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Slip Coefficient Testing of ASTM A709 Grade 50CR Steel and Dissimilar Metal Slip-Critical Bolted Connections

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JASON T. PROVINES, P.E.
Research Scientist

HADDIS ABEBE
Research Assistant

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

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16. Abstract:

The purpose of this study was to conduct slip coefficient testing of bolted connections made from ASTM A709 Grade 50CR steel (hereinafter "50CR steel") to determine how they fit into the current AASHTO LRFD Bridge Design Specifications (hereinafter "the AASHTO BDS") surface condition classifications. Currently, 50CR steel is not included in these classifications because it was not being used for bridges when the existing surface condition classifications were developed in the 1980s. The slip coefficient tests conducted in this study included both compression slip and tension creep tests as specified by the Research Council of Structural Connections. The test specimens consisted of both uniform and dissimilar metal connections; uniform connections were made up entirely of 50CR steel, and dissimilar metal connections were made up of both 50CR steel and either weathering or galvanized steel. Dissimilar metal connections were included in the testing because their future use is anticipated in which a bridge girder would be constructed using both 50CR and other ASTM A709 bridge steels. In these cases, 50CR steel would be used in highly corrosive parts of a bridge, such as near joints or close to water, and either weathering or galvanized steel would be used in less corrosive parts of the bridge to provide cost savings. In addition to different steel types, the test specimens included various surface finishes, including unblasted, steel shot blast-cleaned, and garnet blast-cleaned surfaces. In total, 55 slip tests and 33 creep tests were conducted as part of this study.

The test results showed that unblasted 50CR steel has a slip coefficient value of at least 0.30, which meets the current AASHTO BDS Class A surface condition for unblasted steel. Additional testing should be conducted to determine if unblasted 50CR steel could provide a greater slip coefficient value. If additional testing shows this to be true, using a greater slip coefficient for unblasted 50CR steel would provide additional cost savings since blast cleaning would not be necessary to reach a greater slip coefficient value. Blast-cleaned 50CR steel from either steel shot or garnet media has a slip coefficient value of 0.50, which meets the current AASHTO BDS Class B surface condition for blast-cleaned steel. When dissimilar metal connections are made with 50CR steel, the design slip coefficient value of the connection can be taken equal to the smaller of the two slip coefficient values being jointed.

The study recommends that the Virginia Transportation Research Council conduct a technical assistance study to determine the appropriate sample size for slip coefficient tests on 50CR steel and dissimilar metal bolted connections that is necessary to recommend changes to the surface classification and slip coefficient value of 50CR steel in the AASHTO BDS and the Virginia Department of Transportation bridge design specifications.

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FINAL REPORT

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Jason T. Provines, P.E.
Research Scientist

Haddis Abebe
Research Assistant

In Cooperation with the U.S. Department of Transportation
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Virginia Transportation Research Council
(A partnership of the Virginia Department of Transportation
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ABSTRACT

The purpose of this study was to conduct slip coefficient testing of bolted connections made from ASTM A709 Grade 50CR steel (hereinafter "50CR steel") to determine how they fit into the current *AASHTO LRFD Bridge Design Specifications* (hereinafter "the AASHTO BDS") surface condition classifications. Currently, 50CR steel is not included in these classifications because it was not being used for bridges when the existing surface condition classifications were developed in the 1980s. The slip coefficient tests conducted in this study included both compression slip and tension creep tests as specified by the Research Council of Structural Connections. The test specimens consisted of both uniform and dissimilar metal connections; uniform connections were made up entirely of 50CR steel, and dissimilar metal connections were made up of both 50CR steel and either weathering or galvanized steel. Dissimilar metal connections were included in the testing because their future use is anticipated in which a bridge girder would be constructed using both 50CR and other ASTM A709 bridge steels. In these cases, 50CR steel would be used in highly corrosive parts of a bridge, such as near joints or close to water, and either weathering or galvanized steel would be used in less corrosive parts of the bridge to provide cost savings. In addition to different steel types, the test specimens included various surface finishes, including unblasted, steel shot blast-cleaned, and garnet blast-cleaned surfaces. In total, 55 slip tests and 33 creep tests were conducted as part of this study.

The test results showed that unblasted 50CR steel has a slip coefficient value of at least 0.30, which meets the current AASHTO BDS Class A surface condition for unblasted steel. Additional testing should be conducted to determine if unblasted 50CR steel could provide a greater slip coefficient value. If additional testing shows this to be true, using a greater slip coefficient for unblasted 50CR steel would provide additional cost savings since blast cleaning would not be necessary to reach a greater slip coefficient value. Blast-cleaned 50CR steel from either steel shot or garnet media has a slip coefficient value of 0.50, which meets the current AASHTO BDS Class B surface condition for blast-cleaned steel. When dissimilar metal connections are made with 50CR steel, the design slip coefficient value of the connection can be taken equal to the smaller of the two slip coefficient values being jointed.

The study recommends that the Virginia Transportation Research Council conduct a technical assistance study to determine the appropriate sample size for slip coefficient tests on 50CR steel and dissimilar metal bolted connections that is necessary to recommend changes to the surface classification and slip coefficient value of 50CR steel in the AASHTO BDS and the Virginia Department of Transportation bridge design specifications.

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INTRODUCTION

Corrosion is a leading cause of bridge deterioration and can lead to costly maintenance cycles throughout the life of a bridge. One of the new ways the steel bridge community has combatted corrosion is through the use of ASTM A709 (hereinafter "A709") Grade 50CR steel (hereinafter "50CR steel") as a means of providing inherent corrosion resistance to steel structures in aggressive environments. To date, 50CR steel (formerly referred to as ASTM A1010 steel) (ASTM International [ASTM], 2013)) has been used on six bridges in the United States (Sharp et al., 2018). Although the use of 50CR steel has been successful, there are still a few unknowns regarding its use, including its slip coefficient when designing a slip-critical bolted connection.

According to the *AASHTO LRFD Bridge Design Specifications* (hereinafter "the AASHTO BDS") (American Association of State Highway and Transportation Officials [AASHTO], 2017), nearly all bolted connections in steel bridges must be designed as slip critical. Slip-critical connections are a type of bolted connection where forces are transferred from one component to the next through friction, rather than through bearing on the bolts. This type of connection is required in areas of a bridge subject to stress reversal, heavy impact loads, severe vibration, or at any locations where stress and strain attributable to joint slippage would be detrimental to the serviceability of the structure. Slip-critical connections are achieved by tightening high-strength bolts to a specified level of pretension to clamp connected parts together; this allows the connection to transfer load by friction of the faying surfaces, which are the surfaces in contact in a bolted joint.

Section 6.13.2.8 of the AASHTO BDS specifies the nominal slip resistance of a bolt in a slip-critical connection as provided in Equation 1 (AASHTO, 2017):

$$R_n = K_h K_s N_s P_t \qquad \text{[Eq. 1]}$$

where

R_n = nominal slip resistance of a bolt (kips)
N_s = number of slip planes per bolt

P_t = minimum required bolt tension, specified depending on bolt diameter (kips), specified in Table 1

K_h = hole size factor, specified depending on type of hole, specified in Table 2

K_s = surface condition factor, specified in Table 3.

Tables 1 through 3 provide the information for the minimum bolt pretension, hole size factor, and surface condition factor, respectively, referred to in Equation 1. The tables contain information from the AASHTO BDS for ASTM F3125 Grade A325 and ASTM F3125 Grade A490 (hereinafter "A490") bolts, both of which are commonly used by the Virginia Department of Transportation (VDOT) and the national bridge community.

Table 1. Minimum Required Bolt Pretension

Bolt Diameter (in)	Required Pretension in Bolt, P_t (kip)	
	Grade A325	Grade A490
5/8	19	24
3/4	28	35
7/8	39	49
1	51	64
1 1/8	64	80
1 1/4	81	102
1 3/8	97	121
1 1/2	118	148

Source: AASHTO LRFD Bridge Design Specifications (AASHTO, 2017).

Table 2. Hole Size Factor, K_h

Hole Description	K_h
For standard holes	1.00
For oversize and short-slotted holes	0.85
For long-slotted holes with the slot perpendicular to the direction of the force	0.70
For long-slotted holes with the slot parallel to the direction of the force	0.60

Source: AASHTO LRFD Bridge Design Specifications (AASHTO, 2017).

Table 3. Surface Condition Factor, K_s

Surface Condition Description	K_s
For Class A surface conditions	0.30
For Class B surface conditions	0.50
For Class C surface conditions	0.30
For Class D surface conditions	0.45

Source: AASHTO LRFD Bridge Design Specifications (AASHTO, 2017).

The descriptions of surface conditions in Table 3 are as follows:

- *Class A surface:* unpainted clean mill scale and blast-cleaned surfaces with Class A coatings

- *Class B surface:* unpainted blast-cleaned surfaces in accordance with Society for Protective Coatings Surface Preparation 6 (SSPC-SP 6) or better and blast-cleaned surfaces with Class B coatings, or unsealed pure zinc or 85/15 zinc/aluminum thermal-sprayed coatings with a thickness less than or equal to 16 mils (NACE International, 1999)

- *Class C surface:* hot-dip galvanized surfaces

- *Class D surface:* blast-cleaned surfaces with Class D coatings.

The surface condition values (K_s from Table 3), also called slip coefficients, were determined through historical experimental tests on carbon steel faying surfaces with mill scale, blast-cleaned steel surfaces, unsealed thermal-sprayed surfaces, zinc-rich primers, and galvanized surfaces (Frank and Yura, 1981). More recent tests have shown that galvanized surfaces provide comparable slip coefficient values whether they have been roughened or unroughened (Donahue et al., 2014). Overall, there is a large amount of data for slip coefficient tests in the literature (Stankevicius et al., 2009; Yura et al., 1981).

Typical carbon steels fall into Class A, B, or D; bare steels are classified based on whether or not they have been blast cleaned; and coated steels are classified based on the type of coating that has been applied. Weathering steels are also classified in the same fashion as typical carbon steels. Galvanized steel surfaces fall into their own category, Class C.

With regard to 50CR steel, it was not specifically included in Equation 1 or Table 3 because the testing used to determine the slip coefficients did not include 50CR steel, as it was not being used for bridges at the time (ASTM, 2017). Therefore, it is unknown if the material behaves significantly different than traditional carbon steel in slip-critical bolted joints. An American Institute of Steel Construction (AISC) stainless steel design guide (Baddoo, 2013) written for austenitic and duplex stainless steels stated that stainless steel faying surfaces are likely to have lower slip coefficient values than typical carbon steel faying surfaces. Since 50CR steel is a martensitic stainless steel, it was unknown if it also has a lower slip coefficient than other types of stainless steels.

Besides the material difference, the studies that produced the current AASHTO slip coefficient specifications did not include any testing on surfaces blast cleaned using non-metallic media or dissimilar steel bolted connections. Traditional steel girders can be blast cleaned with steel shot before leaving the fabrication plant. Blast cleaning in the areas of bolted connections is especially common so that the faying surface can qualify as a Class B surface condition, which reduces the number of bolts required in a connection because of the increased slip coefficient. In the case of 50CR steel, it can be blast cleaned with non-metallic media to avoid in-service staining (Wright, 2015). This was the case for the first VDOT bridge constructed of 50CR steel (Provines et al., 2018). Since this bridge, i.e., the Route 340 Bridge, contained a bolted field splice, there were questions about how to classify the slip coefficient of the 50CR steel faying surfaces; two potential options were discussed. One option was to apply a coating with a known slip coefficient to the faying surfaces of the bolted splice. The second option was to blast clean the entire surface of the steel girders, including the faying surfaces, with garnet media. The second option was eventually chosen because of time constraints. However, one disadvantage of using a garnet blast media is the increased cost over that of the traditionally used steel shot. Although this solution did provide VDOT engineers with more confidence that an increased level of friction would be present in the faying surfaces because of the garnet blast cleaning, the exact slip coefficient value was unknown since there are no test data available for 50CR steel that has been blast cleaned using non-metallic media.

