotted together as one.

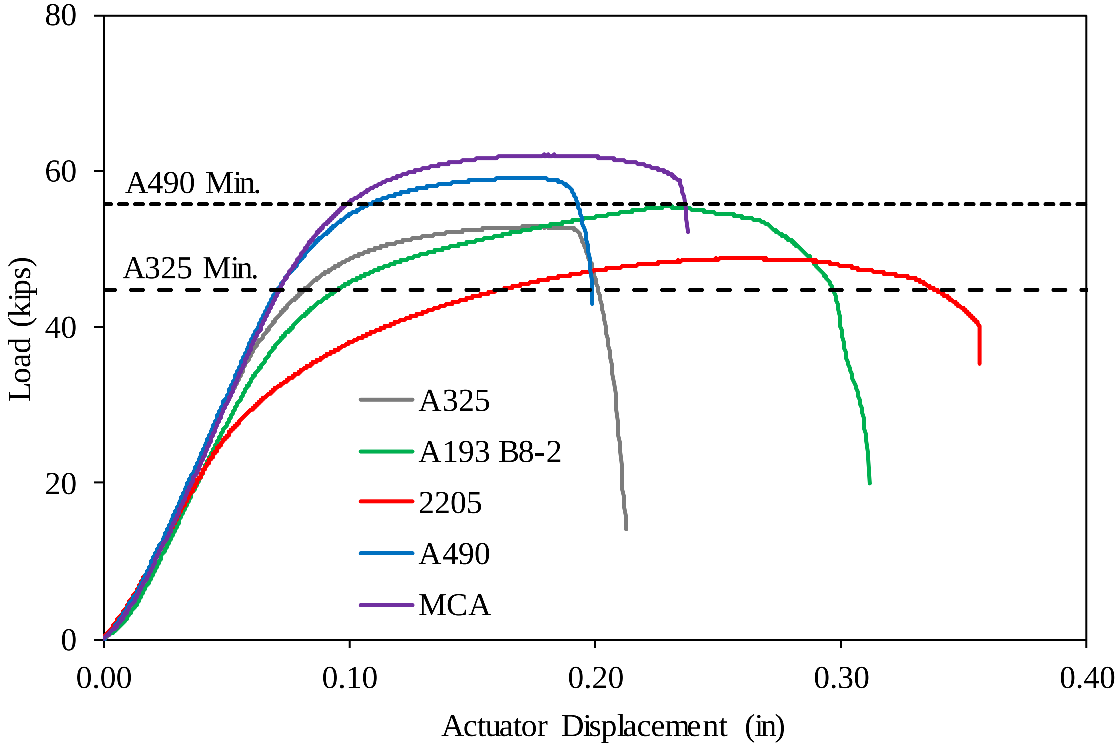


Figure 17. Shear Test Load vs. Actuator Displacement Comparison of Bolts. MCA = martensitic chromium alloy.

As expected, it is clear that the A193 B8-2 and 2205 bolts met the A325 shear load requirements and the MCA bolts met the A490 shear load requirements. Similar to the proof loading, the A193 B8-2 and the 2205 bolts had greater ductility than the other bolts tested. The MCA bolts also had greater shear ductility than the A490 bolts.

Table 11 shows the average maximum shear load for each bolt type reached during the single shear test. A325 and A490 bolts must reach a maximum shear load of at least 44.7 kip and 55.9 kip, respectively. From the table it is clear that the A193 B8-2 and 2205 bolts met the requirements for A325 bolts and the MCA bolts met the requirements for A490 bolts.

Table 11. Average Results From Shear Tests of Bolts

Bolt Type	Maximum Shear Load (kip)
A325	52.2
A193 B8-2	55.3
2205	48.5
A490	59.0
MCA	62.1

MCA = martensitic chromium alloy.

Wedge Testing of Bolts

Similar to the shear tests, wedge tests were evaluated using the load and actuator displacement measurements from the test frame. Individual load vs. actuator displacement curves for each of the bolts tested are provided in Appendix A. Figure 18 shows a representative wedge load vs. actuator displacement curve for each of the bolts tested. Dashed lines show the minimum loads required for A325 and A490 bolts, which are equal to their specified ultimate strength multiplied by the gross area of the bolt. These values were calculated using the net tensile area of the bolts. The MCA bolts showed negligible differences between the two different heats, so they were plotted as one.

Similar to the shear tests, the A193 B8-2 and 2205 bolts met the requirements for A325 bolts. The MCA bolts also met the A490 requirements. Similar to other tests, the A193 B8-2 and 2205 bolts displayed much more ductility than the other three types of bolts.

Table 12 shows the average maximum wedge test load for each bolt type. A325 and A490 bolts with a 7/8-in diameter must reach a maximum wedge load of at least 55.4 kip and 69.3 kip, respectively. As shown in the plot and the table, all bolts met their anticipated wedge load requirements.

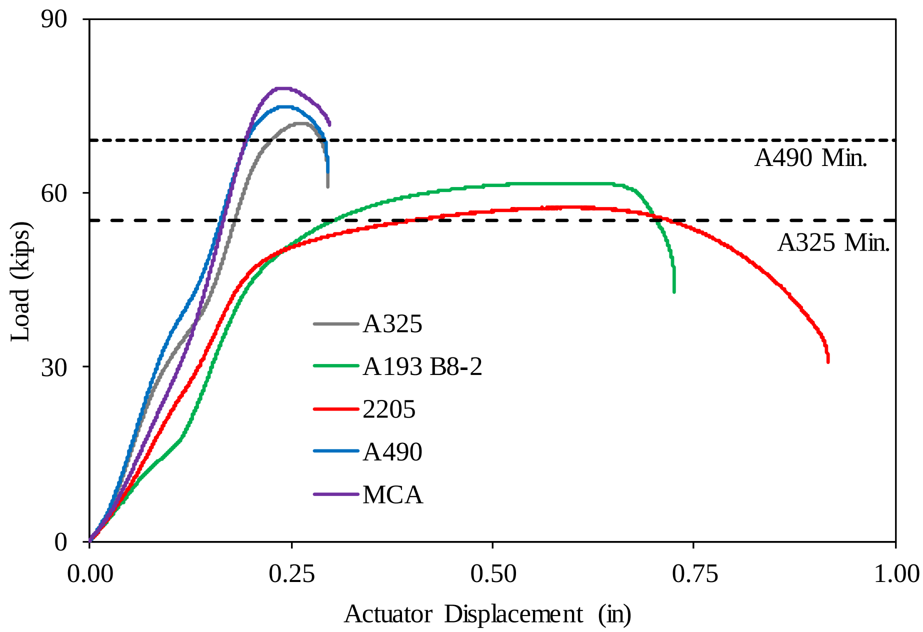


Figure 18. Wedge Test Load vs. Actuator Displacement Comparison of Bolts. MCA = martensitic chromium alloy.

Table 12. Average Results From Wedge Tests of Bolts

Bolt Type	Maximum Wedge Load (kip)
A325	72.4
A193 B8-2	61.9
2205	57.5
A490	74.6
MCA	77.6

MCA = martensitic chromium alloy.

Based on results from the tension, shear, and wedge tests, all of the corrosion-resistant bolts met their anticipated mechanical test requirements for either the A325 or A490 specification.

Proof Testing of Nuts

The proof testing was the first mechanical test conducted on each nut. As previously described, proof testing nuts requires only that nuts be loaded to a specified proof load without failure to be deemed acceptable. Table 13 shows the required proof load for the A563 and A194 nut specifications.

As shown in the table, the proof load requirement in A563 is much greater than in A194; therefore, all nuts tested (i.e., A563, A194, 2205, and MCA) were loaded to a proof load of 80.85 kip to match the A563 specification. All nuts were able to sustain that load without stripping or rupture and could be removed from the test mandrel by hand after the load was released. Thus, all nuts were deemed to have passed the proof test in accordance with the F606 specification and met the A563 requirements.

Table 13. Required Proof Load for Nuts

Nut Specification	Required Proof Load (kip)
A563 Grade DH (non-zinc-coated) heavy hex	80.85
A194 Grade 8 heavy hex	36.96

Cone Proof Testing of Nuts

The cone proof test was the second mechanical test conducted on each of the nuts. Similar to the proof test, it requires only that nuts be loaded to a specified load without failure to be deemed acceptable. Table 14 shows the required cone proof load for the A563 and A194 nut specifications.

Since the A194 specification does not have any requirements for the cone proof load, all of the corrosion-resistant nuts (i.e., A194, 2205, and MCA) were loaded to a cone proof load of 59.6 kip to meet the A563 specification. All of the nuts were able to sustain that load without stripping or rupture and thus were deemed to have passed the cone proof test in accordance with the F606 specification and met the A563 requirements.

Table 14. Required Cone Proof Load for Nuts

Nut Specification	Required Proof Load (kip)
A563 Grade DH (non-zinc-coated) heavy hex	59.6
A194 Grade 8 heavy hex	None

Hardness Testing of Fasteners

Hardness testing was the final test conducted in accordance with the F606 specification. The following sections describe the test results for the bolts, nuts, and washers.

Hardness Tests on Bolts

As described previously, hardness tests were conducted in various locations on each of the different bolts in accordance with ASTM F606. Individual hardness values for each bolt are provided in Appendix A. Average hardness values for all bolts are shown in Figure 19 for comparison. Error bars in the figure represent one standard deviation around the mean of the test results. The figure also shows the maximum HRC hardness limits according to the A325, A193, and A490 specifications for bolts with a diameter of less than 1 in and a length greater than twice the bolt diameter. These values are shown with horizontal dashed lines. Vertical dashed lines are also used to illustrate test locations on the bolt. These vertical lines refer to the bolt drawing directly underneath the hardness plot. Vertical lines are located at the top and bottom of the bolt head, bolt shank to thread interface, and end of threaded portion of the bolt.

From examination of Figure 19 it is clear that the hardness of the MCA bolts is similar to that of the A490 bolts and is of greater magnitude than that of the other bolt types. This makes sense given that both bolt types are manufactured of higher strength material. In general, the 2205 bolt appeared to have a lower hardness than the other bolt types. This is reasonable since the 2205 bolts had the lowest ultimate strength of all the bolts tested, and hardness is generally a good predictor of ultimate strength. The hardness of the A193 B8-2 bolts appeared to be similar to that of the other standard-type bolts tested, though it was less in the bolt head. All of the bolts met their anticipated or specified hardness limit. The hardness of the A193 B8-2 bolts met the A325 and A193 maximum hardness limits of 34 HRC and 35 HRC, respectively. The 2205 bolts also met the A325 hardness requirements, and the MCA bolts met the A490 limits of 38 HRC.

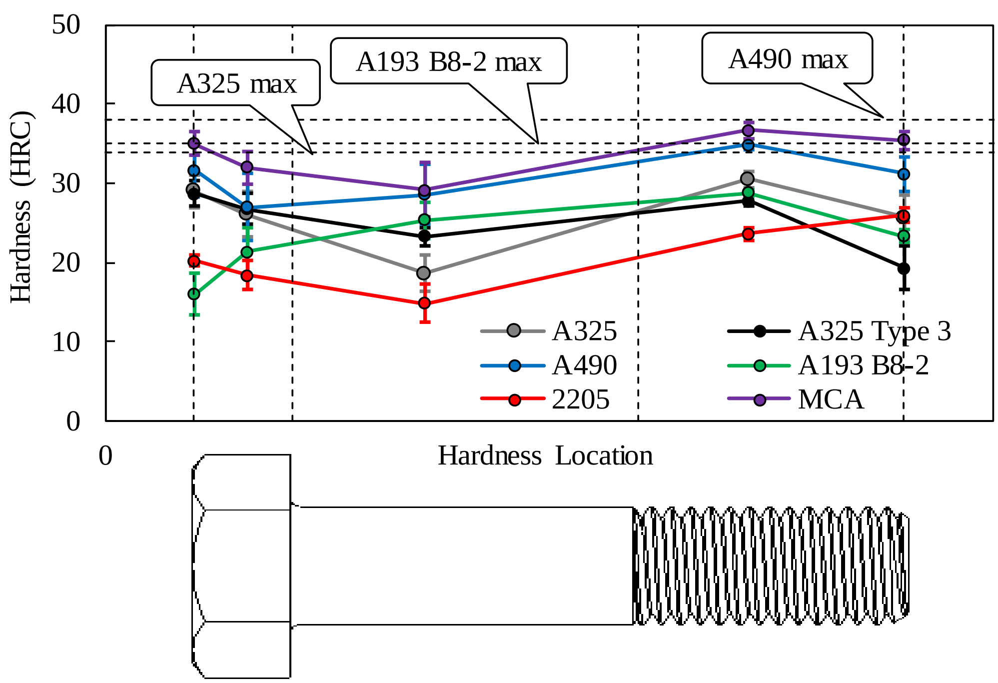


Figure 19. Average Hardness Test Results Comparison of Bolts. Error bars represent one standard deviation around the mean.

As discussed previously, Figure 19 shows how cold working can affect the hardness of a component, or in this case, a bolt. This is evident when the hardness of the unthreaded shank of the bolt is compared to the hardness of the threaded portion. For all of the bolt types, the hardness increased when traversing from the unthreaded shank to the threads. This is because threads are formed with some type of cold work process, typically by either forming or cutting, whereas minimum or no cold work is required to form the unthreaded shank. This increased hardness in the threaded portion of the bolts is likely due to this cold work process.

Hardness Tests on Nuts

As previously mentioned, hardness tests were conducted primarily at three locations on the nuts: on the wrench flats; on a bearing face between the major diameter of the thread and one corner; and on a section identical to the bearing face section located halfway through the nut. Results from the first and third of these locations are presented because these test locations are required in the F606 specification. Figure 20 shows a box and whisker plot for the hardness of each of the four types of nuts tested. The graph also includes horizontal dashed lines to show the minimum and maximum specified hardness limits for A563 and the maximum specified HRC hardness limit for A194 nuts.

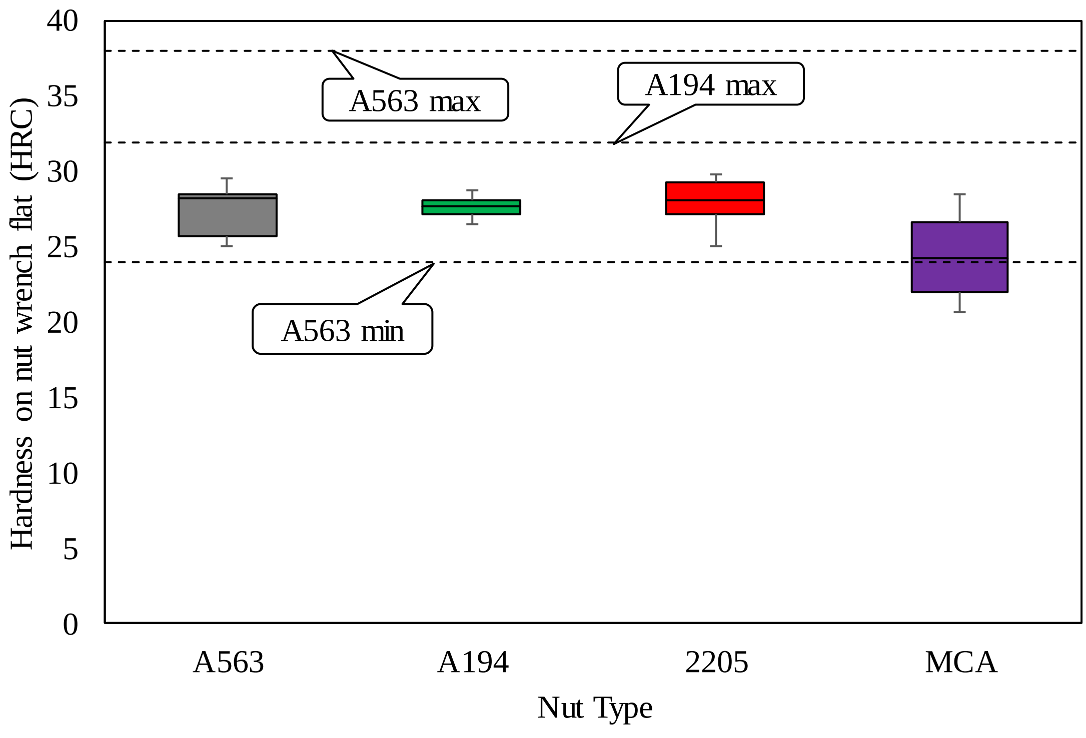


Figure 20. Box and Whisker Plot for Hardness on Wrench Flats for All Nuts

As shown in the figure, the average hardness on the wrench flats of the A194 and 2205 nuts is similar to that of the A563 nuts. The A194 and 2205 nuts had average wrench flat hardness values meeting the A563 specification (minimum and maximum of 24 HRC and 38 HRC, respectively). The average wrench flat hardness of the A194 nuts also met the A194 specification of a maximum of 32 HRC. The MCA nuts, on the other hand, had an average wrench flat hardness lower than that of the other three nut types tested. Although the average wrench flat hardness for the MCA nuts was approximately 24 HRC, two of the four measurements were less than the A563 minimum limit. Although the slightly lower wrench flat hardness is not expected to result in any detrimental effects to an MCA fastener assembly, they would be important to consider if VDOT were to develop specifications for using MCA fasteners in future applications.

A similar comparison was made between the measurements taken at the half nut height between the major diameter of the thread and one corner of each nut. Individual hardness test results for this location for each bolt type are provided in Appendix A. Figure 21 shows the average hardness test results at the half nut height for each of the nuts. Hardness tests were conducted in the Rockwell C scale. The figure includes horizontal dashed lines to show the minimum and maximum specified hardness limits for A563 and the maximum specified hardness limit for A194. Vertical dashed lines are used to indicate the location of the test on the nut. A drawing of the nut with test locations is shown below the plot of hardness test results.

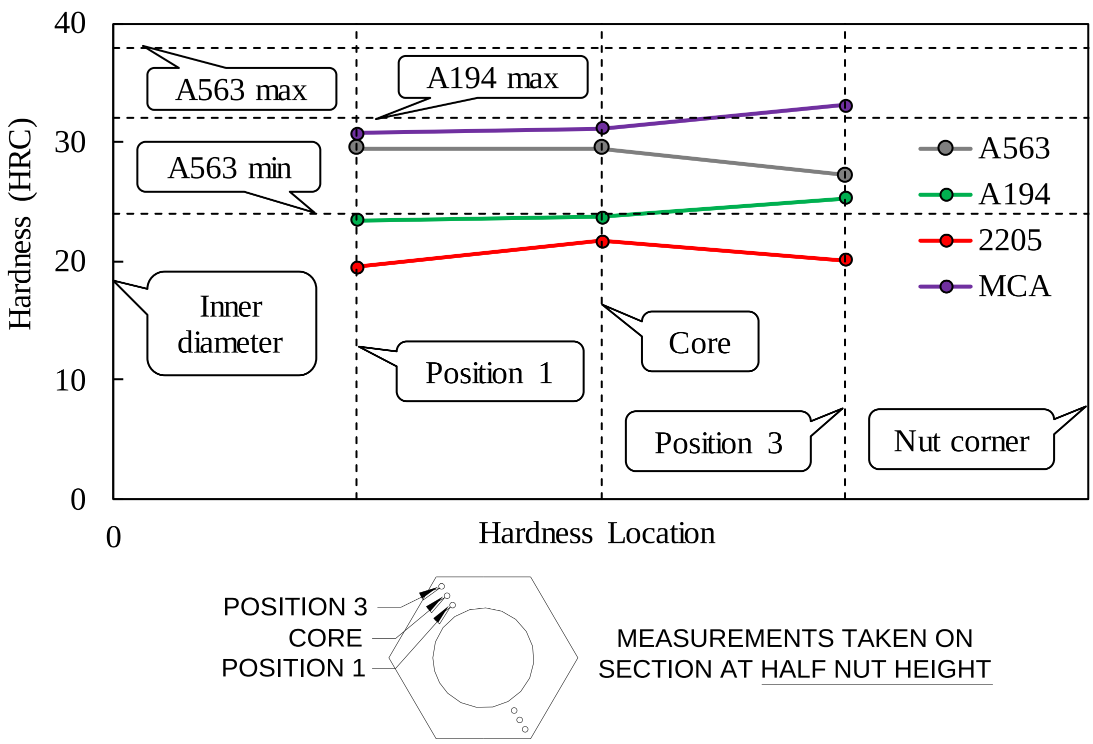


Figure 21. Average Hardness at Half Nut Height for All Nuts

As is seen in the figure, the A194 and 2205 nuts had smaller hardness values at the half nut height compared to those of the other nuts tested. Similar to previous test results, this was not surprising since these materials also had smaller ultimate strength values for the proof loading of bolts. The A194 and 2205 tests all showed hardness values below the required minimum of 24 HRC for the A563 requirements, although the A194 nuts did meet the maximum 32 HRC requirements for the A194 specification. These would also be important results to consider if VDOT were to develop specifications for using A194 or 2205 stainless steel nuts. The MCA nuts, on the other hand, had hardness values that met the requirements of A563. These values were in line with expected results based on the tensile strength and hardness results for the MCA bolts. However, the lower hardness values for the MCA nut wrench flats do seem unusual.

Hardness Tests on Washers

As described in the "Methods" section, hardness tests were conducted on the surface of the washers and at a minimum depth of 0.015 in into the core of the washer. Both test values are discussed since both are required by the F606 specification for through-hardened washers, as were used in this study. Individual hardness tests results for the washer surface are provided in Appendix A. Hardness tests were conducted using the HRC scale for all of the washers except for the 303 washers, which were conducted using the HRB scale. The HRB scale was used for the 303 washers because their hardness values were too small to be measured accurately in the HRC scale.

Figure 22 shows a box and whisker plot for the hardness values for the F436, 2205, and MCA washers at the surface location. Hardness values for the 303 washers were not included in this figure because they were too small to be converted from HRB to HRC based on the hardness conversions for austenitic stainless steel in ASTM E140 (ASTM, 2012). Dashed horizontal lines show the minimum and maximum hardness values of 38 and 45 HRC, respectively, for the F436 specification.

As shown in the figure, hardness values for the 2205 washers were well below the minimum hardness specified in the F436 specification. The average hardness value for the MCA washers was only slightly below the minimum F436 value, but approximately one-half of the individual hardness test results were below this threshold. Similar trends were noted for the hardness measurements at the core location of the washers. Hardness data at the core of these washers are provided in Appendix A. In order to include the 303 washers in this comparison, all HRC values were converted to HRB values. The average hardness results in the HRB scale for all washers are shown in Figure 23. A box and whisker plot was not used in this case because some hardness values were converted to another scale and others were not.

This comparison shows that the 303 washers had a hardness of approximately 75% that of the F436 washers in the HRB scale. This was consistent for the surface and core hardness measurements. This percentage may seem somewhat misleading since the values for the 303 washers could not be converted to the HRC scale. In any case, the important finding is that the 303 washers used in this study were significantly softer than the F436 and other corrosion-resistant washers used in the study.

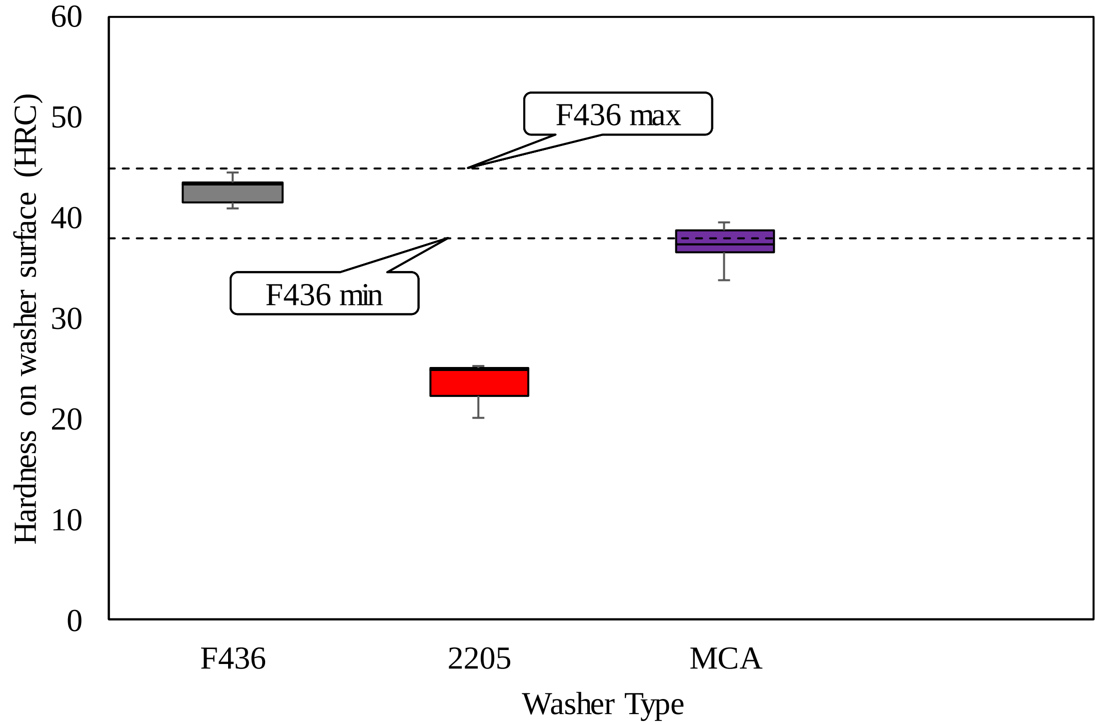


Figure 22. Box and Whisker Plot for Hardness Measured at the Surface Location for F436, 2205, and MCA Washers. MCA = martensitic chromium alloy.

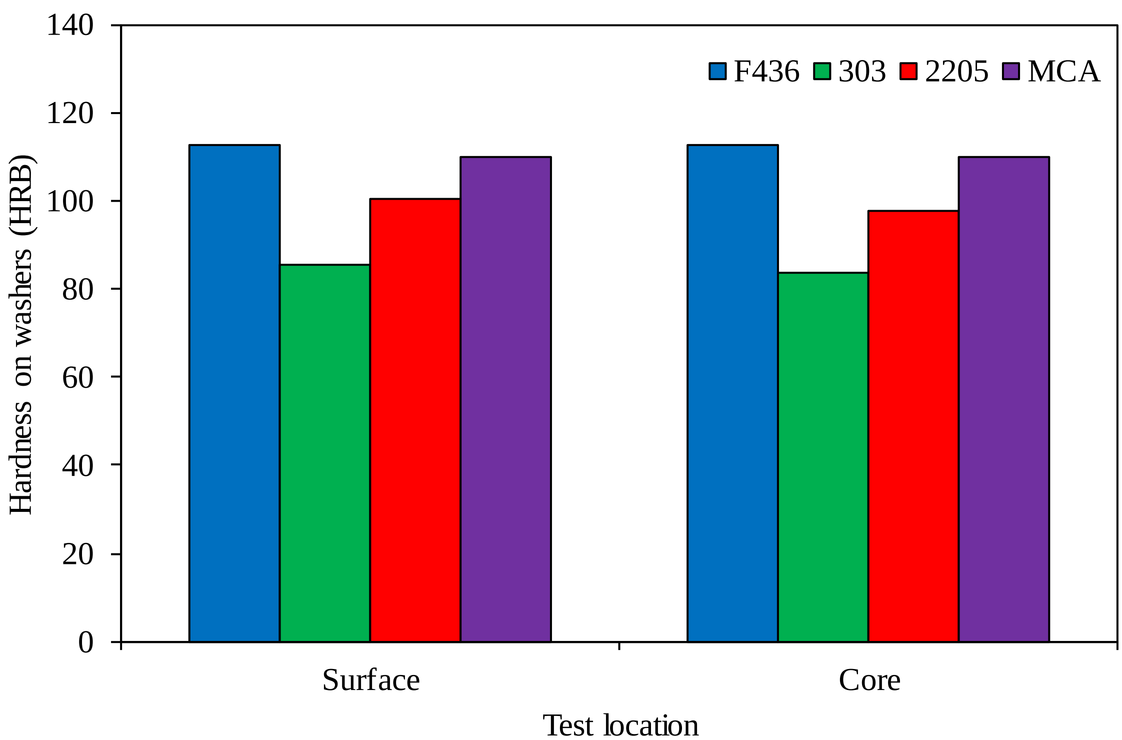


Figure 23. Bar Chart Showing Average Hardness Test Results for the Surface and Core Locations for All Washers. Hardness values for the F436, 2205, and MCA washers were converted from the Rockwell C scale to the Rockwell B scale. MCA = martensitic chromium alloy.

Since the hardness values for the 303 washers were much lower than for the rest of the washers, they were compared to the hardness of the 303 washers from the Route 340 Bridge. In both datasets, hardness measurements were taken at the washer surface. Results from this comparison are shown in the box and whisker plot in Figure 24. From the figure it is clear that the 303 washers used in this study were, on average, softer than those from the Route 340 Bridge.

The low hardness values for the 303 and 2205 washers used in this study comprise an important finding that could have implications for structural bolted connections using corrosion-resistant fasteners. In a bolted connection, the washer is typically located between the connection ply and the nut. The washer must be hard enough to resist deformation during nut rotation during bolt installation. If the washer is too soft, it can cause galling between the nut and washer. This can lead to difficulty in tightening and an increase in torque in the bolt, neither of which is desirable. To alleviate this concern, hardening of the washers is likely necessary. For example, unlike traditional washers that might be heat treated, the 303 austenitic stainless steel washers might have improved hardness through stain hardening or cold working the material during the fabrication process. It is important to consider whether corrosion-resistant washers should be specified not only by alloy type but also by a specified minimum hardness. The effect of the hardness of the washers during bolt installation was examined during the torqued tension tests.

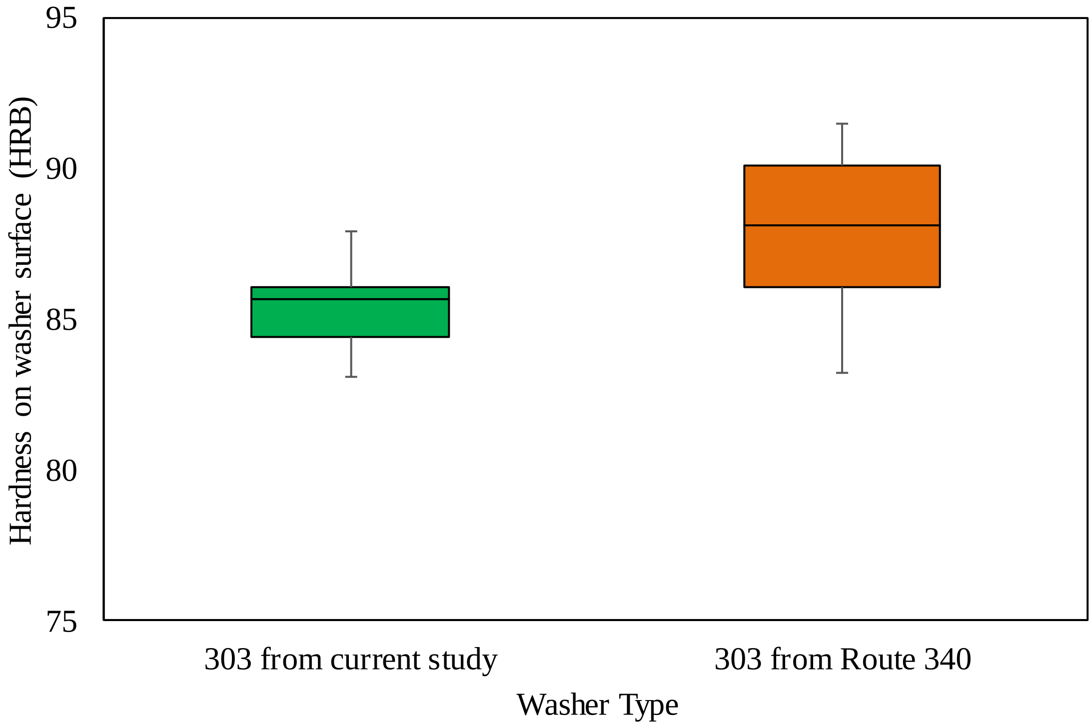


Figure 24. Box and Whisker Plot of Hardness Results From 303 Washers in the Current Study and 303 Washers Used in the Route 340 Bridge

Energy Dispersive Spectroscopy of Lubricants

The EDS results were used to identify selected elements in each lubricant included in the study. Figure 25 shows a bar chart with the chemical composition of each of the five lubricants. The bar chart includes 18 elements that were above detectable limits in at least one of the lubricants. As can be seen in the figure, carbon (C) made up a significant portion of the EDS results and therefore disproportionately skewed the vertical scale of the figure. This is not surprising since lubricants generally contain organic compounds such as hydrocarbons. However, for this work, the disproportionately large percentage of carbon relative to the other elements made it difficult to identify distinguishable elements from each lubricant.

To identify elements of interest from each lubricant better, a second bar chart with chemical compositions of each lubricants was created. Figure 26 shows this bar chart, which is similar to Figure 25 but with only selected elements included. When compared to Figure 25, the following elements were removed to produce Figure 26: carbon (C), sodium (Na), phosphorus (P), potassium (K), calcium (Ca), titanium (Ti), and manganese (Mn). Carbon was removed from the figure for the previously mentioned reason: it skewed the required vertical scale of the bar chart such that it was difficult to see differences in the elements of smaller amounts. However, for carbon it was noted that Lubricant 4 had the highest peak, followed by Lubricant 1, which was then closely followed by Lubricant 2, with Lubricants 3 and 5 having the shortest but similar carbon peaks. The other elements were removed from the figure because each of the lubricants contained less than 0.23% of each of the elements and thus were not distinguishable among the lubricant types.

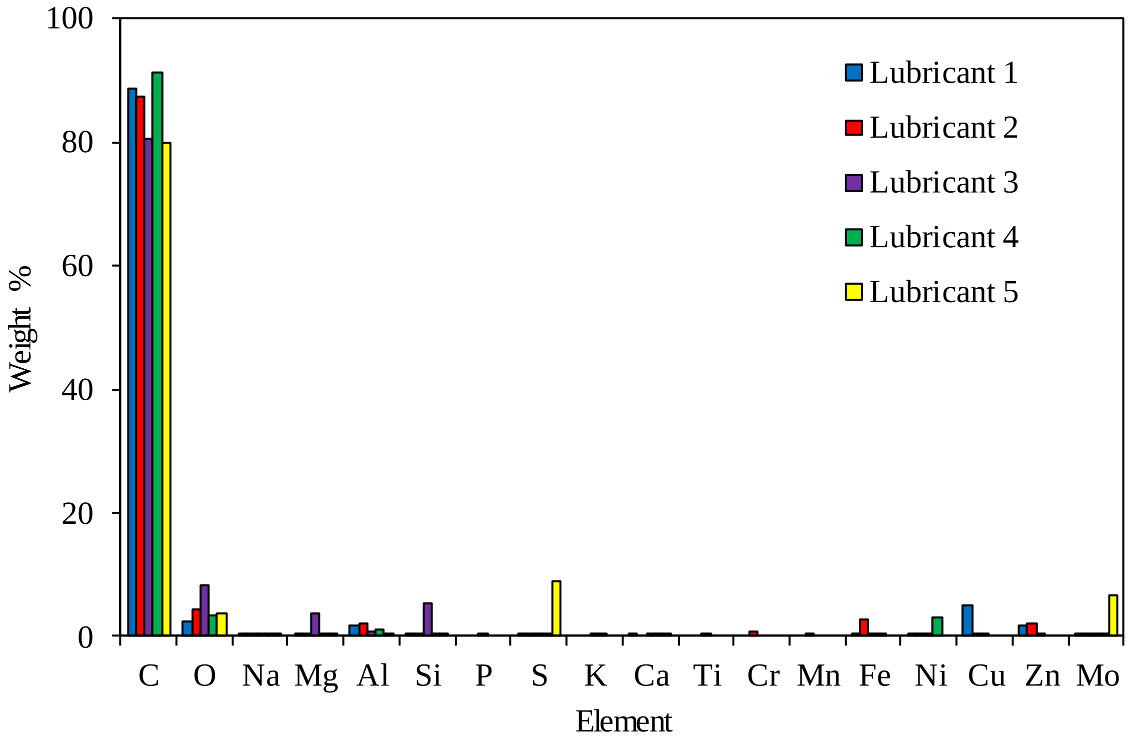


Figure 25. Comparison of Elemental Composition Among Lubricants

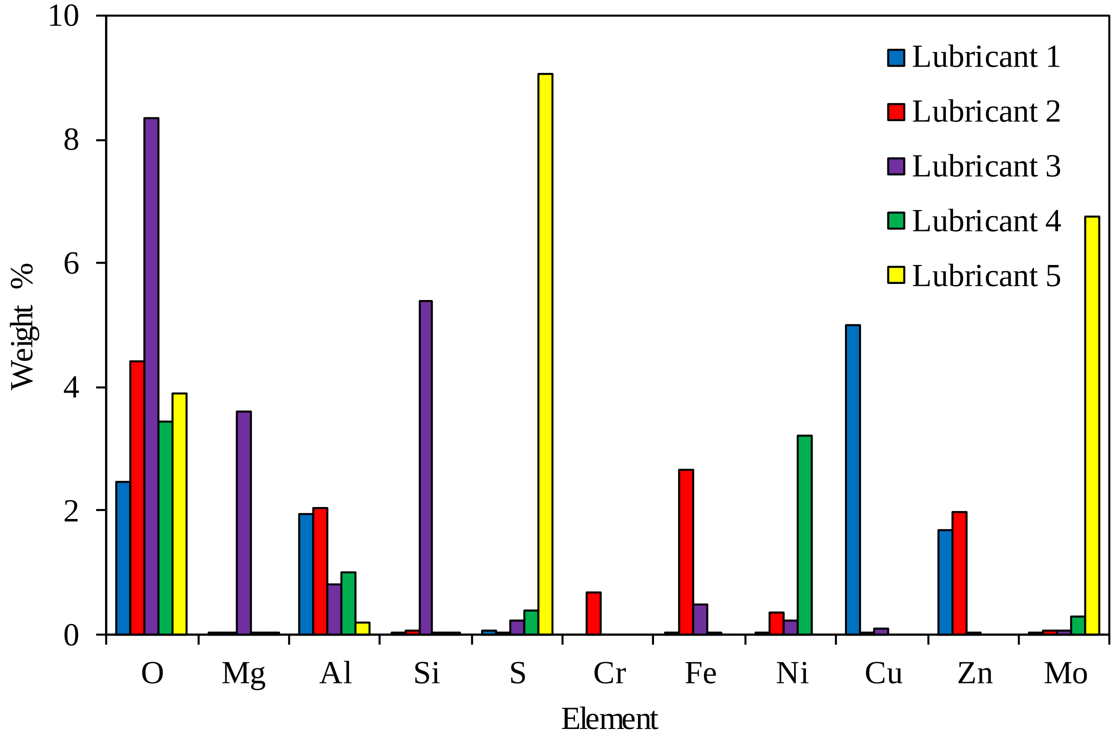


Figure 26. Comparison of Selected Elemental Composition Among Lubricants

Figure 26 shows that the elemental makeup of each lubricant was different. This figure was used to determine which elements could be used to distinguish among lubricants; distinguishable lubricants were defined as those having a clearly larger percentage in one lubricant compared to other lubricants. These distinguishable elements for each lubricant are listed in Table 15.

Table 15. Distinguishable Chemical Elements in Lubricants

Lubricant	Distinguishable Chemical Element(s)
Lubricant 1	Copper (Cu)
Lubricant 2	Iron (Fe), chromium (Cr), and zinc (Zn)
Lubricant 3	Oxygen (O), magnesium (Mg), and silicon (Si)
Lubricant 4	Nickel (Ni)
Lubricant 5	Sulfur (S) and molybdenum (Mo)

Friction Testing of Lubricants

As mentioned in the "Methods" section, friction tests were conducted until it was clear that the plot of bolt force vs. nut rotation had become non-linear. Figure 27 provides an example of this behavior by showing a plot of bolt tension vs. nut rotation angle for friction tests on A325 bolts with Lubricant 1.

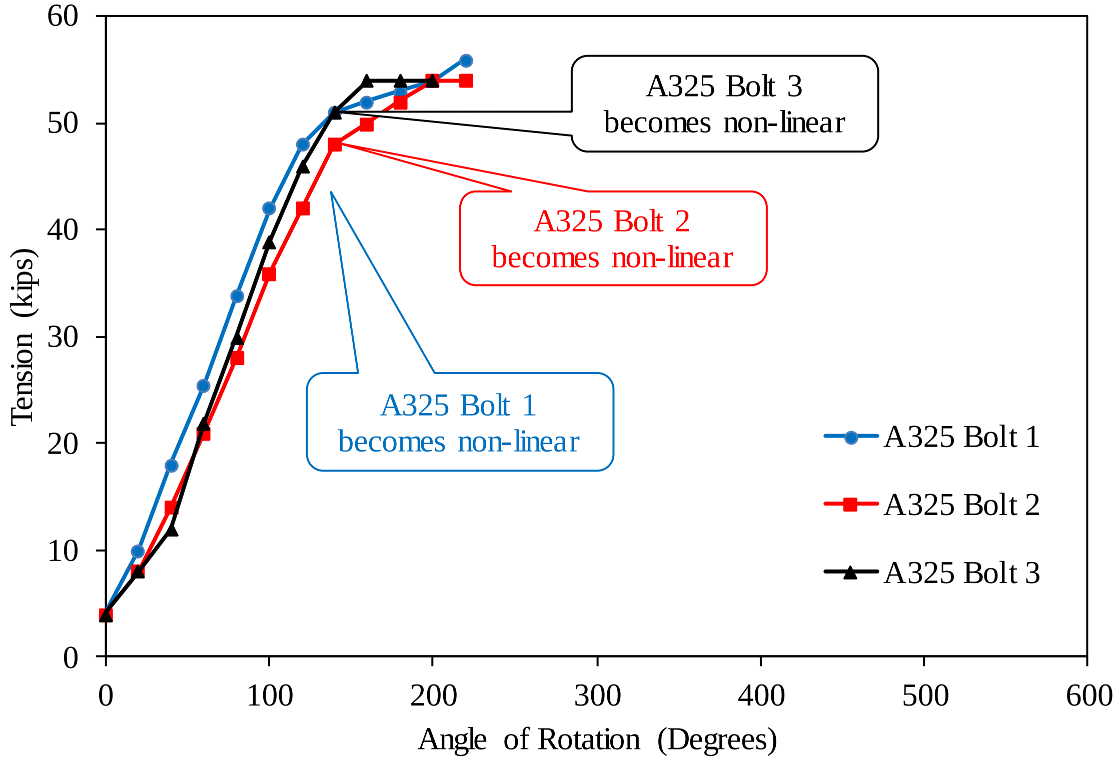


Figure 27. Friction Testing Plot of Bolt Tension vs. Nut Angle of Rotation for A325 Bolts With Lubricant 1

The figure uses callout bubbles to indicate the point at which the curve for each of the three bolts became non-linear. The transition from linear to non-linear behavior was selected to correspond with the curve having either its slope become distinctly shallower or its shape becoming distinctly more round. Not all A325 bolts with Lubricant 1 reached this point at the same nut rotation. Bolt 1 reached non-linear behavior at 120 degrees, and Bolts 2 and 3 reached it at 140 degrees. This process was used to determine the transition point to non-linear behavior for each of the bolt and lubricant pairings. Only data obtained up to and including this transition point were included in friction test data analysis.