It is also anticipated that as 50CR steel is used more frequently and designers and fabricators become more familiar with it, dissimilar metal steel girders employing both 50CR steel and other A709 steels will be constructed. For these dissimilar metal steel bridge girders, 50CR steel will be used in highly corrosive, targeted areas of the bridge such as near joints and abutments. Other A709 bridge steels can then be used in less corrosive areas of the bridge to provide a cost savings. In these cases, it is likely that uncoated weathering steel (A709 Grade 50W) or galvanized steel will be used rather than painted steel to minimize overall maintenance to the structure over its service life. There is no known literature that includes slip coefficient tests conducted on bolted joints of differing steel types.

With the emergence of the use of 50CR steel in longer span bridges, slip-critical bolted field splices are necessary. Currently, the AASHTO BDS do not provide guidance on how to classify either 50CR steel faying surfaces or dissimilar metal connections made with 50CR steel and other A709 steel bolted connections. Since there are limited test data on slip coefficients of 50CR steel materials for bridge applications, this study included testing on 50CR steel with various surface finishes in uniform and dissimilar metal configurations to determine how to classify the surface condition of each.

PURPOSE AND SCOPE

The purpose of this study was to conduct slip coefficient testing of 50CR steel in uniform and dissimilar metal slip-critical bolted connections to determine how they fit into the current AASHTO BDS surface condition classifications.

The scope of the study included static and creep experimental testing on 50CR steel uniform and dissimilar metal test specimens. The 50CR steel faying surfaces tested included unblasted, steel shot blast-cleaned, and garnet blast-cleaned finishes. Other faying surfaces included both weathering steel and galvanized steel since both are anticipated for use in future dissimilar metal steel bridge applications. The weathering steel included both unblasted and steel shot blast-cleaned surfaces, and the galvanized steel was tested in the as-galvanized condition. The study included 11 different faying surface combinations, with 5 replicate compression slip and 3 replicate tension creep specimens within each combination. The large amount of faying surface combinations allowed for evaluating which combinations performed better than the others, with the potential that additional slip coefficient testing could conducted, if necessary, on favorable combinations in a future study.

METHODS

All tests were conducted in accordance with the procedure described in Appendix A of the Research Council of Structural Connections (RCSC) *Specification for Structural Joints Using High-Strength Bolts* (RCSC, 2014). There were 55 static test specimens and 33 creep test specimens, for a total of 88 test specimens.

The overall method for determining the slip coefficient of a faying surface begins with conducting a series of five compression slip tests. The results of those five tests are then used to calculate the mean slip coefficient for the group of test specimens. A series of three tension creep tests are then conducted using the mean slip coefficient value to determine if the specimens provide satisfactory performance under sustained loads. These procedures are all based on the RCSC specification, which was developed based on research conducted by Frank and Yura (Frank and Yura, 1981; RCSC, 2014). The committee that votes on changes to the RCSC specification has a current ballot item that contains several proposed revisions to the RCSC specification. Where applicable, the test methods in this study reflected the proposed changes in the ballot item rather than the current specification. All alterations to the current RCSC specification test methods are noted in this report. In instances where the proposed test methods in the ballot were used, both the currently specified test methods and the proposed test methods are described.

In addition to tests conducted in accordance with the RCSC, surface profile measurements were made on each type of faying surface to determine if any correlations could be made with the slip coefficient performance. Therefore, methods in this study included the following tasks:

1. Compression slip tests were conducted and analyzed.
2. Tension creep tests were conducted and analyzed.
3. Surface profile measurements were recorded and analyzed.

Compression Slip Tests

The slip coefficient tests included 11 different combinations of uniform and dissimilar metal connections. These combinations are shown in the test matrix for the compression slip tests in Table 4.

Table 4. Text Matrix for Compression Slip Tests

Specimen Name	Faying Surface 1		Faying Surface 2		No. of Slip Tests
	Steel Type	Surface Finish	Steel Type	Surface Finish	
AU-AU-S#	50CR	Unblasted	50CR	Unblasted	5
WU-AU-S#	A588	Unblasted	50CR	Unblasted	5
ZN-AU-S#	Galvanized	As-received	50CR	Unblasted	5
AS-AS-S#	50CR	Steel shot blasted	50CR	Steel shot blasted	5
WS-AS-S#	A588	Steel shot blasted	50CR	Steel shot blasted	5
ZN-AS-S#	Galvanized	As-received	50CR	Steel shot blasted	5
AG-AG-S#	50CR	Garnet blasted	50CR	Garnet blasted	5
WS-AG-S#	A588	Steel shot blasted	50CR	Garnet blasted	5
ZN-AG-S#	Galvanized	As-received	50CR	Garnet blasted	5
WS-WS-S#	A588	Steel shot blasted	A588	Steel shot blasted	5
ZN-ZN-S#	Galvanized	As-received	Galvanized	As-received	5

AU = 50CR steel unblasted; AS = 50CR steel blasted with steel shot; AG = 50CR steel blasted with garnet; WU = weathering steel unblasted; WS = weathering steel blasted with steel shot; ZN = galvanized steel.

The specimens were named using three pairs of designators, with hyphens between them. The first pair was two letters to designate the steel type and surface finish on faying surface 1. The second pair was the same, except for faying surface 2. The third pair was the letter “S,” to indicate that these were slip tests, and a test number, since there were five replicate tests for each combination of faying surfaces.

The test specimens were generally divided into four groups, where the variable between the first three groups was the surface finish of the 50CR steel faying surfaces. Within each of the surface finish groups, there were three types of specimens: 50CR to 50CR faying surfaces, 50CR to ASTM A588 (hereinafter “A588”) steel (i.e., weathering steel), and 50CR to galvanized steel (ASTM, 2015). Within these surface finish groups, each group of the faying surfaces was generally prepared in a similar fashion; that is, surfaces in a group were either left as mill scale or blast cleaned. The exception to this was the galvanized surfaces, which were left in the as-galvanized condition.

The first three specimens belonged to the first surface finish group and consisted of unblasted, clean mill scale surfaces. The next three specimens belonged to the second surface finish group that contained steel shot-blasted surfaces. The steel shot blast media used in this study met the requirements of SAE Size No. S330. The next three specimens belonged to the third surface finish group that contained garnet blast-cleaned 50CR steel faying surfaces. The garnet blast media used in this study qualified as a 30/60 blend, meaning that 95% of the media passed through a No. 30 sieve but none of it passed through a No. 60 sieve. Since garnet is not expected to be used on any surface other than 50CR steel for future VDOT applications, only steel shot media was used on the A588 steel.

The last two specimens belonged to the fourth group made up of A588 and galvanized steel specimens. The A588 specimens were used as a control group. Since there is a large amount of test data on steel shot-blast-cleaned weathering steel test specimens (Frank and Yura, 1981), they were used primarily to validate the static and creep test frames and loading procedure used in this study. The galvanized steel test specimens were included to foster a better understanding of the slip behavior of the galvanized steel specifically being used in this study. One 2014 study (Donahue et al., 2014) showed that there can be significant variability in slip coefficient results for galvanized steel, which can be dependent on steel chemistry, pickling bath chemistry, and the galvanizing process. All galvanized steel consisted of ASTM A36 (hereinafter “A36”) steel that was galvanized by a VDOT-approved galvanizer (ASTM, 2014). The chemistry of the A36 steel was analyzed using optical emission spectroscopy to determine if the steel was considered a reactive or nonreactive steel for galvanizing. Reactive steels cause a thicker zinc galvanizing coating to form on the steel. The chemical analysis of the A36 steel is shown in Table 5.

Table 5. Chemistry of ASTM A36 Steel Used

Sample	Carbon (Weight %)	Manganese (Weight %)	Phosphorus (Weight %)	Sulfur (Weight %)	Silicon (Weight %)	Copper (Weight %)
A36 steel	0.17	1.14	0.014	0.02	0.27	0.23

According to the American Galvanizers Association, steels with a silicon content of greater than 0.22 weight % are reactive (American Galvanizers Association, 2019). Since the A36 steel used in this study had a silicon content of 0.27 weight %, it was considered to be reactive. Both reactive and nonreactive steels are allowed by AASHTO, and no distinction is made between them in the Class D surface condition.

The standard test specimens used for the compression tests are shown in Figure 1. The specimens consisted of three plates, each having dimensions of 4 in × 4 in × 5/8 in thick. Each plate had a 1-in-diameter hole drilled 1 1/2 in from one edge of the plate. The clamping force was applied through a 7/8-in-diameter threaded rod passing through this hole. The hole was oversized to ensure adequate slippage during the test. The contact surfaces of each of the three plates needed to be flat enough to ensure that they were in full contact over the entire 4 in x 3 in faying surfaces. Faying surfaces 1 and 2, referred to in Table 5, are also shown in the figure.

The test specimens containing 50CR steel were slightly altered because of a machining error. All of the 50CR steel plates were originally cut to the correct outer dimensions of 4 in x 4 in, but the 1-in-diameter hole was drilled in the center of the plate, rather than at a distance of 1.5 in from one edge of the plate; having the hole in the center of all three plates did not allow for compression testing to take place. This issue was alleviated by cutting 1/2 in off one side of each plate, making each plate 3 1/2 in x 4 in with the hole off center. This still allowed for a contact faying surface area of 3 in vertically x 4 in horizontally, which is the same as specified by the RCSC (RCSC, 2014) for both the uniform and dissimilar metal 50CR steel test specimens. Figure 2 shows a dissimilar 50CR steel specimen, with the smaller 50CR steel middle plate. The uniform 50CR steel specimens differed in that the outer two 50CR steel plates also had a height of 3 1/2 in.

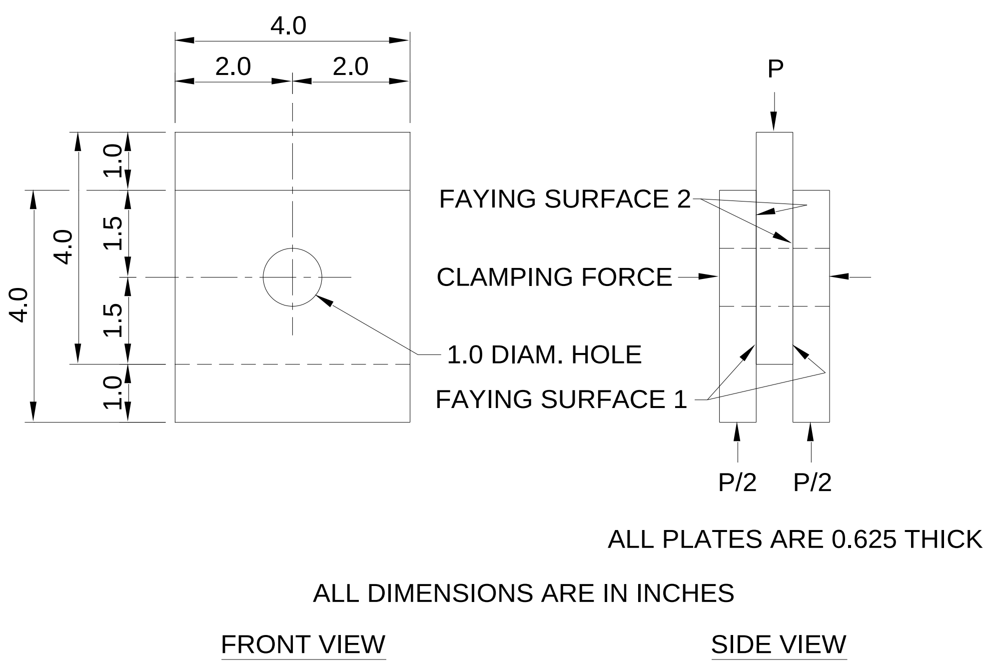

Figure 1. Drawing of Standard Compression Slip Test Specimens

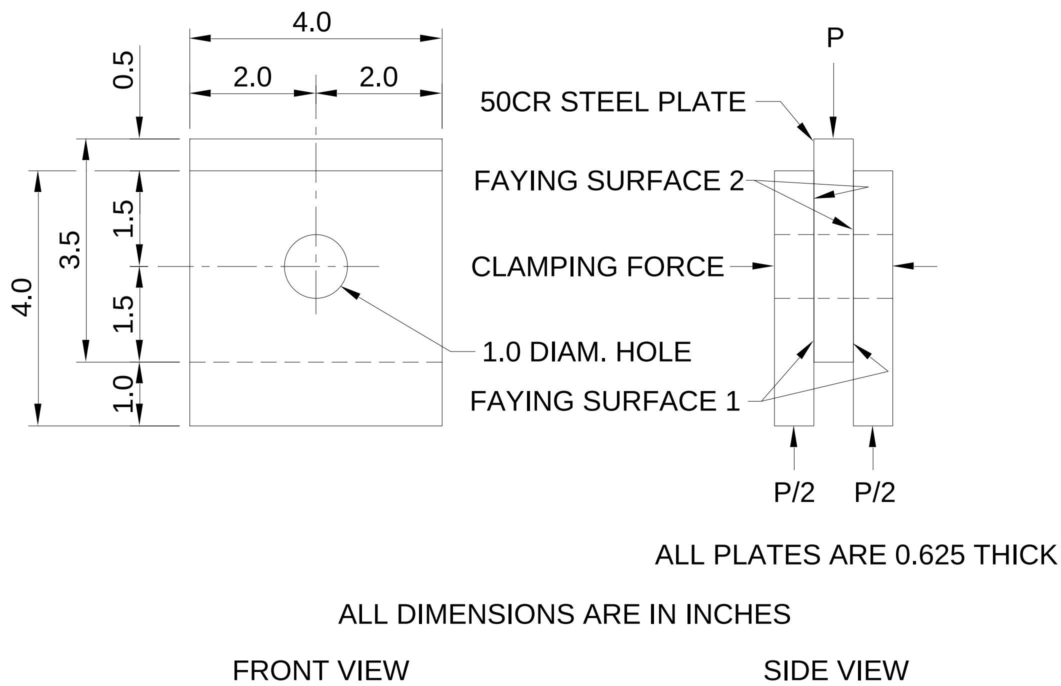

Figure 2. Drawing of Dissimilar Metal 50CR Steel Compression Test Specimens

Details of the clamping and compressive force system are shown in Figure 3. The clamping force system included the 7/8-in-diameter, high-strength threaded rod that passed through the specimen and a center-hole compression jack. An ASTM A563 Grade DH nut was used at both ends of the rod, and a hardened washer was used at each side of the test specimen. Between the jack and the specimen was a center-hole load cell with a capacity of 100 kips used to measure the tension applied to the test specimen through the threaded rod. Between the load cell and the specimen was a 7/8-in-diameter drilled-out ASTM A563 Grade DH nut that could slide with no resistance along the threaded rod. Overall, the clamping force system was meant to simulate a fully pretensioned bolted connection using an A490 high-strength bolt in a controlled and measureable manner.

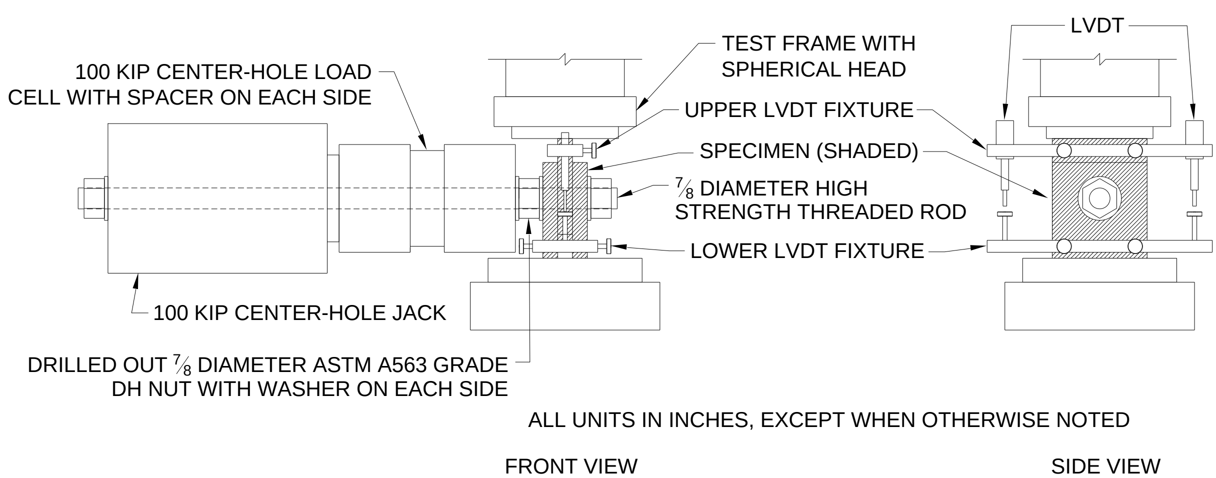

Figure 3. Drawing of Compression Slip Test Setup

A servo-hydraulic, uniaxial load frame with a maximum load capacity of 220 kips was used to apply the vertical load to the specimens. During testing, load and displacement were recorded from the load frame's load cell and linear variable differential transducer (LVDT), respectively.

As shown in Figure 3, LVDTs were used to measure the relative displacement, or slip, between the inner plate and outer plates during loading. Although the 2014 version of the RCSC specification (RCSC, 2014) requires the use of a single slip measurement device, a study by Ocel et al. (2014) of the variability of slip coefficient testing practices recommended that two slip displacement measurement devices be used: one on each side of the specimen. Aluminum plates were fabricated similar to those prescribed by Ocel et al. (2014) to use as the upper and lower LVDT fixtures mounted to the specimen. This allowed for a direct measurement of slip between the inner and outer plates without inclusion of any compliance from the test frame. The average of the two LVDTs was then used as the slip for a given test. A photograph of the compression test setup is also shown in Figure 4.

The compression test procedure began by first positioning the three plates so that they were in bearing with the 7/8-in threaded rod in a direction that was opposite to the planned compressive loading direction. This ensured the full range of motion for slip before the threaded rod began bearing on one of the plates in the direction of loading. The specimen was then centered in the load frame before both platens were brought just into contact with the specimen without any vertical load being applied. An initial clamping force of 5 kips was then slowly applied through the threaded rod. In some cases, this caused one or more of the plates to shift so that they were not in full contact with the appropriate platen. If this occurred, the clamping force was completely released and then reapplied until all three plates remained square and in contact with the platens.

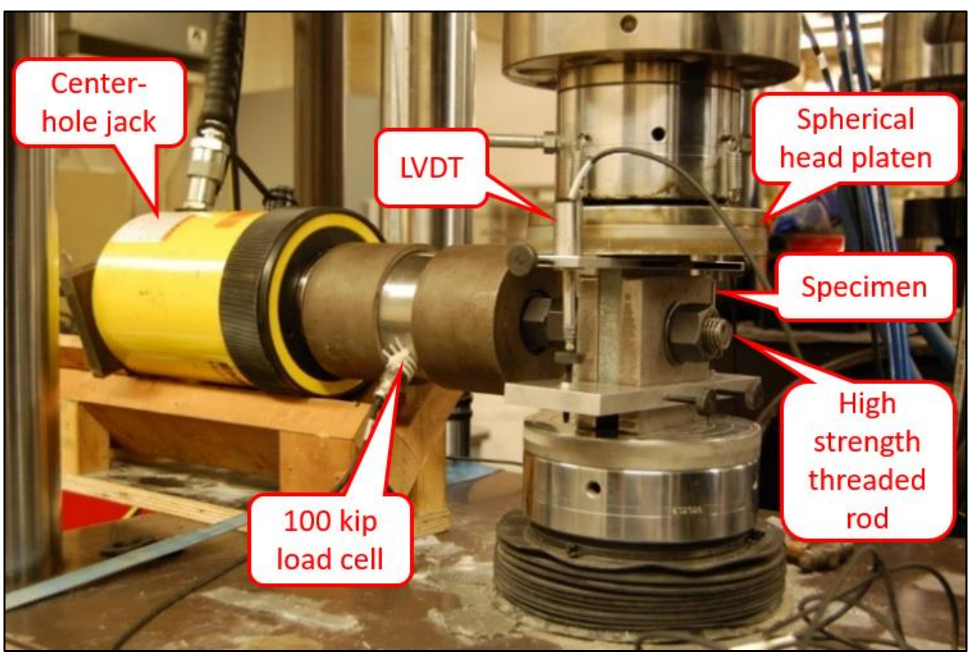

Figure 4. Compression Test Setup

The platens were then moved away from the test specimen to allow for the LVDT fixtures and LVDTs to be installed. Once the LVDTs were in place, the platens were repositioned back into full contact with the specimen without the application of any vertical load. If one or more of the platens were not in full contact with a platen, the clamping force was released and the process was repeated. Once the specimen and platens were in satisfactory position, a clamping force of 50 kips was applied. Although the 2014 version of the RCSC specification specifies that a clamping force of 49 kips be used, the proposed ballot of the RCSC specified changing the clamping force to 50 kips for simplicity's sake; therefore, a 50-kip clamping force was used for this study (RCSC, 2014). Once the clamping force was applied, it was maintained within ±0.5 kips for the duration of testing using a hand pump.

Vertical load was applied at a rate of 0.003 in/min; the loading rate was monitored to ensure it did not exceed 25 kips/min, per the RCSC specification. A compressive load of 5 kips was applied, and then the two LVDTs were zeroed to eliminate recording the seating displacement of the specimen, per the RCSC ballot item. The load was then applied until the average slip value between the two LVDTs reached 0.04 in. The 2014 version of the RCSC specification specifies that tests be concluded once the average slip reaches 0.05 in, but the RCSC ballot item states that 0.04 in is sufficient; therefore, this value was used.

The RCSC also provides guidance for analyzing the compressive test data, including determination of the slip load and calculation of the slip coefficient value. Figure 5 shows a plot that was re-created from a similar one in the RCSC specification showing three types of generic load vs. slip plots.