Once the data for the linear portions of the bolt force vs. nut rotation plots had been established for each bolt and lubricant combination, plots of bolt torque vs. bolt tension were created. For the A325 and A490 bolts, these plots contained results with Lubricant 1, whereas plots for the corrosion-resistant bolts contained results from all of the lubricants tested to determine each lubricant's effectiveness. Figure 28 shows an example of a bolt torque vs. bolt tension plot for A325 bolts with Lubricant 1.

In the figure it is clear that the torque vs. tension behavior for the three bolts tested is similar, which was expected since all three used Lubricant 1. The slope of these lines is equal to torque divided by tension, which is the same as the k-factor, defined in Equation 1, not including the unit conversions. That means that the slope of these lines is proportional to the k-factor and thus can be used for comparing the effectiveness of different lubricants. A shallower slope indicates a more effective lubricant since torque is minimized while tension is maximized. A plot similar to Figure 28 for A490 bolts with Lubricant 1 is shown in Appendix A.

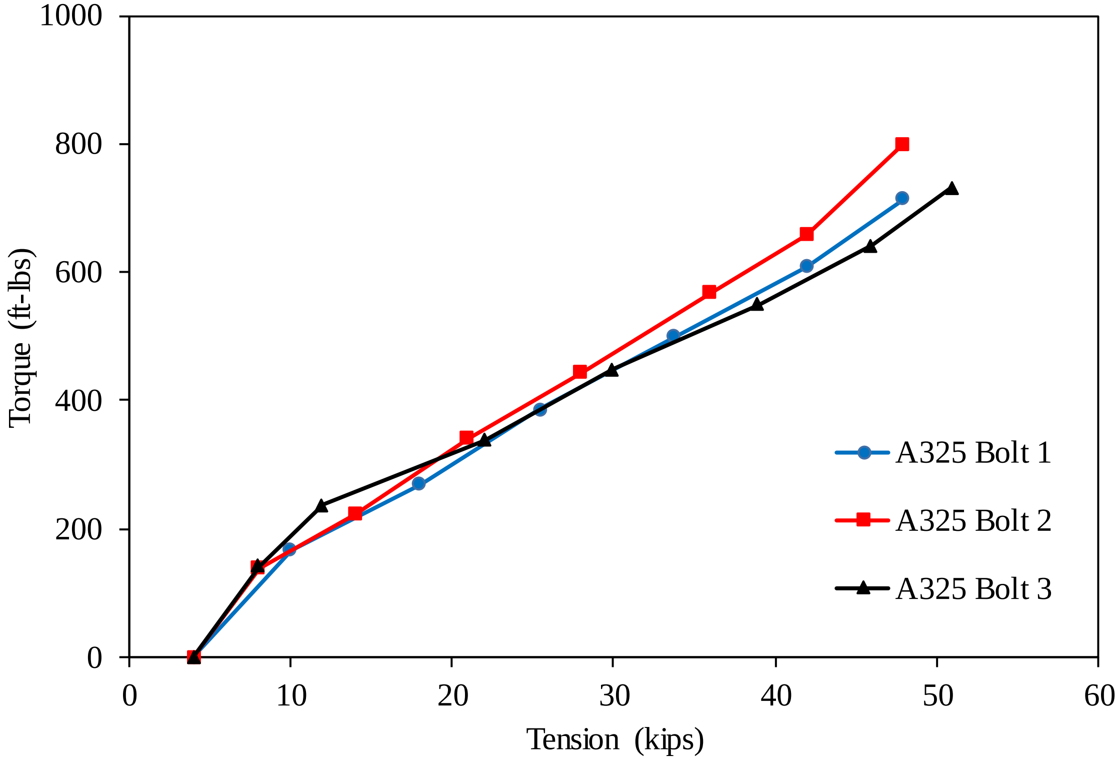


Figure 28. Friction Testing Plot of Bolt Torque vs. Bolt Tension for A325 Bolts With Lubricant 1

Figure 29 shows a similar plot for the A193 B8-2 bolts tested using all lubricants. Lines for each lubricant are differentiated by color. From the figure it is clear that Lubricant 5 was the most effective. The results of the three bolt tests with Lubricant 5 appear to have the shallowest slope of nearly all of the test results. This also means that for a given tension value, Lubricant 5 produced the smallest torque value, which is beneficial during bolt installation. The second most effective lubricant appeared to be Lubricant 1 with the second shallowest slope. This is interesting because Lubricant 1 was used as a control lubricant since it is intended for carbon steel fasteners and is not specifically made for stainless steel fasteners like the lubricants. Lubricants 2, 3, and 4 appear have similar effectiveness when used with A193 B8-2 bolts.

Figure 30 shows the bolt torque vs. tension test results for 2205 bolts with all lubricants. Similar to the previous figure, Lubricant 5 appears to be the most effective of the five lubricants tested. This seems even clearer for the 2205 bolts than for the A193 B8-2 bolts. Lubricant 4 appears to be the least effective lubricant, with two of its curves having a greater slope than the rest. The effectiveness of Lubricants 1, 2, and 3 appears to be similar to that of the 2205 bolts, with the slopes of these curves being similar.

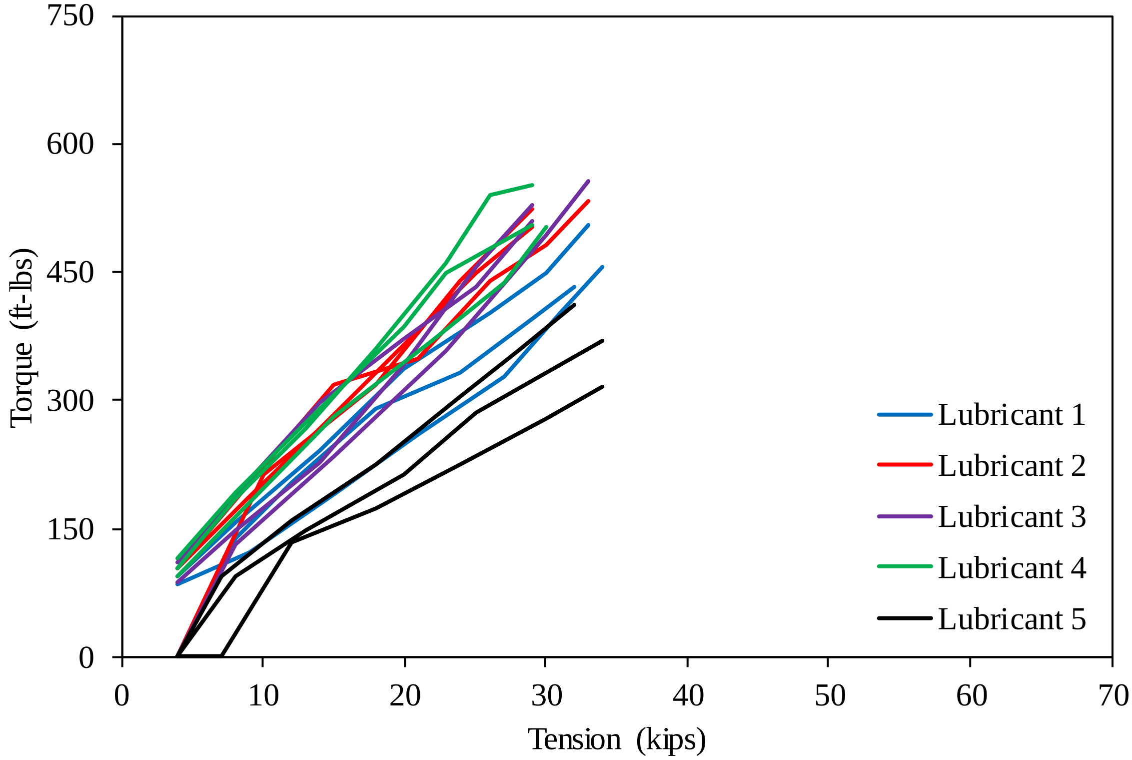


Figure 29. Friction Testing Plot of Bolt Torque vs. Bolt Tension for A193 B8-2 Bolts With All Lubricants

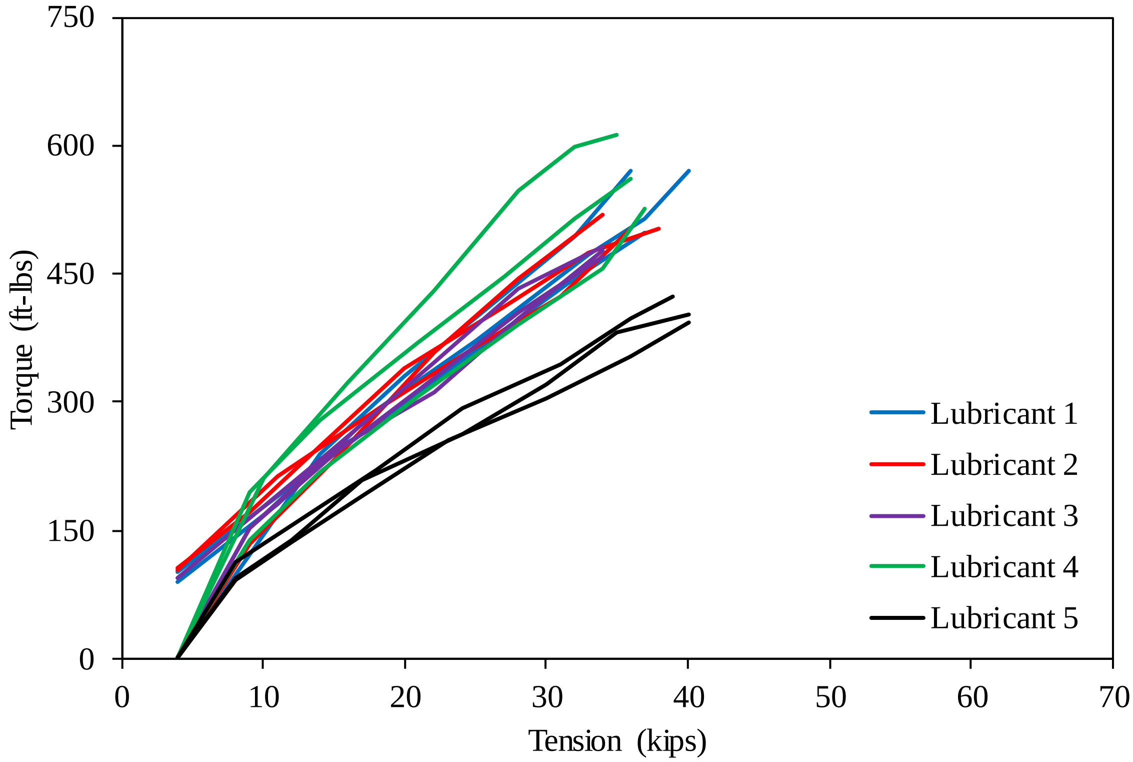


Figure 30. Friction Testing Plot of Bolt Torque vs. Bolt Tension for 2205 Bolts With All Lubricants

Figure 31 shows the torque vs. tension plot for the MCA bolts tested with all lubricants. Similar to the A193 B8-2 and 2205 bolts, Lubricant 5 is clearly the most effective lubricant for the MCA bolts, with its curves having much shallower slopes than the rest. Curves for the other four lubricants have similar slopes, indicating they have similar effectiveness for the MCA bolts.

Average k-factors were determined using Equation 1 and a best fit linear regression of the torque vs. tension plots for each bolt type and lubricant pairing during the friction tests. Average k-factor results are shown numerically in Table 16 and graphically in the bar graph in Figure 32. Included in the figure are error bars for each k-factor, representing one standard deviation around the mean, and a horizontal dashed line to indicate the maximum k-factor of 0.25 for typical bolted connections.

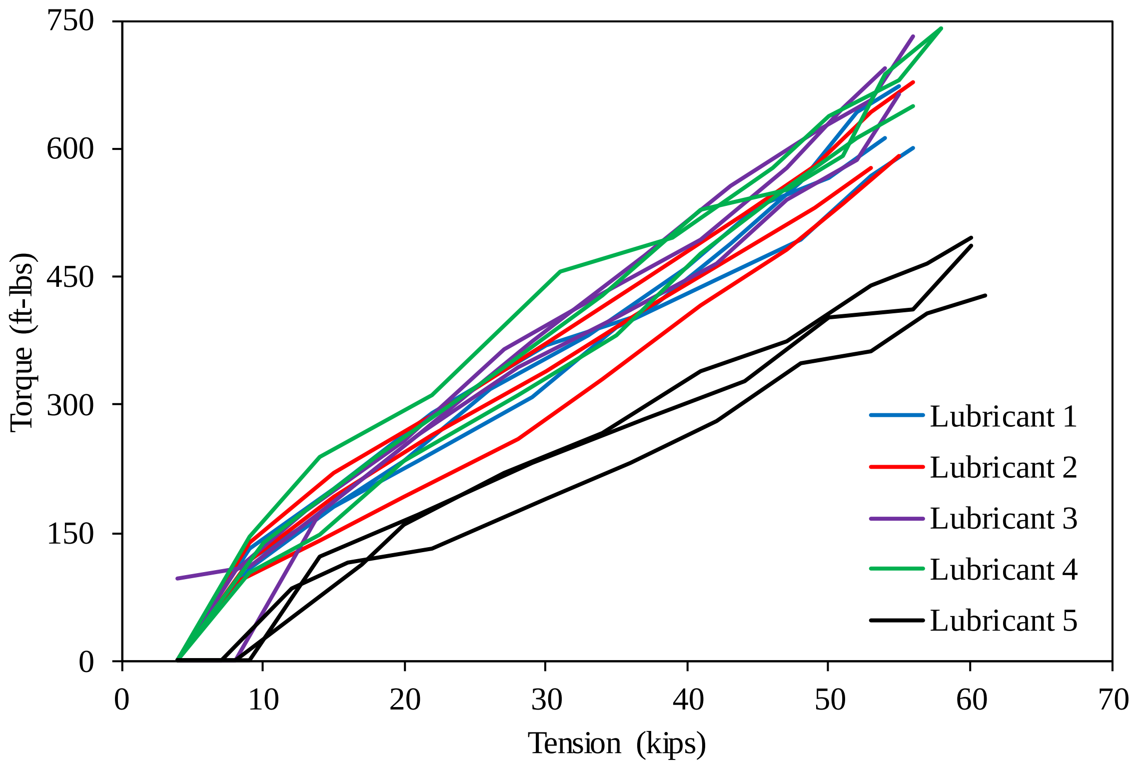


Figure 31. Friction Testing Plot of Bolt Torque vs. Bolt Tension for MCA Bolts With All Lubricants. MCA = martensitic chromium alloy.

Table 16. Friction Testing Average K-factors for Each Bolt and Lubricant Combination

Bolt Type	Lubricant 1	Lubricant 2	Lubricant 3	Lubricant 4	Lubricant 5
A325	0.21	N/A	N/A	N/A	N/A
A193 B8-2	0.21	0.24	0.25	0.23	0.16
2205	0.20	0.18	0.19	0.23	0.15
A490	0.18	N/A	N/A	N/A	N/A
MCA	0.15	0.15	0.17	0.17	0.11

MCA = martensitic chromium alloy.

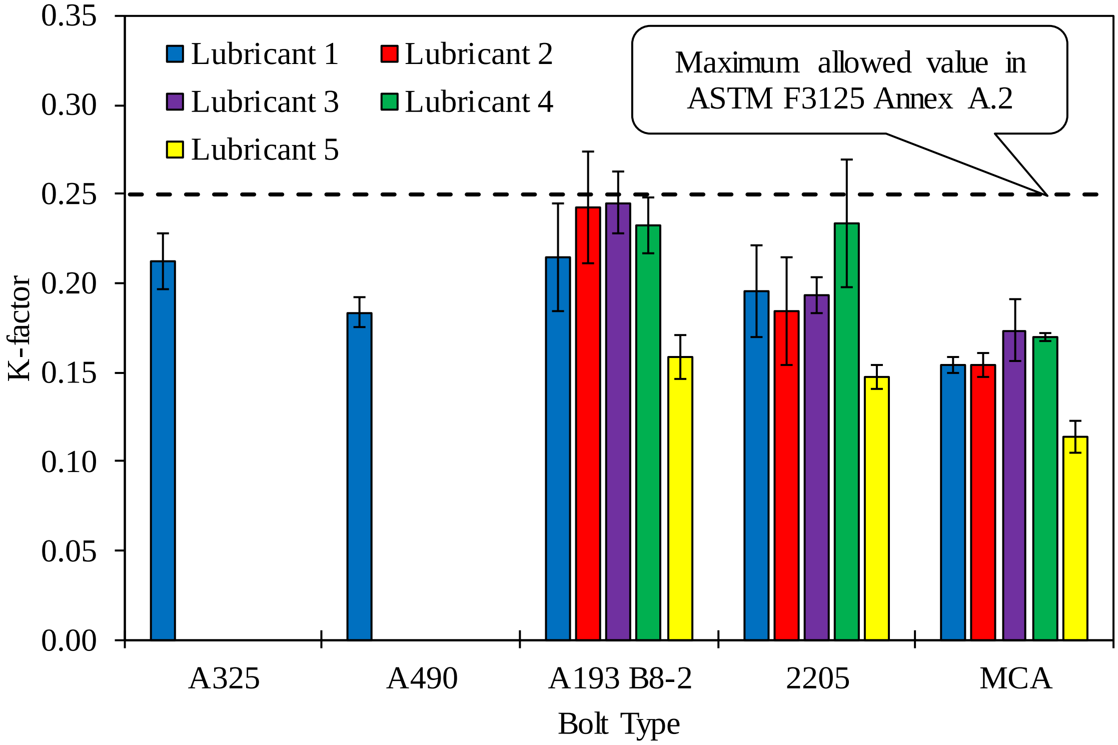


Figure 32. Friction Testing Bar Graph Showing K-factor for Each Bolt Type and Lubricant Combination. Error bars represent one standard deviation around the mean. MCA = martensitic chromium alloy.

The difference in k-factor between bolt type and lubricant combinations is most evidently seen in Figure 32. Trends are similar to those previously described for Figure 29, Figure 30, and Figure 31. Lubricant 5 is clearly the most effective lubricant across all three of the corrosion-resistant fasteners tested. It has an average k-factor of approximately 0.16 or less in all three corrosion-resistant fasteners, which is smaller than the assumed value of 0.2 for bolted connections. The second most effective lubricant for the corrosion-resistant bolts varied between Lubricant 1 and Lubricant 2. As previously mentioned, this is interesting because Lubricant 1 is not specifically designed for stainless steel fasteners, as were the other lubricants.

Another interesting trend shown in Figure 32 comprises the relative k-factors between bolt types. The average k-factors for the MCA bolts used in this study were consistently less than for the other corrosion-resistant bolts. When the k-factors of the A193 B8-2 and 2205 bolts using the same lubricant were compared, the average k-factors for the 2205 bolts were less than those for the A193 B8-2 bolts for all lubricants except Lubricant 4, which were roughly the same between the two bolt types. It is reasonable that the duplex stainless steel 2205 bolts used in this study would have lower k-factors compared to the austenitic stainless steel A193 B8-2 bolts used in this study because austenitic stainless steel fasteners are typically more prone to galling. To determine if the relative k-factors were a function of the materials only, an investigation of the threads of each fastener type would need to be examined. Unfortunately, this was outside the scope of this study.

Based on the results of the friction testing, Lubricant 2 and Lubricant 5 were selected to be used for the corrosion-resistant bolts in the torqued tension tests. Lubricant 5 was selected because it was clearly the most effective lubricant for all of the corrosion-resistant bolts. Lubricant 2 was the second most effective lubricant for two of the three corrosion-resistant bolt types. It was also used for the stainless steel fasteners on the Route 340 Bridge, so additional testing to evaluate its performance was desired.

Results from the EDS analysis and friction tests on the lubricants can be synthesized to make some observations about how the chemical composition affects lubricant performance. There was not a strong trend between the carbon content and performance of the lubricant. Lubricant 5, which had the smallest carbon EDS peak, performed best based on the friction tests, but Lubricant 3, which had a similar carbon content, was outperformed at times by Lubricants 1 and 2. Further, Lubricant 3 showed the worst average performance during the testing of the A193 B8-2 and MCA bolts.

As discussed previously, the chemical elements that distinguished Lubricant 5 from the others were molybdenum and sulfur. Therefore, VDOT should consider developing specifications for lubricants for stainless steel fasteners based on a particular solid content of molybdenum disulfide, which is the chemical compound composed of both elements. To support this effort, additional sampling and chemical analysis would need to be performed to help develop a threshold content.

Torqued Tension Testing of Fasteners

Once the lubricants for the corrosion-resistant fasteners had been selected using the friction test data, a test matrix for the torqued tension tests was developed. Table 17 shows the number of torqued tension tests conducted on three bolt sizes: 3/4-in-diameter x 2-in-long; 7/8-in-diameter x 3.5-in-long; and 7/8-in-diameter x 5.0-in-long bolts. Different bolt sizes were tested to determine the installation behavior for each; the RCSC specification provides different installation parameters for different bolt sizes, dependent on bolt diameter and length (RCSC, 2014).

Table 17. Torqued Tension Test Matrix

		No. of Torqued Tension Tests		
Bolt Size	**Bolt Type**	**Lubricant 1**	**Lubricant 2**	**Lubricant 5**
3/4-in diameter x 2 in long	A325	3	0	0
	A193 B8-2	0	2	2
	2205	0	3	3
	A490	0	0	0
	MCA	0	3 HC and 3 WF	3 HC and 3 WF
7/8-in diameter x 3.5 in long	A325	3	0	0
	A193 B8-2	0	5	3
	2205	0	3	3
	A490	3	0	0
	MCA	0	2 HC and 2 WF	2 HC and 2 WF
7/8-in diameter x 5.0 in long	A325	3	0	0
	A193 B8-2	0	4	3
	2205	0	3	3
	A490	3	0	0
	MCA	0	2 HC and 2 WF	2 HC and 2 WF

MCA = martensitic chromium alloy.

In general, three tests were planned for each bolt and lubricant pairing with a few exceptions, all of which are noted in Table 17. Only two tests were conducted on the 3/4-in x 2-in-long A193 B8-2 bolts because of limited availability. For the 3/4-in x 2-in-diameter MCA bolts, three tests were conducted on each heat. Four 7/8-in-diameter MCA bolts of each length were tested, including two bolts from the HC heat and two from the WF heat. Additional tests were also conducted on the 7/8-in-diameter A193 B8-2 bolts paired with Lubricant 2. This was because the original three tests did not perform as expected, as described in the “Results and Discussion” section, and additional tests were desired.

Additional K-factor Results

Similar to the friction tests, the linear portions of the torqued tension test data were used to develop additional k-factor data for the bolt and lubricant pairings. There was not a noticeable difference in k-factor performance with regard to bolt diameter or length, so k-factor data are presented with no distinction made to bolt size tested, only bolt and lubricant type. The k-factor test data from the torqued tension tests are shown in Table 18 and in a bar graph in Figure 33. The bar graph is similar to the one presented for the friction tests.

Trends seen in Figure 33 are similar to those from the friction tests. Lubricant 5 appears more effective in reducing friction compared to Lubricant 2 for all three of the corrosion-resistant bolts. The MCA bolts also appear to have smaller k-factors with either type of lubricant than those of the other two corrosion-resistant bolts. They are followed by the 2205 bolts and then the A193 B8-2 bolts when ranked in order of ascending k-factors. When the k-factor results from the torqued tension tests in Figure 33 are compared to those from the friction tests in Figure 32, there appears to be greater variability in those from the torqued tension tests, noted by the larger error bars in Figure 33. This is likely a function of the reduced number of samples used in constructing Figure 33 compared to Figure 32. However, the trends noted appear uniform between the two datasets.

Table 18. Torqued Tension Testing Average K-factors for Each Bolt and Lubricant Combination

Bolt Type	Lubricant 1	Lubricant 2	Lubricant 5
A325	0.18	N/A	N/A
A193 B8-2	N/A	0.22	0.21
2205	N/A	0.20	0.16
A490	0.17	N/A	N/A
MCA	N/A	0.16	0.11

MCA = martensitic chromium alloy; N/A = bolt and lubricant pairing not tested.

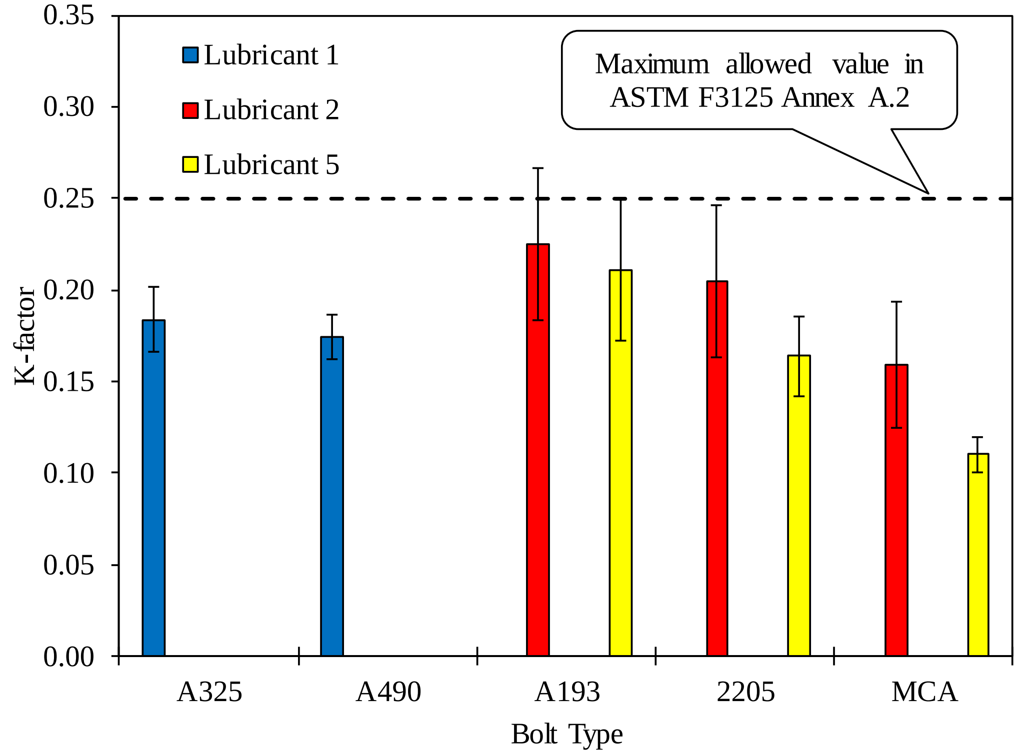


Figure 33. Torqued Tension Testing Bar Graph Showing K-factor for Each Bolt Type and Lubricant Combination. Error bars represent one standard deviation around the mean.

Torqued Tension Test Results

Torqued tension tests were analyzed using three plot types: bolt tension vs. nut angle of rotation, torque vs. angle of rotation, and torque vs. tension. Selected plots are included here, and the remaining plots are provided in Appendix A. Data from the corrosion-resistant bolts were compared to those from their standard bolt counterparts with similar strengths; that is, A193 B8-2 and 2205 bolts were compared to A325 bolts, and MCA bolts were compared to A490 bolts. Figure 34 shows a plot of tension vs. nut rotation for 7/8-in-diameter x 3.5-in-long A193 B8-2 bolts tested with Lubricants 2 and 5, differentiated by color. Included in the plot are A325 bolt test data with Lubricant 1.

The plot shows that the A193 B8-2 bolts clearly offered less pretension compared to the A325 bolts regardless of which lubricant type was used. This result was expected based on the tensile test data. The differences in pretension behavior based on the lubricant is clearly evident in the plot. Although the behavior of some of the A193 B8-2 bolts tested with Lubricant 2 may be similar to that of the bolts tested with Lubricant 5, three of the bolts showed jagged lines, which indicate sudden drops and subsequent increases in load. During testing, these three fastener assemblies were associated with loud popping sounds corresponding to these drops in load. These drops in load were some of the unexpected behaviors that resulted in an increase in the number of torqued tension tests for the A193 B8-2 bolts noted in Table 17. Torque vs. rotation and torque vs. tension plots for the 7/8-in-diameter x 3.5-in-long bolts are provided in Appendix A.

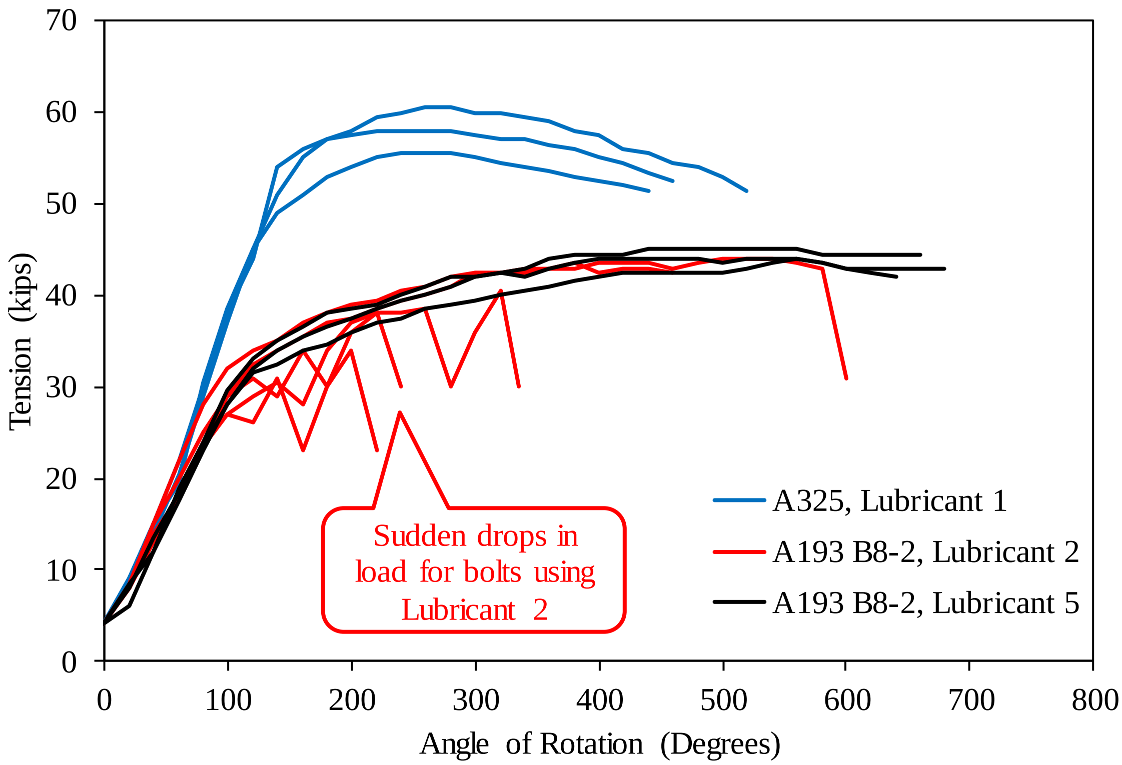


Figure 34. Torqued Tension Testing Tension vs. Angle of Rotation for 7/8-in-Diameter x 3.5-in-Long A193 B8-2 Bolts With Multiple Lubricants

After torqued tension tests were completed for these fastener assemblies, they were inspected for any damage that could have resulted in the sudden drops in load. A visual examination revealed indentations on the 303 washers on the face bearing on the nuts. Figure 35 shows two close-up photographs of 303 washers tested with an A193 B8-2 bolt with Lubricant 2. The photographs clearly show the indentations on the 303 washer.

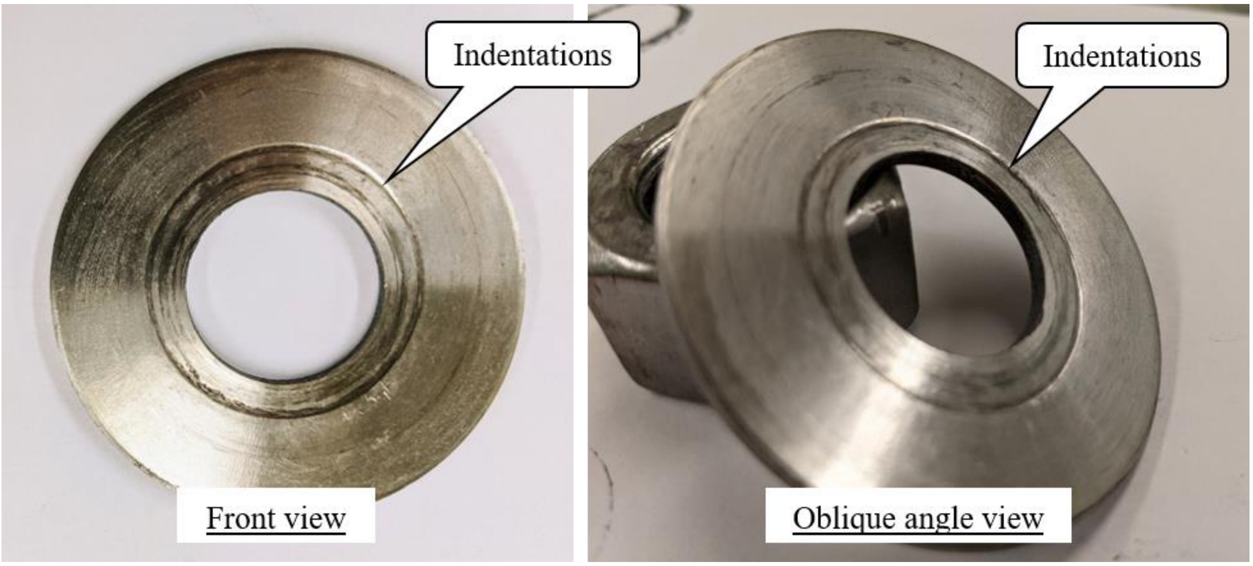


Figure 35. Photograph Showing Indentations on 303 Washer

From Figure 35 it is clear that the indentations on the 303 washer were severe compared to no noticeable indentations on the F436 washer. These indentations could easily be felt by running a finger across the washer. These indentations were present on the 303 washers tested with Lubricant 5 but did not appear or feel as severe as those on the washers tested with Lubricant 2. These indentations are clear indications of galling between the washer and nut that led to an increase in torque and drops in load during testing. The washer indentations correlated well with the hardness test results. Since the 303 washers had hardness values much lower than those of the other washers tested, these indentations are much more likely to occur. This demonstrates the importance of washer hardness in a fastener's torqued tension behavior. It also means that discussions with industry are necessary to determine if the 303 washers can be further hardened or if a different stainless steel product should be evaluated for use with A193 B8-2 bolts. It is possible that a different type of austenitic stainless steel or even a different kind of stainless steel, such as a precipitation hardening stainless steel, could perform better. Either of these options would provide the necessary improved corrosion resistance as compared to a traditional F436 washer. Discussion with stainless steel washer producers would be beneficial in determining which materials would be a better cost value and more viable substitute for VDOT.

Figure 36 shows a tension vs. angle of rotation plot for 7/8-in-diameter x 3.5-in-long 2205 bolts tested with Lubricants 2 and 5. Included in the plot are data for A325 bolts of the same size tested with Lubricant 1. Similar to the A193 B8-2 bolts, it is clear that the 2205 bolts could not reach the same level of pretension as A325 bolts, no matter which lubricant was used. However, a key finding is that the 2205 bolts had much greater tension and rotation values than the A193 B8-2 bolts. The 2205 bolts initially appeared to behave similarly regardless of whether they were used with Lubricant 2 or Lubricant 5. However, bolts tested with Lubricant 5 all had a slight increase in tension and a substantial increase in ductility when compared with those tested with Lubricant 2. Although the 2205 washers were much softer than the minimum F436 hardness requirements, they did not appear to have the negative effects on the installation behavior of the 2205 bolts that the soft 303 washers had on the A193 B8-2 bolts.

An explanation for the difference in ductility between the two lubricants can easily be seen in a plot of torque vs. angle of rotation for the same bolts in Figure 37. In the plot, all three bolts tested with Lubricant 2 had more torque than the bolts tested with Lubricant 5. This is a clear indication that Lubricant 5 was more effective than Lubricant 2, which confirms the observations from the k-factor results. This increase in torque increased the difficulty in tightening the 2205 bolts and led to each of these tests being stopped. The increase in torque with Lubricant 2 was significant because it led to these bolts reaching a smaller tension value compared to those with Lubricant 5. This demonstrates the importance of using an effective lubricant to allow bolts to reach greater pretension values and increased ductility. A plot of torque vs. rotation for these 7/8-in-diameter x 3.5-in-long 2205 bolts is provided in Appendix A.

Figure 38 shows the torqued tension testing tension vs. angle of rotation results for 7/8-in-diameter x 3.5-in-long MCA bolts tested with Lubricants 2 and 5. Results for the same size A490 bolts tested with Lubricant 1 are also shown for comparison. From the plot it is clear that the MCA bolts had slightly greater tension values than the A490 bolts, which was expected based on the proof loading. The results also showed that the MCA bolts tested with Lubricant 5 produced more repeatable results with generally greater tension values than those tested with Lubricant 2.

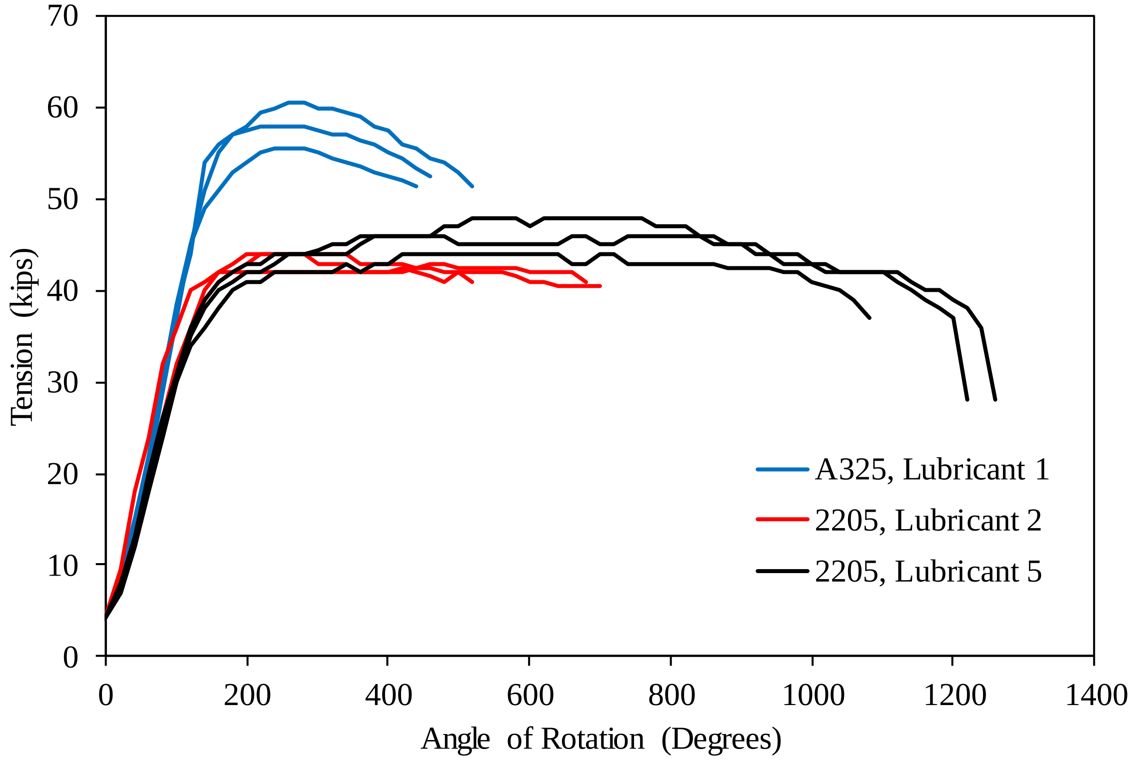


Figure 36. Torqued Tension Testing Tension vs. Angle of Rotation for 7/8-in-Diameter x 3.5-in-Long 2205 Bolts With Multiple Lubricants

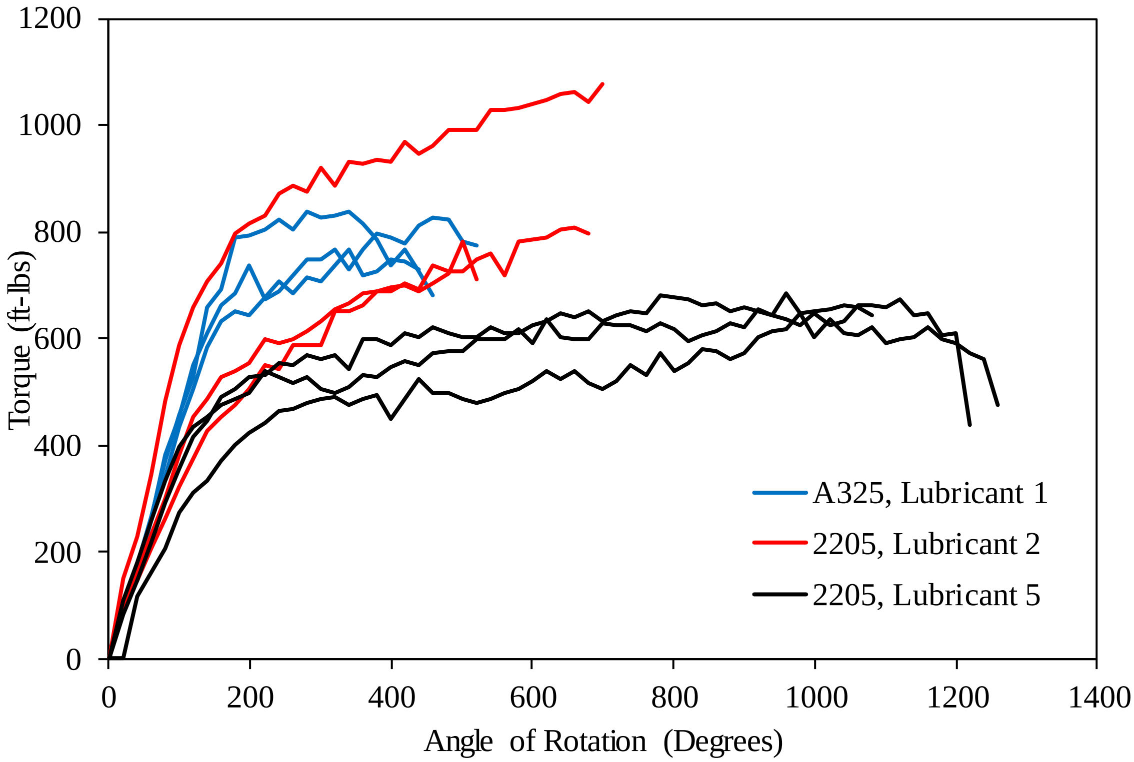


Figure 37. Torqued Tension Testing Torque vs. Angle of Rotation for 7/8-in-Diameter x 3.5-in-Long 2205 Bolts With Multiple Lubricants

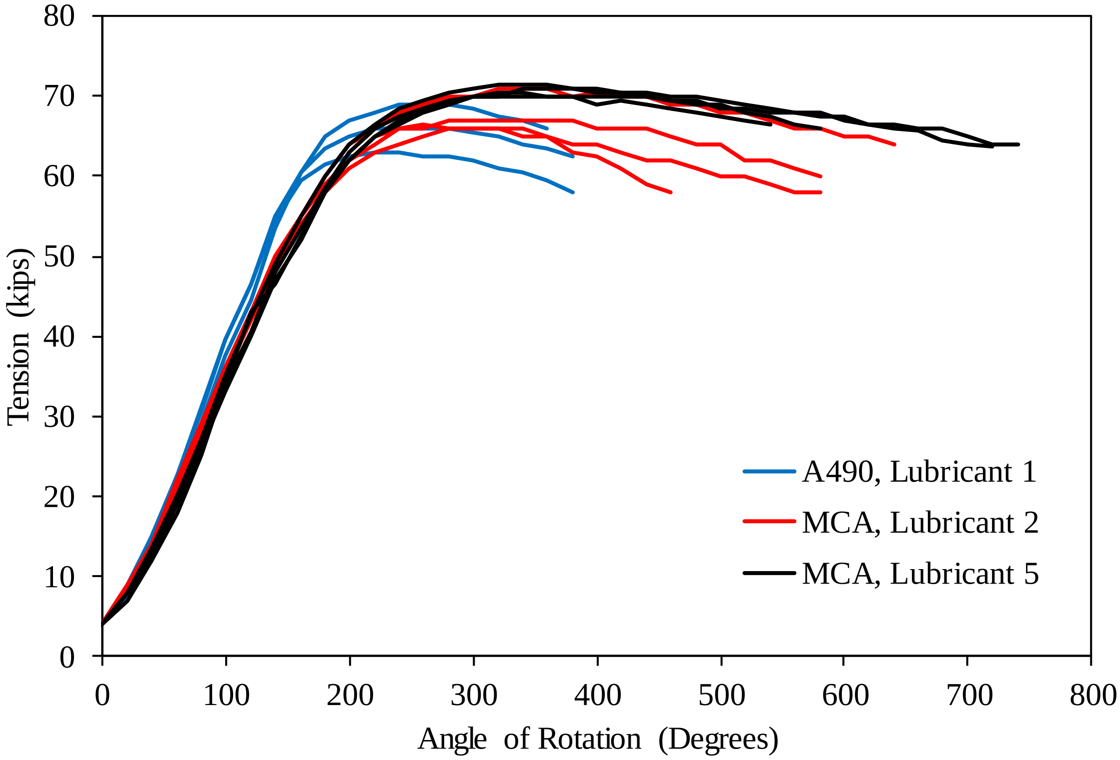


Figure 38. Torqued Tension Testing Tension vs. Angle of Rotation for 7/8-in-Diameter x 3.5-in-Long MCA Bolts With Multiple Lubricants. MCA = martensitic chromium alloy.

These observations were also expected based on the k-factor results, which showed that Lubricant 2 had more variability than Lubricant 5. Based on the plot, it is clear that MCA bolts with Lubricant 2 can perform as well as those with Lubricant 5 but that results are much more repeatable when Lubricant 5 is used. Similar to the 2205 bolts, MCA bolts with Lubricant 5 appeared to provide greater ductility than those with Lubricant 2. The torque vs. angle of rotation plot for these bolts confirmed that this was due to increased torque. Torque vs. rotation and torque vs. tension plots for the 7/8-in-diameter x 3.5-in-long MCA bolts are provided in Appendix A.

To demonstrate the difference in behavior for longer bolts with the same diameter, Figure 39 shows the torqued tension testing tension vs. angle of rotation for 7/8-in-diameter x 5-in-long A193 B8-2 bolts with multiple lubricants. This figure can be directly compared to Figure 34, which was for the same bolts but with a length of 3.5 in. Figure 39 shows sudden drops in load for the 5-in-long bolts with Lubricant 2, similar to what was noted for the 3.5-in-long bolts. However, sudden drops in load also occurred for two of the three bolts with Lubricant 5. None of the 3.5-in-long bolts with Lubricant 5 had these sudden drops in load. The k-factor results indicated that the A193 B8-2 bolts could be more susceptible to increased friction, which could lead to premature failure. Torque vs. rotation and torque vs. tension plots for these bolts are provided in Appendix A.

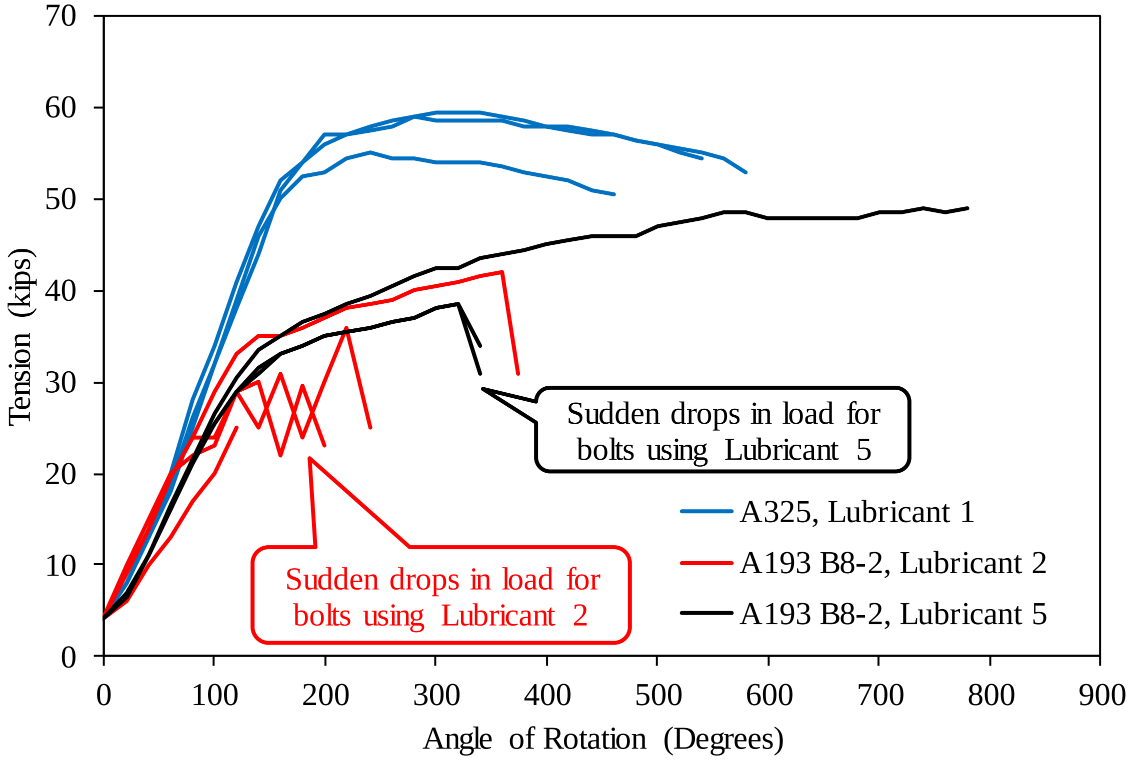


Figure 39. Torqued Tension Testing Tension vs. Angle of Rotation for 7/8-in-Diameter x 5-in-Long A193 B8-2 Bolts With Multiple Lubricants

Torqued tension tests for the 7/8-in-diameter x 5-in-long 2205 and MCA bolts produced results similar to those for the 3.5-in-long bolts. Lubricant 5 was more effective for both bolt types. No sudden drops in load were noted for the 2205 and MCA bolts, regardless of length. This suggests that these two bolt types are more resistant to galling than the A193 B8-2 bolts, confirming the same observations from the k-factor tests. Plots of tension vs. rotation, torque vs. rotation, and torque vs. tension for these bolts are provided in Appendix A. Trends similar to those for the 3.5-in-long bolts were seen during tests on the 3/4-in-diameter x 2-in-long A193 B8-2, 2205, and MCA bolts. Plots for these bolts are also provided in Appendix A.

Since the A193 B8-2 bolts in this study performed poorly, with several test results showing sudden drops in load, the torqued tension test results for the A193 B8-2 bolts in this study were compared to the initial evaluation for bolt selection for the Route 340 Bridge (Williams et al., 2017). Similar to the current study, that evaluation also included torqued tension tests on A193 B8-2 bolts with A194 nuts and 303 washers. The 303 washers used in that evaluation were slightly harder than the 303 washers used in this study, as shown previously in Figure 24. Results from the Williams et al. evaluation provided an easy comparison because it also used 7/8-in-diameter x 3.5-in-long A193 B8-2 bolts with Lubricant 2 during torqued tension tests. A comparison between the torqued tension tests on the A193 B8-2 bolts in this study and the A193 bolts in Williams et al. (2017) is shown in Figure 40.

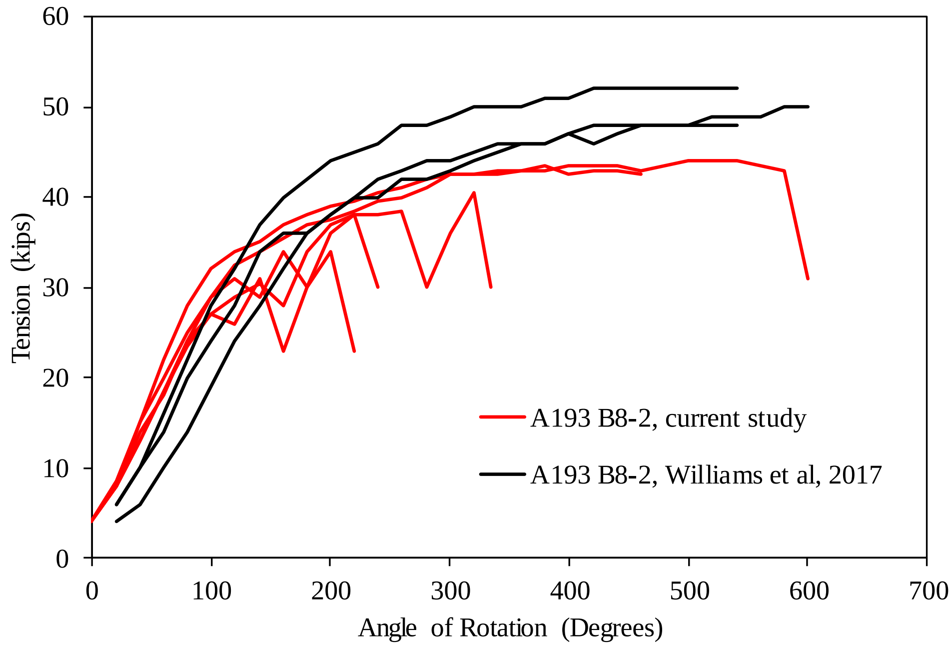


Figure 40. Torqued Tension Testing Tension vs. Angle of Rotation for 7/8-in-Diameter x 3.5-in-Long A193 B8-2 Bolts With Lubricant 2: Comparison Between Current Study and Williams et al. (2017)

As shown in the figure, it is obvious that the A193 B8-2 bolts in Williams et al. (2017) reached relatively high pretension values without any drops in load. This clearly demonstrates that the A193 B8-2 bolted assemblies in Williams et al. performed much better than the A193 B8-2 fastener assemblies in the current study. As previously stated, many of the parameters in the torqued tension tests between the two studies were identical, such as bolt type and size, nut type, and lubricant. However, one parameter that was different was the washer hardness. Figure 24 showed that the 303 washers used in Williams et al. had greater harder values than the 303 washers used in this study. It is possible that this increase in washer hardness led to much better torqued tension test behavior. This further demonstrates the importance of washer hardness during bolt installation.

Development of Bolt Installation Parameters

The method for determining installation procedures described herein was developed based on literature describing how installation parameters were first developed for A325 and A490 bolts and current specifications for bolt acceptance testing and installation. The method involved analysis of the torqued tension test data, which are described in the following sections. This method was applied to the 7/8-in-diameter bolt tests since this is the standard bolt diameter used for VDOT bridges.

Figure 41 shows an ideal torqued tension test tension vs. nut angle of rotation curve, with specific points designated on the curve. On the plot, T_b is defined as the tension value at which the curve becomes non-linear and transitions from elastic to plastic behavior. This is the same point below which data were used in determining k-factors discussed previously. This transition point from elastic to non-linear behavior was used as the design installation pretension for A325 and A490 bolts when installation parameters for these bolts were first developed (Kulak et al., 2001).

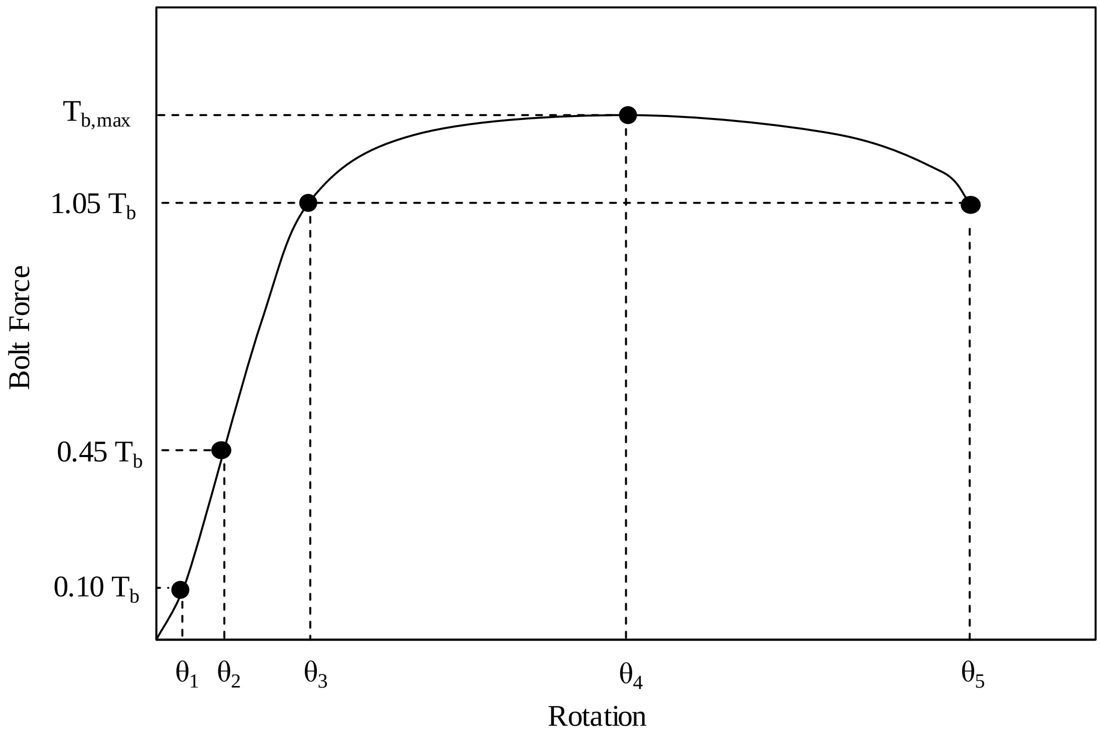


Figure 41. Ideal Torqued Tension Test Tension vs. Angle of Rotation Curve

In the figure, the angle of rotation corresponding to the initial value of T_b is θ_3. This is the angle required during turn-of-nut installation that produces the design installation pretension in the bolt. When a recommended nut rotation angle during installation is developed, the angle must be greater than this to ensure that the design pretension value is reached. When the required nut rotation for turn-of-nut installation was developed for A325 and A490, it was recommended that this angle be located on the plateau of the curve since the bolt tension is much less sensitive to rotation there than on the elastic portion of the curve (Kulak et al., 2001). However, the nut rotation angle during installation also should be less than θ_4, which corresponds to the maximum bolt tension, $T_{b,max}$. This is to ensure that the bolt remains on the ascending portion of the tension vs. rotation curve to allow sufficient ductility to remain after installation.

Values of $0.10T_b$ and θ_1 are noted in the figure to define the snug tight position in which all plies being connected are in firm contact without gaps between them. This definition is equivalent to that used in ASTM F3125 Annex A.2 for rotational capacity tests on A325 and A490 bolts (ASTM, 2015). This value is notable because the required nut rotation for turn-of-nut installation by the RCSC is referenced from the snug tight position (RCSC, 2014). In an effort to maintain consistency with current practices, the decision was made to follow suit for corrosion-resistant bolts.

The angle θ_5 is included on Figure 41 to indicate the maximum angle reached during the torqued tension test. It is defined as either the angle at which the bolt tension reaches a value of T_b on the descending portion of the tension vs. rotation curve after reaching a maximum bolt force or the rotation at which the bolt failed during testing.

Based on this information, Equations 2, 3, and 4 were developed.

$\Delta\theta_{31} = \theta_3 - \theta_1$ [Eq. 2]

where

θ_3 = angle at which the bolt force first reaches T_b (degrees)

θ_1 = angle at which the bolt force first reaches $0.10T_b$ (degrees)

T_b = force at which the force vs. angle of rotation curve transitions from elastic to non-linear

$\Delta\theta_{41} = \theta_4 - \theta_1$ [Eq. 3]

where

θ_4 = angle at which the bolt force first reaches $T_{b,max}$ (degrees)

θ_1 = angle at which the bolt force first reaches $0.10T_b$ (degrees)

T_b = force at which the force vs. angle of rotation curve transitions from elastic to non-linear.

$\Delta\theta_{53} = \theta_5 - \theta_3$ [Eq. 4]

where

θ_5 = angle at which the bolt force reaches T_b on the descending portion of the force vs. angle of rotation curve after reaching a maximum value or the angle at which the bolt fails during torqued tension testing (degrees)

θ_3 = angle at which the bolt force first reaches $0.10T_b$ (degrees)

T_b = force at which the force vs. angle of rotation curve transitions from elastic to non-linear.

The following criteria were then developed to establish installation parameters for turn-of-nut installation for corrosion-resistant bolts. A stand-alone method for determining these parameters is provided in Appendix B.

1. *The specified minimum bolt pretension, defined as T_{des}, should not be taken greater than the minimum T_b value from the torqued tension tests rounded down to the nearest kip. T_{des} should not be taken greater than 39 kip for the A193 B8-2 and 2205 fasteners or 49 kip for the MCA fasteners.* The minimum T_b value is used as a maximum limit to provide conservativism when corrosion-resistant bolts are used. The T_{des} maximum limits of 39 and 49 kip correspond to the specified minimum bolt pretension values of A325 and A490 bolts, respectively. It is not anticipated or

desired that corrosion-resistant fasteners will have a greater specified minimum bolt pretension than typical bolts used in bridges.

2. *The maximum force in all torqued tension tests, $T_{b,max}$, should be greater than $1.30T_{des}$.* The 1.30 value serves as a safety factor to ensure the bolt has sufficient ultimate strength. The safety factor in ASTM F3125 Annex A.2 is 1.15 for A325 and A490 bolts. Although not directly stated in ASTM F3125, 1.15 is the factor that is multiplied by the specified minimum bolt pretension at the required rotation to determine the minimum tension at a full rotation. The portion of that safety factor greater than 1.0 was doubled to produce the factor of 1.30 used for corrosion-resistant bolts. This was done to provide additional conservativism.

3. *All torqued tension tests should have a $\Delta\theta_{53}$ greater than or equal to the minimum value specified in Table 19.* This requirement serves as a check to ensure that the stainless steel bolts have sufficient ductility. The values in Table 19 were recommended in the UDE study on stainless steel fasteners (Stranghöner et al., 2017b).

Table 19. Minimum Values of $\Delta\theta_{53}$ During Torqued Tension Tests

Grip Length, L	Minimum $\Delta\theta_{53}$
$L < 2d$	210°
$2d \leq L < 6d$	240°
$6d \leq L < 10d$	270°

d = diameter of bolt.

4. *All torqued tension tests should have a k-factor less than 0.25.* This requirement ensures that an effective lubricant is used for the fastener assembly. The upper limit of the k-factor is the same as that allowed in the ASTM F3125 Annex A.2 rotational capacity tests. This k-factor of 0.25 is given in terms of a maximum bolt torque, which is 0.25 multiplied by bolt diameter and tension (ASTM, 2015).

5. *The turn-of-nut rotation angle required to achieve the specified minimum bolt pretension in the fastener assembly, defined as θ_r, should be taken equal to the maximum $\Delta\theta_{31}$ value from the torqued tension tests rounded up to the nearest 60° increment.* The maximum $\Delta\theta_{31}$ value from the torqued tension tests is used to ensure that the force in the bolt during installation exceeds $T_{des.}$ The rotation angle is rounded up to the nearest 60° increment to correspond to the next corner point on a nut face or bolt head for conservativism and convenience.

6. *θ_r should not exceed the minimum $\Delta\theta_{41}$ value from the torqued tension tests.* This requirement is another ductility check to ensure that the pretension in the bolt after installation has not exceeded its ultimate strength.

The torqued tension test results were then evaluated using the six criteria. Analysis results are shown in Table 20, and the evaluation of the results relative to the criteria is shown in Table 21. For both tables, results failing to meet requirements or the criteria are noted in red text. These were instances where tests were stopped because of drops in load.

Table 20. Torqued Tension Tests Analysis Results

Bolt Test				Torqued Tension Tests Analysis						
Bolt Type	**Bolt Size**	**Lubrication**	**Test No.**	**0.1 T_b (kip)**	**θ_1 (°)**	**T_b (kip)**	**θ_3 (°)**	**$T_{b,max}$ (kip)**	**θ_4 (°)**	**θ_5 (°)**
A193 B8-2	7/8x3.5	Lubricant 2	1	2.9	0.0	29.0	100	40.5	320	340
A193 B8-2	7/8x3.5	Lubricant 2	2	3.3	0.0	32.5	120	44	520	600
A193 B8-2	7/8 x3.6	Lubricant 2	3	2.7	0.0	27.0	100	34	200	600
A193 B8-2	7/8x3.5	Lubricant 2	4	3.4	0.0	34.0	120	43.5	380	460
A193 B8-2	7/8x3.6	Lubricant 2	5	2.7	0.0	27.0	100	38	220	460
A193 B8-2	7/8x3.5	Lubricant 5	1	3.2	0.0	32.0	120	44	440	640
A193 B8-2	7/8x3.5	Lubricant 5	2	3.3	0.0	33.0	120	45	480	660
A193 B8-2	7/8x3.5	Lubricant 5	3	3.2	0.0	31.5	120	44	560	680
A193 B8-2	7/8x5	Lubricant 2	1	3.5	0.0	35.0	140	42	340	375
A193 B8-2	7/8x5	Lubricant 2	2	N/A	0.0	N/A	N/A	30	140	220
A193 B8-2	7/8x5	Lubricant 2	4	N/A	0.0	N/A	N/A	36	220	240
A193 B8-2	7/8x5	Lubricant 5	1	3.1	0.0	31.0	140	39	320	340
A193 B8-2	7/8x5	Lubricant 5	2	3.4	0.0	33.5	140	49	780	780
A193 B8-2	7/8x5	Lubricant 5	3	3.2	0.0	31.5	140	39	320	340
2205	7/8x3.5	Lubricant 2	1	3.9	0.0	39.0	140	44	250	520
2205	7/8x3.5	Lubricant 2	2	4.0	0.0	40.0	140	44	270	680
2205	7/8x3.5	Lubricant 2	3	4.0	0.0	40.0	120	43.5	450	700
2205	7/8x3.5	Lubricant 5	1	3.6	0.0	36.0	140	44	560	1080
2205	7/8x3.5	Lubricant 5	2	3.8	0.0	38.0	140	46	420	1220
2205	7/8x3.5	Lubricant 5	3	3.9	0.0	39.0	140	48	640	1260
2205	7/8x5	Lubricant 2	1	3.8	0.0	38.0	160	42	520	580
2205	7/8x5	Lubricant 2	2	4.1	0.0	41.0	160	44	300	720
2205	7/8x5	Lubricant 2	4	3.7	0.0	37.0	160	43	410	720
2205	7/8x5	Lubricant 5	1	3.8	0.0	38.0	160	51	1070	1440
2205	7/8x5	Lubricant 5	2	4.3	0.0	42.5	180	50	780	1440
2205	7/8x5	Lubricant 5	3	4.1	0.0	40.5	160	48	680	1420
MCA	7/8x3.5	Lubricant 2	HC1	6.7	0.0	67.0	140	67	320	580
MCA	7/8x3.5	Lubricant 2	HC2	6.6	0.0	66.0	145	66	300	580
MCA	7/8x3.5	Lubricant 2	WF1	7.1	0.0	71.0	140	71	340	640
MCA	7/8x3.5	Lubricant 2	WF2	6.7	0.0	67.0	135	66.5	260	460
MCA	7/8x3.5	Lubricant 5	HC1	7.1	0.0	71.0	145	70.5	320	540
MCA	7/8x3.5	Lubricant 5	HC2	7.2	0.0	72.0	140	72	340	580
MCA	7/8x3.5	Lubricant 5	WF1	7.1	0.0	71.0	150	71	370	740
MCA	7/8x3.5	Lubricant 5	WF2	7.0	0.0	70.0	150	70	360	720
MCA	7/8x5	Lubricant 2	HC1	6.5	0.0	65.0	145	65	300	500
MCA	7/8x5	Lubricant 2	HC2	6.8	0.0	68.0	140	68	280	480
MCA	7/8x5	Lubricant 2	WF1	6.6	0.0	66.0	145	66	280	440
MCA	7/8x5	Lubricant 2	WF2	6.5	0.0	65.0	145	65	280	440
MCA	7/8x5	Lubricant 5	HC1	7.2	0.0	72.0	155	72	300	600
MCA	7/8x5	Lubricant 5	HC2	7.1	0.0	71.0	155	71	360	600
MCA	7/8x5	Lubricant 5	WF1	7.0	0.0	70.0	165	70	380	780
MCA	7/8x5	Lubricant 5	WF2	7.0	0.0	70.0	155	70	370	800

MCA = martensitic chromium alloy.
Red text indicates that the result did not meet the criteria.

Table 21. Evaluation of Torqued Tension Test Data With Regard to Criteria

Bolt Test				Criterion 1			Criterion 2		Criterion 3		Criterion 4		Criterion 5		Criterion 6	
Bolt Type	Bolt Size	Lubrication	Test No.	T_{des} (kip)	$T_{des} \le (T_b)_{min}$	$T_{des} \le 39$ or 49 kip	1.3 T_{des}	$T_{b,max} > 1.3T_{des}$	$\Delta\theta_{53}$ (°)	$\Delta\theta_{53} \le 240°$	k	$k \le 0.25$	$\Delta\theta_{31}$ (°)	θ_r (°)	$\Delta\theta_{41}$ (°)	$\theta_r \le (\Delta\theta_{41})_{min}$
A193 B8-2	7/8x3.5	Lubricant 2	1	26.0	Yes	Yes	33.8	Yes	240	Yes	0.23	Yes	100	120	320	Yes
A193 B8-2	7/8x3.5	Lubricant 2	2					Yes	480	Yes	0.14	Yes	120		520	
A193 B8-2	7/8x3.5	Lubricant 2	3					Yes	500	Yes	0.23	Yes	100		200	
A193 B8-2	7/8x3.5	Lubricant 2	4					Yes	340	Yes	0.18	Yes	120		380	
A193 B8-2	7/8x3.5	Lubricant 2	5					Yes	360	Yes	0.25	Yes	100		220	
A193 B8-2	7/8x3.5	Lubricant 5	1	31.0	Yes	Yes	40.3	Yes	520	Yes	0.27	No	120	120	440	Yes
A193 B8-2	7/8x3.5	Lubricant 5	2					Yes	540	Yes	0.23	Yes	120		480	
A193 B8-2	7/8x3.5	Lubricant 5	3					Yes	560	Yes	0.25	Yes	120		560	
A193 B8-2	7/8x5	Lubricant 2	1	N/A	No	No	N/A	N/A	235	No	0.17	Yes	140	180	340	No
A193 B8-2	7/8x5	Lubricant 2	2					N/A	220	No	0.24	Yes	N/A		140	
A193 B8-2	7/8x5	Lubricant 2	4					N/A	240	Yes	0.23	Yes	N/A		220	
A193 B8-2	7/8x5	Lubricant 5	1	30.0	Yes	Yes	39.0	Yes	200	No	0.18	Yes	140	180	320	Yes
A193 B8-2	7/8x5	Lubricant 5	2					Yes	640	Yes	0.19	Yes	140		780	
A193 B8-2	7/8x5	Lubricant 5	3					Yes	200	No	0.24	Yes	140		320	
2205	7/8x3.5	Lubricant 2	1	33.0	Yes	Yes	42.9	Yes	380	Yes	0.15	Yes	140	180	250	Yes
2205	7/8x3.5	Lubricant 2	2					Yes	540	Yes	0.18	Yes	140		270	
2205	7/8x3.5	Lubricant 2	3					Yes	580	Yes	0.24	Yes	120		450	
2205	7/8x3.5	Lubricant 5	1	33.0	Yes	Yes	42.9	Yes	940	Yes	0.18	Yes	140	180	560	Yes
2205	7/8x3.5	Lubricant 5	2					Yes	1080	Yes	0.19	Yes	140		420	
2205	7/8x3.5	Lubricant 5	3					Yes	1120	Yes	0.14	Yes	140		640	
2205	7/8x5	Lubricant 2	1	32.0	Yes	Yes	41.6	Yes	420	Yes	0.23	Yes	160	180	520	Yes
2205	7/8x5	Lubricant 2	2					Yes	560	Yes	0.16	Yes	160		300	
2205	7/8x5	Lubricant 2	3					Yes	560	Yes	0.19	Yes	160		410	
2205	7/8x5	Lubricant 5	1	36.0	Yes	Yes	46.8	Yes	1280	Yes	0.15	Yes	160	180	1070	Yes
2205	7/8x5	Lubricant 5	2					Yes	1260	Yes	0.14	Yes	180		780	
2205	7/8x5	Lubricant 5	3					Yes	1260	Yes	0.14	Yes	160		680	
MCA	7/8x3.5	Lubricant 2	HC1	49.0	Yes	Yes	63.7	Yes	440	Yes	0.12	Yes	140	180	320	Yes
MCA	7/8x3.5	Lubricant 2	HC2					Yes	435	Yes	0.14	Yes	145		300	
MCA	7/8x3.5	Lubricant 2	WF1					Yes	500	Yes	0.12	Yes	140		340	
MCA	7/8x3.5	Lubricant 2	WF2					Yes	325	Yes	0.13	Yes	135		260	
MCA	7/8x3.5	Lubricant 5	HC1	49.0	Yes	Yes	63.7	Yes	395	Yes	0.12	Yes	145	180	320	Yes
MCA	7/8x3.5	Lubricant 5	HC2					Yes	440	Yes	0.12	Yes	140		340	
MCA	7/8x3.5	Lubricant 5	WF1					Yes	590	Yes	0.12	Yes	150		370	
MCA	7/8x3.5	Lubricant 5	WF2					Yes	570	Yes	0.12	Yes	150		360	
MCA	7/8x5	Lubricant 2	HC1	49.0	Yes	Yes	63.7	Yes	355	Yes	0.14	Yes	145	180	300	Yes
MCA	7/8x5	Lubricant 2	HC2					Yes	340	Yes	0.13	Yes	140		280	
MCA	7/8x5	Lubricant 2	WF1					Yes	295	Yes	0.13	Yes	145		280	
MCA	7/8x5	Lubricant 2	WF2					Yes	295	Yes	0.14	Yes	145		280	
MCA	7/8x5	Lubricant 5	HC1	49.0	Yes	Yes	63.7	Yes	445	Yes	0.11	Yes	155	180	300	Yes

MCA	7/8x5	Lubricant 5	HC2					Yes	445	Yes	0.12	Yes	155		360	
MCA	7/8x5	Lubricant 5	WF1					Yes	615	Yes	0.11	Yes	165		380	
MCA	7/8x5	Lubricant 5	WF2					Yes	645	Yes	0.11	Yes	155		370	

MCA = martensitic chromium alloy.

Red text indicates that the result did not meet the criteria.

As indicated in Table 21, A193 B8-2 bolts appeared to perform the worst of the three corrosion-resistant bolts because they were the only ones that failed some of the criteria. Bolts tested with Lubricant 5 clearly performed better than those tested with Lubricant 2. This was also noted in the k-factor and torqued tension curves presented. For the 3.5-in-long bolts, those tested with Lubricant 5 provided a greater specified minimum bolt pretension (31 kip) compared to those tested with Lubricant 2 (26 kip). Two of the three 5-in-long bolts tested with Lubricant 2 did not meet Criterion 1, so a specified minimum bolt pretension value could not be determined; a value was determined for those tested with Lubricant 5, but those bolts failed the ductility requirements in Criterion 3.

It was surprising that the A193 B8-2 bolts failed multiple criteria in this evaluation since they had been used successfully in Williams et al. (2017) and the Route 340 Bridge (Provines et al., 2018). Lubricant 2 had been used for both instances. The installation parameters from the Route 340 Bridge (Provines et al., 2018) had included a specified minimum bolt pretension of 30 kip and a nut rotation of 180 degrees for 3.5-in-long bolts and 240 degrees for 5-in-long bolts. All three of these values are reasonable based the criteria developed in this study. As stated in the discussion of the torqued tension test data, it is likely that the poor performance of the A193 B8-2 bolts in this study was due to the low washer hardness for the 303 washers used. Hardness values for the 303 washers were significantly less than for other corrosion-resistant washers evaluated in this study. Williams et al. (2017) also showed that harder 303 washers can lead to successful pretensioning of A193 B8-2 bolts. Since A193 B8-2 bolts were successfully used on the Route 340 Bridge and in Williams et al. (2017), their future use is warranted. The results in this study have shown that their performance can be improved through use of effective lubricants and hardened washers.

The results for the 2205 bolts in Table 21 show that the specified minimum bolt pretension was 33 kip for the 3.5-in-long bolts with either Lubricant 2 or Lubricant 5. For the 5-in-long bolts, Lubricant 5 produced a specified minimum bolt pretension of 36 kip; Lubricant 2 produced a value of 32 kip. This shows that Lubricant 5 was slightly more effective than Lubricant 2, but the performance gap between lubricants was not as large as for the A193 B8-2 bolts. Based on these data, a specified minimum bolt pretension value of 32 kip could be conservatively used for all 2205 bolts. A nut rotation angle of 180 degrees was shown to be effective in producing the specified minimum bolt pretension for both the 3.5-in-long and 5-in-long bolts.

Table 21 shows that the specified minimum bolt pretension of the MCA bolts was 49 kip, which was governed by the specified minimum bolt pretension value for A490 bolts. This value was consistent for all of the MCA bolts tested, regardless of lubricant type or bolt length. The nut rotation angle of 180 degrees was effective in producing the specified minimum bolt pretension for both lengths of MCA bolts. Similar to the 2205 bolts, the MCA bolts tested with Lubricant 5 performed better than those tested with Lubricant 2, but the difference in performance was not as large as for the A193 B8-2 bolts.

Table 22 shows a summary of the design installation parameters determined in this evaluation. The table also includes the specified minimum bolt pretension as a function of the nominal tensile strength of each bolt type.

Table 22. Summary of Installation Parameters Determined by Torqued Tension Tests

Bolt Type	Nominal Tensile Strength, P_u (kip)	Specified Minimum Bolt Pretension (kip)	Specified Minimum Bolt Pretension of P_u	Bolt Length (in)	Nut Rotation for Turn-of-Nut Installation (degree)
A193 B8-2[a]	53.1	30	$0.56P_u$	3.5	180
				5	240
2205	55.4[b]	32	$0.58P_u$	3.5	180
				5	180
MCA	69.3[c]	49	$0.71P_u$	3.5	180
				5	180

MCA = martensitic chromium alloy.
[a] Parameters used for Route 340 Bridge (Provines et al., 2018).
[b] 2205 bolts were ordered to meet the mechanical test requirements of A325 bolts.
[c] Assumed value equivalent to A490 bolts.

Typical A325 and A490 bolts have specified minimum bolt pretension values of approximately 70% of their nominal strength (RCSC, 2014). The MCA bolts have a specified minimum bolt pretension equivalent to this, whereas the specified minimum bolt pretension values for the A193 B8-2 and 2205 bolts are slightly less than 60% of their nominal tensile strength.

The specified minimum bolt pretension values in Table 22 are independent of surface condition factors for faying surfaces used in slip-critical bolted connections. The surface condition factor is a function only of the material type and surface finish. Therefore, these specified minimum bolt pretension values adjusted for relaxation (presented in the preceding section) could be used in conjunction with proposed surface condition factors for 50CR steel and dissimilar metal connections (Provines and Abebe, 2020). However, the slip resistance of a slip-critical bolted connection would be affected by these specified minimum bolt pretension values. The slip resistance of a slip-critical bolted connection depends on its surface condition factor and the specified minimum bolt pretension (AASHTO, 2017). Therefore, assuming equal surface condition factors, the slip resistance of a bolted connection using A193 B8-2 or 2205 bolts would be less than a similar bolted connection using A325 bolts.

Relaxation Testing of Bolts

Figure 42 shows a plot of load vs. time for the 3.5-in-long bolts being compared to A325 bolts. As mentioned previously, the A325 bolts were pretensioned to an initial value of at least 39 kip whereas the A193 B8-2 and 2205 bolts were pretensioned to an initial value of at least 30 kip. From the figure it appears that all of the bolt types had a drop in load within the first 24 hours of testing. There is also a more gradual loss of load within the first 200 hours of testing. From that point onward, it appears that the 2205 bolts continued to have a slight decrease in load until approximately 800 hours.

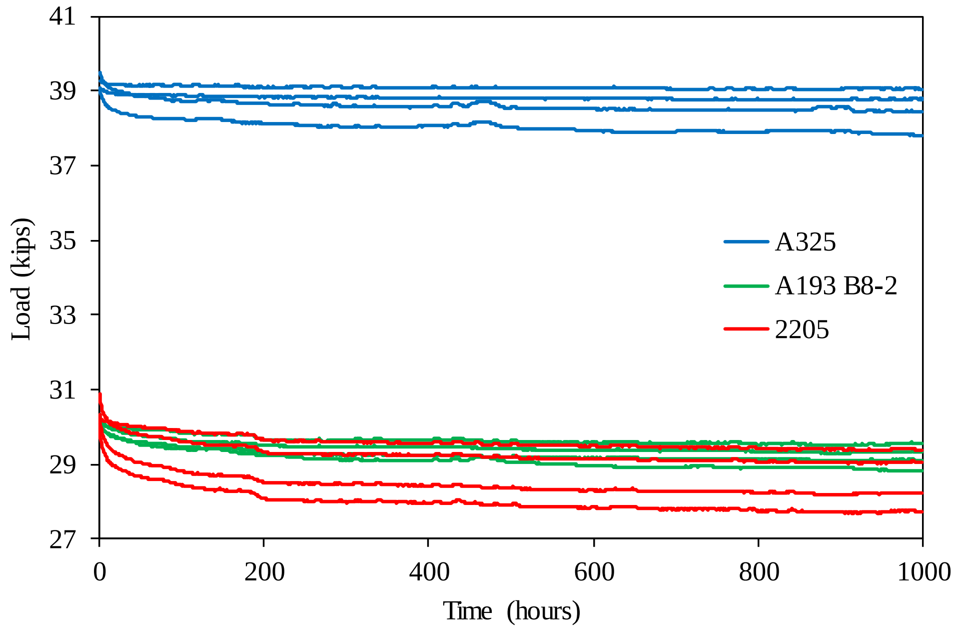


Figure 42. Plot of Load vs. Time for Relaxation Tests on A325, A193 B8-2, and 2205 3.5-in-Long Bolts

Figure 43 shows a similar plot for the A490 and MCA bolts. As mentioned previously, all of these bolts were pretensioned to an initial value of at least 49 kip, which is standard for 7/8-in-diameter A490 bolts. Similar trends were noted for these higher strength bolts. There was an initial drop in load within the first 24 hours for all of the bolts. Then, there was a gradual loss of load, which appeared to stabilize after approximately 200 hours for the A490 bolts and approximately 400 hours for the MCA bolts.

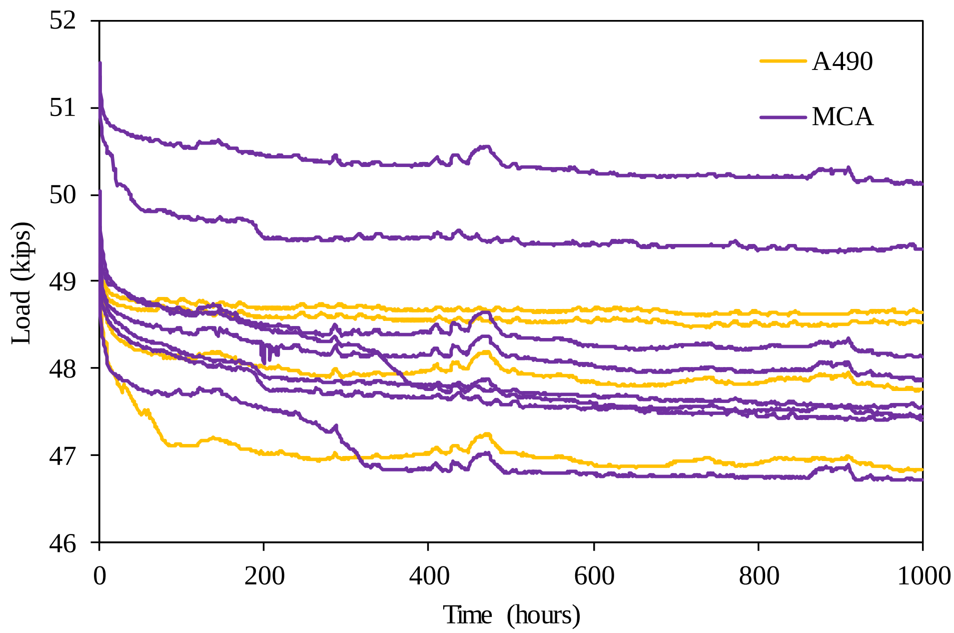


Figure 43. Plot of Load vs. Time for Relaxation Tests on A490 and MCA 3.5-in-Long Bolts. MCA = martensitic chromium alloy.

Data from the previous two plots were combined to create Figure 44, which shows the fraction of initial pretension vs. time for all of the bolts tested. This allowed for an easier comparison between bolts with a different initial pretension value. The most notable observation from the figure is that the 2205 bolts appeared to have the most relaxation compared to all of the other bolts. Three of the four 2205 bolts tested had the largest relative loss in load of all of the tests.

Table 23 shows data similar to that in Figure 44, but in tabular form. The table shows the average percentage of initial pretension after the following set intervals: 24, 200, 400, 600, 800, and 1,000 hours. These intervals were selected to determine if the load for each bolt type consistently decreased or if it became constant at some point. Values in the table are average values for each bolt type of 3.5-in length.