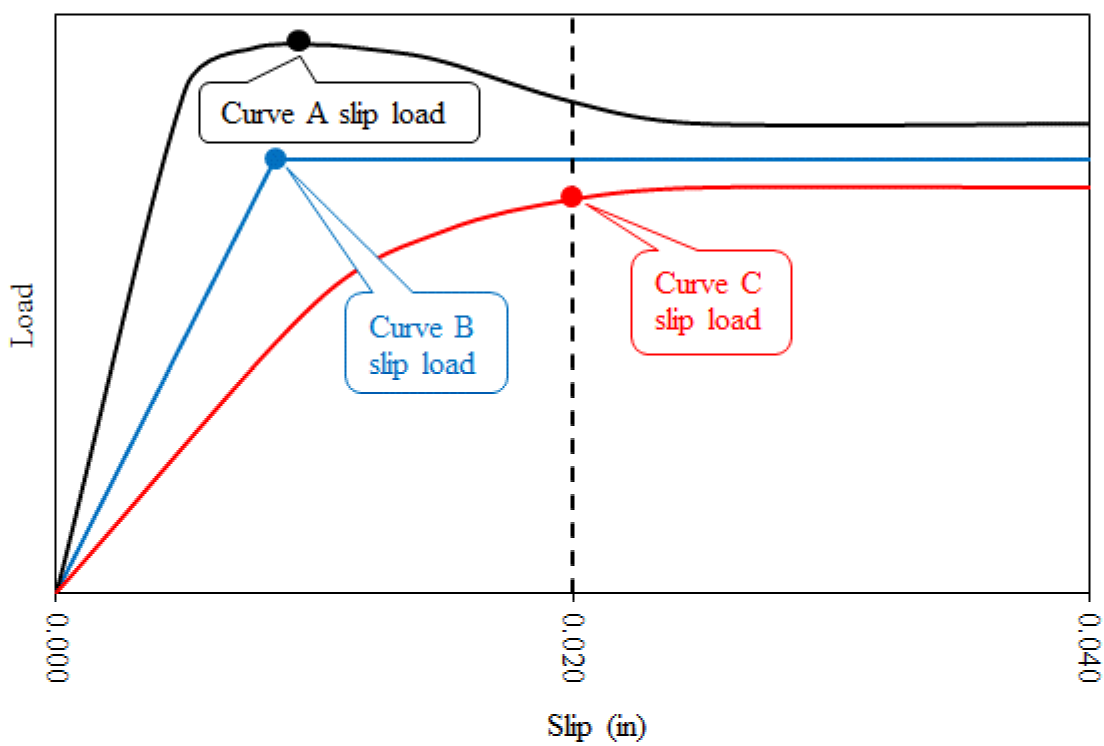

Figure 5. Definition of Slip Load

The RCSC provides guidance for determining the slip load of a given plot type. For Curve A, the slip load is the maximum load reached during testing provided it occurs before a slip of 0.02 in is reached. For Curve B, the slip load is the load at which the slip increases suddenly without an increase in load. For Curve C, the slip load is the load corresponding to a slip of 0.02 in provided the curve shows a gradual change in response and reaches a maximum value after a slip of 0.02 in. The overall slip load for a specimen is taken as the maximum value when all three criteria in Curves A, B, and C are analyzed.

The slip coefficient of an individual specimen can then be calculated as shown in Equation 2

$$k_s = \frac{slip\ load}{2\ x\ clamping\ force} \quad \text{[Eq. 2]}$$

where k_s = slip coefficient of an individual specimen.

The slip coefficient of a specimen group is then calculated by taking the mean slip coefficient of the set of five specimens. The ballot for the RCSC also contains criteria that state if an individual specimen slip coefficient value is substantially lower than the average of the other four, it may be deemed an outlier and discarded. In order for this to occur, the equality in Equation 3 must be true.

$$\frac{\mu - k_{s,min}}{\sigma} \geq 1.71 \quad \text{[Eq. 3]}$$

where

μ = mean of the five k_s values attained
$k_{s,min}$ = lowest k_s value in five samples of a specimen group
σ = standard deviation of the set of five k_s values attained.

Tension Creep Tests

Similar to the slip tests, tension creep tests were performed on the same 11 combinations of uniform and dissimilar metal connections. A naming convention and notation similar to those used for the slip tests were used for each specimen, as described in Table 6.

The only difference in the naming convention of the tension creep tests compared to that of the slip tests is that the third pair of designators in the specimen name included the letter “C” to indicate that these were creep tests. Three replicates of each specimen type were conducted, as specified by the RCSC.

Table 6. Text Matrix for Tension Creep Tests

Specimen Name	Faying Surface 1		Faying Surface 2		No. of Creep Tests
	Steel Type	Surface Finish	Steel Type	Surface Finish	
AU-AU-C#	50CR	Unblasted	50CR	Unblasted	3
WU-AU-C#	A588	Unblasted	50CR	Unblasted	3
ZN-AU-C#	Galvanized	As-received	50CR	Unblasted	3
AS-AS-C#	50CR	Steel shot blasted	50CR	Steel shot blasted	3
WS-AS-C#	A588	Steel shot blasted	50CR	Steel shot blasted	3
ZN-AS-C#	Galvanized	As-received	50CR	Steel shot blasted	3
AG-AG-C#	50CR	Garnet blasted	50CR	Garnet blasted	3
WS-AG-C#	A588	Steel shot blasted	50CR	Garnet blasted	3
ZN-AG-C#	Galvanized	As-received	50CR	Garnet blasted	3
WS-WS-C#	A588	Steel shot blasted	A588	Steel shot blasted	3
ZN-ZN-C#	Galvanized	As-received	Galvanized	As-received	3

AU = 50CR steel unblasted; AS = 50CR steel blasted with steel shot; AG = 50CR steel blasted with garnet; WU = weathering steel unblasted; WS = weathering steel blasted with steel shot; ZN = galvanized steel.

The standard test specimens for the creep tests are shown in Figure 6. Each specimen consisted of three plates, each having dimensions of 4 in x 7 in x 5/8 in thick. Each plate had two 1-in-diameter holes, drilled 1 1/2 in from each end of the plate. Similar to the slip tests, the faying surface of each plate needed to be flat enough to ensure that the faying surfaces were in full contact when bolted together. As shown in the figure, the replicate specimens for the creep tests were tested in series, in a chain-like arrangement with loose bolts between specimens so that the same load was applied to all specimens within the chain. A minimum of three specimens needed to be included in the chain.

The bolts used to clamp a specimen together were A490 bolts, pretensioned to a minimum load level of 50 kips. The 2014 RCSC specification specifies a load level of 49 kips, but the current RCSC ballot specifies a value of 50 kips for simplicity; therefore, this value was used for constructing the creep specimens. All A490 bolts used came from the same lot of bolts, as specified by the RCSC. According to the RCSC, prior to construction of the specimens, the pretension value of the A490 bolts had to be calibrated by testing three bolts. Since the specimens were tightened in three groups, this process was repeated 3 times, once for each tightening group.

The calibration process started by taking three A490 bolts out of the bolt lot. One bolt was then placed into a bolt tension measurement device. The bolt was loaded using the turn-of-nut process as described by the RCSC. First, the nut on the bolt was tightened to a snug-tight position, which occurs when all of the parts being bolted together are in firm contact with one another. This corresponded to a tensile force of 4 kips, as shown on the bolt tension measurement device. Second, a co-linear line was drawn on the nut and the bolt tension measurement device. The nut was then tightened to a rotation of 120 degrees, and the pretension in the bolts was recorded from the bolt tension measurement device. This process was then repeated for the other two A490 bolts initially selected. The pretension values for the three bolts were then verified to ensure they were within ±2 kips to satisfy the RCSC requirements. The average value of the three bolt tests was then considered to be the assumed force in the pretensioned A490 bolts within the particular tightening group.

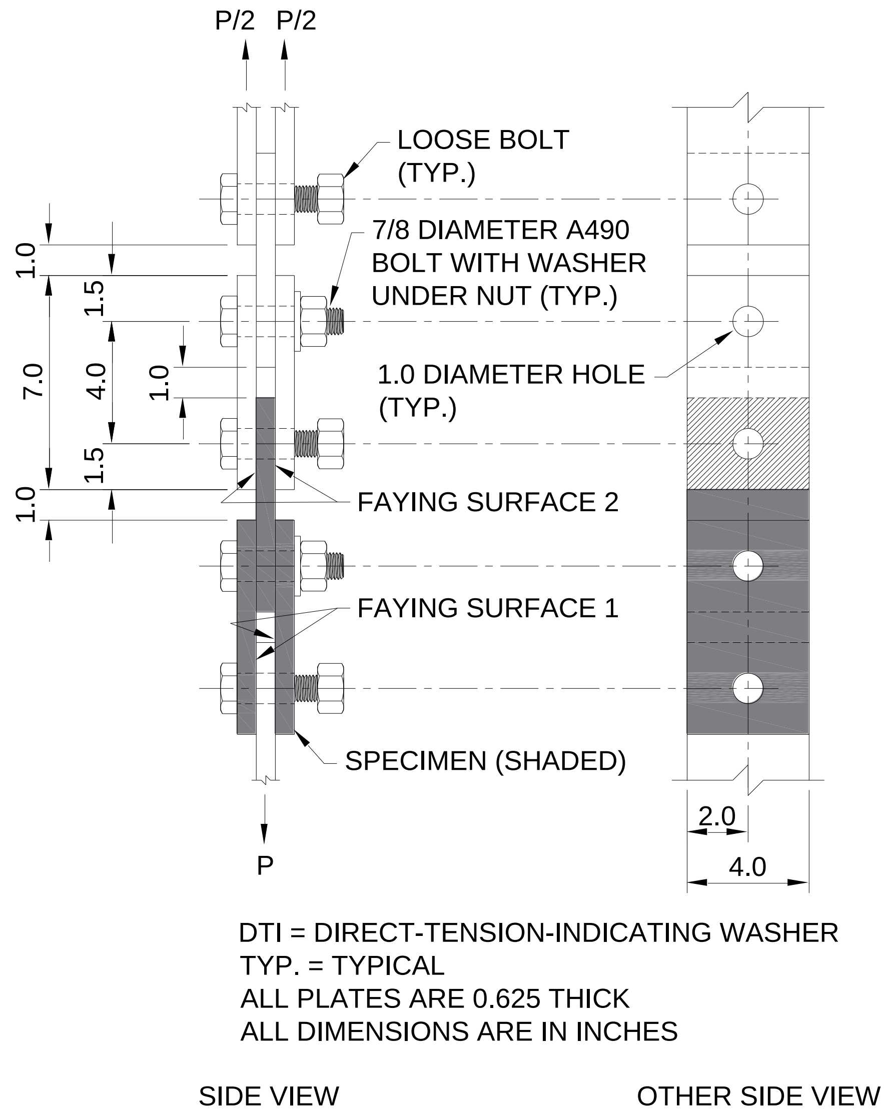

Figure 6. Drawing of Standard Tension Creep Test Specimens

Once the calibration process for each tightening group was completed, the creep specimen chains were bolted together with A490 bolts, washers, and nuts. Plates within the specimen were assembled with each bolt bearing against the plate(s) in the opposite direction of the applied tension loading. This was similar to how the static test specimens were constructed to accommodate the maximum amount of slip.

The creep load frames used in this setup were taken from a previous study conducted at the Virginia Transportation Research Council (VTRC) with some minor modifications to accommodate the slip coefficient specimens. Details of the loading setup are shown in Figure 7. Three concave washers were placed in series below the load cell and spacers to allow the tension load to be kept relatively constant should any slip occur. These assisted in keeping the vertical load within ±1% of its determined value (described later), as specified in the RCSC specification.