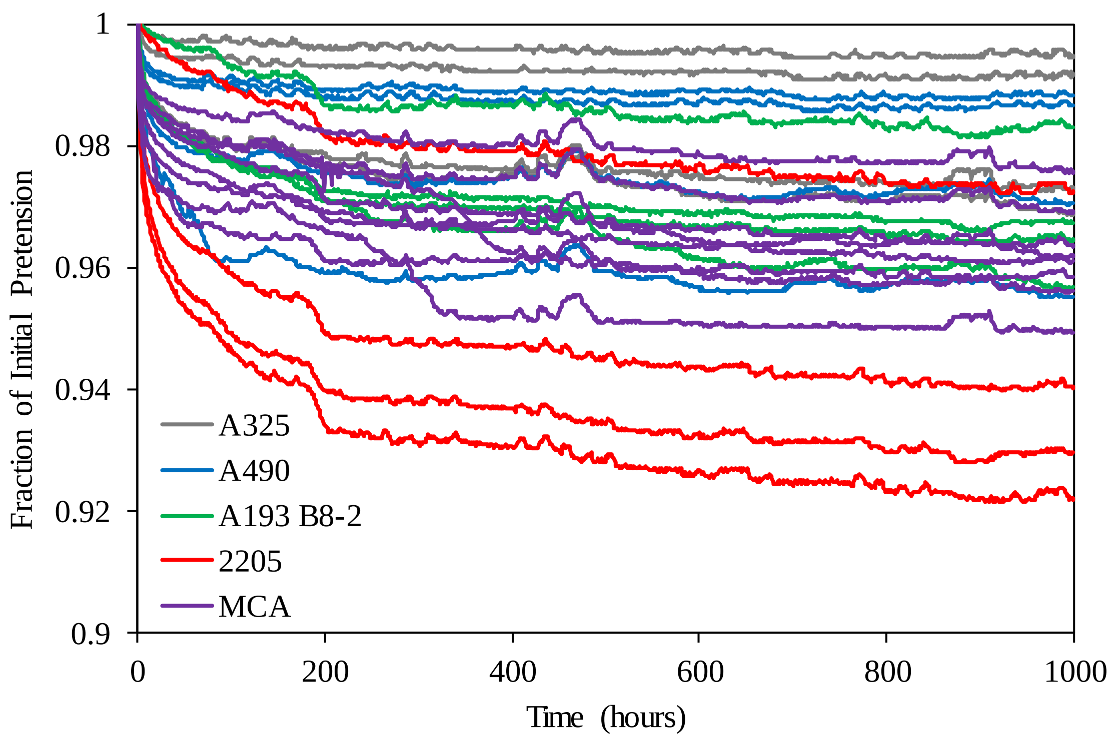


Figure 44. Plot of Fraction of Initial Pretension vs. Time for All 3.5-in-Long Bolts. MCA = martensitic chromium alloy.

Table 23. Average Percentage of Initial Pretension Loss at Various Stages of Relaxation Tests for All 3.5-in-Long Bolts

Bolt Type	Average Percentage of Initial Pretension After					
	24 hours	200 hours	400 hours	600 hours	800 hours	1,000 hours
A325	99.1%	98.6%	98.5%	98.4%	98.3%	98.2%
A193 B8-2	98.8%	97.5%	97.3%	97.1%	96.9%	96.8%
2205	97.3%	95.1%	94.8%	94.5%	94.2%	94.1%
A490	98.5%	97.8%	97.8%	97.6%	97.6%	97.5%
MCA	98.1%	97.1%	96.7%	96.4%	96.3%	96.2%

MCA = martensitic chromium alloy.

Based on Table 23, the 3.5-in-long A325 bolts in this study had an approximate 1% loss in pretension after the first 24 hours and a final reduction of less than 2% at 1,000 hours. The 3.5-in-long A193 B8-2 bolts also had an approximate 1% reduction in pretension after the first 24 hours, but their final loss in pretension was greater than 3%. The 3.5-in-long 2205 bolts had similar behavior, but at a greater magnitude, having an initial relaxation of 2.7% over the first 24 hours and a final pretension loss of approximately 6%. When pretension loss values at intervals of 800 and 1,000 hours of testing were compared, all three bolt types showed a minimal reduction, indicating that their pretension loss had become stable. This is also clear in Figure 44.

Similar observations can be made about the 3.5-in-long A490 and MCA bolts. Table 23 shows that the A490 bolts had a 1.5% reduction in pretension over the first 24 hours and a 2.5% total reduction at the end of the 1,000 hours. The MCA bolts had slightly greater pretension losses of approximately 2% at 24 hours and 3.8% at 1,000 hours. Similar to the other bolt types, the A490 and MCA bolts showed near constant pretension losses when values at 800 and 1,000 hours of testing were compared, indicating their relaxation has become stable. This is also shown in Figure 44.

As stated previously, historical relaxation test data on A325 bolts showed that an average of 5% reduction in load can be expected (Chesson and Munse, 1965; Reuther et al., 2014). If this value is used as a passing criterion, the A193 B8-2 and MCA bolts pass but the 2205 bolts do not. In fact, in Figure 44, three of the four 2205 bolts tested had a reduction in initial pretension greater than 5%; these were the only bolts tested to do so. Therefore, a slight reduction in design installation pretension is recommended for the 2205 bolts to account for this relaxation. The torqued tension test results had previously shown that a design installation pretension of 32 kip was suitable for 2205 bolts. However, reducing this value to 30 kip would account for the relaxation behavior of the 2205 bolts and would make the pretension values for A193 B8-2 and 2205 bolts identical for simplicity.

Plots of load vs. time and fraction of initial pretension vs. time for the relaxation tests on the 5-in-long bolts are provided in Appendix A. Similar to the 3.5-in-long bolt results, data from the 5-in-long bolt tests were summarized in tabular form at the same intervals. These results are shown in Table 24.

Table 24. Average Percentage of Initial Pretension Loss at Various Stages of Relaxation Tests for All 5-in-Long Bolts

Bolt Type	Average Percentage of Initial Pretension After					
	24 hours	**200 hours**	**400 hours**	**600 hours**	**800 hours**	**1,000 hours**
A325	99.6%	99.2%	99.0%	99.0%	98.9%	98.7%
A193 B8-2	99.8%	99.7%	99.6%	99.5%	99.5%	99.4%
2205	98.9%	98.2%	98.0%	97.8%	97.7%	97.6%
A490	99.9%	99.5%	99.3%	99.3%	99.3%	99.3%
MCA	100.0%	99.7%	99.6%	99.6%	99.5%	99.5%

MCA = martensitic chromium alloy.

Overall, results from Table 24 show that the 5-in-long bolts mostly showed less relaxation than the 3.5-in-long bolts. The A193 B8-2, A490, and MCA bolts all showed less than 1% of relaxation over the 1,000 hours of testing, whereas the 5-in-long A325 bolts showed approximately 1.3% relaxation over the same time period. Similar to the 3.5-in-long bolt test results, the 5-in-long 2205 bolts showed the most relaxation compared to all other bolts of the same length. The 5-in-long 2205 bolts showed an approximate 2.4% relaxation over 1,000 hours, which was still less than the 5% expected relaxation found for A325 bolts in the literature.

Long-Term Corrosion Testing of Bolts

The long-term corrosion specimens were assembled using information gleaned from other test results. Lubricant 1 was used for the A325 bolts, including Type 3 and HDG versions, since this is the standard lubricant used for these bolts. Lubricant 5 was used for all corrosion-resistant bolt types since it had produced the lowest k-factors.

The nut rotation values used during bolt installation were determined from the torqued tension tests. These values were 120 degrees for the A325 bolts and 180 degrees for the corrosion-resistant bolts. During bolt installation, the maximum torque on the nut was also recorded. Details from the long-term corrosion test specimen bolt installation are shown in Table 25.

Table 25. Long-Term Corrosion Test Specimen Assembly Details

Specimen No.	Bolt Type	Lubricant	Nut Rotation (°)	Torque (ft-lb)
0	A325	Lubricant 1	120	562
1	A325 Type 3	Lubricant 1	120	505
2	A325 HDG	Lubricant 1	120	328
3	MCA	Lubricant 5	180	552
4	A193 B8-2	Lubricant 5	180	381
6	A325 HDG	Lubricant 1	120	335
7	MCA	Lubricant 5	180	450
8	MCA Zn/Ni plated	Lubricant 5	180	541
9	A193 B8-2	Lubricant 5	180	524
10	A325 HDG	Lubricant 1	120	335
11	MCA	Lubricant 5	180	439
12	MCA Zn/Ni plated	Lubricant 5	180	704
13	A193 B8-2	Lubricant 5	180	598
14	A325 HDG	Lubricant 1	120	335
15	MCA	Lubricant 5	180	539
16	MCA Zn/Ni plated	Lubricant 5	180	524
17	A193 B8-2	Lubricant 5	180	555
18	MCA	Lubricant 5	180	558
19	MCA Zn/Ni plated	Lubricant 5	180	465
20	A193 B8-2	Lubricant 5	180	491
21	2205	Lubricant 5	180	641

MCA = martensitic chromium alloy.

As mentioned previously, the long-term corrosion test specimens were intended to be placed at VTRC's existing exposure site on the north island of the Hampton Roads Bridge-Tunnel. However, construction at this location caused VTRC to move all of its corrosion samples from this site back to VTRC in Charlottesville. Therefore, once the long-term corrosion test specimens from this study were assembled in December 2019, they were placed on exposure racks at VTRC. Figure 45 shows a photograph of these specimens. Eventually, the specimens will be moved to VTRC's new exposure site at VDOT's Temperanceville Area Headquarters.

Individual samples are photographed at 6-week intervals to document existing corrosion. The photographs can then be compared over time to assess visually how each specimen is corroding. It is expected that these samples will be left at the Temperanceville exposure site for many years to evaluate their long-term corrosion resistance. An example of a photograph of a sample is shown in Figure 46.

Figure 45. Photograph of Corrosion-Resistant Fastener Long-Term Corrosion Test Specimens

Figure 46. Photograph of Long-Term Corrosion Sample 16

Cost Evaluation of Fasteners

Unit prices received from the supplier sampling are shown in Table 26. The supplier of the minimum-cost complete fastener assembly (indicated in bold font in the "Total Cost" column) varies for each category, proving that no supplier was the lowest-cost provider of every type of fastener assembly. One important item to note from Table 26 is that when this cost evaluation was conducted, domestically produced 2205 fasteners were not available for purchase from any of the suppliers contacted. Domestically produced materials are required for use on VDOT projects by the Buy America regulations (FHWA, 2017).

Table 26. Costs of Fastener Components in Quotes for 2,000 Units

Fastener Assembly Type	Bolt Type	$/each	Nut Type	$/each	Washer Type	$/each	Total Cost
Standard	A325	S1[a]: $2.79 S2: $1.35 S3: $1.44 S4: $2.10 S5: N/A	A563	S1: $0.82 S2: $0.43 S3: $0.41 S4: $0.85 S5: N/A	F436	S1: $0.25 S2: $0.11 S3: $0.10 S4: $0.20 S5: N/A	S1: $3.86 **S2: $1.89** S3: $1.95 S4: $3.15 S5: N/A
Standard	A325 Type 3	S1: $2.19 S2: $1.55 S3: $1.45 S4: $2.40 S5: N/A	A563 Grade DH3	S1: $0.82 S2: $0.45 S3: $0.48 S4: $0.95 S5: N/A	F436 Type 3	S1: $0.34 S2: $0.15 S3: $0.12 S4: $0.25 S5: N/A	S1: $3.35 S2: $2.15 **S3: $2.05** S4: $3.60 S5: N/A
Standard	A325, HDG	S1: $4.04 S2: $1.60 S3: $1.79 S4: $2.90 S5: N/A	A563 HDG	S1: $1.12 S2: $0.60 S3: $0.53 S4: $0.90 S5: N/A	F436 HDG	S1: $0.27 S2: $0.16 S3: $0.14 S4: $0.25 S5: N/A	S1: $5.43 **S2: $2.36** S3: $2.46 S4: $4.05 S5: N/A
Corrosion-resistant	A193 B8-2	S1: $13.50 S2: $16.95 S3: $12.59 S4: $11.00 S5: N/A	A194	S1: $9.00 S2: $8.85 S3: $10.46 S4: $5.75 S5: N/A	304[b]	S1: $0.59 S2: $2.25 S3: $0.72 S4: $1.45 S5: N/A	S1: $23.09 S2: $28.05 S3: $23.77 **S4: $18.20** S5: N/A
Corrosion-resistant	2205[c]	S1: $15.50 S2: $21.45 S3: $23.96 S4: $13.95 S5: $20.59	2205[c]	S1: $9.75 S2: $12.55 S3: $14.73 S4: $8.15 S5: $12.06	2205[c]	S1: $1.29 S2: $3.00 S3: $3.78 S4: $1.95 S5: $1.99	S1: $26.54 S2: $37.00 S3: $42.47 **S4: $24.05** S5: $34.64
Standard	A490	S1: $3.05 S2: $1.69 S3: $1.62 S4: $2.85 S5: N/A	A563	S1: $0.82 S2: $0.43 S3: $0.41 S4: $0.85 S5: N/A	F436	S1: $0.25 S2: $0.11 S3: $0.10 S4: $0.20 S5: N/A	S1: $4.12 S2: $2.23 **S3: $2.13** S4: $3.90 S5: N/A
Corrosion-resistant	MCA	N/A	MCA	N/A	MCA	N/A	N/A

HDG = hot-dipped galvanized; MCA = martensitic chromium alloy; N/A = price quote for component not provided by given supplier.
[a] S1 = Supplier 1; S2 = Supplier 2, etc.
[b] All 2205 prices pertain to foreign-manufactured items.

The results in Table 26 for fastener assembly total cost by category and supplier are summarized graphically in Figure 47. Average complete fastener prices are shown in Figure 47, but price variation among the suppliers was wide. The average percentage difference from the minimum to maximum price of corrosion-resistant A193 B8-2 and 2205 fastener assemblies was 65% and for standard A325 and A490 bolted assemblies was 99%. For A325 Type 3 and A325 HDG bolted assemblies, the price ranges were 76% and 130%, respectively.

Table 27 shows a summary of the minimum cost of each fastener assembly type in the cost evaluation. The table also shows the cost multiplier relative to A325 bolts and HDG bolts. Relative to the minimum-cost A325 bolts, weatherizing and galvanizing treatments cost approximately 1.08 and 1.25 times as much, respectively. For the two types of corrosion-resistant bolts with cost data (i.e., A193 B8-2 and 2205), the minimum-cost multipliers were approximately 9.6 and 12.7 times, respectively, that of an A325 assembly. However, a more appropriate comparison might be between stainless steel fasteners and A325 HDG fasteners as the latter are the most corrosion-resistant standard fasteners used by VDOT. Thus, compared to minimum-cost A325 HDG fasteners, A193 B8-2 and 2205 assemblies are more expensive by approximately 7.7 and 10.2 times, respectively. This additional cost associated with corrosion-resistant fasteners is expected to be offset by a lack of maintenance required over a structure's service life.

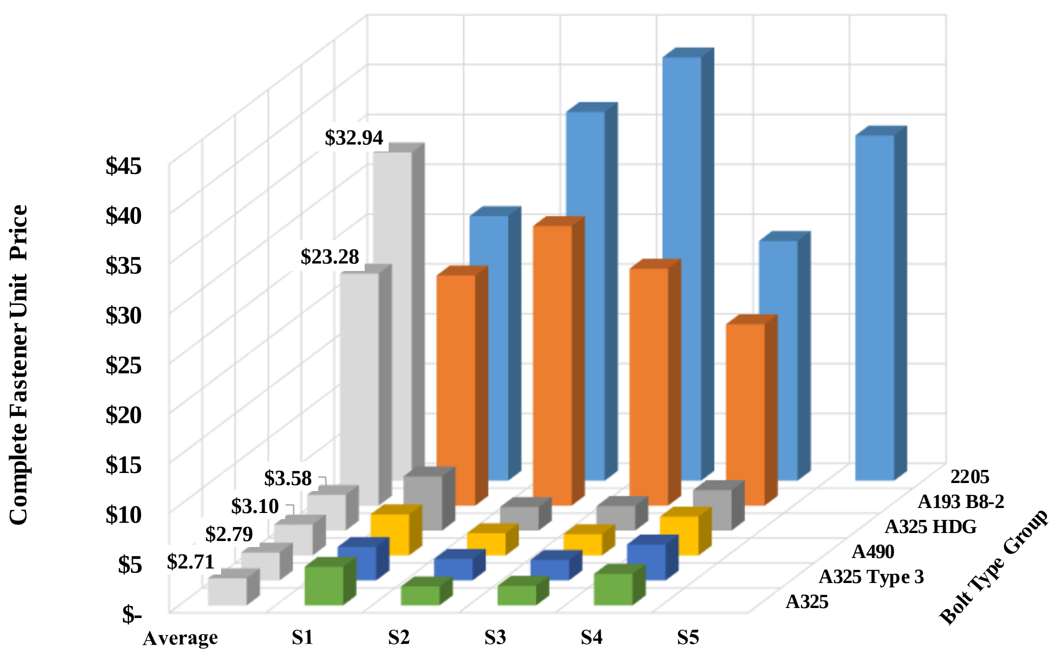


Figure 47. Comparative Prices of Fastener Assemblies. Fastener Assembly Types as in Table 26. S1 = Supplier 1, S2 = Supplier 2, etc.

Table 27. Relative Cost Comparison of Standard and Corrosion-Resistant Fasteners

Fastener Assembly Type	Bolt Type in Fastener Assembly	Minimum Cost From Cost Evaluation	Cost Multiplier Relative to A325	Cost Multiplier Relative to A325 HDG
Standard	A325	$1.89	1.00	0.80
Standard	A325 Type 3	$2.05	1.08	0.87
Standard	A325 HDG	$2.36	1.25	1.00
Corrosion-resistant	A193 B8-2	$18.20	9.63	7.71
Corrosion-resistant	2205	$24.05	12.72	10.19
Standard	A490	$2.13	1.13	0.90
Corrosion-resistant	MCA	N/A	N/A	N/A

HDG = hot dipped galvanized; MCA = martensitic chromium alloy; N/A = price quote for MCA bolts not available.

For corrosion-resistant fasteners, price variation and increased cost relative to standard-type fasteners among suppliers are due to differences in basic prices (sometimes negotiable) and other factors (such as charges for non-standard dimensions and thicknesses, services, packing, and other special costs) and to differences in surcharges on elements in the alloys, which are published regularly by some manufacturers and might account for more than one-third of the final cost (Montanstahl, 2019). The stainless alloy A193 B8-2 and 2205 fastener assemblies incorporate chromium and nickel in higher percentages than other elements, as seen in the chemical compositional results of the fasteners.

To evaluate the influence of surcharge cost in the A193 B8-2 and 2205 fastener assembly cost, chromium and nickel surcharge data were analyzed for Type 304 stainless and 2205 steel. Type 304 stainless steel was analyzed because it is the steel type from which A193 B8-2 fastener assemblies are manufactured. Figure 48 shows that chromium surcharges tracked closely within the two steel grades across a sample of manufacturers that make these surcharge data public. The higher level of chromium surcharges for Grade 2205 partially explains the higher prices for fasteners made of 2205 in Figure 48. All surcharges on chromium showed an apparent downward trend since 2017. To summarize Figure 48, the declining surcharges on chromium would not seem to pose a potential future challenge for consumers of the corrosion-resistant steels investigated in this study.

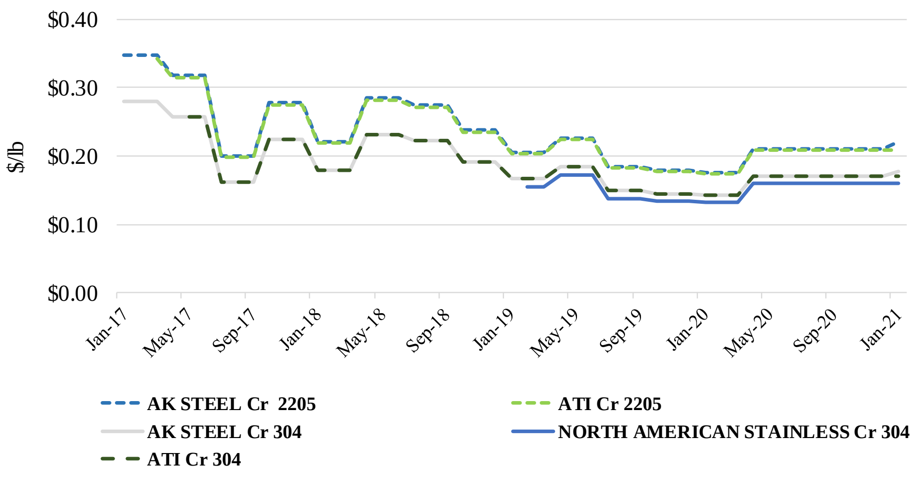


Figure 48. Sample of Chromium Surcharges by Steel Grade and Manufacturer

By contrast, Figure 49 shows that nickel surcharges have trended upward since 2017, with significant price volatility for reasons not discussed here. In addition, nickel surcharges for 2205 steel were less than those for 304 steel for all manufacturers. One potential reason is the larger market for 304 steel and therefore potentially more aggressive bidding for its compositional elements, such as nickel. As with chromium, however, manufacturers still track each other's nickel surcharges closely within steel grades.

Explaining the general upward trend in nickel surcharges shown in Figure 49 requires taking stock of other products that compete with the stainless steel industry for world nickel supplies. For the present and near future, a leading competitor for nickel supplies are electric and hybrid vehicle batteries, particularly since the recent enactment of European and U.S. state legislation (e.g., in Virginia and California) that enforces cap-and-trade carbon emission policies and incentivizes ambitious drops in (or, as in Europe, bans of) sales of internal combustion vehicles within a decade. One reputable energy forecast states that there is a looming crisis in the worldwide nickel market raised by the possibility that demand for Class 1 nickel (from which all raw material for batteries is drawn, under current technology) will surpass supply by year 2029 if not earlier (Azevedo et al., 2020). The potential challenge for the stainless steel market, which consumes about 74% of nickel produced today using a mix of Class 1 (46% of nickel market) and Class 2 (54% of nickel market), is that its current sources may be siphoned off by means of price wars in the production of vehicle batteries.

Figure 50 shows that nickel prices have risen slightly on average over the last two decades, with significant price spikes since 2008 (MINING.com, 2021). For the time being, Class 2 nickel is ruled out for use in the electric vehicle battery industry, but with sufficient demand for nickel, battery technology will adapt.

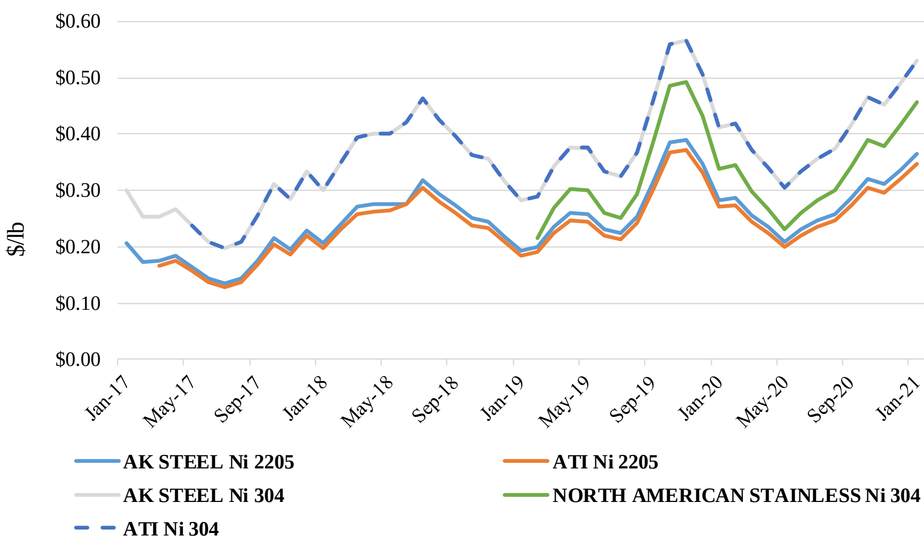


Figure 49. Sample of Nickel Surcharges by Steel Grade and Manufacturer

Figure 50. Nickel Prices Since 1990. Reprinted With Permission of MINING.com.

In the future, consumers of stainless steel products should perhaps expect stainless steel prices to reflect somewhat steadier upward price pressure than in the last decade, attributable largely to sustained rising demand for nickel in electric vehicle batteries if not for other products as well.

Summary of Findings

- Dimensional measurements of the corrosion-resistant fastener assemblies used in this study showed that they did not have the same dimensions as traditional fastener assemblies.

- Proof loading showed that the A193 B8-2 and 2205 bolts have sufficient strength and ductility to meet A325 requirements. The strength and ductility of MCA bolts met the A490 and A325 requirements.

- The A193 B8-2 and 2205 bolts met the shear and wedge requirements for A325, and the MCA bolts did the same for A490.

- All of the corrosion-resistant nuts passed the proof load and cone proof load requirements for A563 nuts.

- Hardness tests revealed that the 2205 washers were approximately two-thirds as hard as typical F436 washers and that the MCA washers fell approximately 1% short of being as hard as typical F436 washers. The hardness of the 303 washers tested in this study was significantly less than that of typical F436 washers. Hardness of components, such as washers, can be improved through strain hardening.

- Friction tests showed that the type of lubricant used has a large impact on galling of stainless steel fasteners. Lubricant 5 was much more effective in preventing galling for all three corrosion-resistant bolt types tested.

- The A193 B8-2 bolts were more susceptible to galling than the 2205 and MCA bolts. The MCA bolts showed good performance with all of the lubricants tested, showing good resistance to galling.

- Torqued tension test results showed that use of the soft 303 washers used in this study, which were not strain hardened, with A193 B8-2 bolts can produce poor installation results, causing the bolts to fail to reach their specified minimum bolt pretension value. Comparisons made with the results of a previous study showed that A193 B8-2 performance can be improved through use of harder 303 washers. Torqued tension tests also confirmed that Lubricant 5 was most effective in preventing galling of the corrosion-resistant steel fasteners.

- Relaxation tests showed that the 2205 bolts had approximately 6% relaxation, which is slightly greater than the 5% expected relaxation for A325 bolts, and the A193 B8-2 and MCA bolts had comparable relaxation to A325 and A490 bolts.

- A method was developed to determine the specified minimum bolt pretension and the nut rotation required to reach that pretension using the turn-of-nut installation method.

- The aforementioned method was used to show that 2205 bolts can be reliably pretensioned to 30 kip whereas the MCA bolts can be reliably pretensioned to 49 kip. Nut rotation values for turn-of-nut installation to achieve these pretension values for 3.5-in-long and 5-in-long bolts are included in this report. A previous study had shown that 193 B8-2 bolts could be reliably pretensioned to 30 kip.

- A cost evaluation showed that the A193 B8-2 and 2205 fastener assemblies can be expected to cost approximately 9 to 13 times more than A325 fastener assemblies, but this cost is decreased to approximately 8 to 10 times more when compared to the cost of A325 HDG fastener assemblies.

- The cost evaluation showed that domestically produced 2205 fastener assemblies were not available for purchase at the time the evaluation was conducted in February 2020.

CONCLUSIONS

- *Suitable corrosion-resistant bolt, nut, and washer combinations exist for 50CR steel.* Suitable fastener assemblies include the 2205 bolts, nuts, and washers and the MCA bolts, nuts, and washers included in this study. The A193 B8-2 bolts and A194 nuts used in this study are also suitable, but the accompanying 303 or 304 austenitic stainless steel washers must be strain hardened.

- *The 2205 and MCA washers performed well, but the sample of 303 washers used in this study was insufficiently hardened.* Washer hardness is critical to the pretensioning of bolts in slip-critical connections, and strain hardening must be performed to ensure that the austenitic stainless steel washers meet a minimum hardness value.

- *Specified minimum bolt pretension values and installation parameters, such as the nut rotation for turn-of-nut installation, can be determined for corrosion-resistant bolts.* A method for determining these values was developed in this study based on existing fastener specifications and the literature. Based on this method, A193 B8-2 and 2205 bolts can be pretensioned to 30 kip and MCA bolts can be pretensioned to 49 kip provided the washers used during installation are sufficiently hardened.

- *Although many lubricants are advertised for use with stainless steel fasteners, some are much more effective than others at preventing galling.*

- *Corrosion-resistant bolts lack standard dimensional requirements.* Non-standard dimensions prevent corrosion-resistant bolts from being specified and detailed in the same manner as A325 bolts.

- *The commercial and domestic availability of corrosion-resistant steel fasteners needs to be evaluated.* The MCA fasteners used in this study were produced as a trial batch and are not yet commercially available. The cost evaluation revealed that as of February 2020, a large quantity of 2205 fasteners was not domestically available.

RECOMMENDATIONS

1. *VTRC should initiate a technical assistance project to continue evaluating corrosion-resistant steel fasteners. This project would address issues such as dimensional standards, acceptable hardness limits, and domestic availability of corrosion-resistant fasteners.*

2. *VTRC should develop a research needs statement (RNS) to continue evaluating the corrosion performance of standard and corrosion-resistant steel fastener assemblies and submit this RNS to VTRC's Bridge Research Advisory Committee (BRAC).*

3. *VDOT's Structure and Bridge Division, VDOT's Materials Division, and VTRC should work together to initiate development of a special provision for corrosion-resistant steel fastener assemblies on VDOT projects, including their use with 50CR steel and in corrosive environments. The special provision should include allowable bolt/nut/washer combinations, dimensional requirements, necessity of washer, acceptable hardness limits, installation procedure, specified minimum bolt pretension, allowable lubricants, surface condition factors, and acceptance testing.*

IMPLEMENTATION AND BENEFITS

Implementation

The implementation of Recommendation 1 will include VTRC initiating discussions with the FHWA and corrosion-resistant fastener producers and conducting additional hardness and torqued tension tests on newly supplied washers and potentially washers taken from the Route 340 Bridge. Discussions could include VDOT's Structure and Bridge Division. These discussions and initial testing may result in the need for future additional tests. Recommendation 1 will be implemented within 1 year of the publication of this report.

The implementation of Recommendation 2 will include VTRC developing an RNS and submitting it to BRAC. This RNS will detail a proposed research project to conduct short-term, laboratory corrosion tests on standard and corrosion-resistant steel fastener assemblies. This will include an evaluation of the galvanic corrosion and environmental cracking between the corrosion-resistant steel fasteners included in this study and tests to evaluate the corrosion performance of A325 Type 3 and galvanized bolts with painted, weathering, and galvanized steel girders. This report described the mechanical behavior of corrosion-resistant steel fastener assemblies and the study initiated long-term corrosion tests that will provide valuable data on the corrosion performance of the specimens used in this testing. However, since the fastener assemblies used in these long-term corrosion tests are corrosion resistant, relative comparisons between the specimens may not be available for several years. Short-term corrosion tests conducted in a laboratory would provide for faster results that could be incorporated into VDOT specifications in the near term. Results from these short-term tests will be compared to results from the long-term tests to confirm their accuracy. An RNS for this research will be submitted to BRAC. If the RNS is voted to be a priority research project by BRAC, then the proposed research project can commence, depending on the researchers' workload, budget, etc. Recommendation 2 is expected to be implemented at the BRAC spring 2021 meeting.

The implementation of Recommendation 3 will include VTRC, VDOT's Structure and Bridge Division, and VDOT's Materials Division working together to initiate development of a special provision for corrosion-resistant steel fastener assemblies to be used with 50CR steel. Although this recommendation is only for the initiation of the development of a special provision, it is expected that this special provision would be revised regularly to include the results from implementing Recommendations 1 and 2 and the results of other relevant research. Future revision of this special provision should also include VTRC, VDOT's Structure and Bridge Division, and VDOT's Materials Division. Recommendation 3 will be implemented within 1 year of the publication of this report.

Benefits

The benefit of implementing Recommendation 1 is that VTRC and VDOT will know the types and properties of corrosion-resistant fastener assemblies that are being produced domestically. By knowing which types of corrosion-resistant fastener assemblies are readily available, such as 2205 and MCA, and the properties of those fasteners, such as washer hardness, VDOT can develop better specifications that align with the current industry practice.

The benefit of implementing Recommendation 2 is that it allows VTRC to continue evaluating the corrosion performance of steel fastener assemblies and provide a relative corrosion resistance ranking of these fasteners for use in VDOT specifications. It has already been established that the corrosion-resistant steel fastener assemblies will perform adequately with 50CR steel, but additional research and test data will allow for quantitative results, which could be used to provide guidance for fastener selection depending on the corrosion environment. This additional research will also allow for quantitative data to be developed for standard fastener assemblies with various steel girder corrosion protection systems.

The benefit of implementing Recommendation 3 is that VDOT will have formal guidance on corrosion-resistant fastener assemblies for use with 50CR steel. Provisions for fasteners on past projects using 50CR steel have been developed on a project-by-project basis. The proposed special provision would allow for the design, acceptance, and installation procedures to be combined into a single document for ease of use.

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REFERENCES

Afzali, N., Pilhagen, J., Manninen, T., Schedin, E., and Natalie Stranghöner, N. Preload Losses in Stainless Steel Bolting Assemblies. *Steel Construction*, Vol. 10, No. 4, 2017, pp. 310-318.

American Association of State Highway and Transportation Officials. *AASHTO LRFD Bridge Design Specifications*. 8th Edition. Washington, DC, 2017.

American Society of Mechanical Engineers. *ASME B18.2.6: Fastener for Use in Structural Applications.* New York, 2010.

ASTM International. *ASTM F594: Standard Specification for Stainless Steel Nuts*. West Conshohocken, PA, 2009.

ASTM International. *ASTM E140: Standard Hardness Conversion Tables for Metals Relationship Among Brinell Hardness, Vickers Hardness, Rockwell Hardness, Superficial Hardness, Knoop Hardness, Scleroscop Hardness, and Leeb Hardness*. West Conshohocken, PA, 2012.

ASTM International. *ASTM A1010: Standard Specification for Higher-Strength Martensitic Stainless Steel Plate, Sheet, and Strip*. West Conshohocken, PA, 2013a.

ASTM International. *ASTM F593: Standard Specification for Stainless Steel Bolts, Hex Cap Screws, and Studs*. West Conshohocken, PA, 2013b.

ASTM International. *ASTM F3125: Standard Specification for High Strength Structural Bolts, Steel and Alloy Steel, Heat Treated, 120 ksi (830 MPa) and 150 ksi (1040 MPa) Minimum Tensile Strength, Inch and Metric Dimensions*. West Conshohocken, PA, 2015.

ASTM International. *ASTM F436/F436M: Standard Specification for Hardened Steel Washers Inch and Metric Dimensions*. West Conshohocken, PA, 2016a.

ASTM International. *ASTM F606/F606M: Standard Test Methods for Determining the Mechanical Properties of Externally and Internally Threaded Fasteners, Washers, Direct Tension Indicators, and Rivets*. West Conshohocken, PA, 2016b.

ASTM International. *ASTM A194: Standard Specification for Carbon Steel, Alloy Steel, and Stainless Steel Nuts for Bolts for High Pressure or High Temperature Service, or Both*. West Conshohocken, PA, 2017a.

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

ASTM International. *ASTM E18: Standard Test Methods for Rockwell Hardness of Metallic Materials*. West Conshohocken, PA, 2017c.

ASTM International. *ASTM A320/A320M: Standard Specification for Alloy-Steel and Stainless Steel Bolting for Low-Temperature Service*. West Conshohocken, PA, 2018.

ASTM International. *ASTM A1082/A1082M: Standard Specification for High Strength Precipitation Hardening and Duplex Stainless Steel Bolting for Special Purpose Applications*. West Conshohocken, PA, 2019.

ASTM International. *ASTM A193: Standard Specification for Alloy-Steel and Stainless Steel Bolting for High Temperature or High Pressure Service and Other Special Purpose Applications*. West Conshohocken, PA, 2020a.

ASTM International. *ASTM A1035: Standard Specification for Deformed and Plain, Low-Carbon, Chromium, Steel Bars for Concrete Reinforcement.* West Conshohocken, PA, 2020b.

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#.

Baddoo, N. *Steel Design Guide 27: Structural Stainless Steel.* American Institute of Steel Construction, Chicago, 2013.

Chesson, E., Jr., and Munse, W.H. *Studies on the Behavior of High-Strength Bolts and Bolted Joints.* Engineering Experiment Station Bulletin 469. University of Illinois, Urbana, 1965.

Federal Highway Administration. Construction Program Guide: Buy America. June 27, 2017. https://www.fhwa.dot.gov/construction/cqit/buyam.cfm.

Kulak, G.L., Fisher, J.W., and Struik, J.H.A. *Guide to Design Criteria for Bolted and Riveted Joints*. 2nd Edition. American Institute of Steel Construction, Chicago, 2001.

MINING.com. Nickel Price. 2021. https://www.mining.com/markets/commodity/nickel/.

Montanstahl. Alloy Surcharge, What Is It and How to Calculate It. September 11, 2019. https://www.montanstahl.com/blog/alloy-surcharge/.

Provines, J.T., and Abebe, H. *Slip Coefficient Testing of ASTM A709 Grade 50CR Steel and Dissimilar Metal Slip-Critical Bolted Connections.* VTRC 20-R12. Virginia Transportation Research Council, Charlottesville, 2020.

Provines, J., Ocel, J., Harrop, K., Darby, T.E., Sharp, S., and Moruza, A. Analysis and Construction of the United States' First Completely Stainless Steel Bolted Splice on a Steel Girder Bridge. In *Proceedings of the 2018 World Steel Bridge Symposium,* Baltimore, MD, 2018.

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.

Research Council on Structural Connections. *Specification for Structural Joints Using High-Strength Bolts.* Chicago, 2014.

Reuther, D., Baker, I., Yetka, A., Cleary, D.B., and Riddell, W. Relaxation of ASTM A325 Bolted Assemblies. *Journal of Structural Engineering,* Vol. 140, No. 9, 2014.

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

Stranghöner, N. *Execution and Reliability of Slip Resistant Connections for Steel Structures Using CS and SS.* University of Duisburg-Essen, Essen, Germany, 2018.

Stranghöner, N., Afzali, N., de Vries, P., Schedin, E., Pilhagen, J., and Cardwell, S. Slip-Resistant Bolted Connections of Stainless Steel. *Steel Construction,* Vol. 10, No. 4, 2017a, pp. 333-343.

Stranghöner, N., Jungbluth, D., Abraham, C., and Söderman, A. Tightening Behaviour of Preloaded Stainless Steel Bolting Assemblies. *Steel Construction,* Vol. 10, No. 4, 2017b, pp. 319-332.

Williams, T.R., Xia, X., Darby, T.E., and Sharp, S.R. Evaluation of Stainless Steel Fasteners for Bolted Field Splice Connections of ASTM A1010 Corrosion-Resistant Steel Plate Girders. *Transportation Research Record: Journal of the Transportation Research Board,* No. 2630, 2017, pp. 85-94.