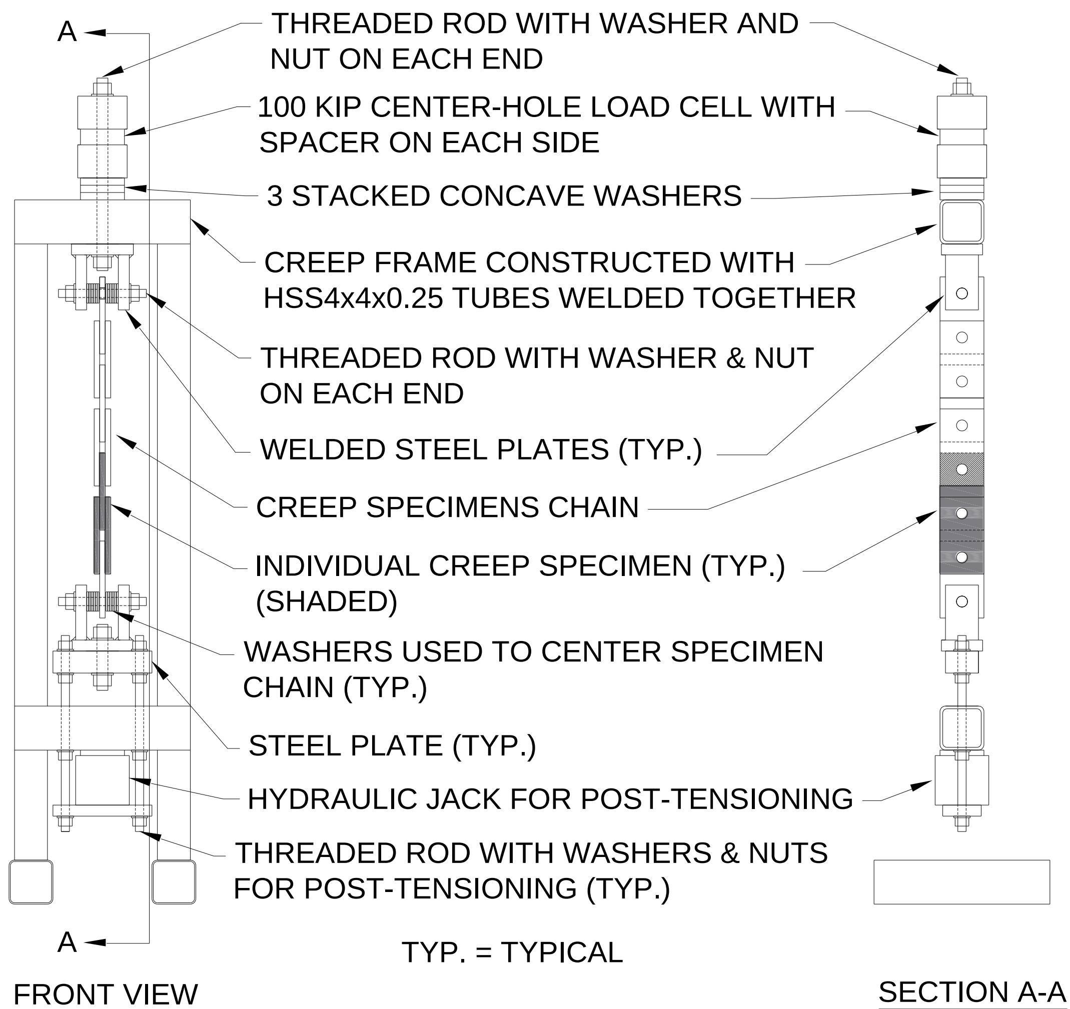

Figure 7. Drawing of Tension Creep Test Setup

As specified by the RCSC, the relative slip between the outer and center plates of each specimen was measured on both sides. This was achieved by mounting dial gauges onto the specimens via magnetic base fixtures and aluminum plates. For each specimen, a dial gauge with a resolution of 0.0001 in was attached to a magnetic base placed vertically on the center plate. An aluminum plate was then attached to a horizontal magnetic base attached to the outer plates, such that the plunger of the dial gauge could react on the aluminum plate. A drawing of the dial gauges used to measure the slip is shown in Figure 8. A photograph of three creep test frames is shown in Figure 9.

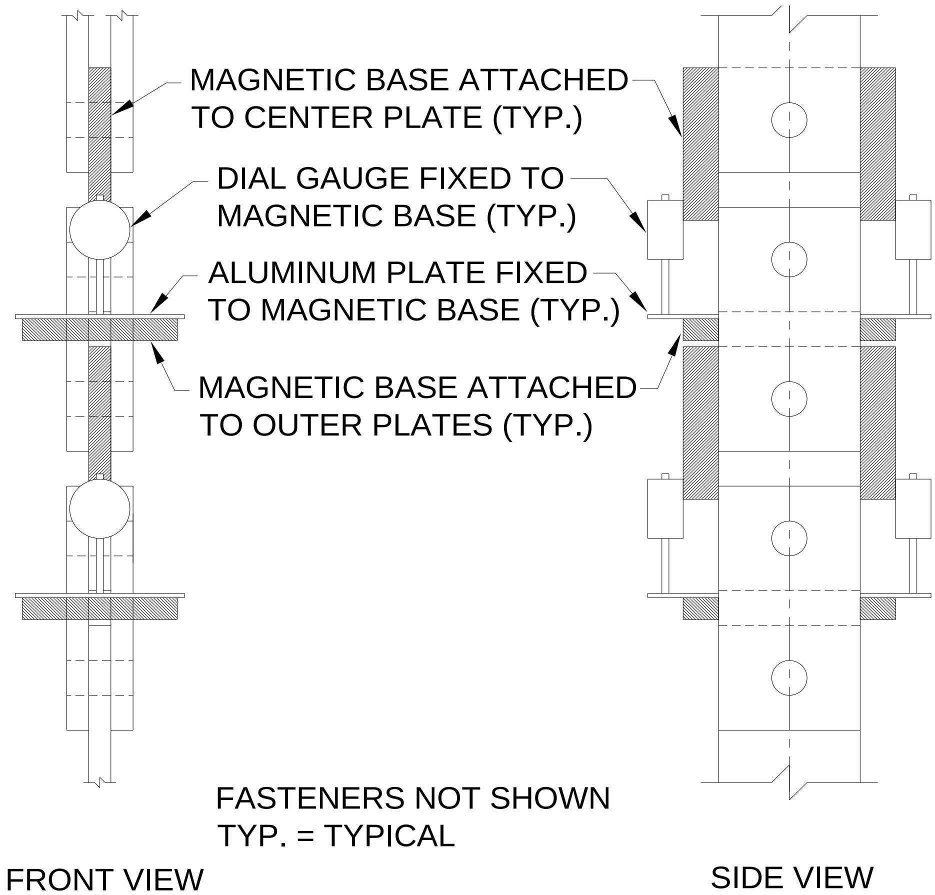

Figure 8. Drawing of Slip Measurement Instrumentation on Creep Test

Once the chain of specimens was installed into the creep frame, the specimens were tensioned to a load calculated using Equation 4.

$$R_s = \frac{2\mu_t T_t}{1.5} \qquad \text{[Eq. 4]}$$

where

R_s= tension load applied to creep test specimen chain (kips)
μ_t= slip coefficient for particular category under consideration
T_t= average clamping force from three-bolt calibrations (kips), must be ≥49 kips.

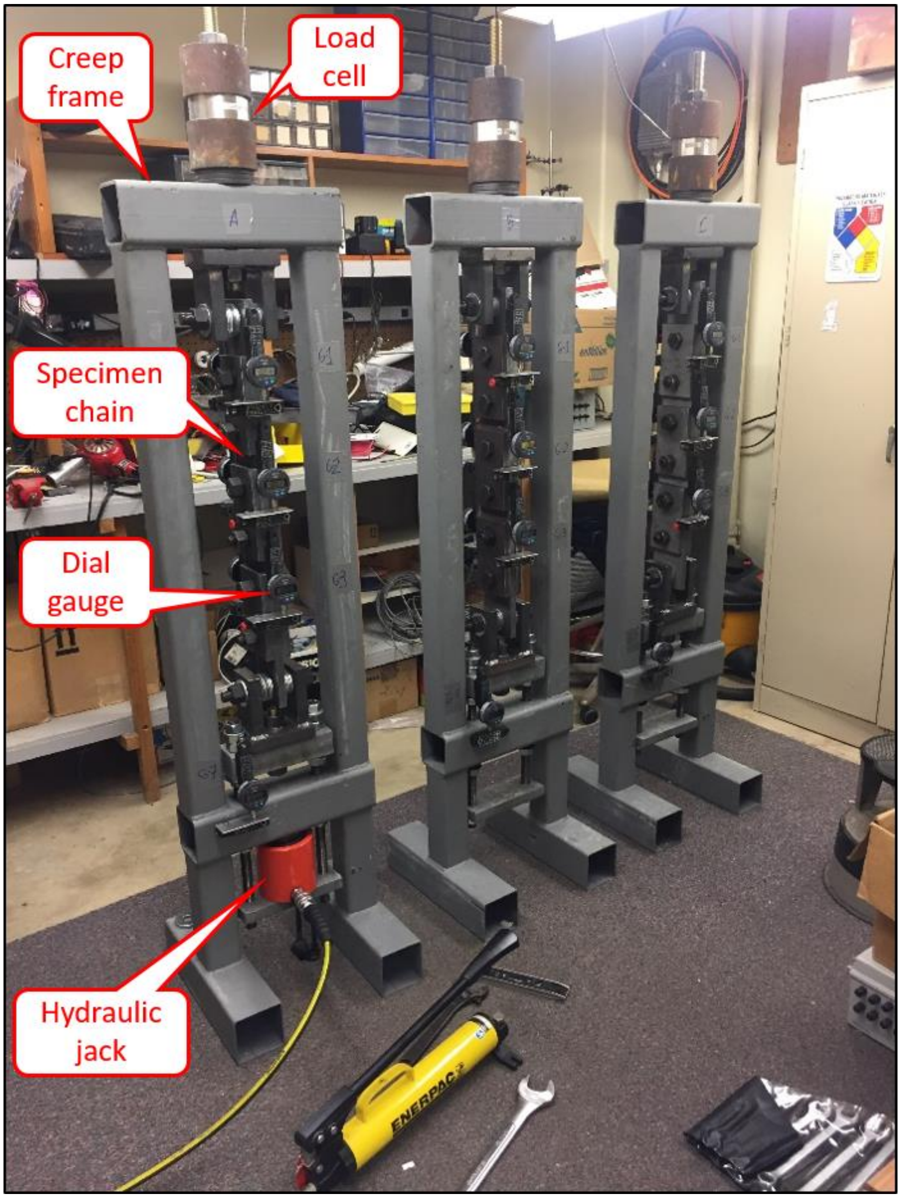

Figure 9. Photograph of Tension Creep Tests

The slip coefficient for a particular category, μ_t, was uniquely selected for each specimen type. It was dependent upon both the mean slip coefficient value determined from the static tests and the surface condition class (from Table 3) in which the specimen was expected to behave. The average clamping force from the bolt calibrations was selected from the appropriate tightening group in which each specimen was assembled.

Once the vertical tension load was applied, it was held constant for at least 1,000 hours. Within 30 minutes of the load application, the dial gauges were reset to a value of zero to serve as the reference point of no slip. After that point, the slip of a specimen was defined as the average value of the two dial gauges on both sides of the specimen. Slip measurements were recorded daily, Monday through Friday, until at least 1,000 hours had passed. If any specimen reached a slip value of 0.005 in, it was considered to have failed the creep test.