APPENDIX A

ADDITIONAL TEST DATA ON FASTENERS

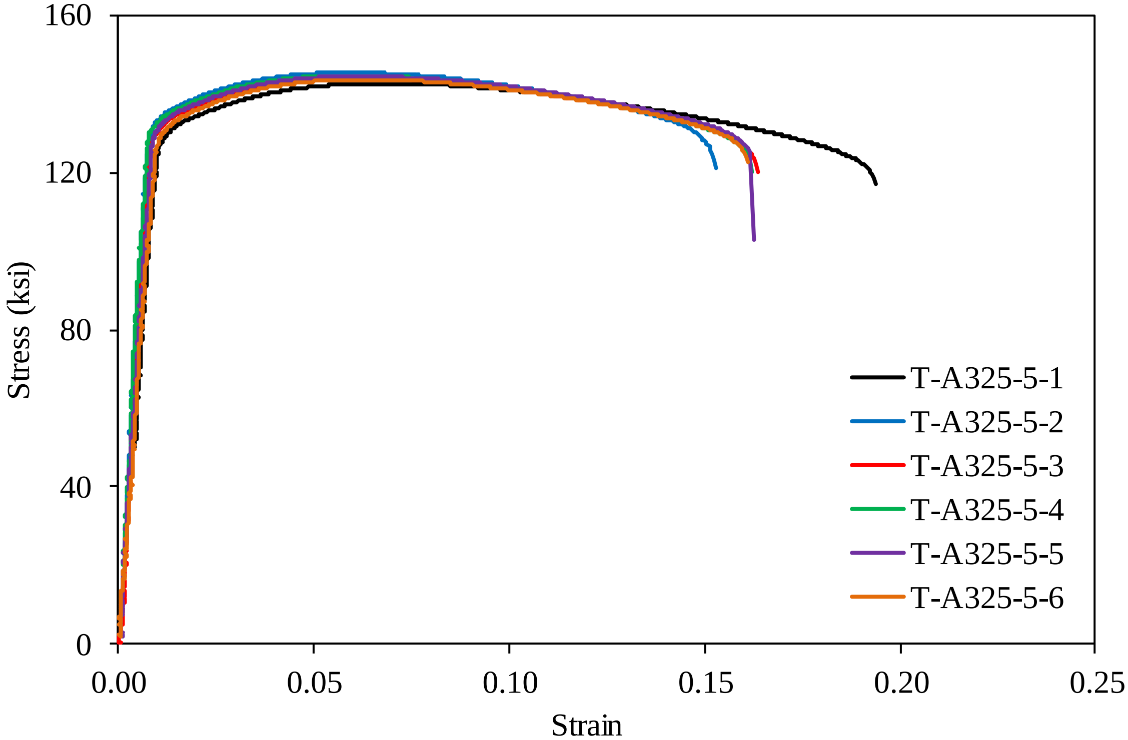

Figure A1. Plot of Stress vs. Strain for A325, 5-in-Long Bolt Proof Loading

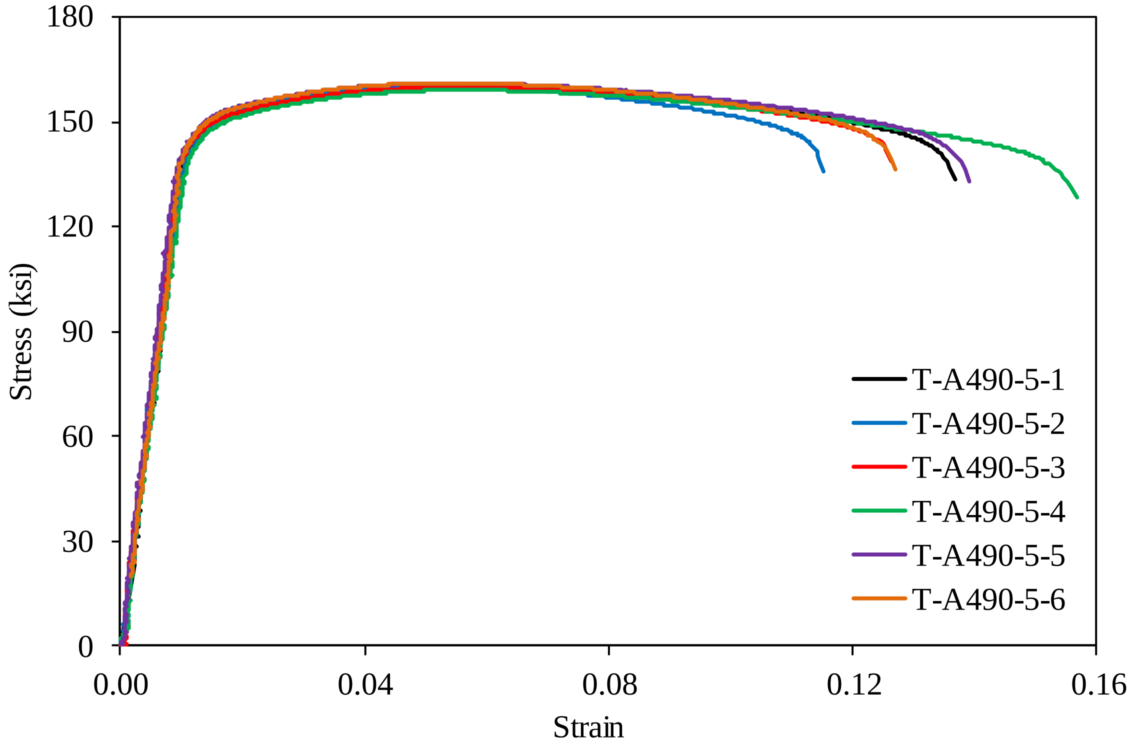

Figure A2. Plot of Stress vs. Strain for A490, 5-in-Long Bolt Proof Loading

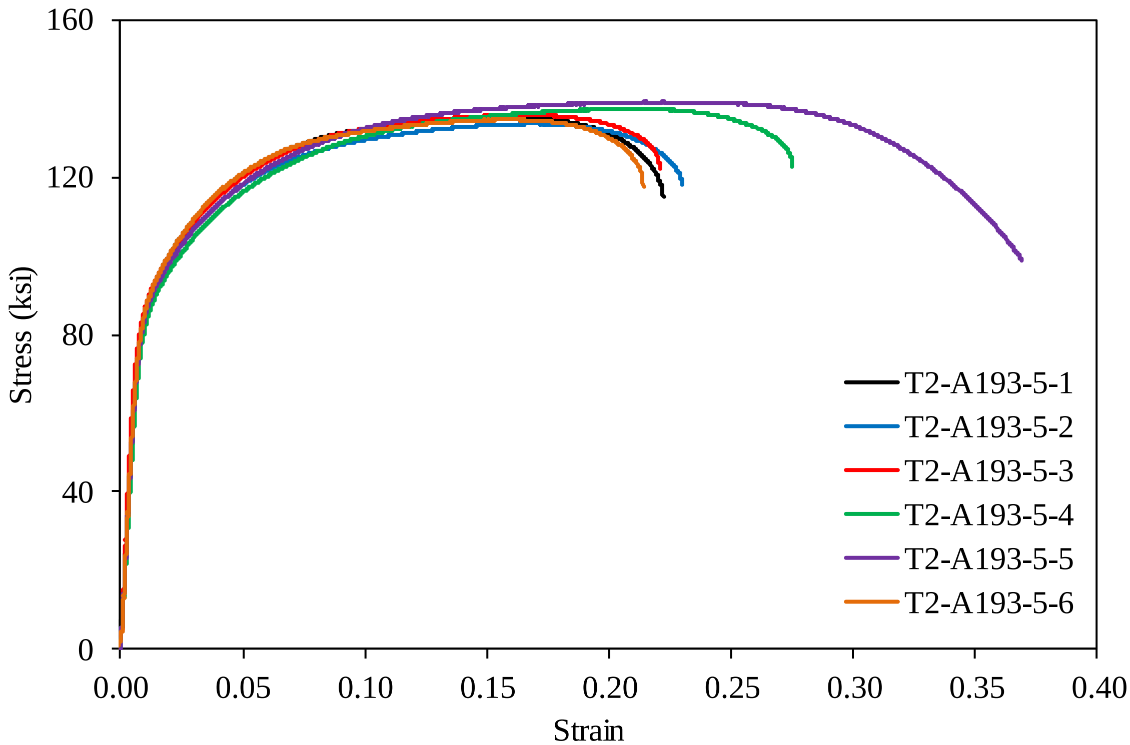

Figure A3. Plot of Stress vs. Strain for A193 B8-2, 5-in-Long Bolt Proof Loading

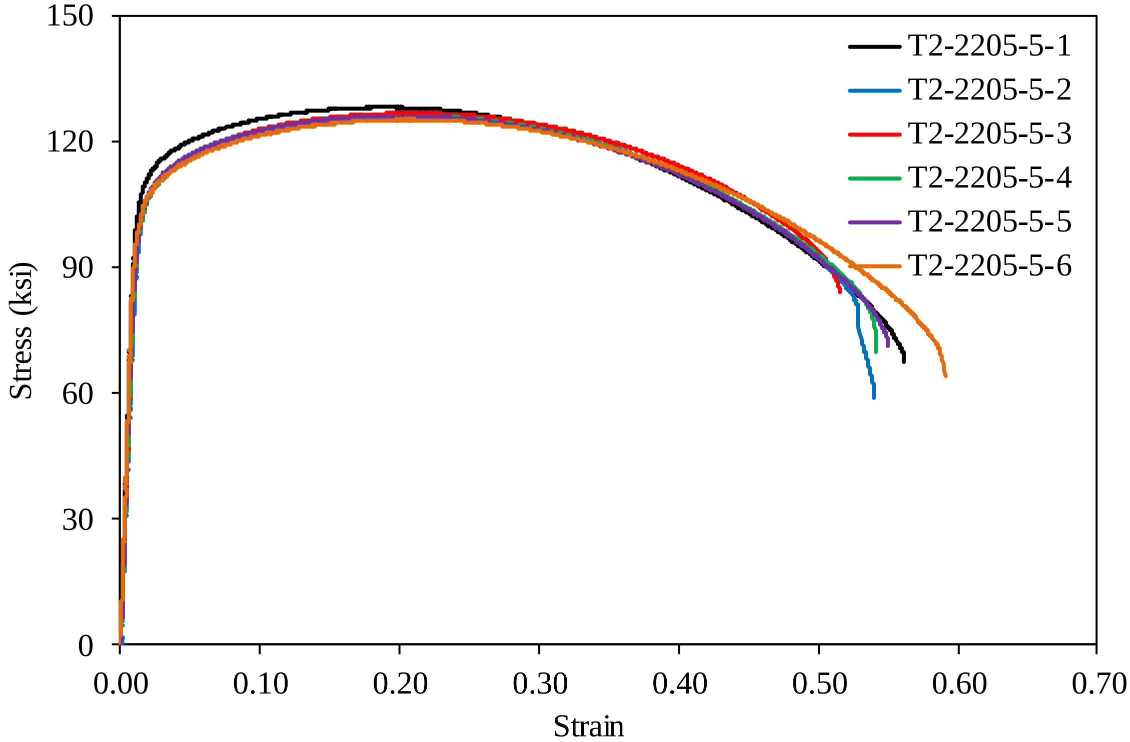

Figure A4. Plot of Stress vs. Strain for 2205, 5-in-Long Bolt Proof Loading

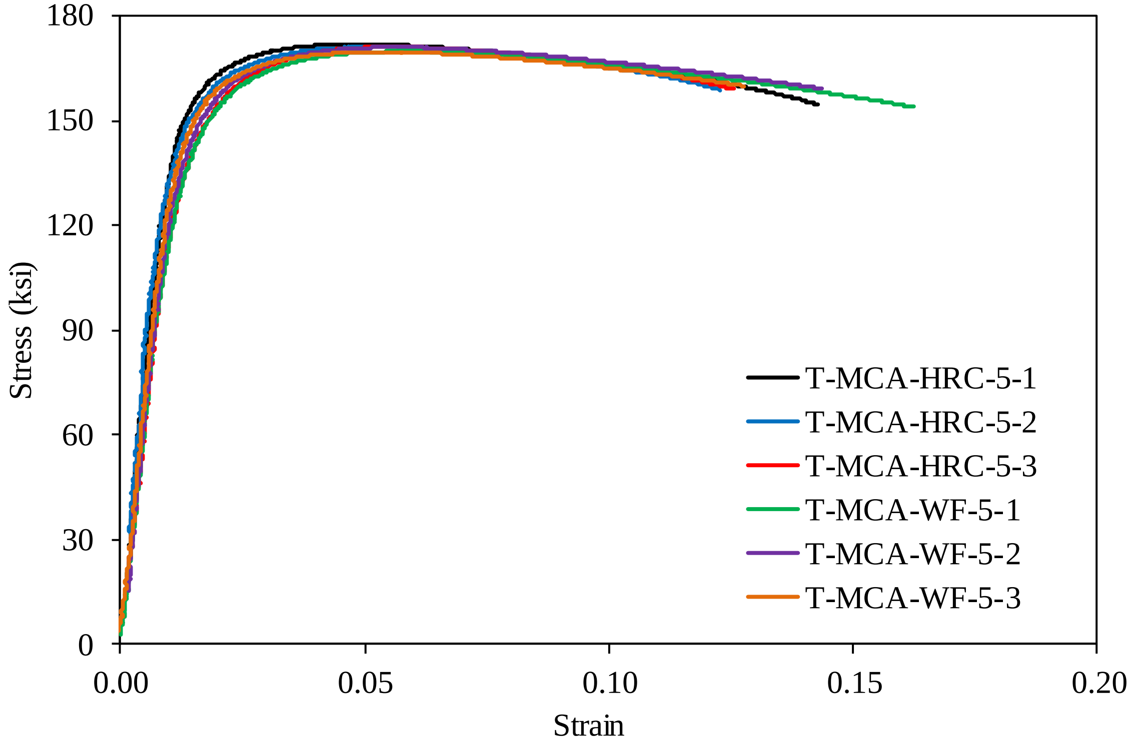

Figure A5. Plot of Stress vs. Strain for MCA, 5-in-Long Bolt Proof Loading. MCA = martensitic chromium alloy.

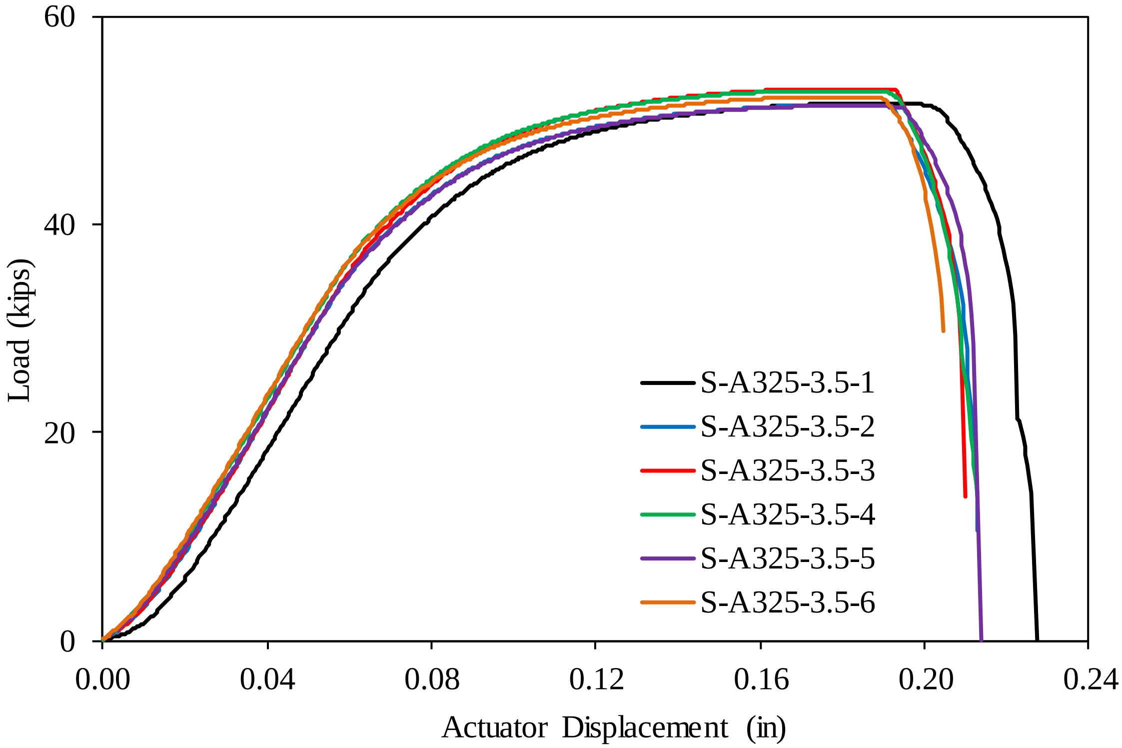

Figure A6. Plot of Load vs. Actuator Displacement for A325, 3.5-in-Long Bolt Shear Tests

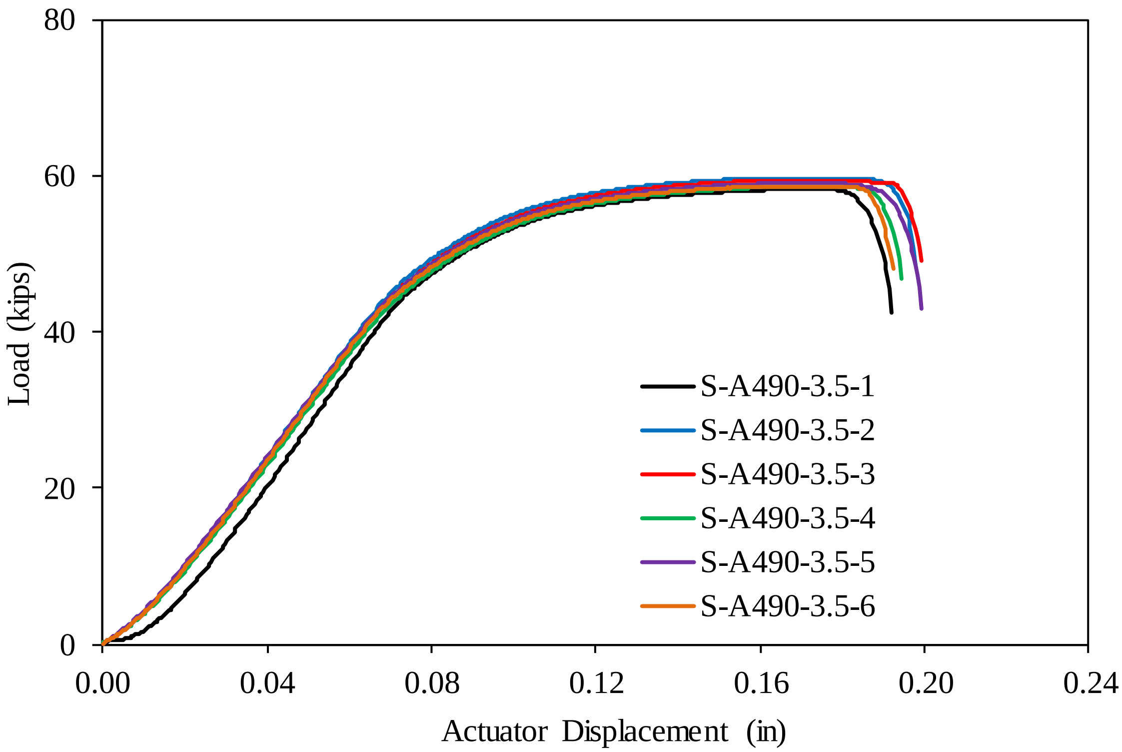

Figure A7. Plot of Load vs. Actuator Displacement for A490, 3.5-in-Long Bolt Shear Tests

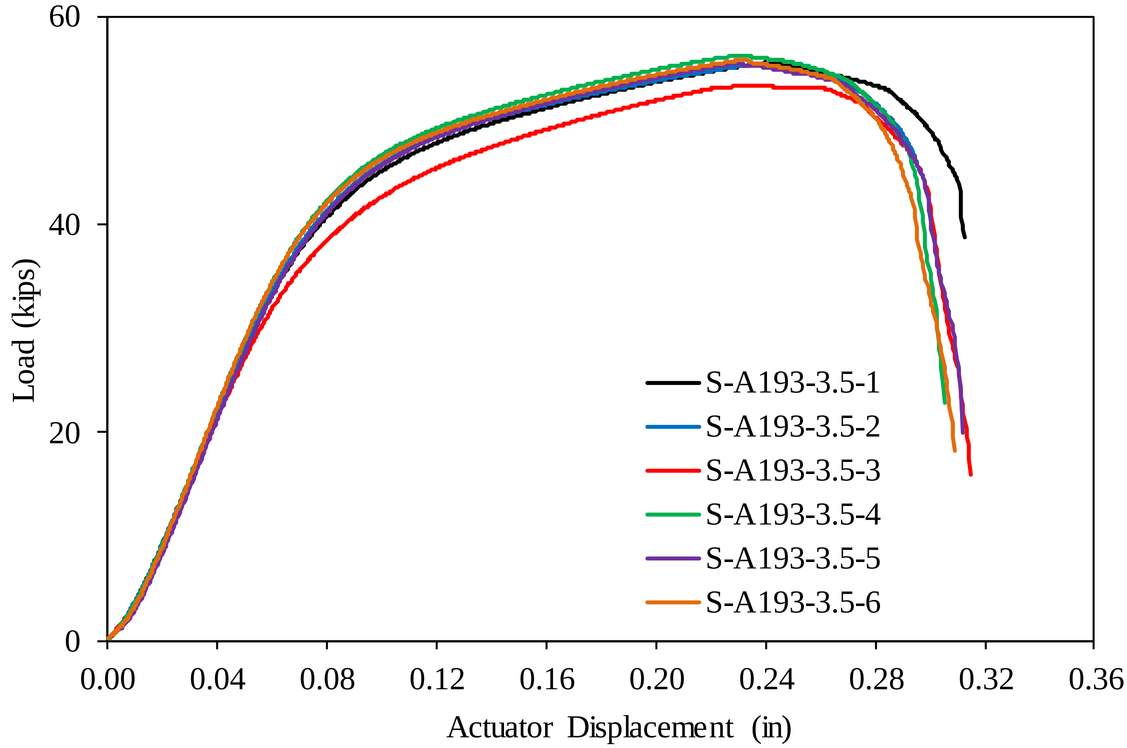

Figure A8. Plot of Load vs. Actuator Displacement for A193 B8-2, 3.5-in-Long Bolt Shear Tests

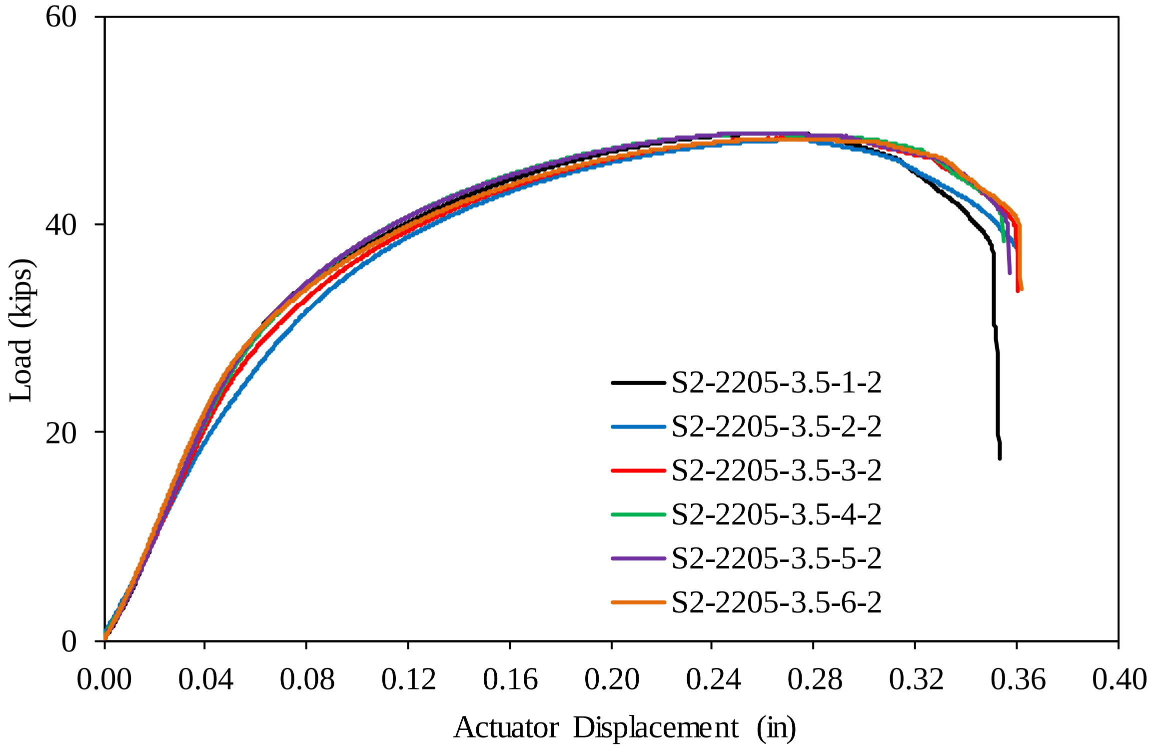

Figure A9. Plot of Load vs. Actuator Displacement for 2205, 3.5-in-Long Bolt Shear Tests

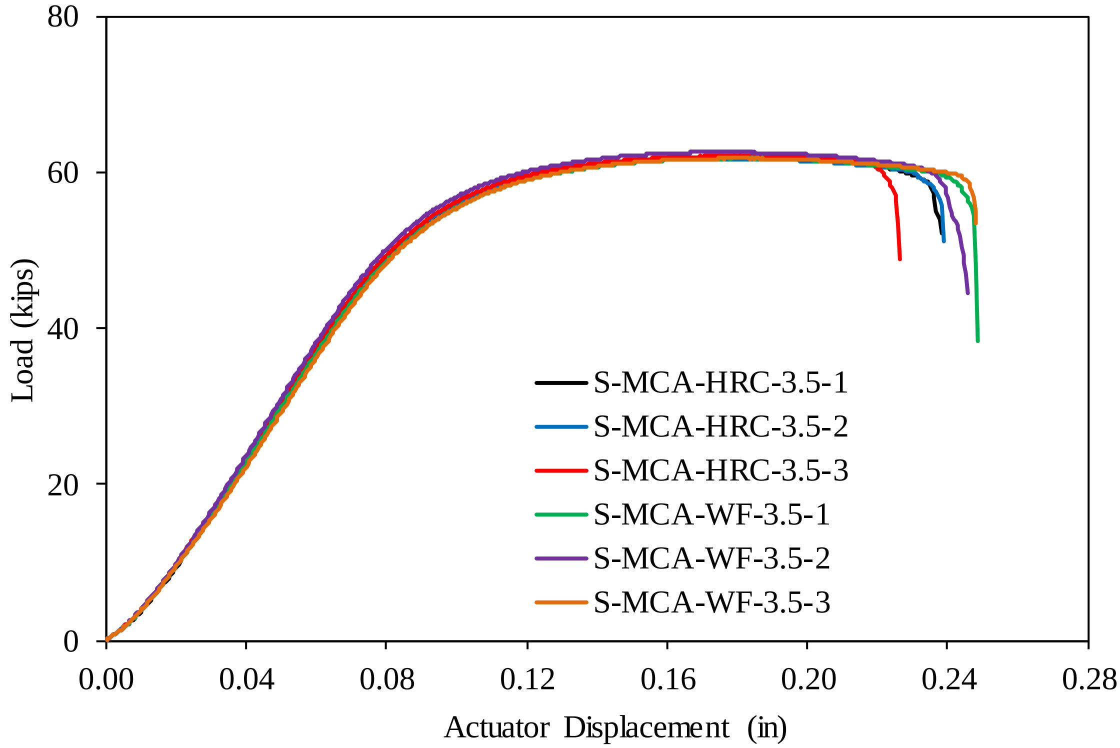

Figure A10. Plot of Load vs. Actuator Displacement for MCA, 3.5-in-Long Bolt Shear Tests. MCA = martensitic chromium alloy.

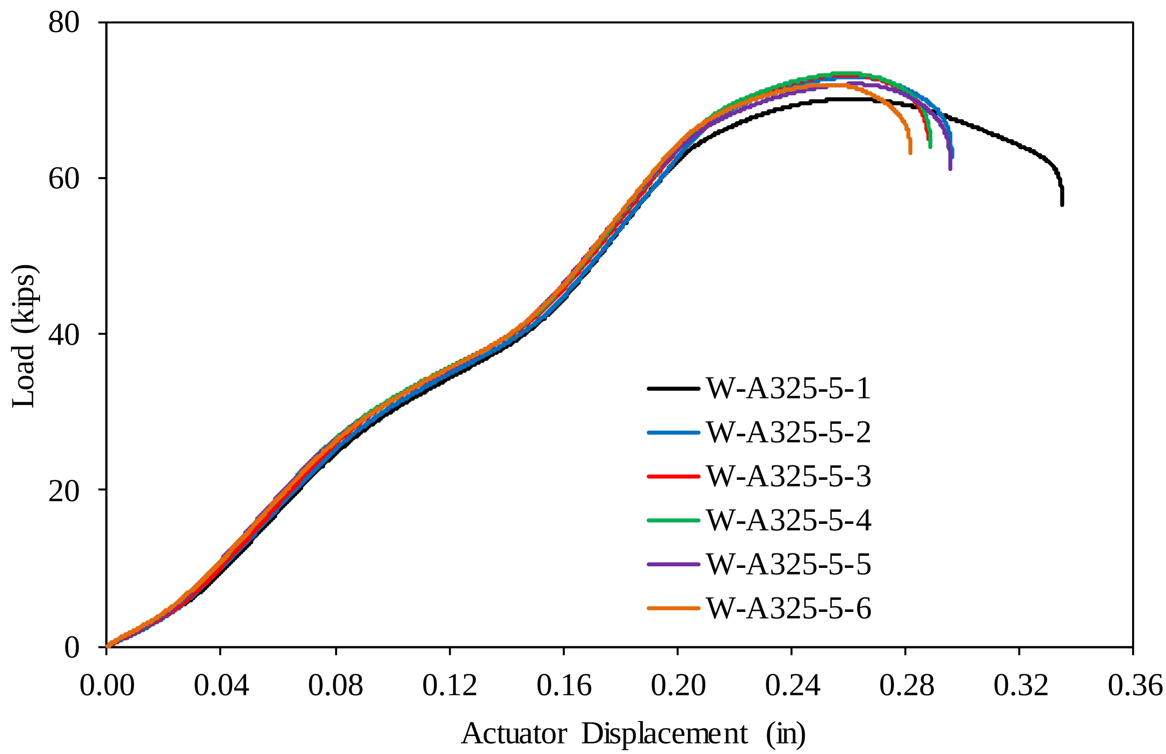

Figure A11. Plot of Load vs. Actuator Displacement for A325, 5-in-Long Bolt Wedge Tests

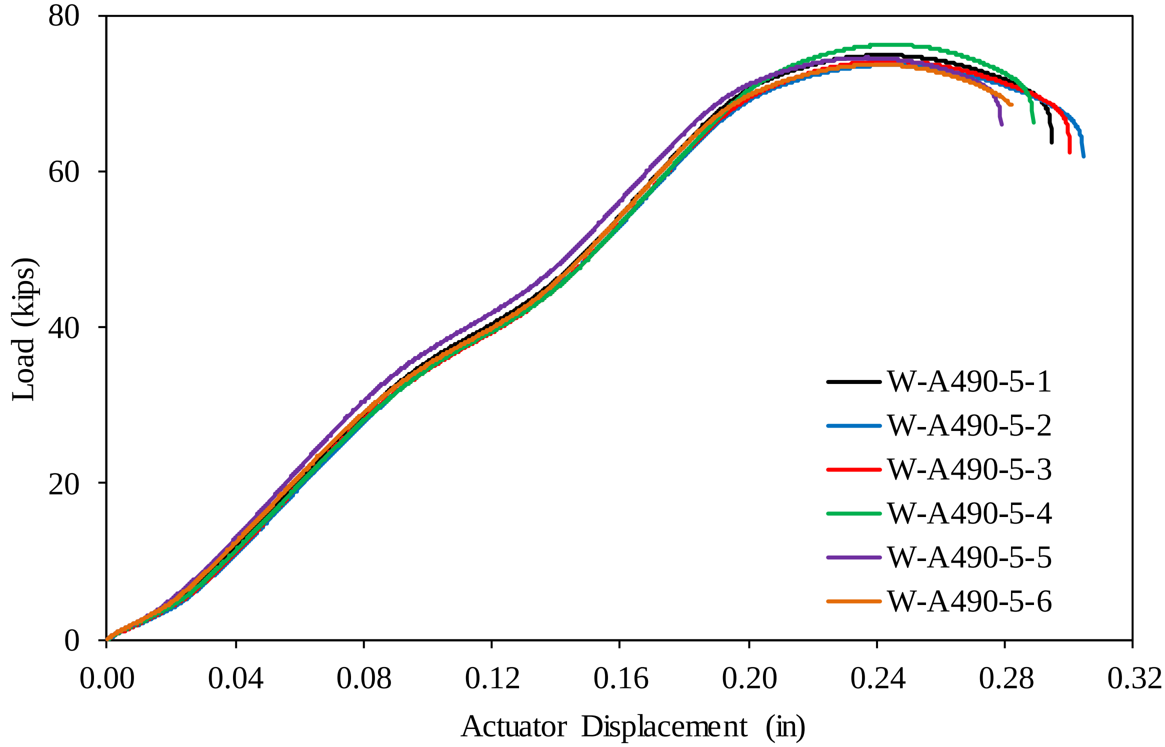

Figure A12. Plot of Load vs. Actuator Displacement for A490, 5-in-Long Bolt Wedge Tests

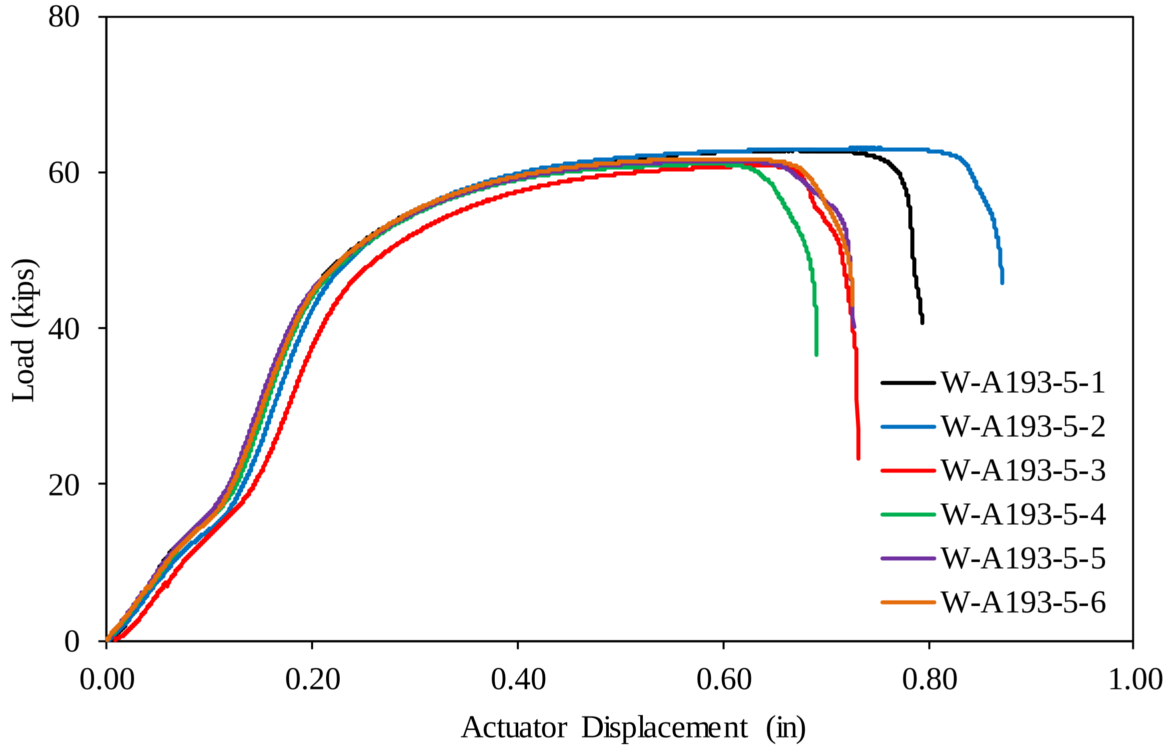

Figure A13. Plot of Load vs. Actuator Displacement for A193 B8-2, 5-in-Long Bolt Wedge Tests

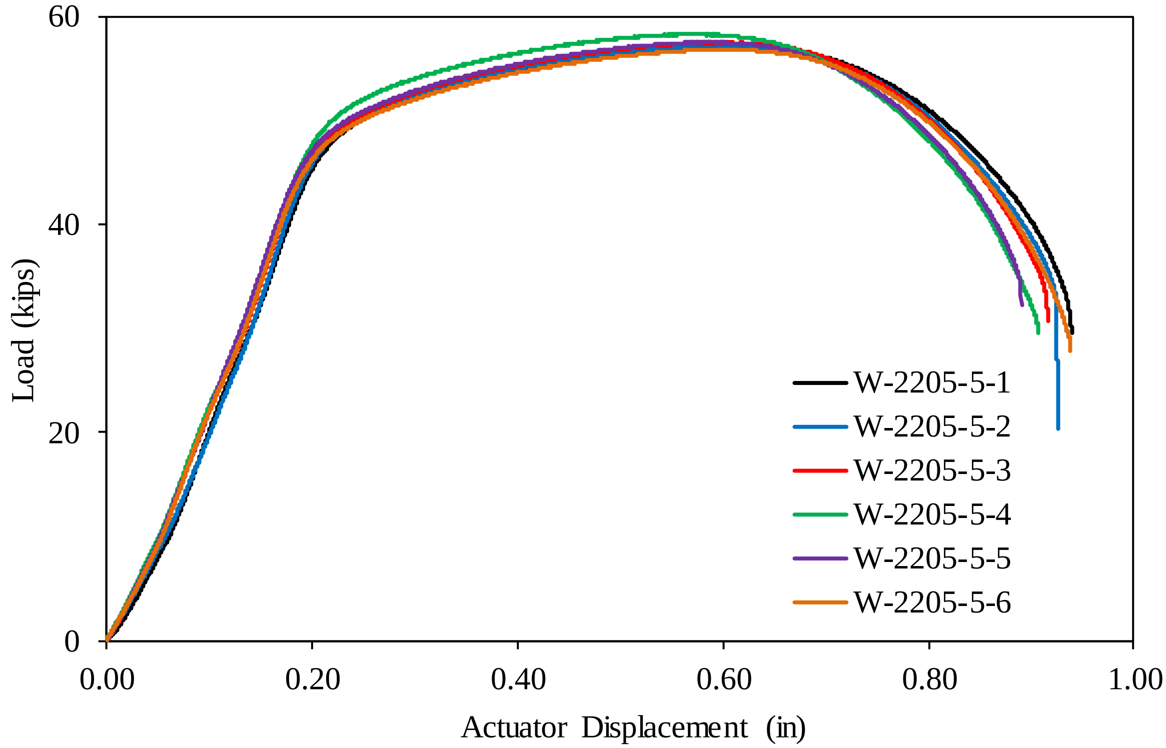

Figure A14. Plot of Load vs. Actuator Displacement for 2205, 5-in-Long Bolt Wedge Tests

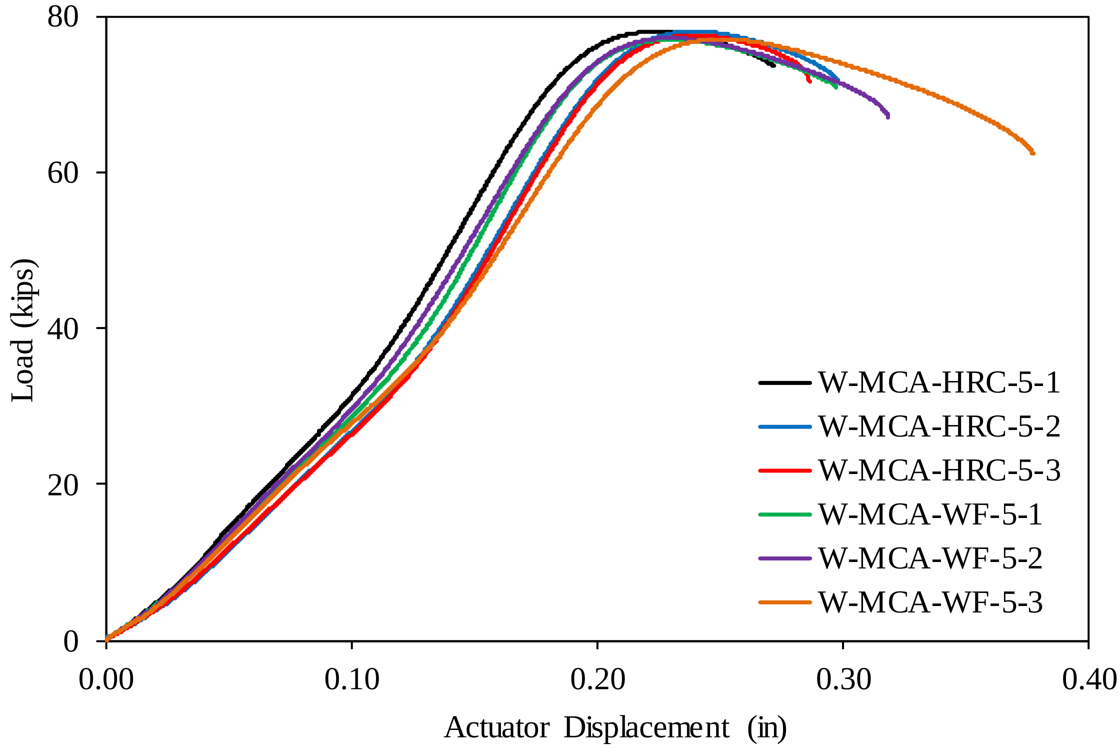

Figure A15. Plot of Load vs. Actuator Displacement for MCA, 5-in-Long Bolt Wedge Tests. MCA = martensitic chromium alloy.

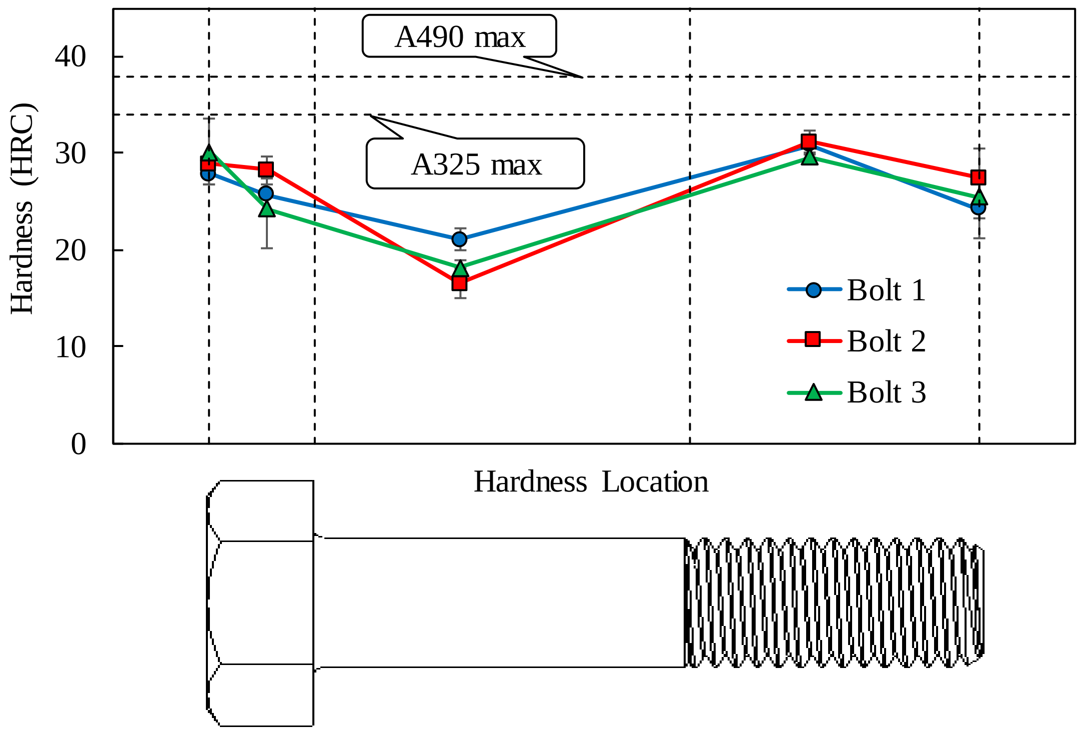

Figure A16. Average Hardness Test Results on A325, 3.5-in-Long Bolts. Error bars are one standard deviation around the mean.

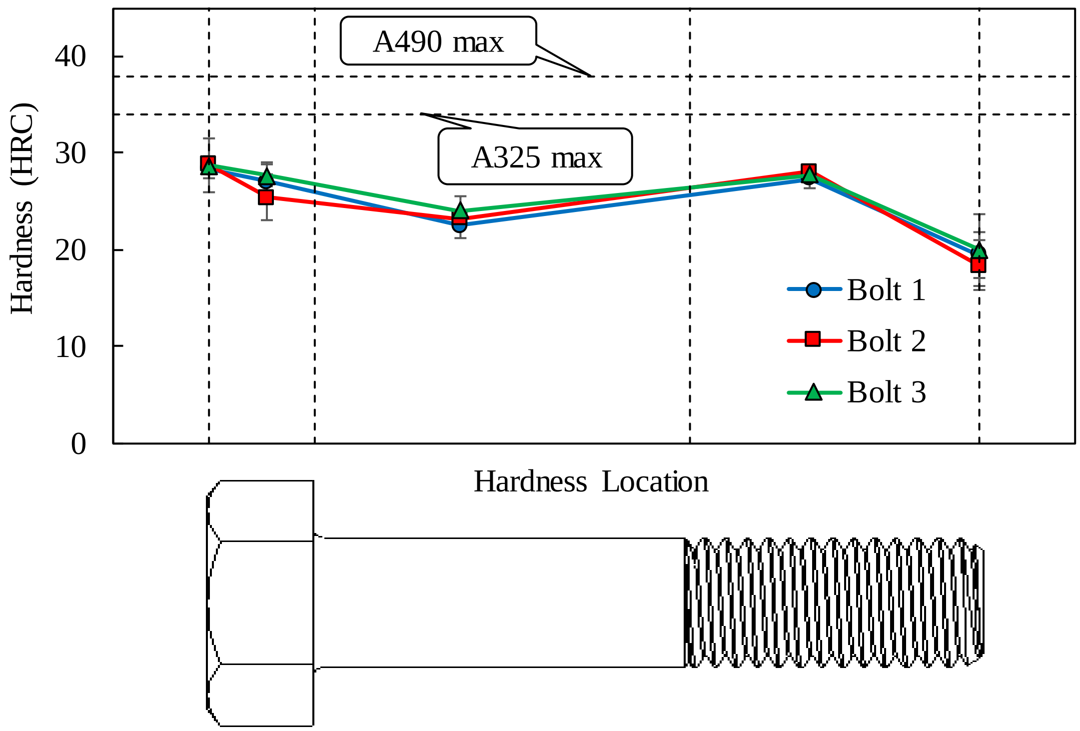

Figure A17. Average Hardness Test Results on A325 Type 3, 3.5-in-Long Bolts. Error bars represent one standard deviation around the mean.

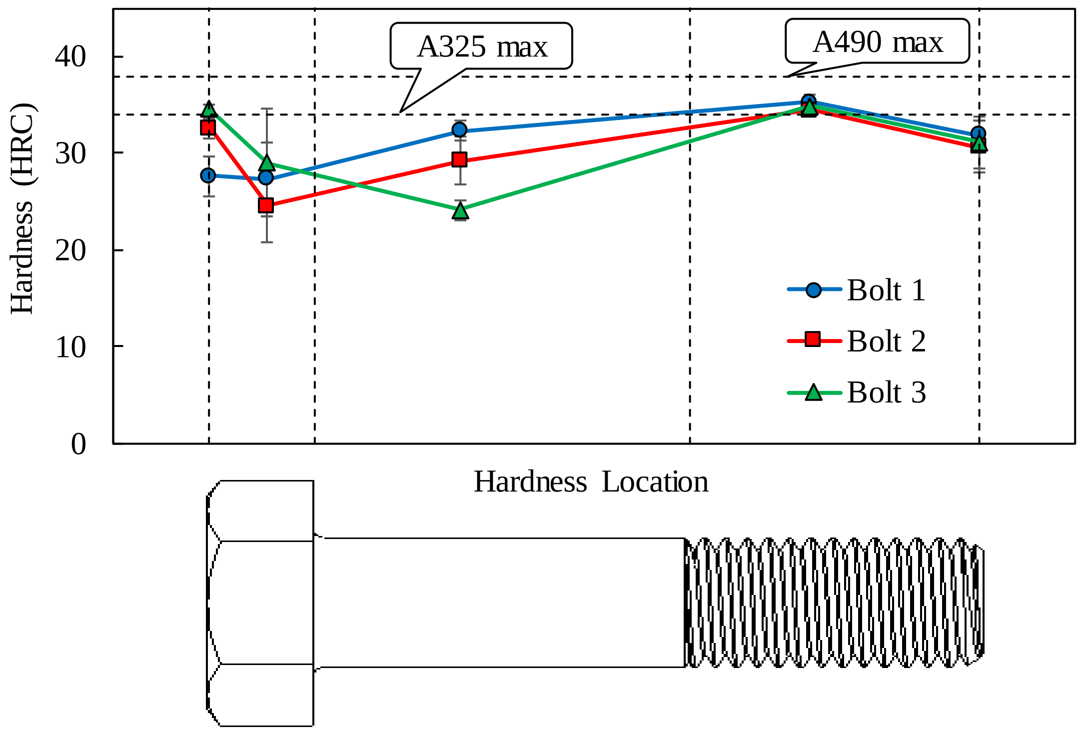

Figure A18. Average Hardness Test Results on A490, 3.5-in-Long Bolts. Error bars represent one standard deviation around the mean.

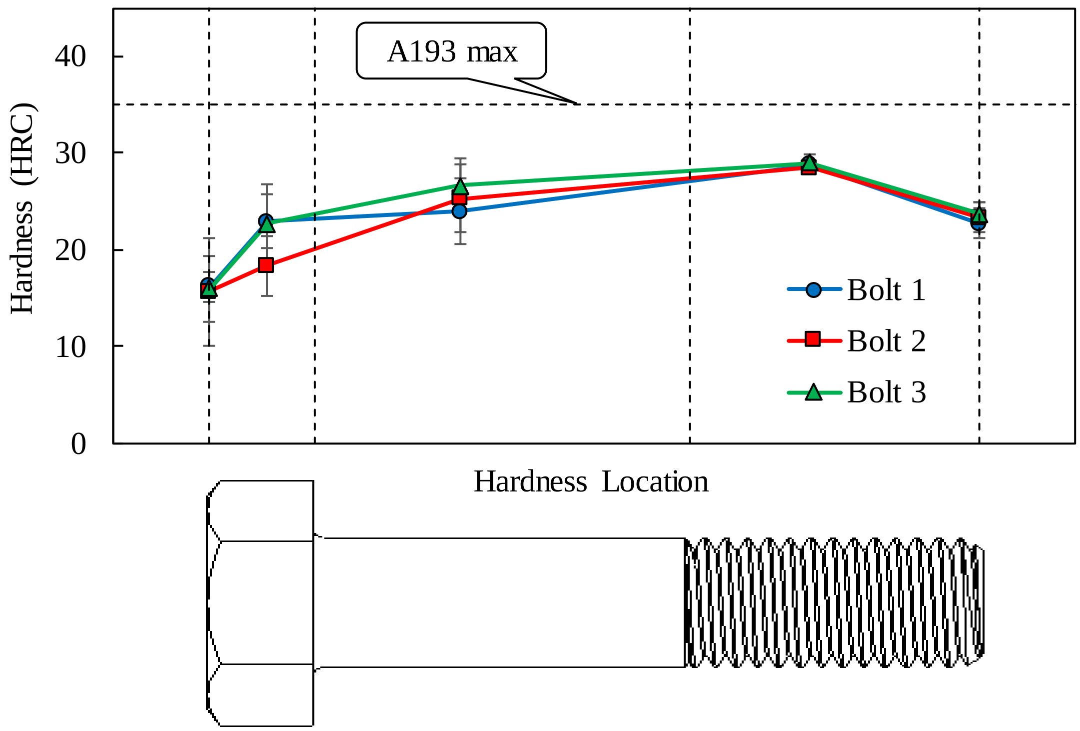

Figure A19. Average Hardness Test Results on A193 B8-2, 3.5-in-Long Bolts. Error bars represent one standard deviation around the mean.

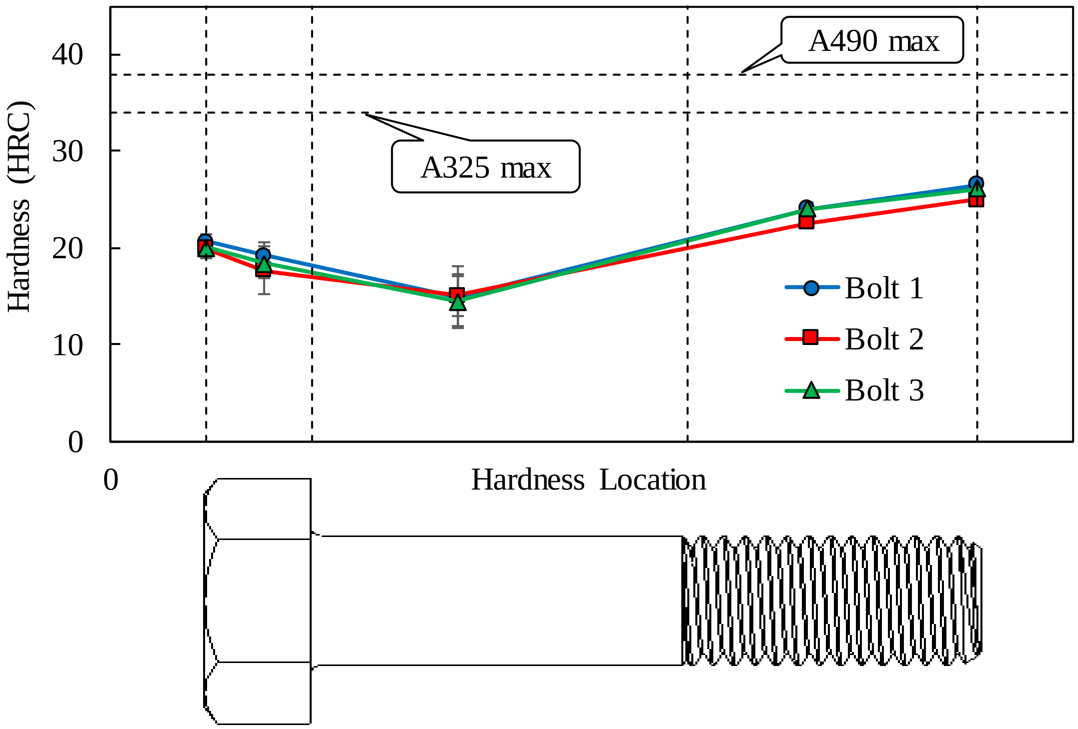

Figure A20. Average Hardness Test Results on 2205, 3.5-in-Long Bolts. Error bars represent one standard deviation around the mean.

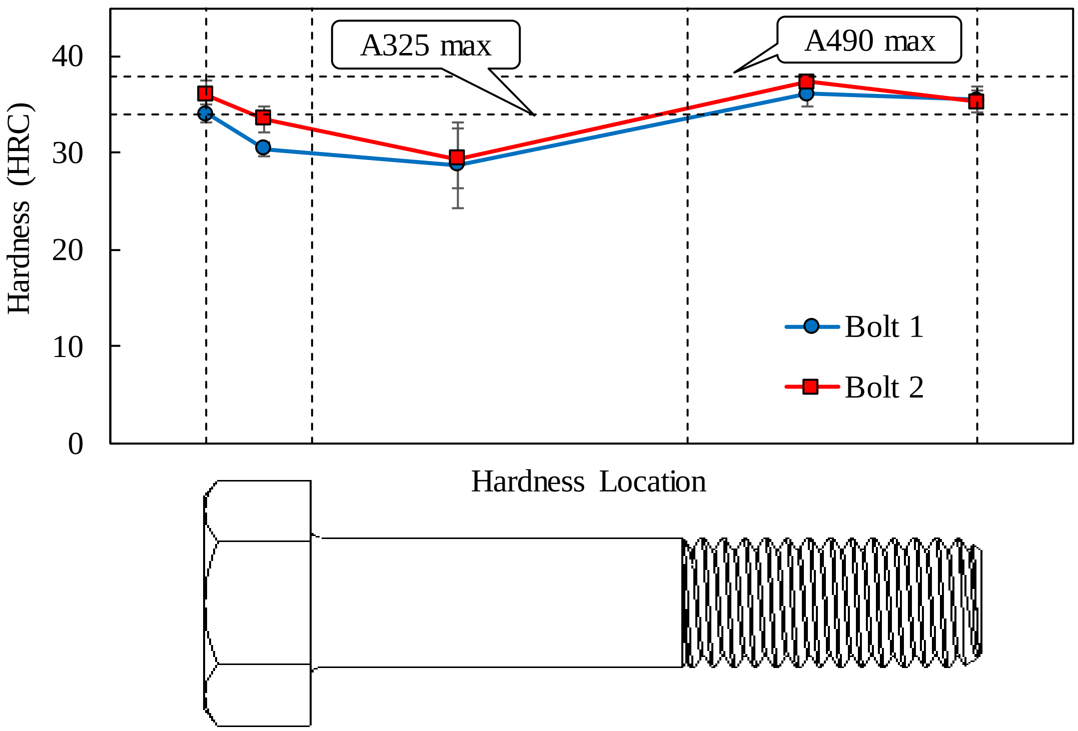

Figure A21. Average hardness test results on MCA, 3.5-in-long bolts. Error bars represent one standard deviation around the mean. MCA = martensitic chromium alloy.

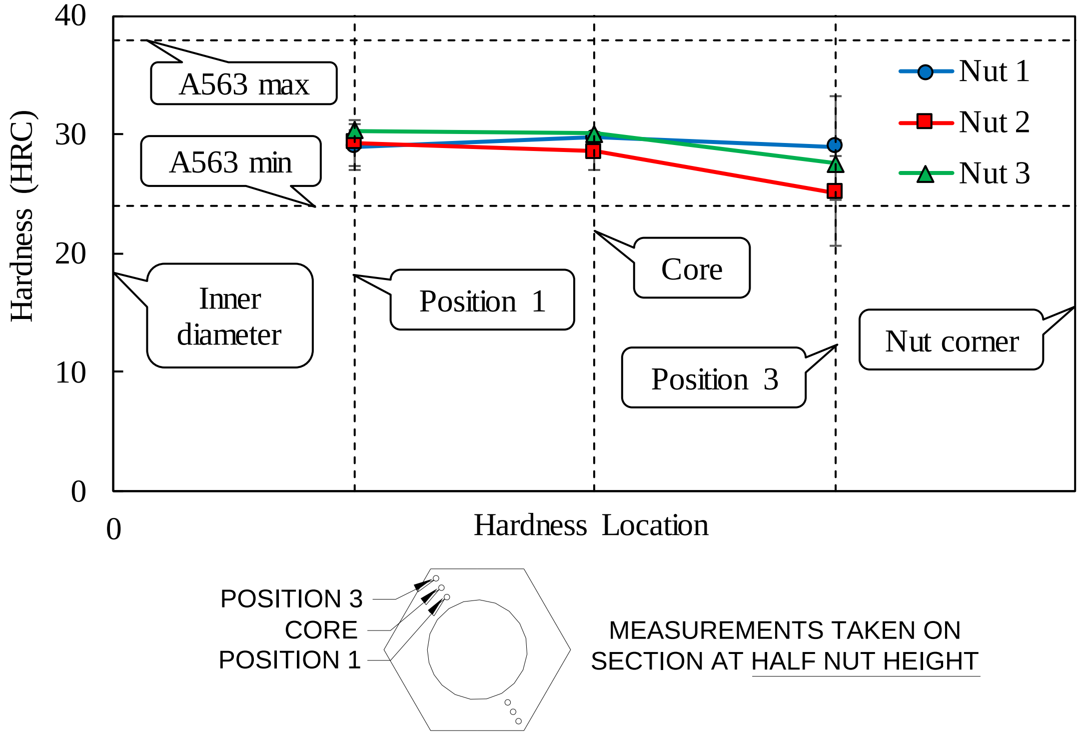

Figure A22. Average Hardness Test Results on A563 Half Nut Height. Error bars represent one standard deviation around the mean.

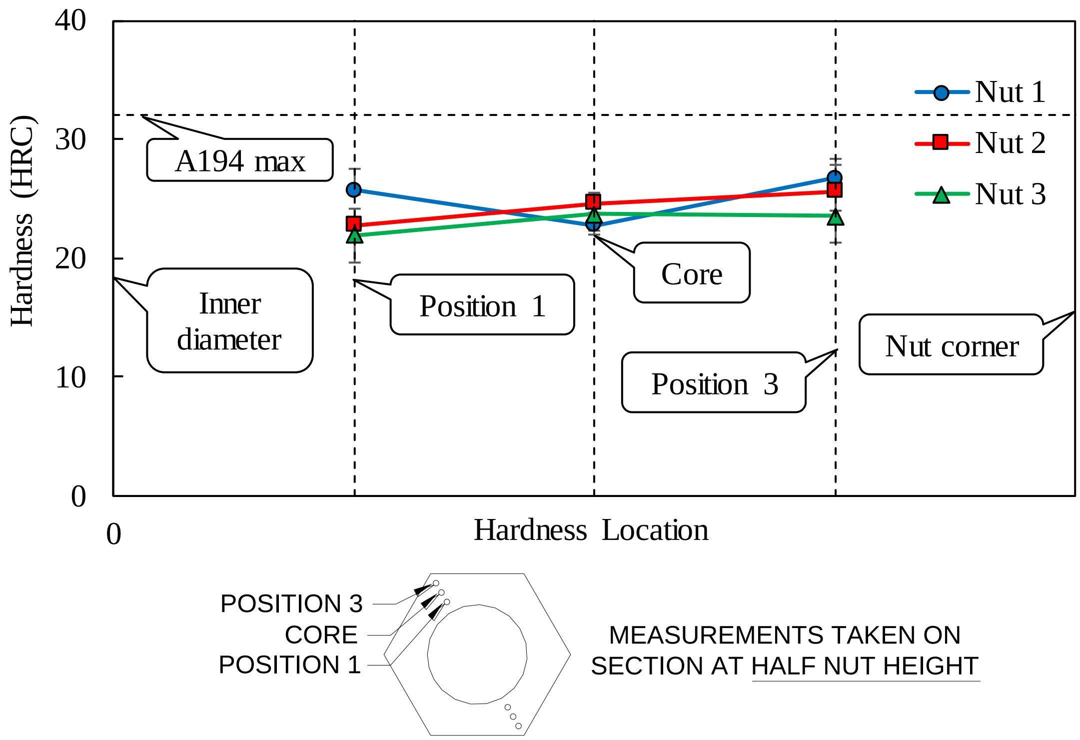

Figure A23. Average Hardness Test Results on A194 Half Nut Height. Error bars represent one standard deviation around the mean.

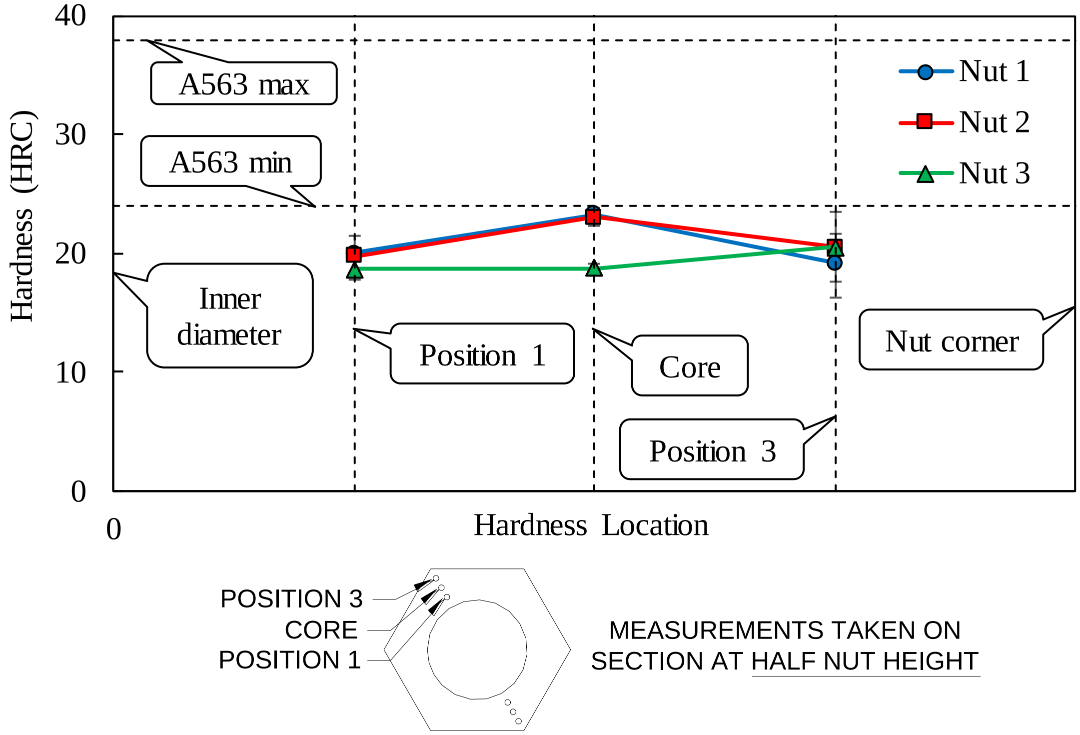

Figure A24. Average Hardness Test Results on 2205 Half Nut Height. Error bars represent one standard deviation around the mean.

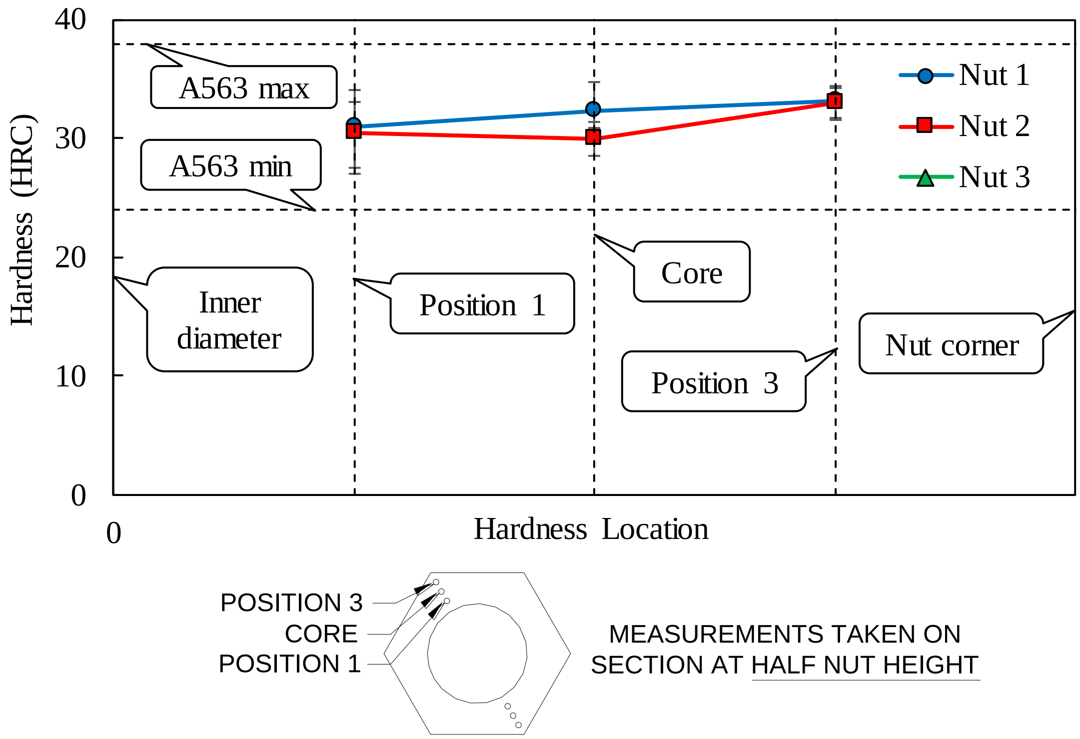

Figure A25. Average Hardness Test Results on MCA Half Nut Height. Error bars represent one standard deviation around the mean. MCA = martensitic chromium alloy.

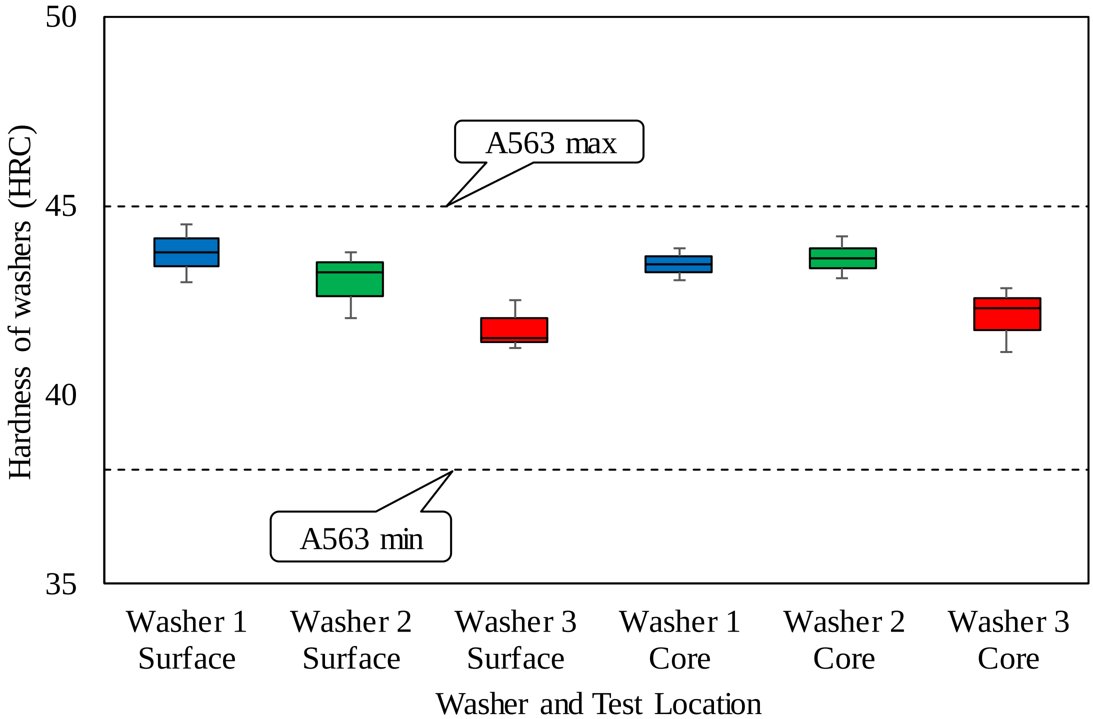

Figure A26. Box and Whisker Plot of Hardness Test Results on F436 Washers

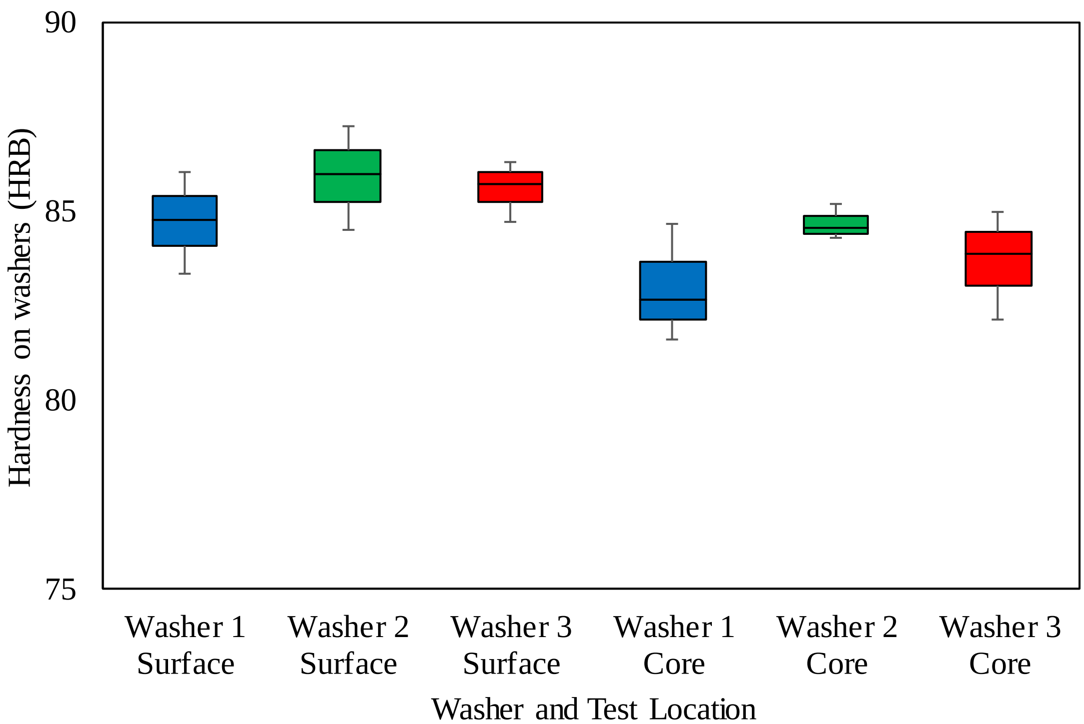

Figure A27. Box and Whisker Plot of Hardness Test Results on 303 Washers

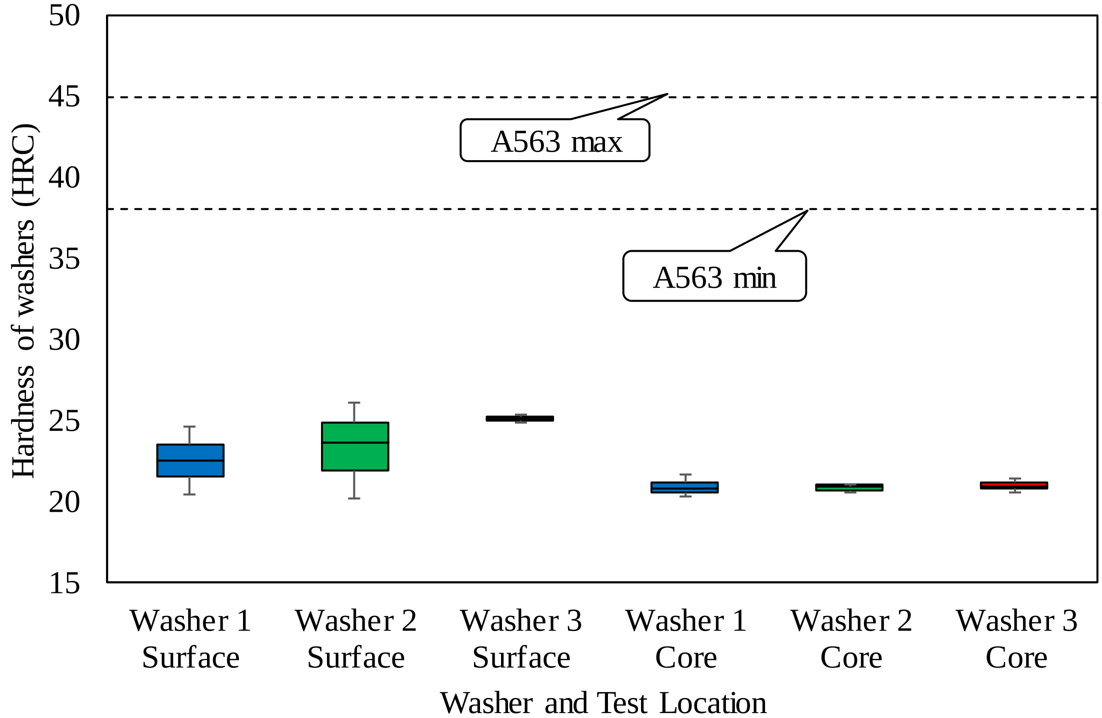

Figure A28. Box and Whisker Plot of Hardness Test Results on 2205 Washers

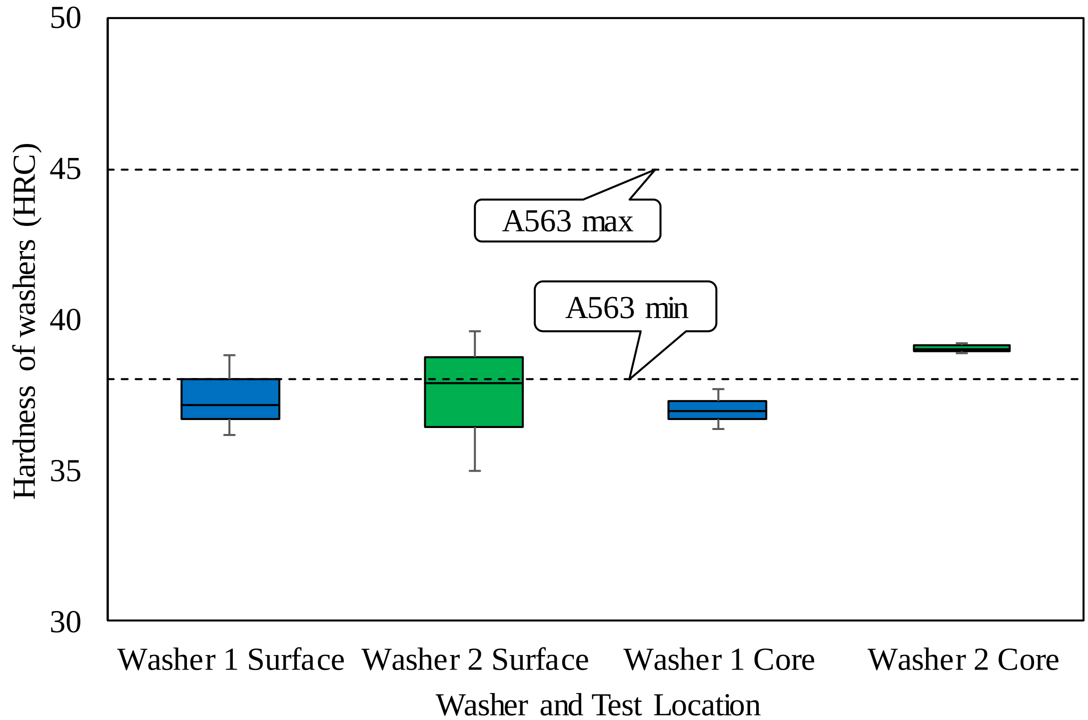

Figure A29. Box and Whisker Plot of Hardness Test Results on MCA Washers. MCA = martensitic chromium alloy.

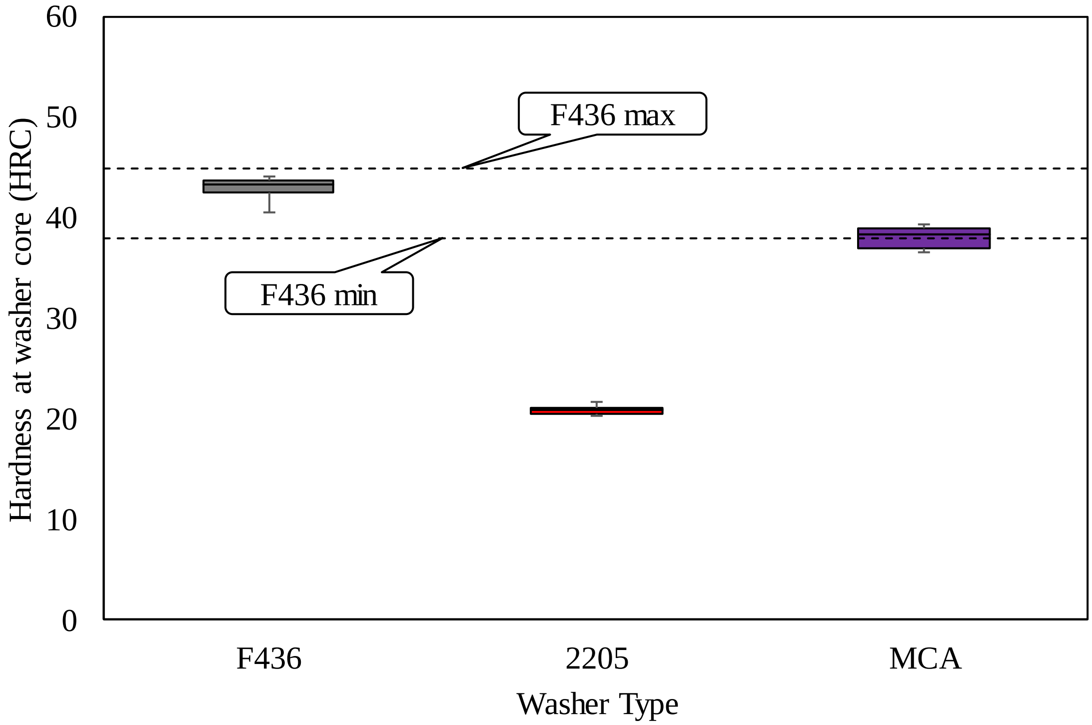

Figure A30. Box and Whisker Plot of Washer Hardness at Core of F436, 2205, and MCA Washers. MCA = martensitic chromium alloy.

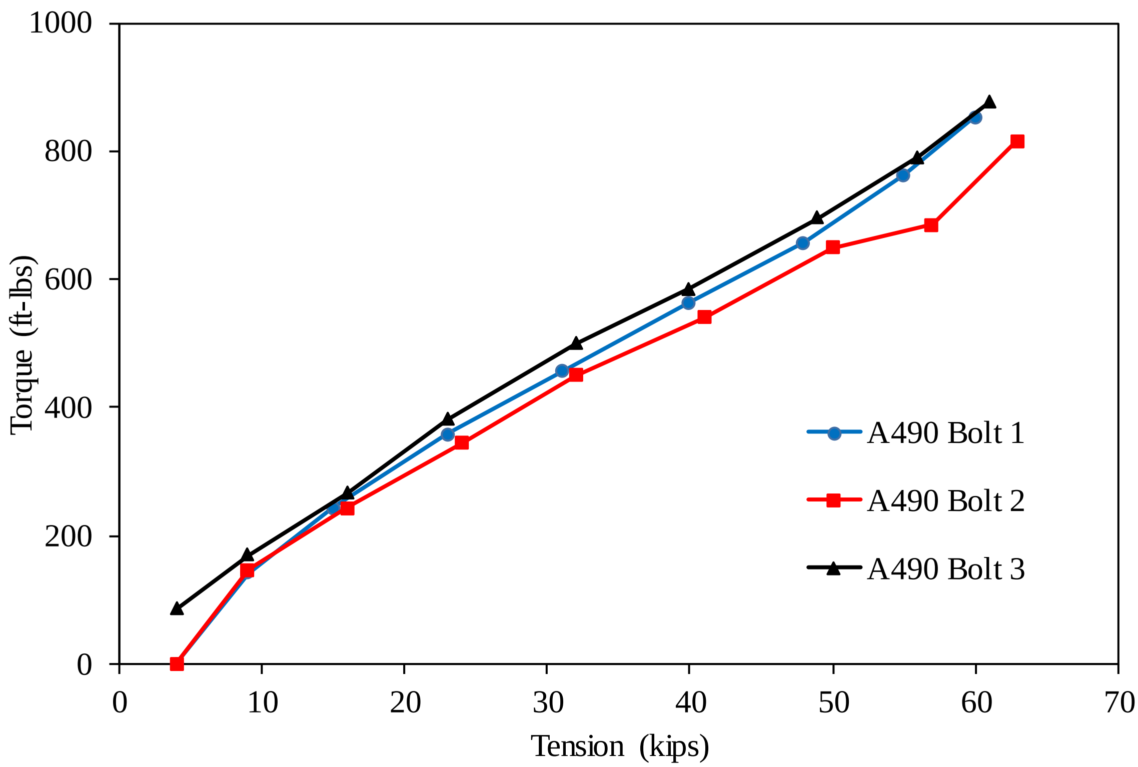

Figure A31. Friction Testing Plot of Bolt Torque vs. Bolt Tension for A490 Bolts With Lubricant 1

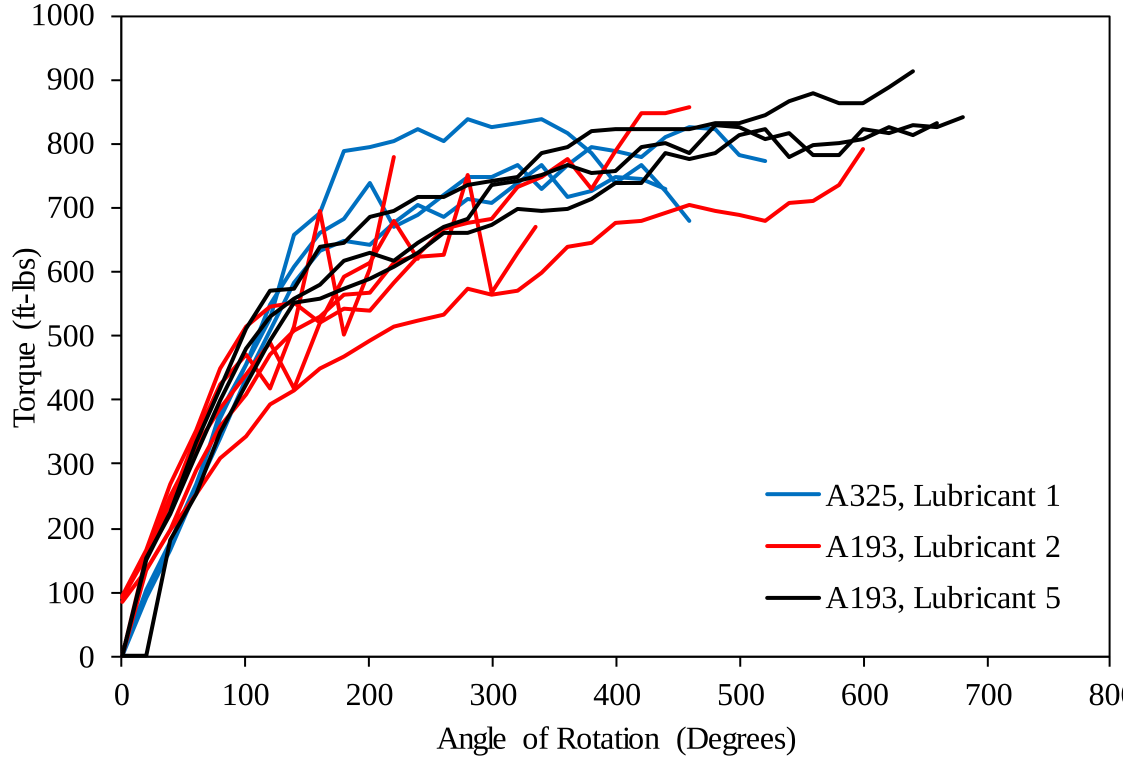

Figure A32. Torqued Tension Testing Torque vs. Angle of Rotation for 7/8-in-Diameter x 3.5-in-Long A193 B8-2 Bolts With Multiple Lubricants

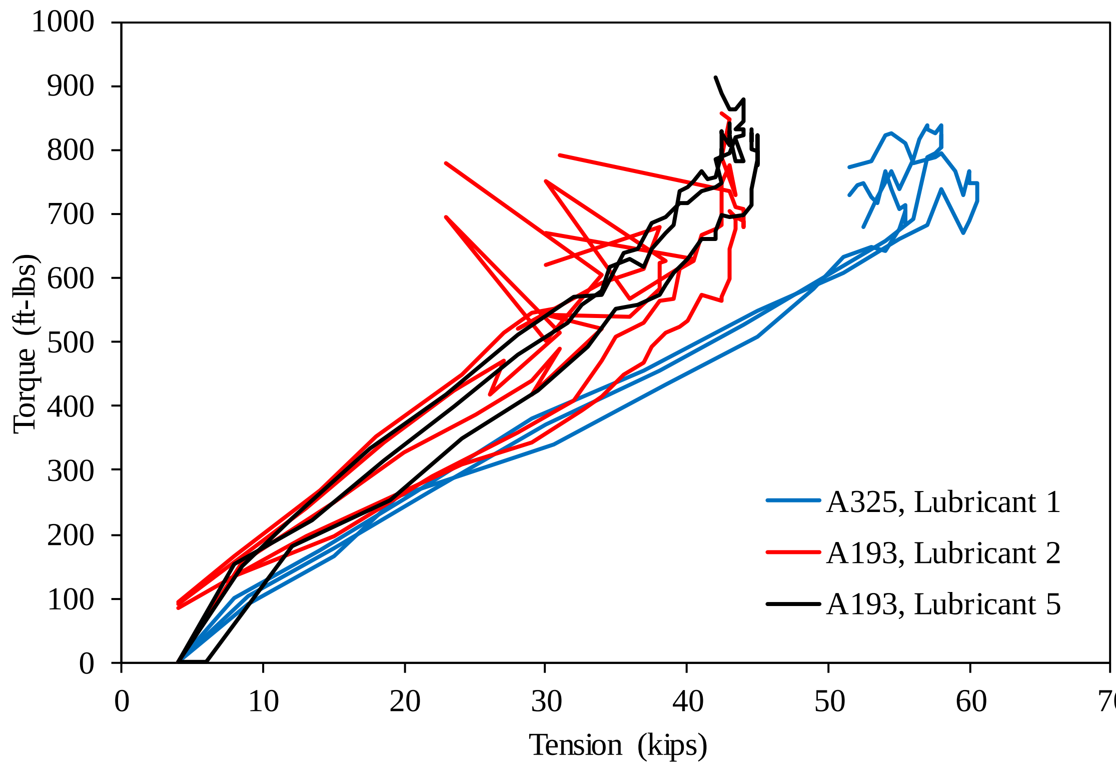

Figure A33. Torqued Tension Testing Torque vs. Tension for 7/8-in-Diameter x 3.5-in-Long A193 B8-2 Bolts With Multiple Lubricants

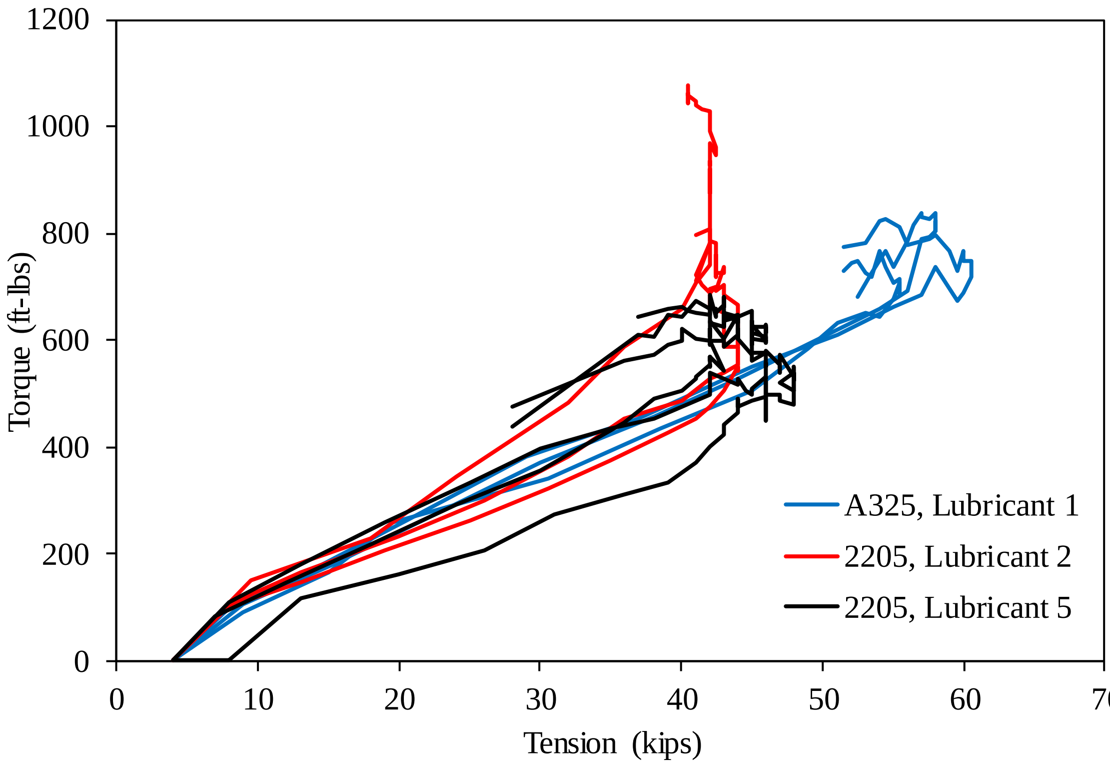

Figure A34. Torqued Tension Testing Torque vs. Tension for 7/8-in-Diameter x 3.5-in-Long 2205 Bolts With Multiple Lubricants

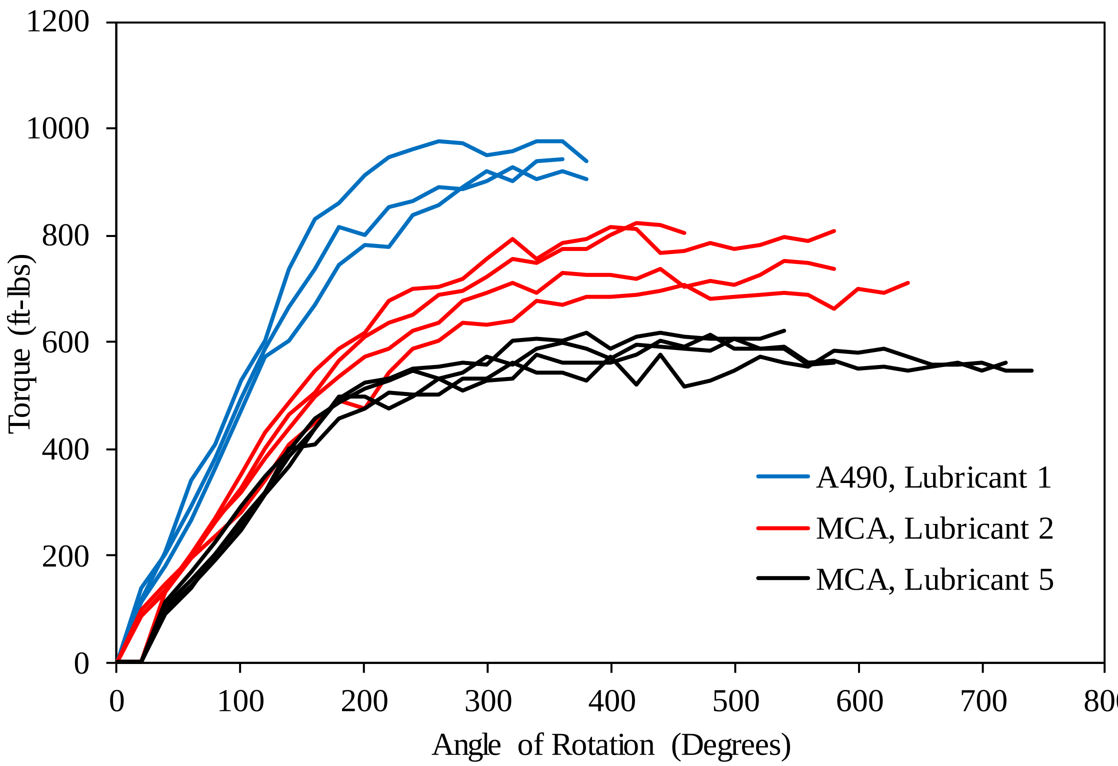

Figure A35. Torqued Tension Testing Torque vs. Angle of Rotation for 7/8-in-Diameter x 3.5-in-Long MCA Bolts With Multiple Lubricants. MCA = martensitic chromium alloy.