Summary of Compression Slip and Tension Creep Tests

Since the final slip coefficient determination depends on both the slip and creep tests, the results from both were used to develop conclusions about the slip coefficient of each specimen type. Prior to any testing, the slip coefficient value for each specimen type was hypothesized based on the surface finishes of the faying surfaces using during testing. For the traditional steels, such as weathering and galvanized steels, the slip coefficient value was already known based on the current AASHTO specifications. For the 50CR steel faying surfaces, the expected slip coefficient values were determined based on whether the surface had been blast cleaned or not. Unblasted 50CR steel surfaces were expected to have a slip coefficient of 0.30, and those that were blasted (with either steel shot or garnet blast media) were expected to have a slip coefficient of 0.50. In cases where the specimen contained two different faying surfaces, the smaller slip coefficient value was deemed to be controlling. For example, Specimen ZN-AS contained a galvanized surface having a design slip coefficient of 0.30 and a 50CR steel shot-blasted surface having an expected design slip coefficient of 0.50. In this case, the expected slip coefficient value was expected to be 0.30 since it is the lower of the two surface finish conditions. The results of this hypothesis are provided in Table 7. After the tension and creep tests were conducted, their results were compared to the expected slip coefficient values in Table 7.

Table 7. Expected Slip Coefficient Values for Each Specimen Type

Specimen	Faying Surface 1: Known or Expected Surface Condition	Faying Surface 1: Known or Expected Slip Coefficient	Faying Surface 2: Known or Expected Surface Condition	Faying Surface 2: Known or Expected Slip Coefficient	Controlling Expected Slip Coefficient Value
AU-AU	Class A	0.30	Class A	0.30	0.30
WU-AU	Class A	0.30	Class A	0.30	0.30
ZN-AU	Class C	0.30	Class A	0.30	0.30
AS-AS	Class B	0.50	Class B	0.50	0.50
WS-AS	Class B	0.50	Class B	0.50	0.50
ZN-AS	Class C	0.30	Class B	0.50	0.30
AG-AG	Class B	0.50	Class B	0.50	0.50
WS-AG	Class B	0.50	Class B	0.50	0.50
ZN-AG	Class C	0.30	Class B	0.50	0.30
WS-WS	Class B	0.50	Class B	0.50	0.50
ZN-ZN	Class C	0.30	Class C	0.30	0.30

AU = 50CR steel unblasted; AS = 50CR steel blasted with steel shot; AG = 50CR steel blasted with garnet; WU = weathering steel unblasted; WS = weathering steel blasted with steel shot; ZN = galvanized steel.

Surface Profile Measurements

Surface profile measurements were taken on each type of faying surface used in the slip coefficient tests to determine if a correlation exists between surface profile and slip coefficient. In order to obtain profile measurements, an untested static test plate of each surface type was randomly selected. The plate was then compared with others of the same kind to ensure it could serve as a representative sample. The plate was then examined under a digital microscope with multifocal plane functionality, which allows the microscope to focus on multiple depth levels at once to view a surface profile. The entire plate was examined, and a representative area away from any holes or edges was selected for surface measurements. Height measurements were then recorded every 1 μm over an area of 1920 μm x 1200 μm for a total of 2,304,000 height measurements for each plate.

Once height measurements were obtained for each of the surface finish types, height values were made relative to the minimum height recorded on each sample and the following statistical parameters were calculated: maximum value, average, standard deviation, coefficient of variation, root mean square, skewness, and excess kurtosis. Although some of these parameters are commonly used in the engineering field, others are not. The root mean square is often used in waveform statistics and is calculated by taking the square root of the arithmetic mean. Skewness and excess kurtosis are often calculated in statistics for characterizing datasets. Skewness is a measure of how symmetric the data are about the arithmetic mean. Skewness for a normal distribution is zero; a positive value indicates that more of the data are greater than the mean and a negative value indicates the opposite. Excess kurtosis is a measure of the peakedness of the dataset compared to a normal distribution with the same standard deviation. A larger value of excess kurtosis indicates that a dataset contains longer tails, or more outliers. A smaller value indicates shorter tails, and a value of 0 indicates a normal distribution. Results from the statistical analyses were then compared with the slip test results to determine if there were any correlations between surface profiles and slip coefficient.

RESULTS AND DISCUSSION

Compression Slip Tests

The load vs. slip data from all five specimens of a particular surface condition were plotted and compared. Selected plots are presented here, and the remaining are presented in Appendix A. Plots are followed by a summary table of all slip test data. Figure 10 shows a load vs. slip plot for all five AU-AU specimens (AU = 50CR steel unblasted), labeled S1 through S5 (S = slip test specimen). A vertical dashed line is shown at a slip of 0.02 in since this was one of the criteria when the maximum slip load was determined.

As shown in the figure, all five plots were relatively similar. Specimens AU-AU-S4 and AU-AU-S5 were stopped prior to reaching a slip of 0.04 in. This was done because either the specimen began rotating, which was observed in the individual LVDT data, or popping sounds originated from the specimen. In either case, stopping the testing before 0.04 in was reached was justified since a slip load could already be determined. The jagged behavior in all five specimens represented repetitive, small, sudden slip increases between increases in load. This jagged slip behavior was present only in this specimen group and the WU-AU group (WU = weathering steel unblasted). Since both of these specimen groups consisted of unblasted 50CR steel with another unblasted faying surface (either 50CR or weathering steel), it was suspected that this behavior was due to the unblasted surface. This type of jagged slip behavior is not known to have occurred with uniform unblasted weathering steel faying surfaces, so it is likely due to 50CR steel having an unblasted surface. Plots for the WU-AU specimen group are shown in Appendix A.

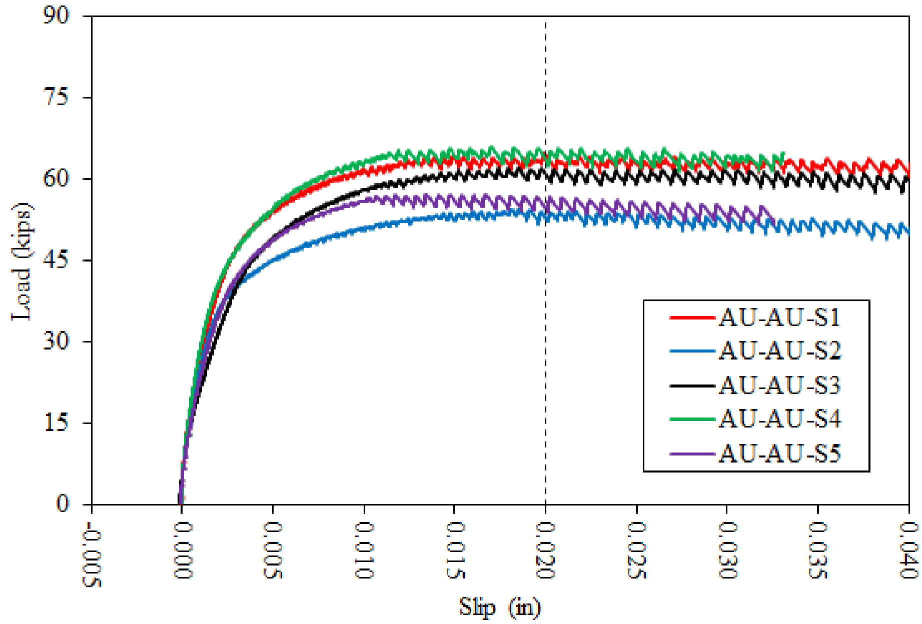

Figure 10. Plot of Compression Slip Test Data for AU-AU Specimens

Figure 11 shows a load vs. slip plot of the ZN-AU (ZN = galvanized steel) specimens. Four of the specimens appear similar, with the ZN-ZN-S5 specimens reaching smaller loads than the others. Unlike with the AU-AU and WU-AU specimens, the jagged slip behavior was not present. Instead, all five specimens had smooth curves; the jagged behavior appeared to occur only when one or both steels were 50CR steel and both faying surfaces were unblasted.

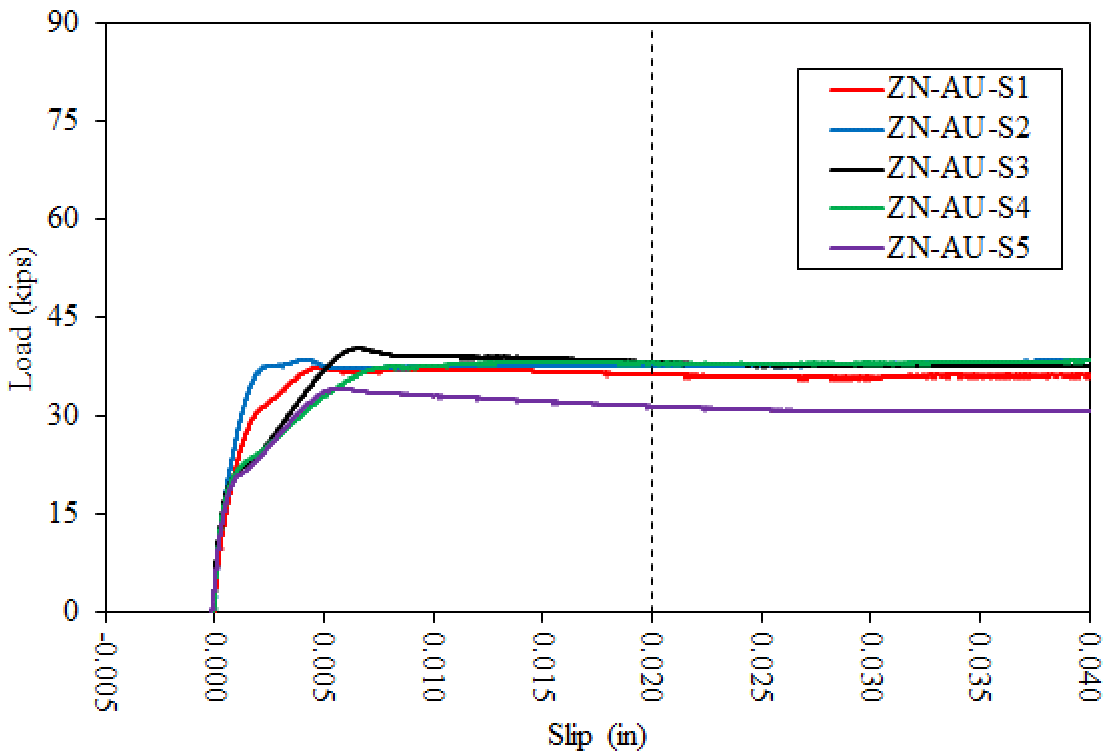

Figure 11. Plot of Compression Slip Test Data for ZN-AU Specimens

Figure 12 shows load vs. slip for the AS-AS (AS =50CR steel blasted with steel shot) specimens. Three of the specimens (AS-AS-S1, AS-AS-S4, and AS-AS-S5) showed relatively similar behavior, whereas Specimen AS-AS-S3 showed lower loads than the others. Since this specimen had much lower loads, it was evaluated to determine if it was an outlier. Since the equality in Equation 3 was true, it was deemed an outlier. The results of this analysis were shown previously. The remaining specimen, AS-AS-S2, exhibited a double plateau response, which, according to the RCSC ballot, indicates that it was probably not completely seated evenly between the two outer plates. Since the load vs. slip response of this specimen reached its greatest load value and remained relatively constant before a slip of 0.02 in, the specimen was considered to have reached an even seating and therefore was included in the analysis. All of the AS-AS curves were smooth, with no jagged slip behavior. Specimen groups WS-AS (WS = weathering steel blasted with steel shot) and ZN-AS also showed similar behavior, and their plots are shown in Appendix A.