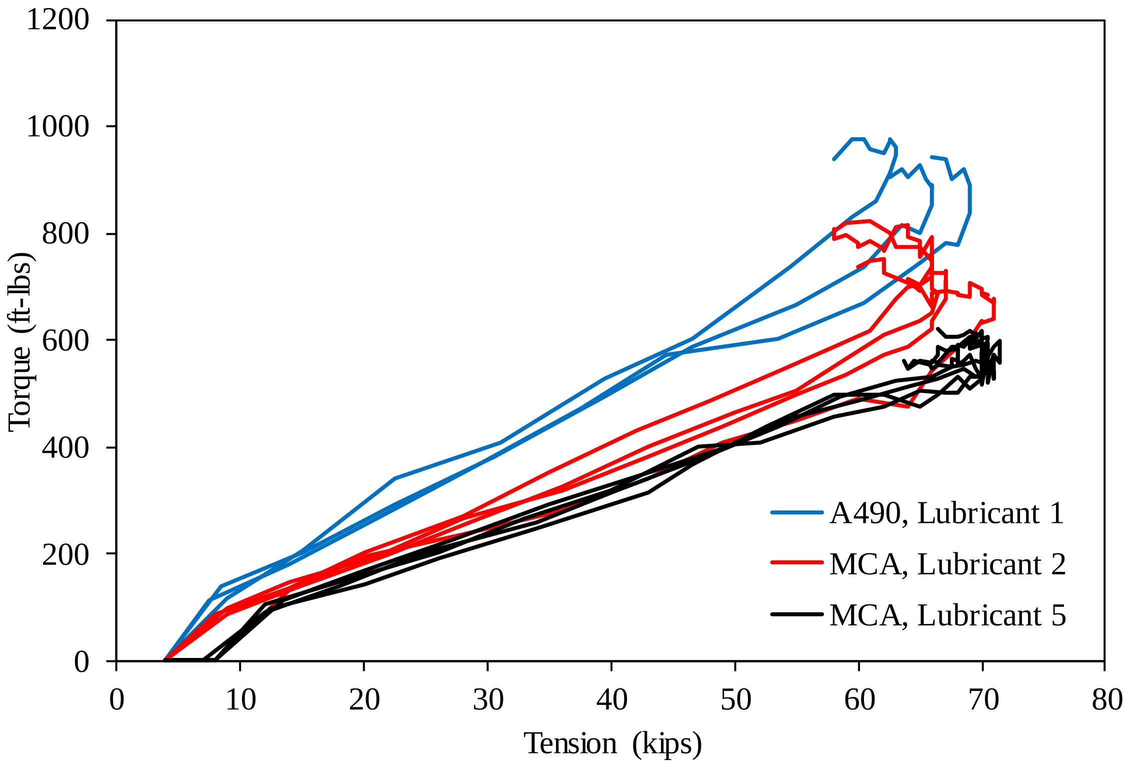

Figure A36. Torqued Tension Testing Torque vs. Tension for 7/8-in-Diameter x 3.5-in-Long MCA Bolts With Multiple Lubricants. MCA = martensitic chromium alloy.

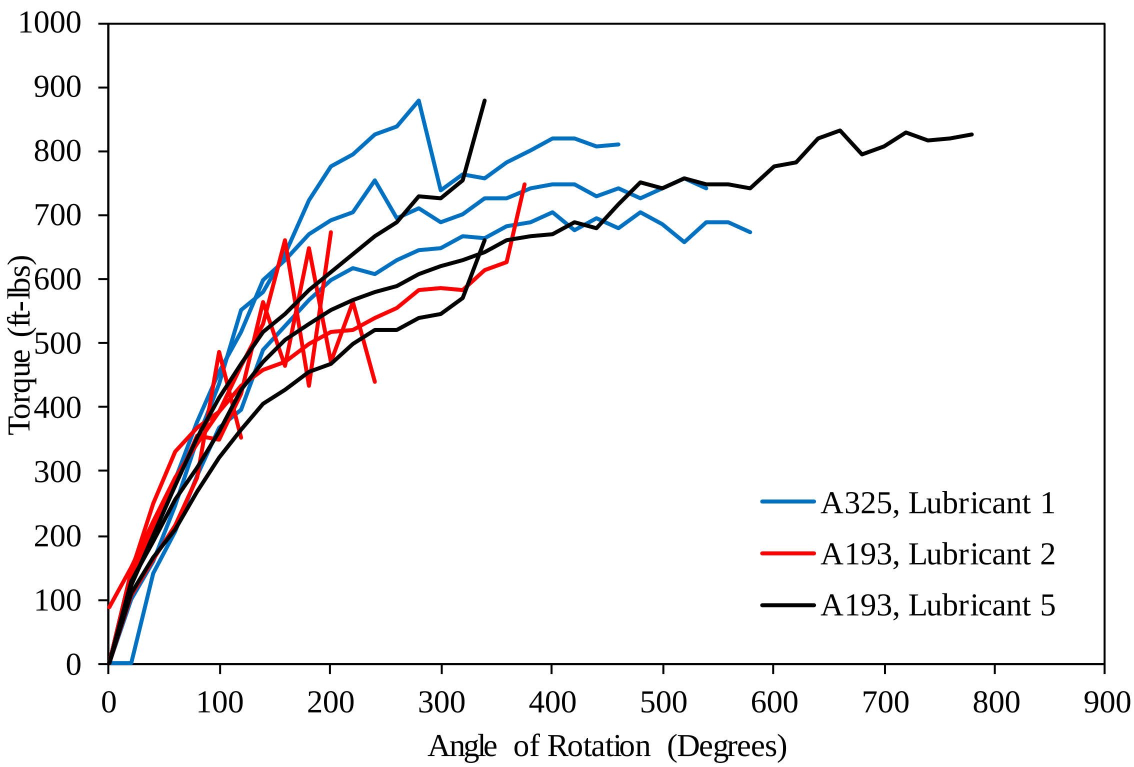

Figure A37. Torqued Tension Testing Torque vs. Angle of Rotation for 7/8-in-Diameter x 5-in-Long A193 B8-2 Bolts With Multiple Lubricants

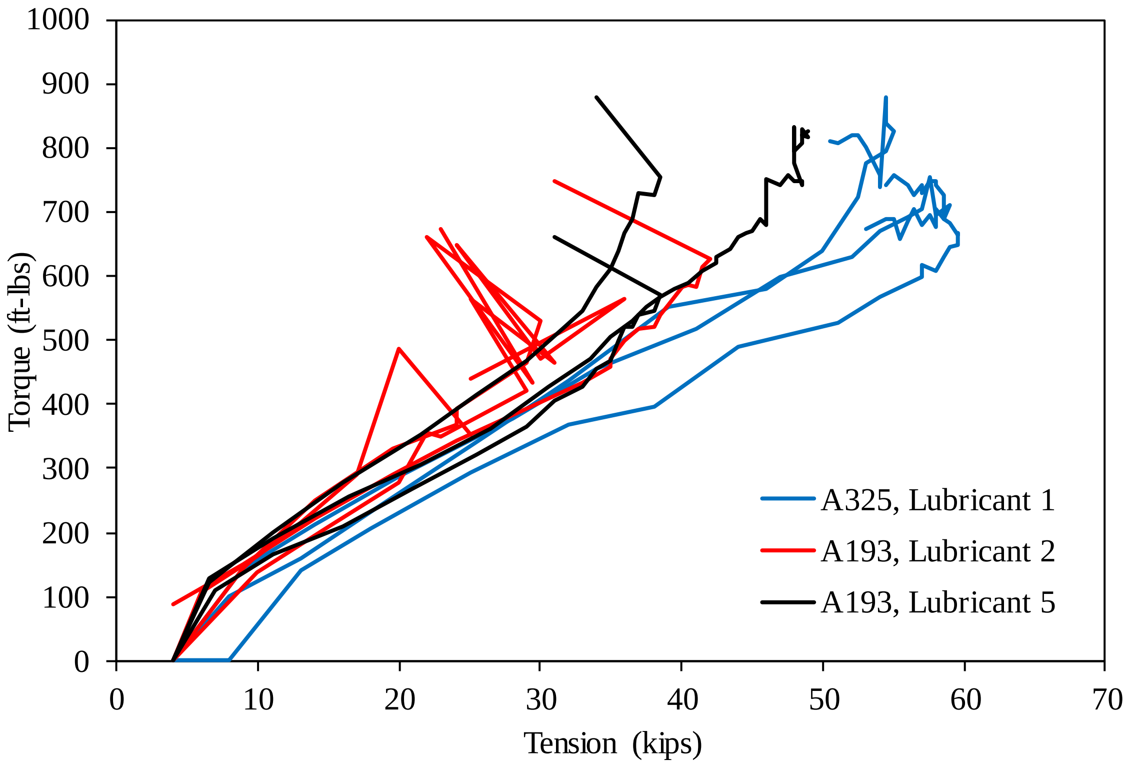

Figure A38. Torqued Tension Testing Torque vs. Tension for 7/8-in-Diameter x 5-in-Long A193 B8-2 Bolts With Multiple Lubricants

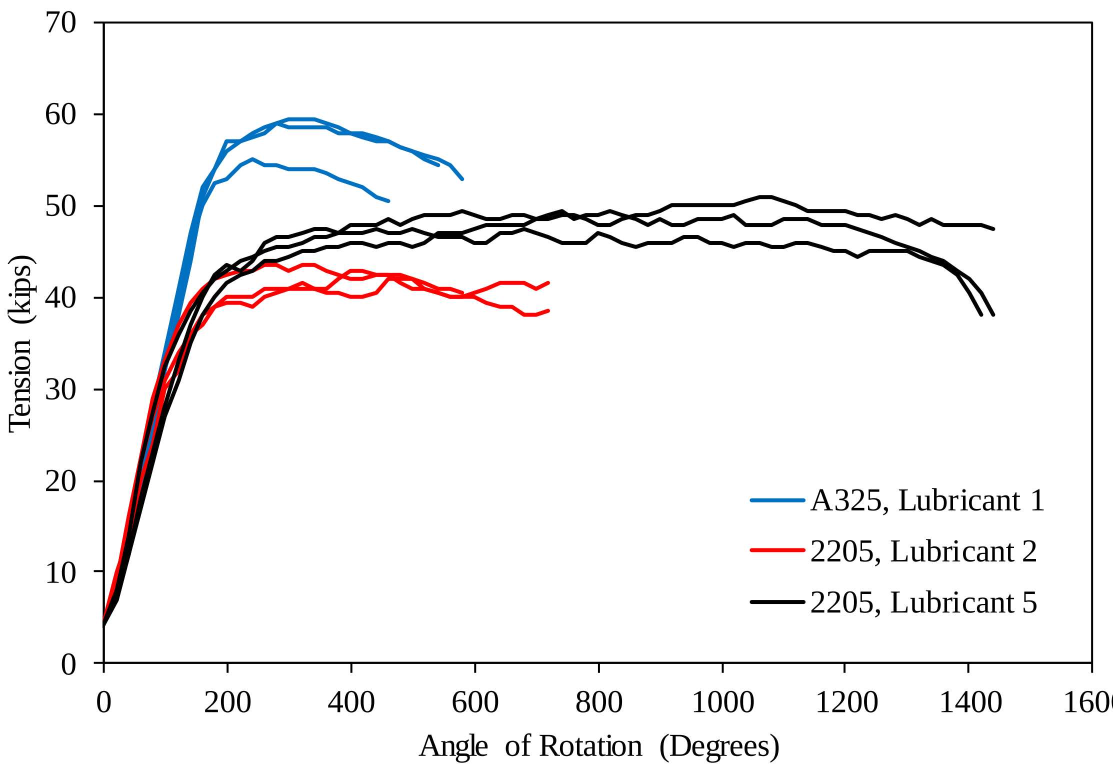

Figure A39. Torqued Tension Testing Tension vs. Angle of Rotation for 7/8-in-Diameter x 5-in-Long 2205 Bolts With Multiple Lubricants

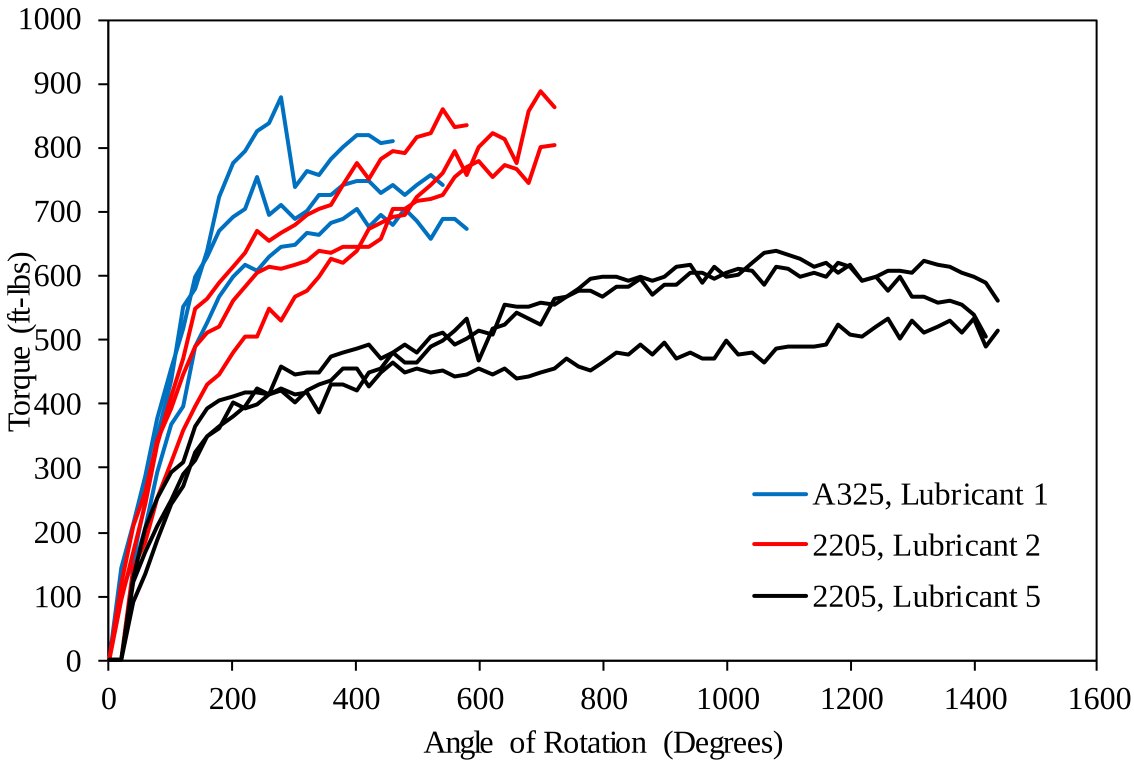

Figure A40. Torqued Tension Testing Torque vs. Angle of Rotation for 7/8-in-Diameter x 5-in-Long 2205 Bolts With Multiple Lubricants

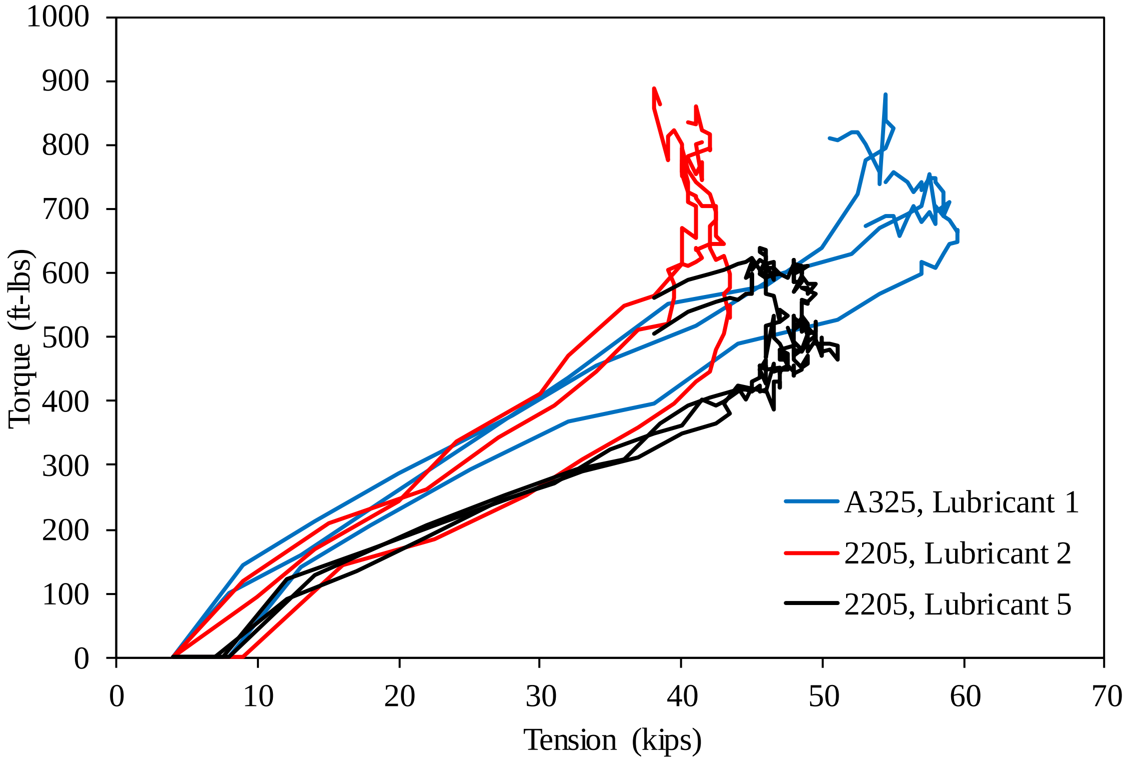

Figure A41. Torqued Tension Testing Torque vs. Tension for 7/8-in-Diameter x 5-in-Long 2205 Bolts With Multiple Lubricants

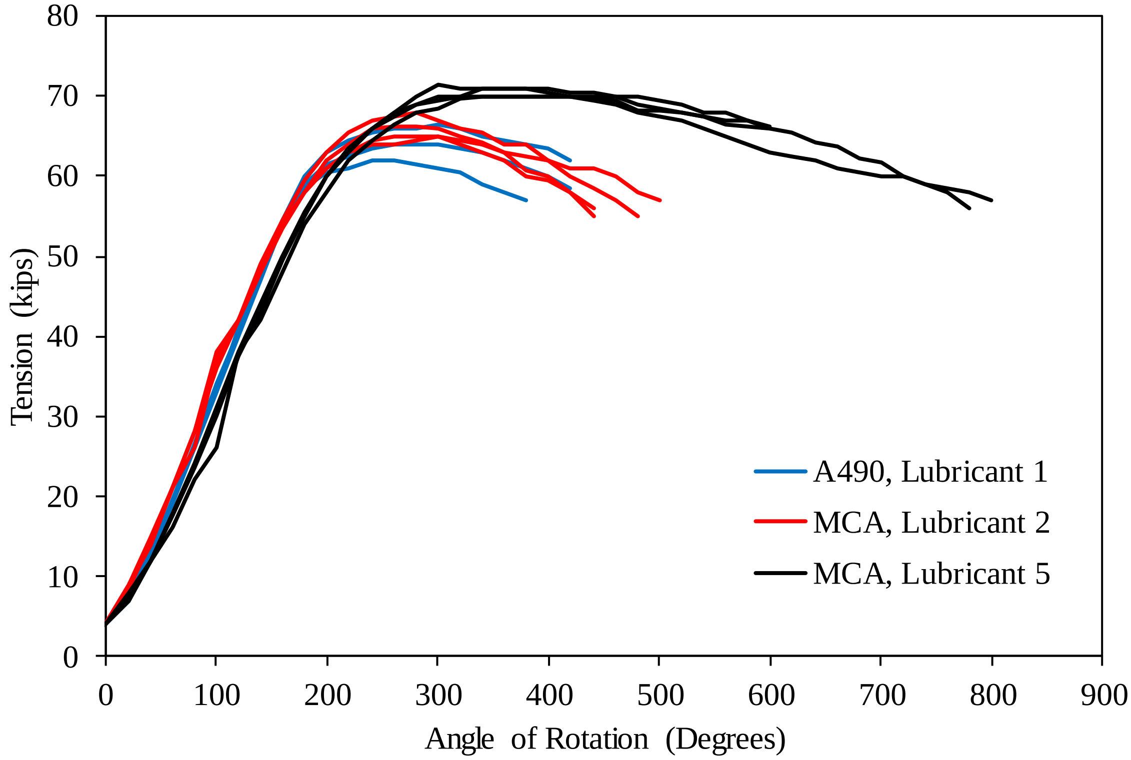

Figure A42. Torqued Tension Testing Tension vs. Angle of Rotation for 7/8-in-Diameter x 5-in-Long MCA Bolts With Multiple Lubricants. MCA = martensitic chromium alloy.

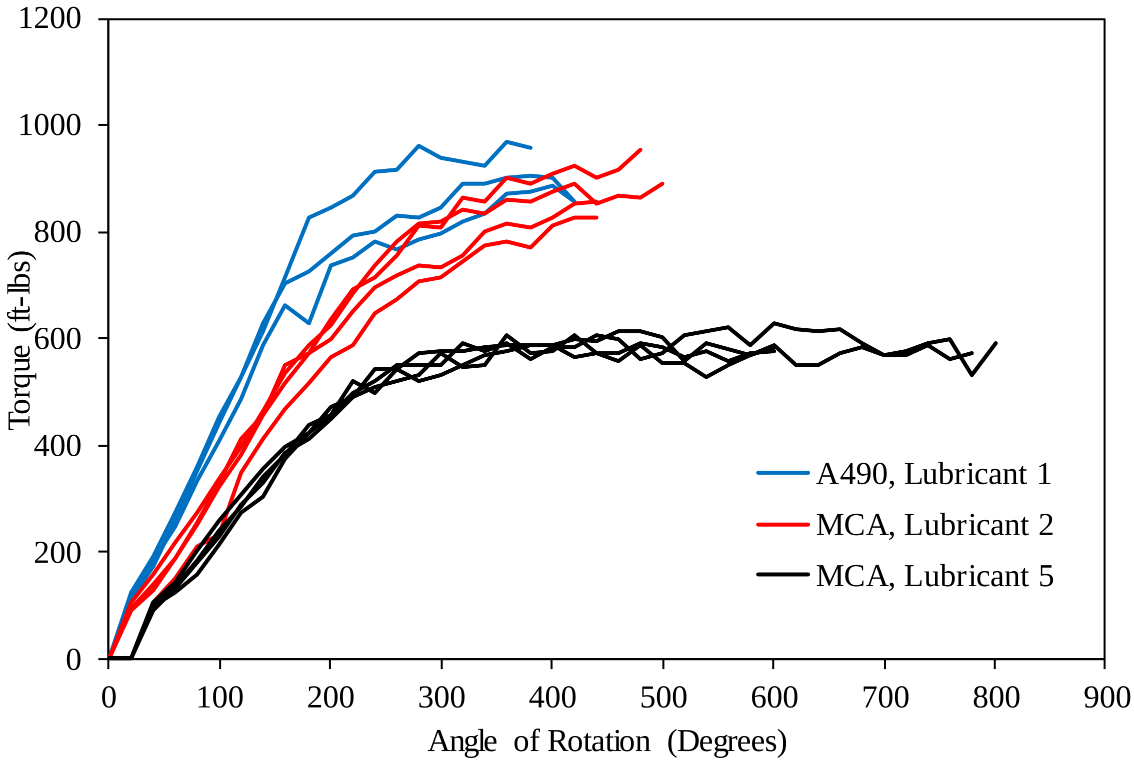

Figure A43. Torqued Tension Testing Torque vs. Angle of Rotation for 7/8-in-Diameter x 5-in-long MCA Bolts With Multiple Lubricants. MCA = martensitic chromium alloy.

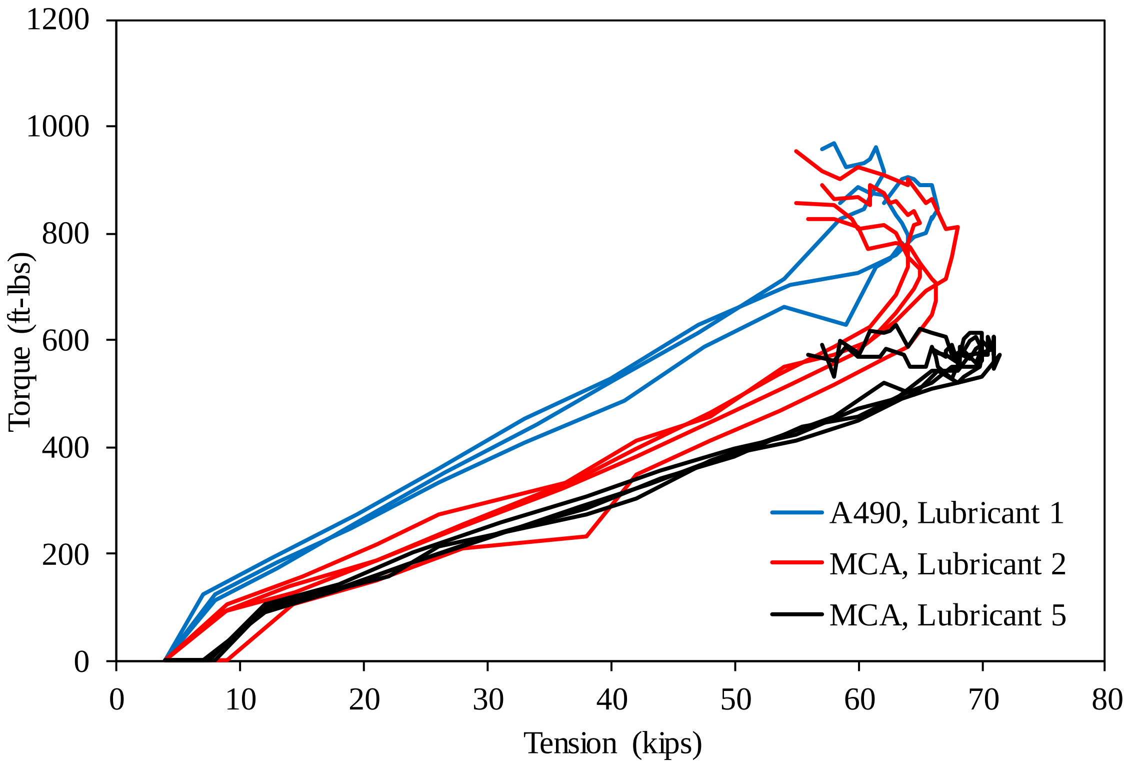

Figure A44. Torqued Tension Testing Torque vs. Tension for 7/8-in-Diameter x 5-in-Long MCA Bolts With Multiple Lubricants. MCA = martensitic chromium alloy.

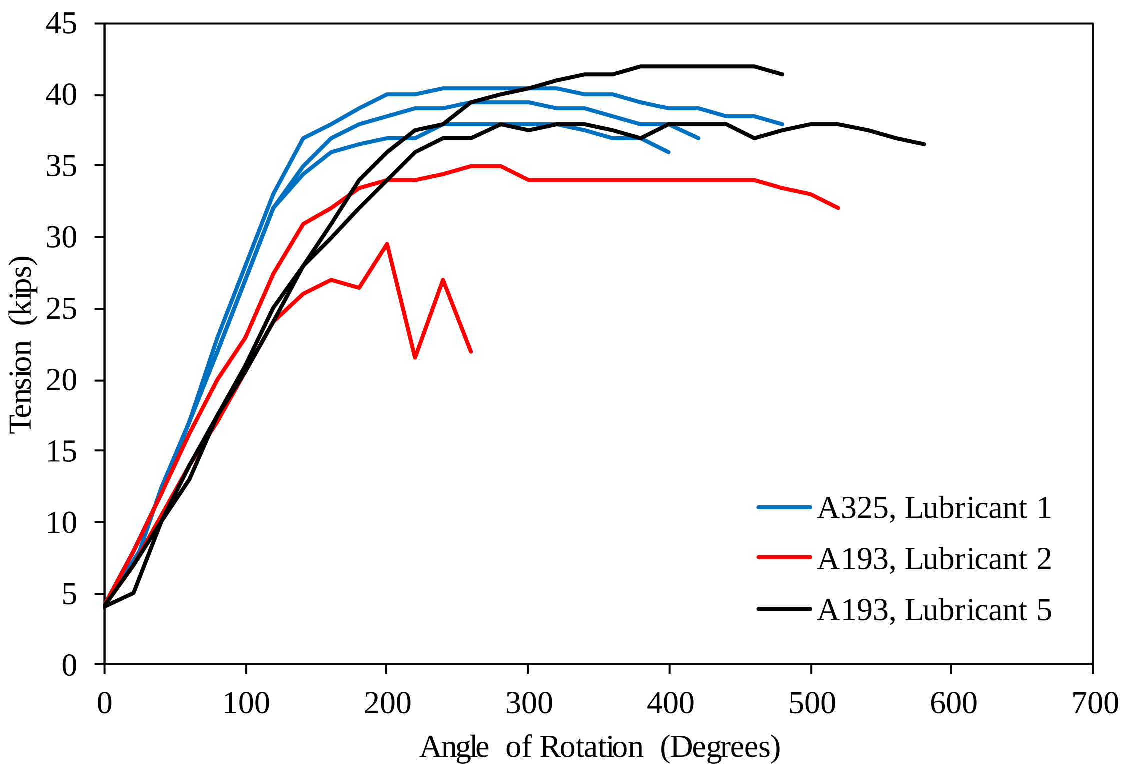

Figure A45. Torqued Tension Testing Tension vs. Angle of Rotation for 3/4-in-Diameter x 2-in-Long A193 B8-2 Bolts With Multiple Lubricants

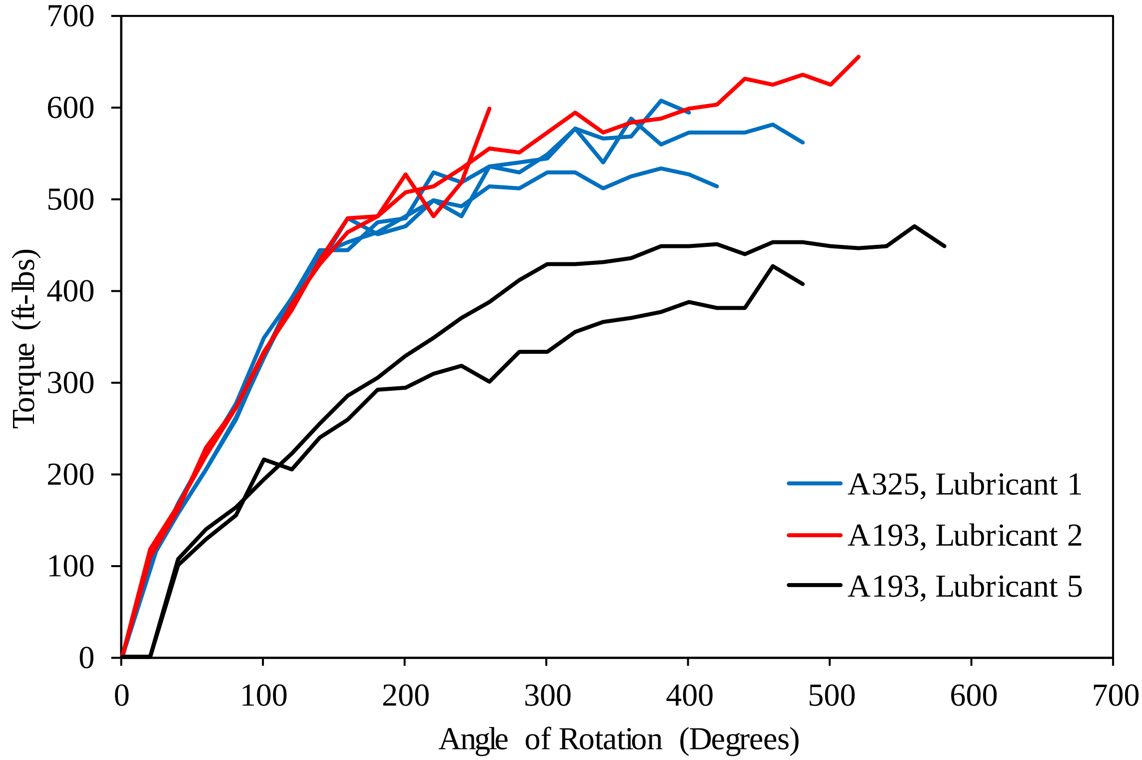

Figure A46. Torqued Tension Testing Torque vs. Angle of Rotation for 3/4-in-Diameter x 2-in-Long A193 B8-2 Bolts With Multiple Lubricants

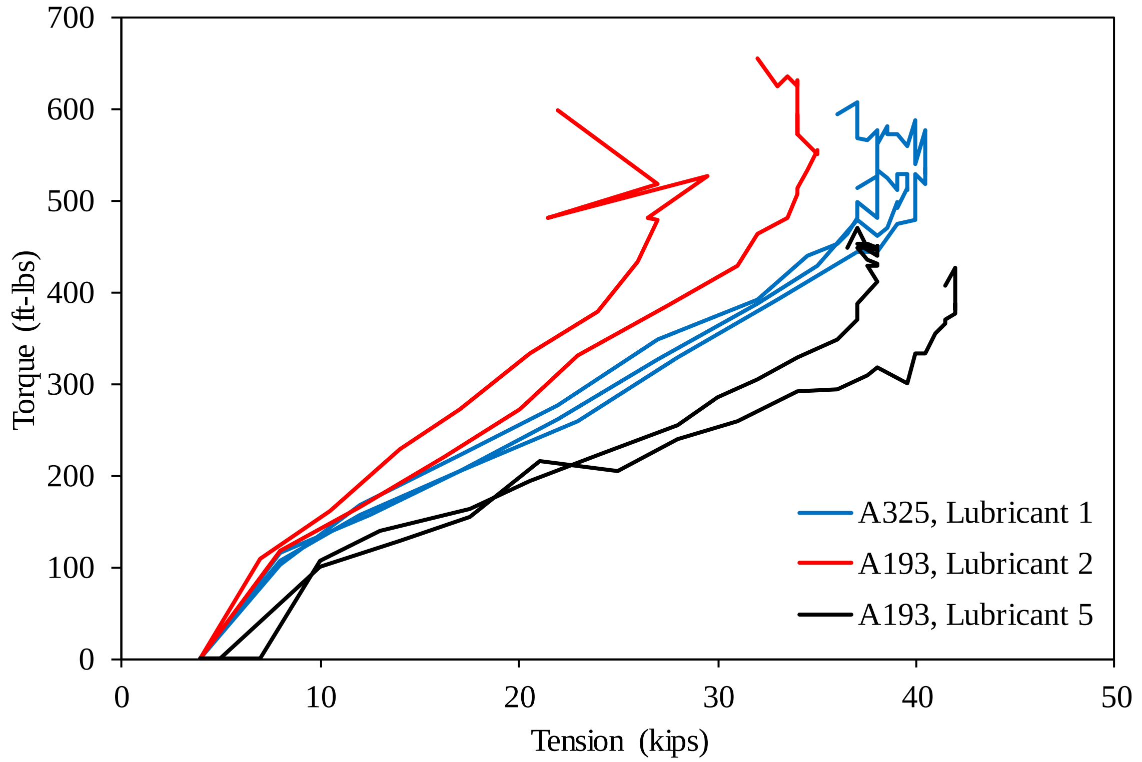

Figure A47. Torqued Tension Testing Torque vs. Tension for 3/4-in-Diameter x 2-in-Long A193 B8-2 Bolts With Multiple Lubricants

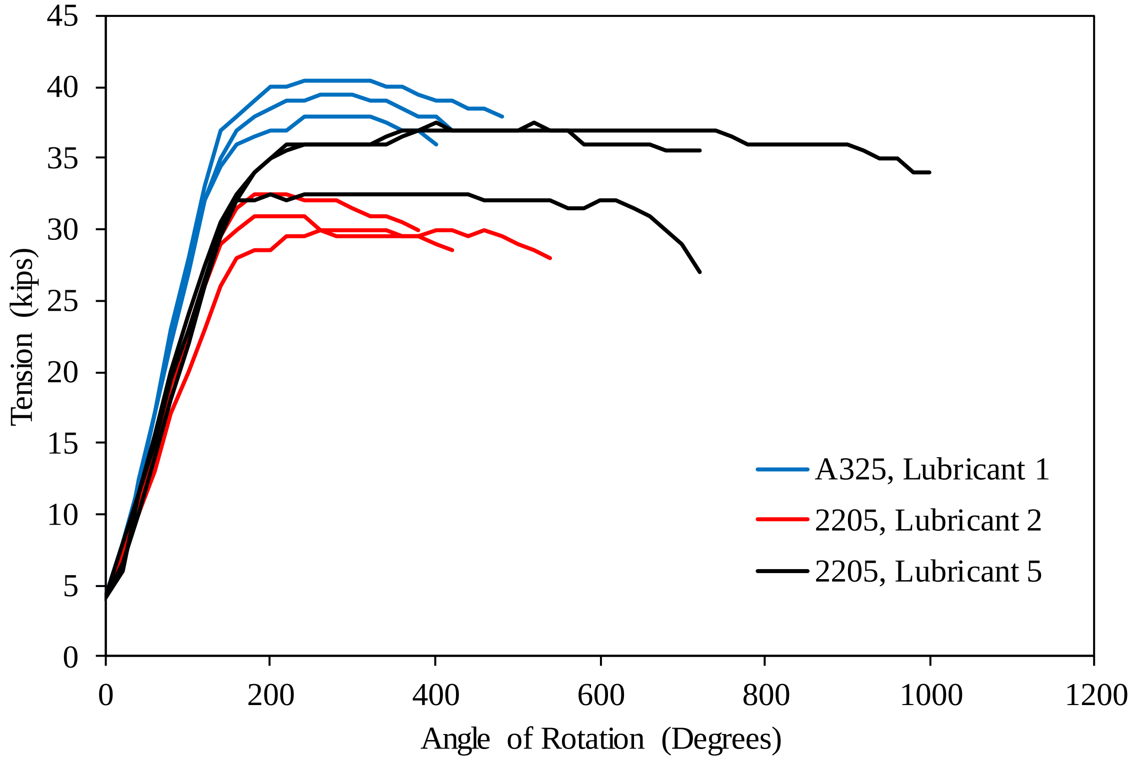

Figure A48. Torqued Tension Testing Tension vs. Angle of Rotation for 3/4-in-Diameter x 2-in-Long 2205 Bolts With Multiple Lubricants