Figure 13 shows a load vs. slip plot of the AG-AG (AG = 50CR steel blasted with garnet) specimen group. Four of the specimens appeared to be similar, whereas Specimen AG-AG-S3 had much greater loads. It is likely that the specimen was not loaded properly and there was not enough clearance between the horizontal threaded rod and the edge of one of the holes in the specimens. This would have put the threaded rod in bearing, rather than allowing slip to occur. Once this was realized during testing, loading was stopped to prevent damage to the specimen or loading setup. This specimen was deemed an outlier because of this behavior. Aside from this outlier, specimen groups WS-AG and ZN-AG showed similar behavior, and their plots are provided in Appendix A. Since specimen groups WS-WS and ZN-ZN were control groups, their results are also presented in Appendix A.

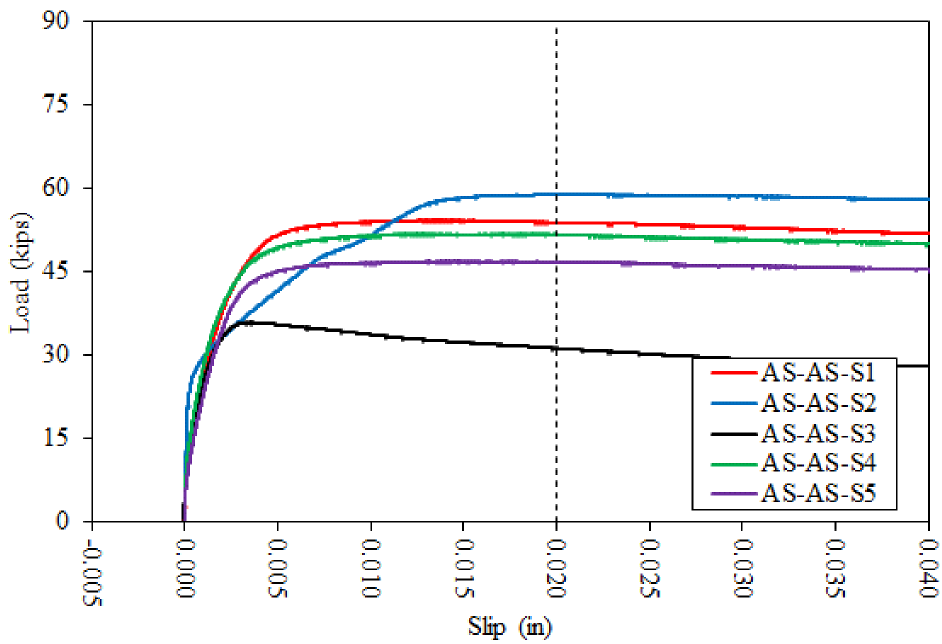

Figure 12. Plot of Compression Slip Test Data for AS-AS Specimens

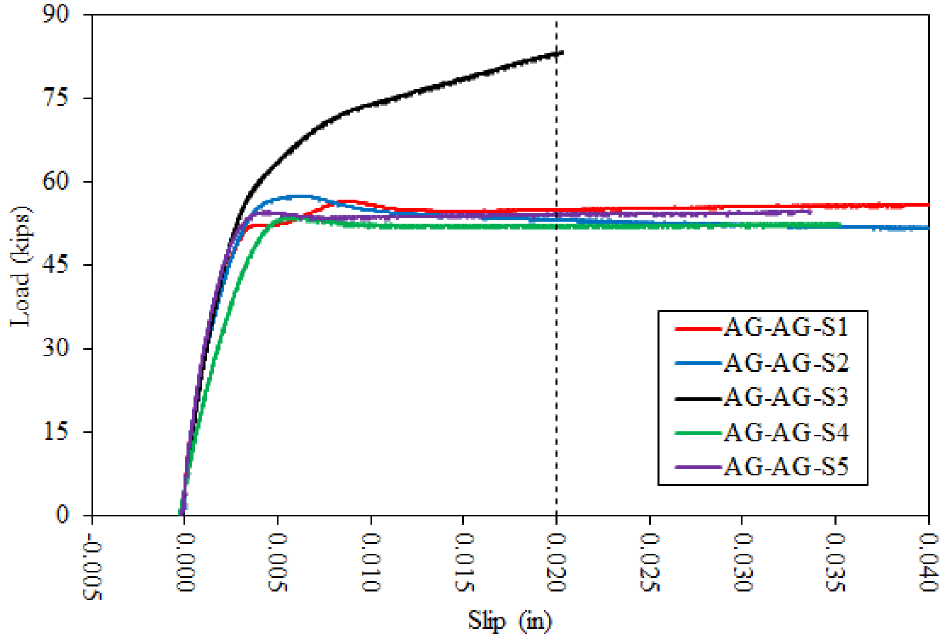

Figure 13. Plot of Compression Slip Test Data for AG-AG Specimens

All of the test data were analyzed to determine the slip coefficient values for each individual test using methods shown in Figure 5 and Equation 2. The average slip coefficient value and standard deviation for each specimen are shown in Table 8. The table also contains the expected slip coefficient values determined previously in Table 7.

The outlier analysis, as described in Equation 3, was conducted on the test results to determine if any test results should be discarded. Based on the analysis, Specimen AS-AS-S3 was deemed an outlier since it had a much lower value than the rest of those in the AS-AS specimen group. Specimen AG-AG-S3 was also deemed an outlier since it was noted that the threaded rod was bearing on the specimen plates during testing; this produced a slip coefficient value that was much greater than for the other tests within the specimen group.

Table 8. Slip Coefficient Values From Compression Slip Tests

Specimen Group	Experimental Slip Coefficient							Expected Slip Coefficient Value
	S1	S2	S3	S4	S5	Average	Standard Deviation	
AU-AU	0.65	0.54	0.62	0.66	0.57	0.61	0.04	0.30
WU-AU	0.54	0.38	0.47	0.45	0.43	0.45	0.05	0.30
ZN-AU	0.37	0.39	0.40	0.38	0.34	0.38	0.02	0.30
AS-AS	0.54	0.59	~~0.36~~	0.52	0.47	0.53	0.04	0.50
WS-AS	0.58	0.62	0.67	0.60	0.52	0.60	0.05	0.50
ZN-AS	0.44	0.43	0.39	0.42	0.41	0.42	0.02	0.30
AG-AG	0.56	0.57	~~0.83~~	0.54	0.55	0.56	0.01	0.50
WS-AG	0.76	0.69	0.61	0.76	0.57	0.68	0.08	0.50
ZN-AG	0.44	0.40	0.45	0.47	0.44	0.44	0.02	0.30
WS-WS	0.43	0.48	0.62	0.67	0.49	0.54	0.09	0.50
ZN-ZN	0.30	0.34	0.33	0.33	0.29	0.32	0.02	0.30

AU = 50CR steel unblasted; AS = 50CR steel blasted with steel shot; AG = 50CR steel blasted with garnet; WU = weathering steel unblasted; WS = weathering steel blasted with steel shot; ZN = galvanized steel. Strikethroughs indicate outliers as determined by Equation 3, which were excluded from the average and standard deviation calculations.

The slip coefficient values for Specimens AS-AS-S3 and AG-AG-S3 are shown in Table 8 with strikethrough text. These values were excluded in the average and standard deviation values within each respective specimen group.

When the experimental average was compared to the expected design slip coefficient in Table 8, it was apparent that all specimen groups had met their expected values. The unblasted 50CR steel specimen (AU-AU) had a much greater slip coefficient test value, 0.61, than its expected value of 0.30, which corresponds to a Class A unblasted surface from Table 3. Although it appears that unblasted 50CR steel would exceed the 0.50 slip coefficient value required for a Class B surface, the decision was made to categorize unblasted 50CR steel with other unblasted bridge steels for simplicity and because of material limitations in the study. For simplicity's sake, unblasted 50CR steel was categorized as a Class A surface so that all unblasted steel plate, whether 50CR or carbon steel, could be classified under a single category. Also, since only one set of three unblasted 50CR steel creep test specimens was available from the steel supplier for this study, the decision was made to test them under lower creep loads corresponding to a slip coefficient value of 0.30. This was done because if the creep specimens were tested under higher loads corresponding to a slip coefficient of 0.50 and failed the creep test, then the unblasted 50CR steel would not pass the RCSC tension creep test specification and a replicate test could not be performed.

The blast-cleaned 50CR steel surfaces, Specimens AS-AS and AG-AG, had slip coefficient values of 0.53 and 0.56, respectively. These values clearly met the Class B surface requirements of a slip coefficient of 0.50. This indicates that 50CR steel can be blast cleaned with either steel shot or garnet blast media to meet the Class B requirements. All of the dissimilar metal specimens with 50CR steel also produced experimental slip coefficient values that were larger than their expected values. These results suggest that 50CR steel uniform and dissimilar metal specimens can be categorized for compression slip tests using the AASHTO surface conditions; when dissimilar metals are used in a connection, the smaller slip coefficient of the two metals should be used for design.

Tension Creep Tests

As described previously, the creep specimens were assembled in three groups, which meant that the A490 bolt tightening calibration process had to be completed 3 times, one for each tightening group. The bolt clamping force and specimens within each tightening group are shown in Table 9.

Once the specimens were assembled, the average clamping force in the bolt tightening process was used to calculate the vertical tension load applied to each specimen. This load was calculated using Equation 4 along with the expected design slip coefficient values shown previously in Table 8. The calculated vertical tension loads applied to each specimen are shown in Table 10.

Table 9. Clamping Force in A490 Bolts During Calibration Process for Creep Tests

Specimen	Tightening Group	Clamping Force During Calibration (kip)			
		Bolt 1	Bolt 2	Bolt 3	Average
AU-AU	1	50.0	50.0	51.5	50.5
WU-AU	1	50.0	50.0	51.5	50.5
ZN-AU	2	52.2	51.5	50.3	51.3
AS-AS	3	50.0	50.3	51.0	50.4
WS-AS	3	50.0	50.3	51.0	50.4
ZN-AS	2	52.2	51.5	50.3	51.3
AG-AG	3	50.0	50.3	51.0	50.4
WS-AG	3	50.0	50.3	51.0	50.4
ZN-AG	2	52.2	51.5	50.3	51.3
WS-WS	3	50.0	50.3	51.0	50.4
ZN-ZN	2	52.2	51.5	50.3	51.3

AU = 50CR steel unblasted; AS = 50CR steel blasted with steel shot; AG = 50CR steel blasted with garnet; WU = weathering steel unblasted; WS = weathering steel blasted with steel shot; ZN = galvanized steel.

Table 10. Tension Load Applied to Creep Specimens

Specimen	Tension Load Applied to Specimen (kips)
AU-AU	20.2
WU-AU	20.2
ZN-AU	20.5
AS-AS	33.6
WS-AS	33.6
ZN-AS	20.5
AG-AG	33.6
WS-AG	33.6
ZN-AG	20.5
WS-WS	33.6
ZN-ZN	20.5

AU = 50CR steel unblasted; AS = 50CR steel blasted with steel shot; AG = 50CR steel blasted with garnet; WU = weathering steel unblasted; WS = weathering steel blasted with steel shot; ZN = galvanized steel.