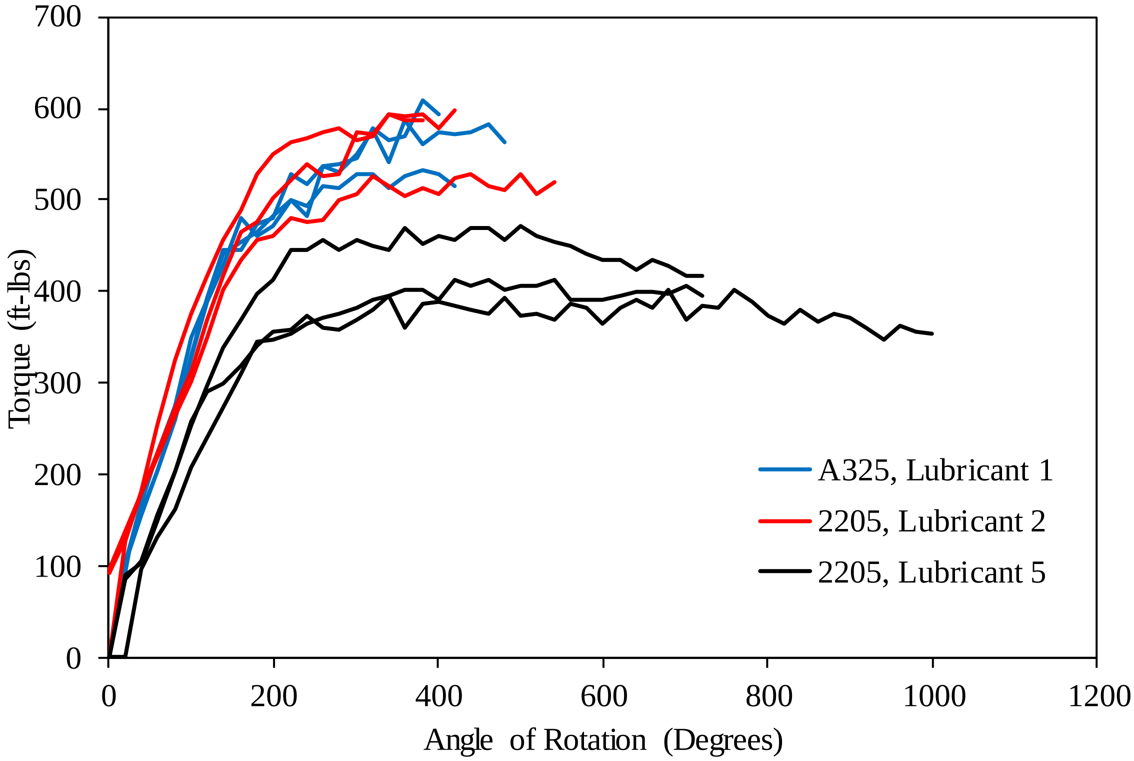

Figure A49. Torqued Tension Testing Torque vs. Angle of Rotation for 3/4-in-Diameter x 2-in-Long 2205 Bolts With Multiple Lubricants

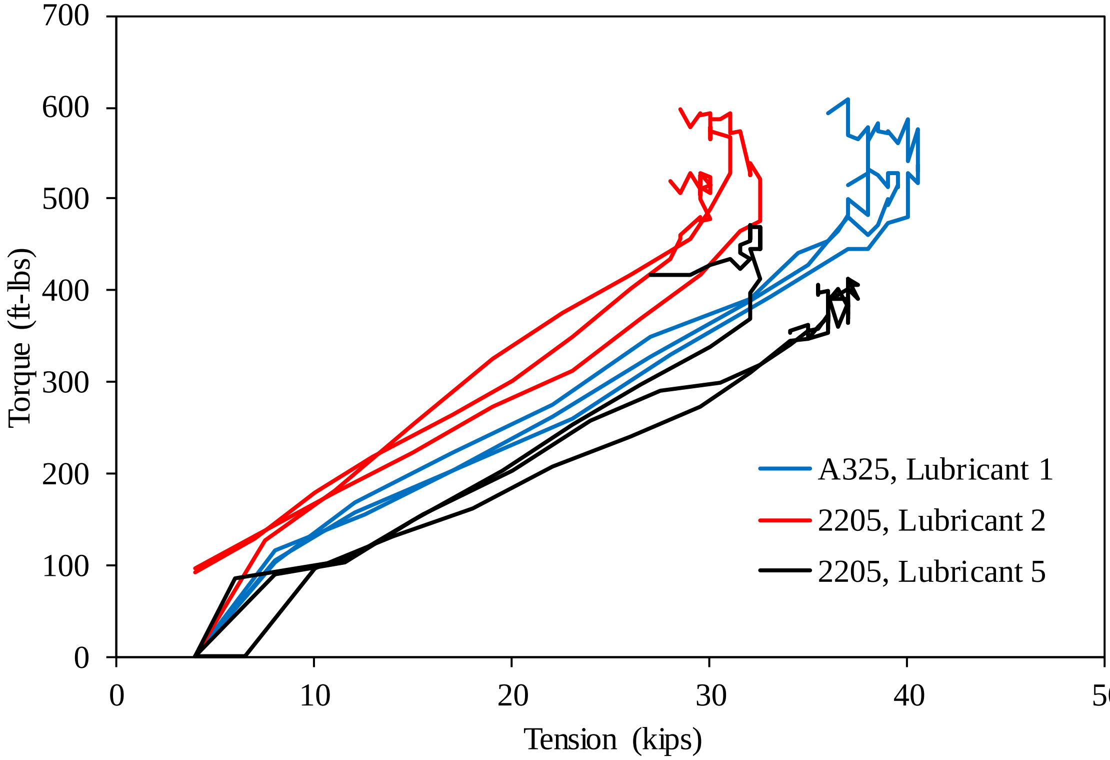

Figure A50. Torqued Tension Testing Torque vs. Tension for 3/4-in-Diameter x 2-in-Long 2205 Bolts With Multiple Lubricants

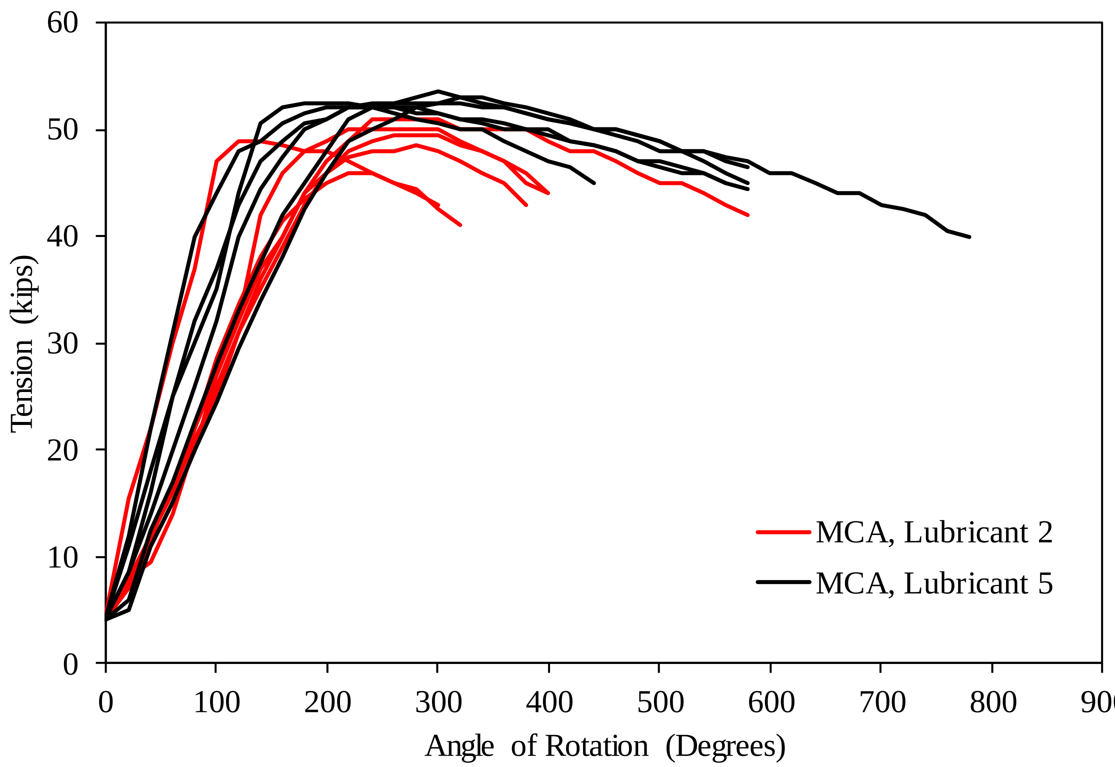

Figure A51. Torqued Tension Testing Tension vs. Angle of Rotation for 3/4-In-Diameter x 2-in-Long MCA Bolts With Multiple Lubricants. MCA = martensitic chromium alloy.

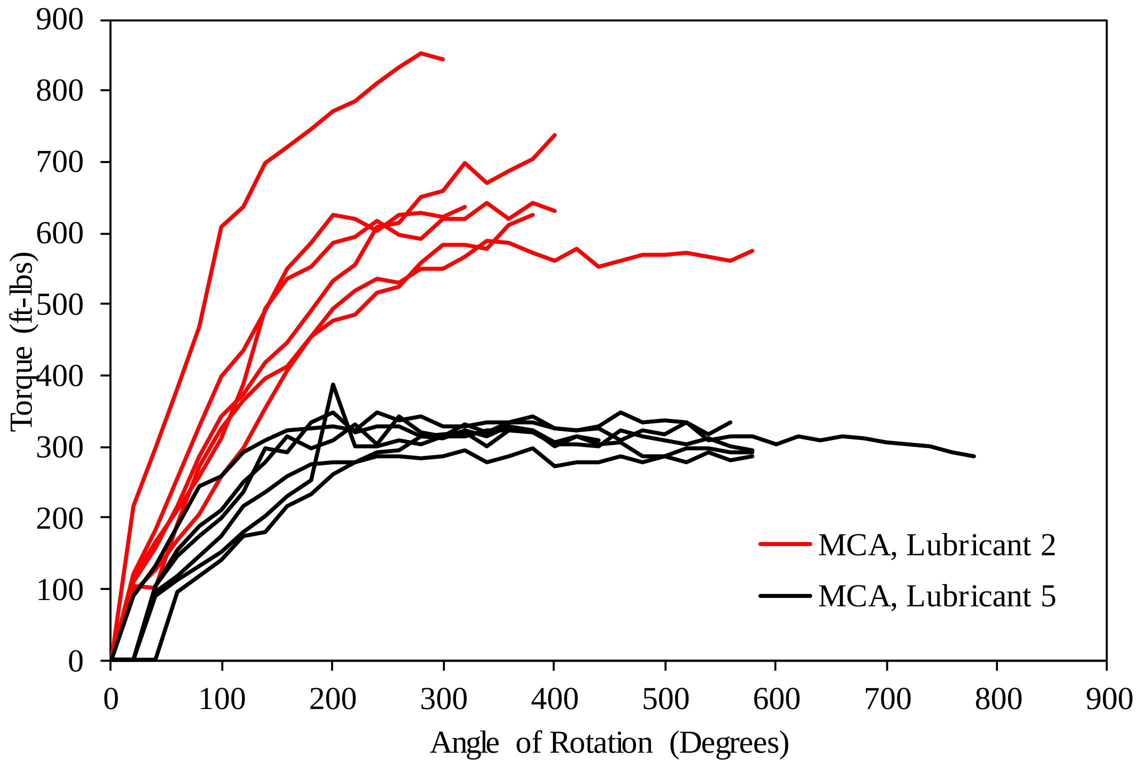

Figure A52. Torqued Tension Testing Torque vs. Angle of Rotation for 3/4-in-Diameter x 2-in-Long MCA Bolts With Multiple Lubricants. MCA = martensitic chromium alloy.

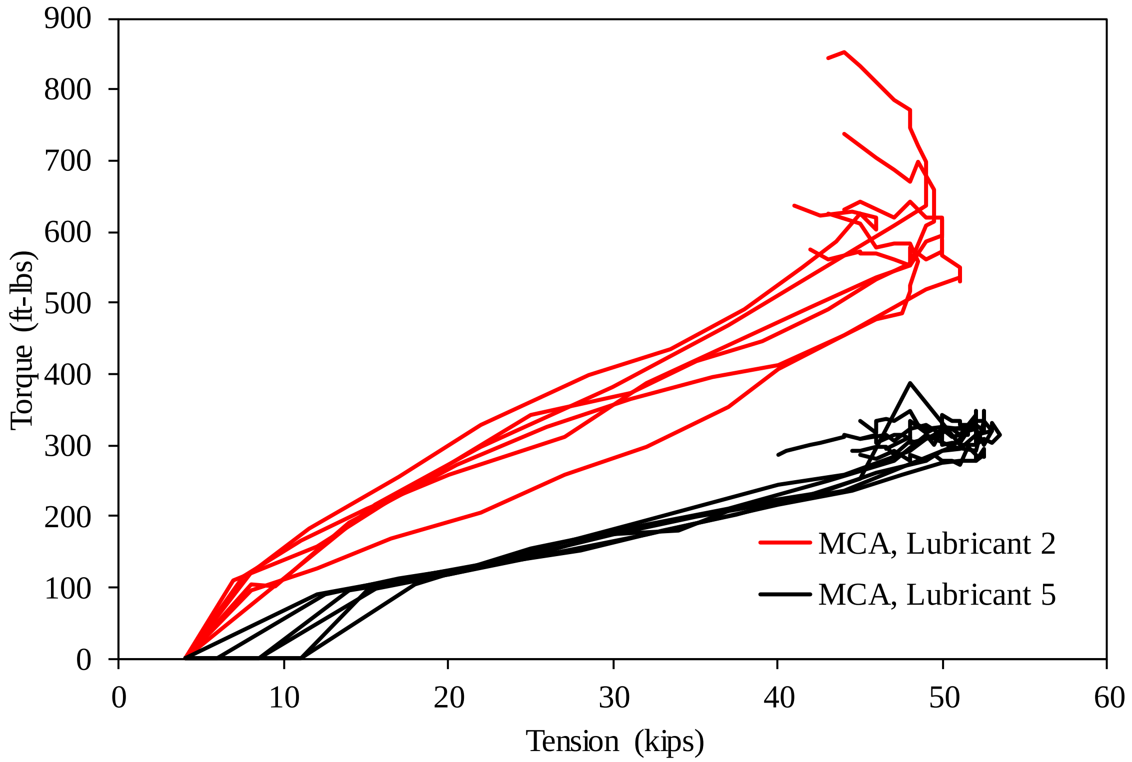

Figure A53. Torqued Tension Testing Torque vs. Tension for 3/4-in-Diameter x 2-in-Long MCA Bolts With Multiple Lubricants. MCA = martensitic chromium alloy.

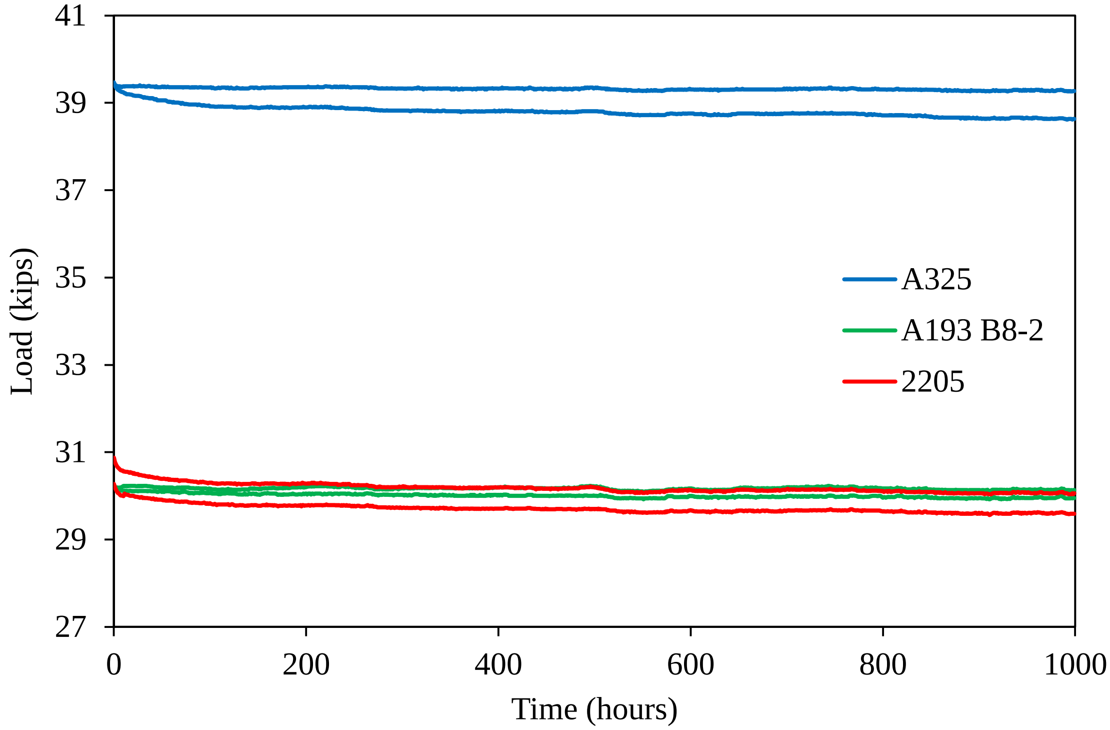

Figure A54. Plot of Load vs. Time for Relaxation Tests on A325, A193 B8-2, and 2205 5-in-Long Bolts

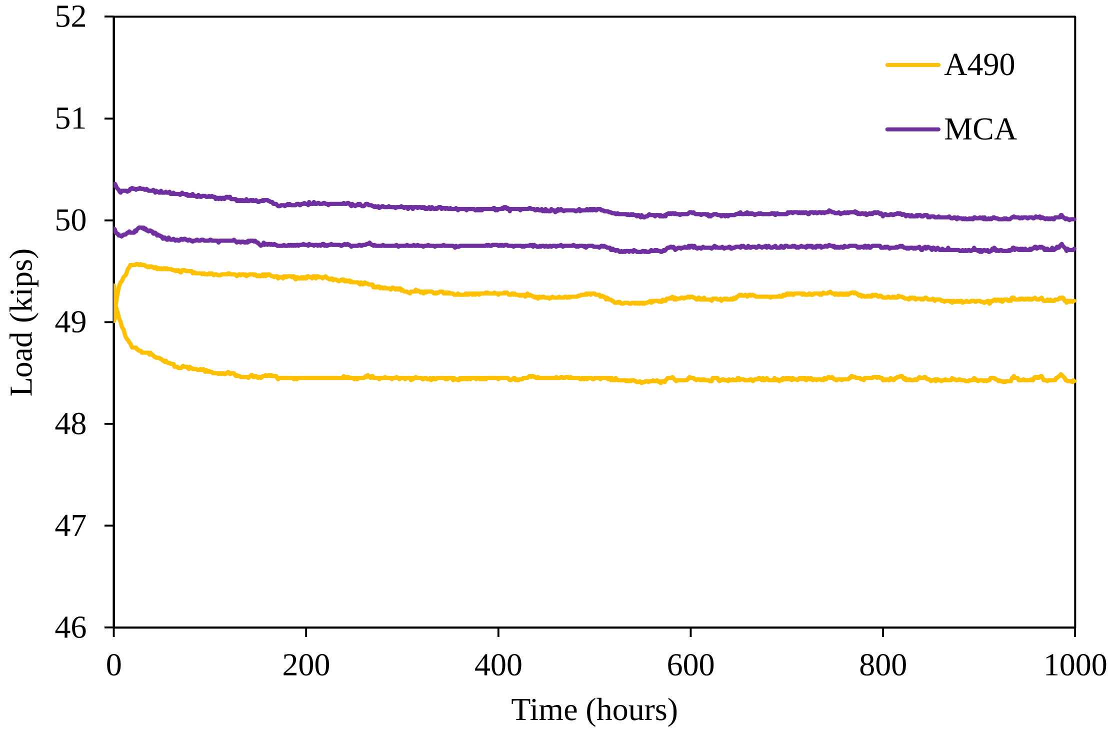

Figure A55. Plot of Load vs. Time for Relaxation Tests on A490 and MCA 5-in-Long Bolts. MCA = martensitic chromium alloy.

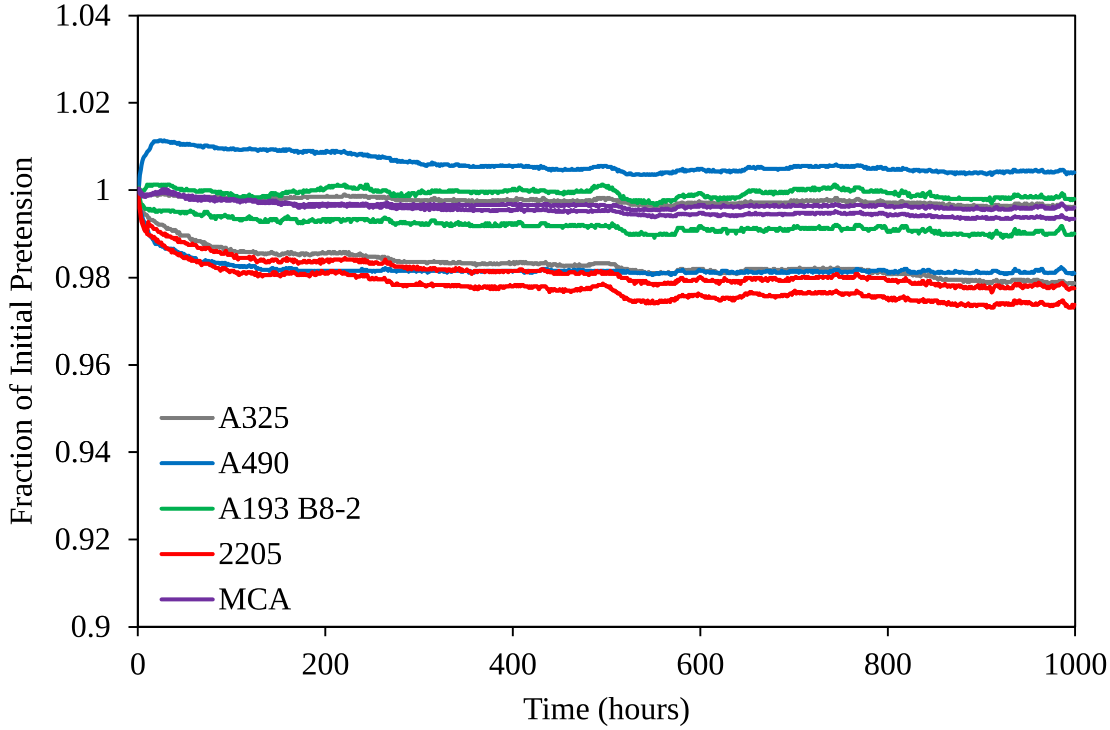

Figure A56. Plot of Fraction of Initial Pretension vs. Time for All 5-in-Long Bolts

APPENDIX B

METHOD TO DETERMINE INSTALLATION PARAMETERS FOR CORROSION-RESISTANT STEEL BOLTS

1. Purpose and Scope

1.1. The purpose of this procedure is to determine the suitability and installation nut rotation angle for turn-of-nut installation of slip-critical corrosion-resistant steel fastener assemblies.

Commentary:

The procedure is intended to align with the Research Council on Structural Connections Specification for Structural Joints Using High-Strength Bolts (hereinafter "RCSC Specifications") whenever possible (RCSC, 2014). Therefore, terms used in this procedure follow the definitions provided in the RCSC Specifications unless otherwise noted.

This procedure is necessary because general installation parameters for corrosion-resistant steel fasteners have not yet been developed. Therefore, installation parameters must be determined on a fastener assembly lot basis. This procedure is not intended to be a substitute for the pre-installation verification as described in the RCSC Specifications. Rather, the installation nut rotation angle determined using this procedure can be used during the pre-installation verification to prove that the contractor on the structural application can successfully pretension the corrosion-resistant steel bolts. Once this has been confirmed, the installation nut rotation angle for turn-of-nut installation can be used on the structural application.

1.2. A corrosion-resistant steel fastener assembly should consist of one bolt, one nut, one washer, and a lubricant. The lubricant is explicitly included in a corrosion-resistant steel fastener assembly because stainless steel threaded parts, especially austenitic stainless steels, are susceptible to galling. Some lubricants are better than others at preventing galling, thus whenever a different lubricant is used with the same type of bolt, nut, and washer, it should be considered a different fastener assembly.

Commentary:

Stainless steel washers are typically softer than carbon steel washers specified by ASTM F436/F436M (ASTM, 2016a). Having softer washers can lead to galling.

1.3. This procedure is valid only for a fastener assembly lot and should be performed for each new assembly lot. A fastener assembly lot is defined as a quantity of uniquely identified structural bolts, nuts, or washers of the same nominal size produced consecutively at the initial operation from a single mill heat of material and processed at one time, by the same process, in the same manner so that statistical sampling is valid.

Commentary:

The definition of a lot is equivalent to that used in ASTM F3125 (ASTM F3125 2015).

1.4. This procedure includes:

- Bolt tension tests or material test reports to confirm that the bolts meet the specifications in which they were ordered;
- Torqued tension tests and analysis of test results to determine key parameters of the fastener assembly installation behavior;
- Evaluation of the torqued tension tests to determine the design installation pretension and to establish if the fastener assemblies have sufficient strength, ductility, and lubrication; and
- Determination of tightening parameters to ensure that fastener assemblies can reliably be installed to their specified pretension using the turn-of-nut installation method.

2. Bolt Tension Tests

Tension tests should be performed on bolts from the fastener assembly lot in question. All bolts should be taken from the same lot. The lot sample size should consist of at least three bolts. Tension tests should be conducted according to ASTM F606/F606M (ASTM F606/F606M 2016b). The mechanical properties from the tensile tests should fulfil the requirements of the specification to which the bolts were ordered.

This requirement can also be satisfied if the bolt manufacturer provides a material test report showing that the lot of bolts meet the appropriate specifications.

3. Torqued Tension Tests

3.1. General

Torqued tension tests are used to experimentally determine the tightening behavior of a corrosion-resistant steel fastener assembly. Results from the torqued tension tests are evaluated to determine the design installation pretension and turn-of-nut rotation to reliably achieve this pretension in the fastener assembly. The number of torqued tension tests to be conducted for each fastener assembly lot is at least three.

3.2. Test Setup

3.2.1. The test setup consists of the fastener assembly, spare ASTM F436 washers (if necessary), a calibrated torque wrench to tighten the fastener assembly, and a means to measure and record the following parameters during tightening:

- The bolt force;
- The relative rotation between the nut and the bolt; and
- The torque on the turned element.

The test setup should have the ability to tighten the turned element and measure the bolt force, rotation, and torque at every 20° increment of rotation for the duration of the test.

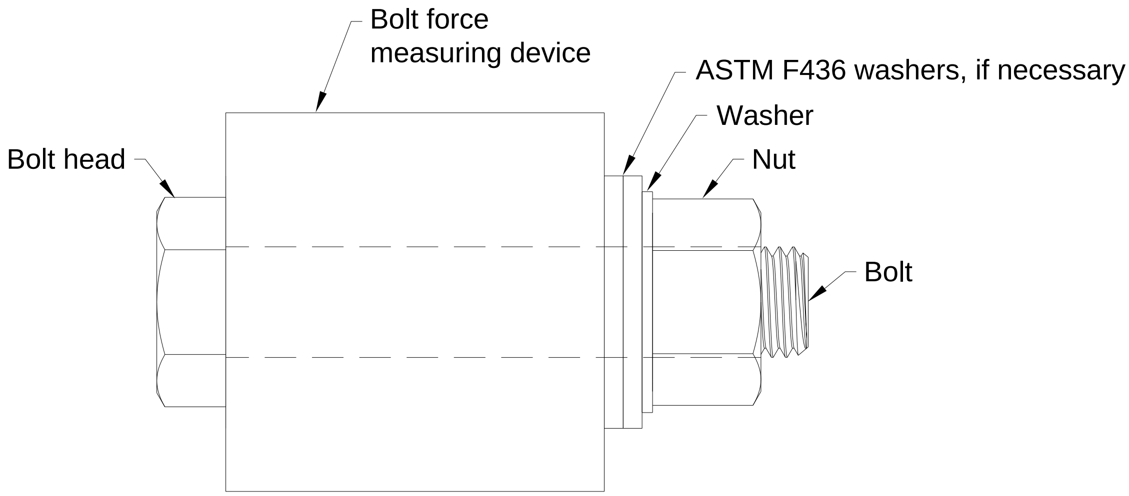

Figure B1. Test Setup

3.2.2. The bolt force measuring device must be appropriate for the bolts being tested. A hydraulic tension calibrator, such as a Skidmore Wilhelm, is an acceptable means of measuring bolt force. The bolt force measuring device must be calibrated annually. It should have an accuracy of ±2% and have a repeatability error of ±1%.

3.2.3. The relative rotation between the nut and bolt should be measured with an accuracy of ±5°. An angle of turn protractor is an acceptable means of angle measurement.

3.2.4. The torque on the nut should be measured by a torque measuring device and should be calibrated annually. A torque wrench is an acceptable means of measuring torque. The torque measuring device should have an accuracy and a repeatability error of ±1%.

3.2.5. The bolt should be installed so that three to five threads are within the grip length of the bolt. The grip length of the bolt may be adjusted by adding ASTM F436 washers between the bolt force measuring device and the corrosion-resistant washers as shown Figure B1.

3.3. Test Procedure

3.3.1. The test should be conducted at an ambient temperature range of 50 °F to 95 °F. However, if bolts will be installed in the structural application outside this temperature range, the suitability tests should be conducted at the extreme temperature expected at the site of the structural application.

3.3.2. The threads of the nuts and bolts should be inspected to ensure no damage is present. If damage to the threads of any part is found, the damaged part should be discarded and replaced with an undamaged part.

3.3.3. Lubrication should be applied to the threads of the nut and to the turning face of the nut.

Commentary:

If lubrication conditions are changed during the torqued tension tests, those conditions should be noted in the test report and those same conditions should be used during field installation of the fasteners at the structural application. For example, if lubrication is only applied to the threads of the nut for the torqued tension tests, it should be noted in the test report and field installation of fasteners should be conducted with lubrication applied only to the threads of the nut. Better fastener installation performance is expected if lubrication is applied to the turning face of the turned element.

3.3.4. The bolt, washers, and ASTM F436 washers (if necessary) should be installed into the bolt force measurement device as shown in Figure B1 with the proper number of threads in the grip. The nut should then be installed finger tight.

3.3.5. Tightening should occur by rotation of the nut, unless otherwise specified. The procedures can be modified accordingly if tightening by rotation of the bolt head is desired.

3.3.6. The nut should be rotated until reaching a bolt force of 4 kip. This point is considered snug tight and the angle measurement device should be set to zero. Rotation of the nut should occur in 20° increments, recording bolt tension, rotation, and torque at each increment.

Commentary:

The snug tight definition used here was taken from that in ASTM F3125 Annex A.2 used for A325 and A490 bolts.

It is preferable that a plot of the bolt force vs. nut rotation be monitored in real-time during testing.

3.3.7. The bolt should not rotate during the test. If it does, a new test should be conducted to replace the test in question.

3.3.8. The test should be terminated when any one of the following conditions occurs:

- The bolt force first reaches a maximum value and then drops below T_b on the descending portion of the bolt force vs. nut rotation curve, or
- The bolt fails by fracture or stripping.

Commentary:

If a plot of the bolt force vs. nut rotation is being monitored during testing, the test may also be stopped when the nut rotation angle reaches a value of θ_3 (specified in Section 3.4.2) plus the minimum $\Delta\theta_{53}$ specified in Table B1.

3.4. Analysis of Torqued Tension Test Results

3.4.1. For each test specimen, the following curves should be generated:

- Bolt force vs. nut rotation, and
- Bolt force vs. torque on nut.

These curves should have sufficient resolution to permit accurate interpretation of the results.

3.4.2. The following defined parameters should be determined from the bolt force vs. nut rotation and bolt force vs. torque curves. Definitions of these parameters are also graphically shown in Figure B2 and Figure B3:

- T_b = the force at which the force vs. rotation curve transitions from linear to non-linear behavior;
- θ_1 = the angle at which the bolt force first reaches $0.10T_{b,}$ (this value is expected to be 0°);
- θ_3 = the angle at which the bolt force first reaches T_b;
- $T_{b,max}$ = the maximum bolt force recorded during testing;
- θ_4 = the angle at which the bolt force reaches T_{max};
- θ_5 = the angle at which the bolt force reaches T_b on the descending portion of the bolt force vs. nut rotation curve after reaching a maximum bolt force;
- $\Delta\theta_{31} = \theta_3 - \theta_1$; (Eq. B1)
- $\Delta\theta_{41} = \theta_4 - \theta_1$; (Eq. B2)
- $\Delta\theta_{53} = \theta_5 - \theta_3$; (Eq. B3)
- M_1 = the torque at which the bolt force first reaches $0.10T_b$;
- M_3 = the torque at which the bolt force first reaches T_b; and
- k-factor (unitless):

$$k = \frac{M_3 - M_1}{d\ (T_b - 0.10T_b)} \tag{Eq. B4}$$

where d = nominal diameter of bolt.

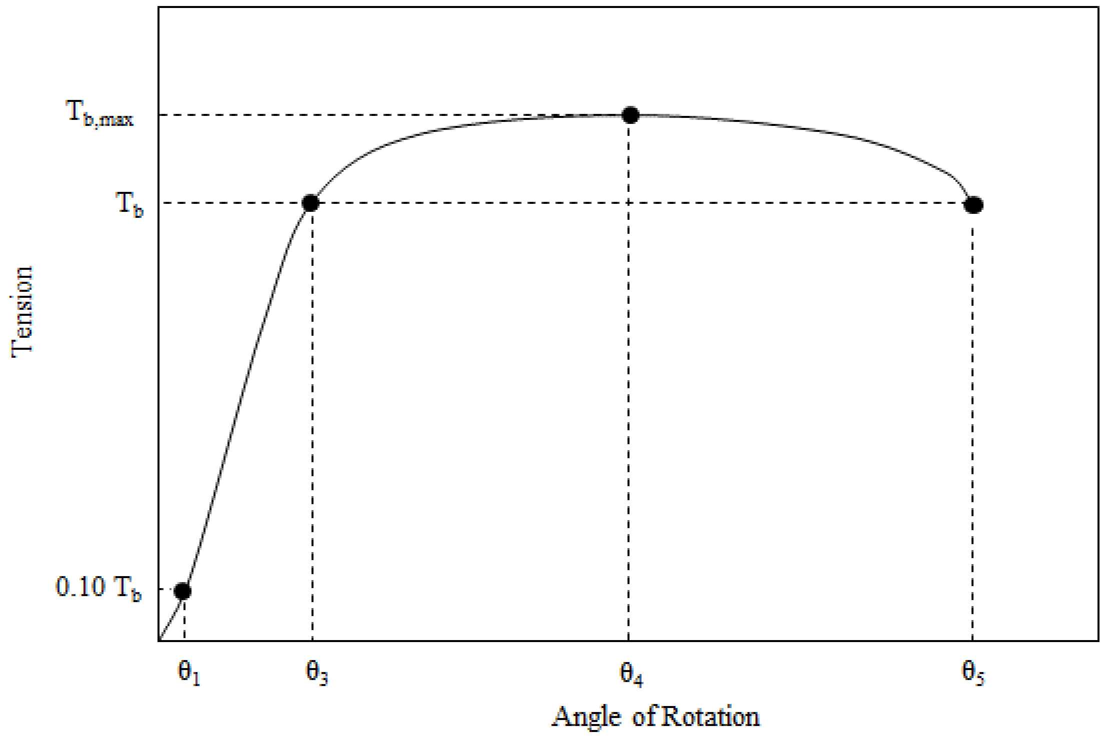

Figure B2. Definition of Parameters in Bolt Force vs. Nut Rotation Curve

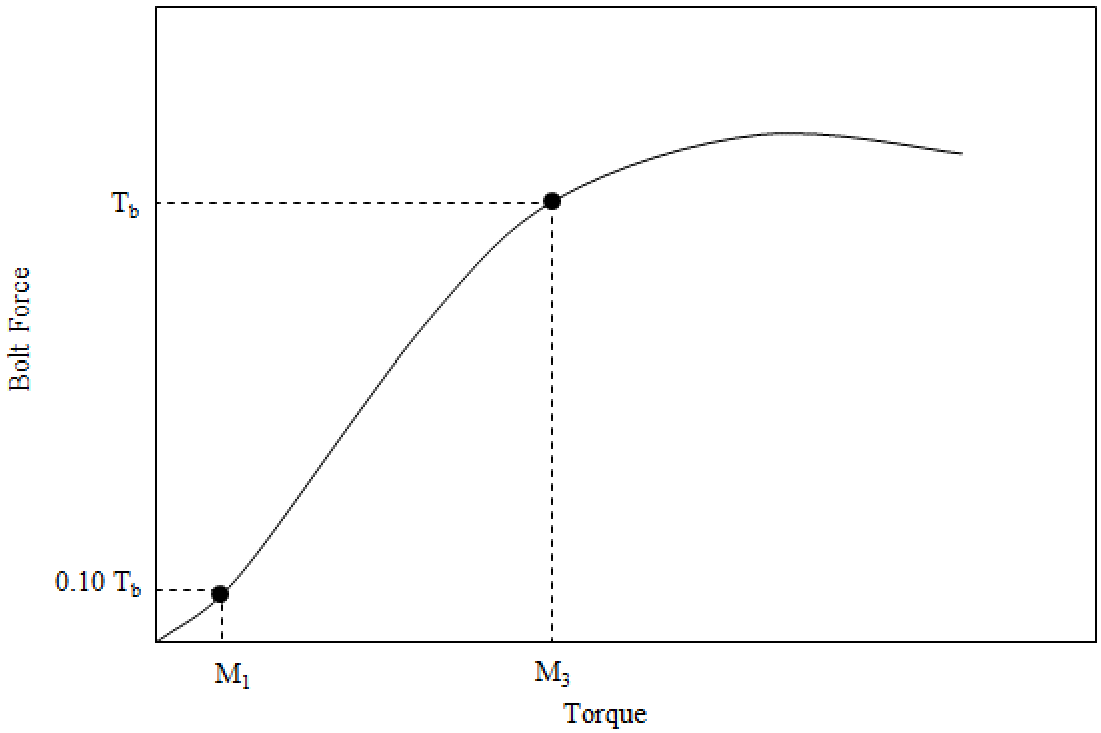

Figure B3. Definition of Parameters in Bolt Force vs. Torque Curve

3.5. Determination of Nut Rotation Angle for Turn-of-Nut Installation

3.5.1. The specified minimum bolt pretension, defined as T_{des}, should not be taken greater than the minimum T_b value from the torqued tension tests, rounded down to the nearest kip. T_{des} should not be taken greater than 39 kip or 49 kip, depending on if the corrosion-resistant bolts are expected to behave similar to ASTM F3125 Grade A325 or Grade A490 bolts, respectively. The value of T_{des} may be further reduced by discretion to meet the requirements of this procedure.

Commentary:

The minimum T_b value is used as an upper limit to provide conservativism when using corrosion-resistant bolts. The T_{des} maximum limits of 39 and 49 kip correspond to the specified minimum bolt pretension values of ASTM F3125 Grade A325 and Grade A490 bolts, respectively. It is not anticipated or desired that corrosion-resistant fasteners have greater specified minimum bolt pretension values than typical bolts used in bridges. Determining a value of T_{des} may be an iterative process to meet the rest of the requirements in this procedure.

3.5.2. All torqued tension tests should satisfy the following:

$$T_{b,max} \geq 1.3\ T_{des} \qquad \text{(Eq. B5)}$$

Commentary:

The factor of 1.3 serves as a safety factor to ensure the bolt has sufficient ultimate strength. The safety factor in ASTM F3125 Annex A.2 for rotational capacity tests is 1.15 (ASTM F3125 2015) for heavy hex carbon steel structural bolts. Although not directly stated in ASTM F3125, 1.15 is the factor that is multiplied by the specified minimum bolt pretension at the required rotation to determine the minimum tension at a full rotation. The portion of that safety factor greater than 1.0 was doubled for additional conservativism to produce the 1.3 factor used in this procedure.

3.5.3. All torqued tension tests should have a $\Delta\theta_{53}$ greater than or equal to the minimum specified in Table B1.

Table B1. Minimum Values for $\Delta\theta_{53}$

Grip Length, L	Minimum $\Delta\theta_{53}$
L < 2d	210°
2d ≤ L < 6d	240°
6d ≤ L < 10d	270°
d = diameter of bolt	

Commentary:

Guidance for the maximum additional nut rotation angle past that required to achieve T_b is to ensure that the bolt has sufficient ductility remaining once it has been pretensioned. The values in Table B1 have been successful in demonstrating sufficient ductility in experimental testing of pretensioned stainless steel bolts (Stranghöner et al., 2017b).

3.5.4. All torqued tension tests should have a k-factor in the range of $0.10 \leq k \leq 0.25$.

Commentary:

The k-factor of a fastener assembly indicates the level of friction in the system. An increase in friction indicates an increase in torsion, which can lead to premature failure of a bolted fastener. The upper limit of the allowable k-factor of 0.25 was taken from ASTM F3125 Annex A.2 for rotational capacity tests. This maximum allowable k-factor is given in terms of a maximum torque, stating that the maximum torque shall not exceed 0.25 times the tension in the bolt and the bolt diameter (ASTM F3125 2015).

3.5.5. The turn-of-nut rotation angle required to achieve the pretension force in the fastener assembly, defined as θ_r, should be taken equal to the maximum $\Delta\theta_{31}$ value in the torqued tension tests, rounded up to the nearest 60° increment.

Commentary:

The turn-of-nut rotation angle required to achieve the specified minimum bolt pretension is taken equal to the maximum $\Delta\theta_{31}$ value, rounded up, to ensure that the force in the bolt during installation exceeds T_{des}. It is rounded up to the nearest 60° to correspond to the next corner point on a nut face or bolt head for convenience.

3.5.6. θ_r should not exceed the minimum $\Delta\theta_{41}$ value from the torqued tension tests.

Commentary:

This requirement ensures that pretension in the bolt has not exceeded its ultimate strength at the required nut rotation. This allows sufficient ductility to remain after pretensioning.

4. Test Report

4.1. The following minimum information should be included in the test documentation.

- Identification of individual(s) performing the tests and analysis;
- Date the fastener assemblies were received;
- Date of testing;
- Specifications to which the components of the fastener assembly were ordered;
- Identification number of the lots of the bolts, nuts, and washers used in the fastener assembly;
- Lubricant type included in the fastener assembly;
- Lubricant placement in the fastener assembly;
- Marking of bolts, nuts and washers;
- Bolt grip length and number of ASTM F436 washers used during torqued tension tests;
- Observations noted during torqued tension tests;
- Torqued tension tests data including bolt force vs. nut rotation curve, bolt force vs. torque curve, and all values determined from these two curves for each bolt tested;
- Torqued tension tests evaluation, including Suitability tests evaluation results of maximum bolt force, ductility, and lubrication; and

- Installation parameters for each pretensioning method and intermediate values used to determine installation parameters.