The corresponding load was applied to each specimen to begin the compression tests. Slip vs. time data for all three specimens of a particular surface condition were plotted and compared. Similar to the slip test results, selected creep test data are presented here and the remaining data are presented in Appendix B. Figure 14 shows a slip vs. time plot of all three AU-AU specimens, labeled C1 through C3 and differentiated by color.

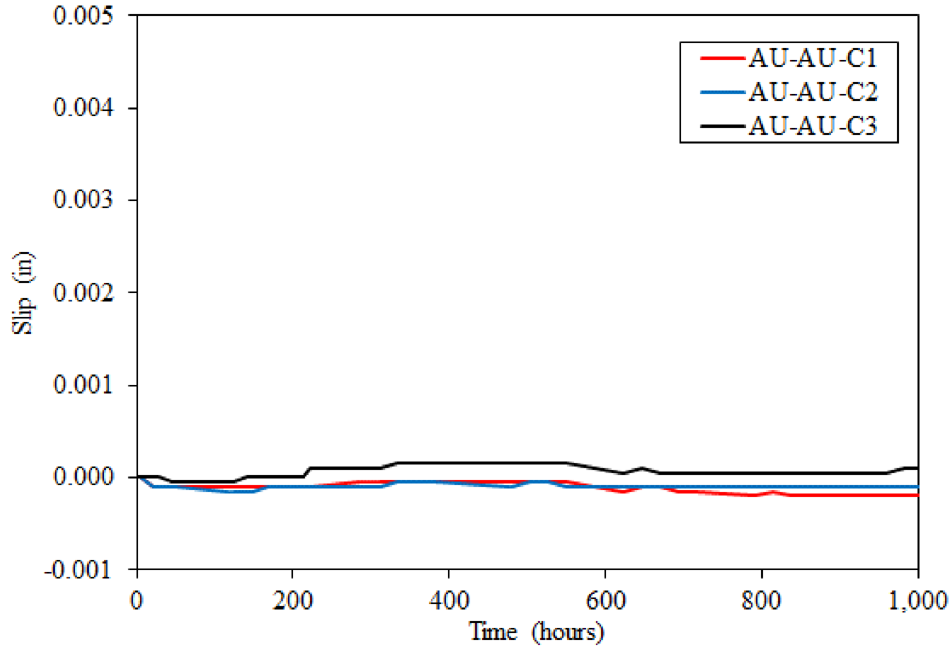

Figure 14. Plot of Tension Creep Test Data for AU-AU Specimens

As shown in the figure, all three of the AU-AU specimens showed only a small amount of slip, some of which was "noise" in the measurement system, with all of them having a magnitude of less than approximately 0.0002 in. This is much less than the maximum allowable slip of 0.005 in for the specimens to pass the creep test. The slip for all three specimens remained relatively constant throughout the 1,000 hours of creep loading.

Figure 15 shows a similar slip vs. time plot for the three WU-AU specimens. One notable difference from the previous plot is that for Specimen WU-AU-C3, slip increased approximately 0.002 in over the first 20 hours and then remained relatively constant throughout the remainder of creep loading. The other two WU-AU specimens had smaller and more constant slip values throughout. Though there were slight differences in performance, the slip of all three specimens remained well below the maximum slip limit of 0.005 in.

The slip vs. time plots for all of the remaining specimens appeared similar to that shown in Figure 14. All had relatively small and constant slip values that remained well below the 0.005 in maximum limit. Therefore, all 33 specimens tested met the tension creep requirements for their expected slip coefficient values. Slip vs. time plots for the remaining specimens are shown in Appendix B.

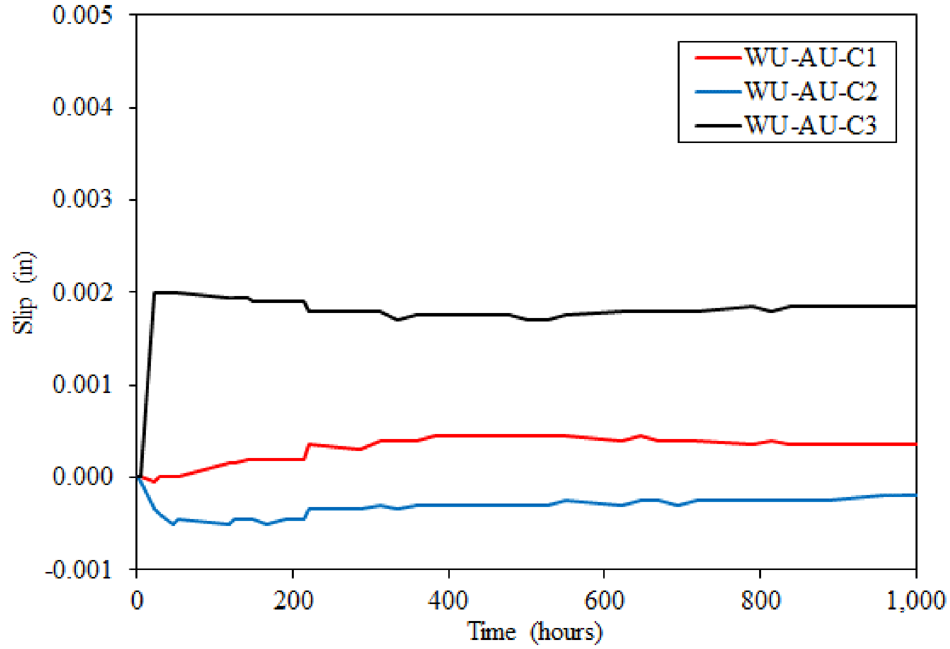

Figure 15. Plot of Tension Creep Test Data for WU-AU Specimens

Summary of Compression Slip and Tension Creep Tests

Based on the compression slip tests, all test groups exceeded their expected slip coefficient values. The tension creep tests then confirmed these results. Table 11 shows the recommended surface condition and slip coefficient values to be used for designing a slip-critical bolted connection. The WS-WS and ZN-ZN specimens are not included in this table since both of these conditions are addressed in the current AASHTO BDS surface conditions.

The recommended slip coefficient values are the same as what was expected prior to testing. The unblasted 50CR steel met the Class A surface requirements with a minimum slip coefficient value of 0.30. This allows unblasted 50CR steel to be categorized into the same surface condition as other unblasted steels. However, the unblasted 50CR steel did show significantly better performance, having an experimental compression slip coefficient of 0.61.

Table 11. Recommended Slip Coefficient Values for Design

Specimen Group	Recommended Surface Condition	Recommended Slip Coefficient for Design
AU-AU	Class A	0.30
WU-AU	Class A	0.30
ZN-AU	Class A	0.30
AS-AS	Class B	0.50
WS-AS	Class B	0.50
ZN-AS	Class A	0.30
AG-AG	Class B	0.50
WS-AG	Class B	0.50
ZN-AG	Class a	0.30

AU = 50CR steel unblasted; AS = 50CR steel blasted with steel shot; AG = 50CR steel blasted with garnet; WU = weathering steel unblasted; WS = weathering steel blasted with steel shot; ZN = galvanized steel.

Future research could potentially justify unblasted 50CR steel having an increased design slip coefficient value. This would be beneficial because blasting would not be required to provide a Class B faying surface, which would reduce the cost of using 50CR steel. This is notable because using garnet blast media was determined to be costly in the fabrication of VDOT's Route 340 Bridge (Sharp et al., 2019). Steel shot and garnet blast-cleaned 50CR steel met the Class B surface requirements with a minimum slip coefficient value of 0.50. When dissimilar metal specimens are used, the minimum slip coefficient of the two faying surfaces is recommended for design.

Surface Profile Measurements

The surface profile measurements for each steel surface finish type were analyzed to determine if there was any correlation between the surface profiles and experimental slip coefficient values. Only the uncoated steel samples, which did not include the galvanized steel, were included in this analysis. Since a large number of height measurements were recorded for each surface type, the height data were represented using histograms. As discussed previously, the height values of each surface are relative to the minimum height, so the maximum height is equal to the range of height on the surface. To encompass all of the height data recorded between all specimens, the histograms were constructed over a height range of 0 μm to 80 μm. The histograms were divided into 16 bins, with each bin having a width of 5 μm. Figure 16 shows the line histograms developed for the height data of each surface finish type.

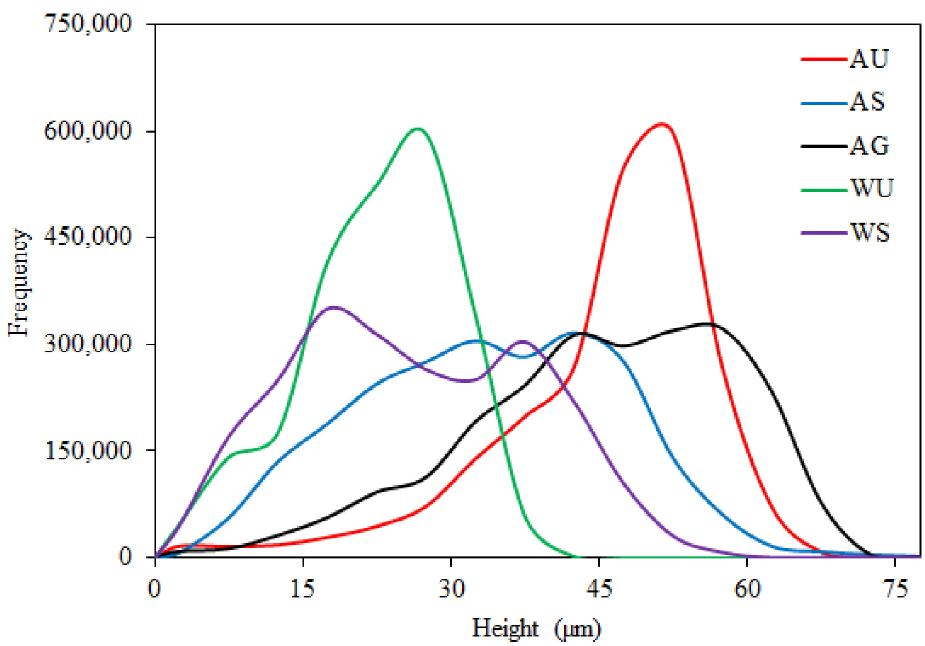

Figure 16. Line Histograms for Surface Profile Measurements of Selected Faying Surface Types

A few observations can be made from comparing the histograms of the selected surface finish types. The WU and AU histograms clearly have sharper peaks than the rest. This indicates that the unblasted surface finishes have more height measurements near the mean height, with fewer measurements far from the mean values. The other three histograms (WS, AS, and AG) have less distinct means, meaning the height measurements are more spread out throughout the height range. This is likely because the blasting process, using either steel shot or garnet media, created a more uniformly distributed profile, lacking distinct mean, median, and mode values.

Figure 17 shows cumulative distribution graphs for the height data of the selected faying surfaces. When the 50CR steel surface finishes (AU, AS, and AG) are compared to the weathering steel surface finishes (WU and WS), it is clear the 50CR steel cumulative distributions are shifted to the right, meaning that more of the 50CR steel height values fall in the higher range than the weathering steel height values. This suggests that 50CR steel has more peaks relative to both valleys and the mean. The cumulative distribution graphs of the three blasted surfaces (WS, AS, and AG) also all have similar slopes, with the garnet-blasted 50CR steel (AG) being shifted rightmost.

Statistical parameters, such as maximum height, average height, standard deviation, coefficient of variation, root mean square, skewness, and excess kurtosis, were also calculated for selected faying surfaces. These values were combined with experimental slip coefficients from Table 8 and are shown together in Table 12.

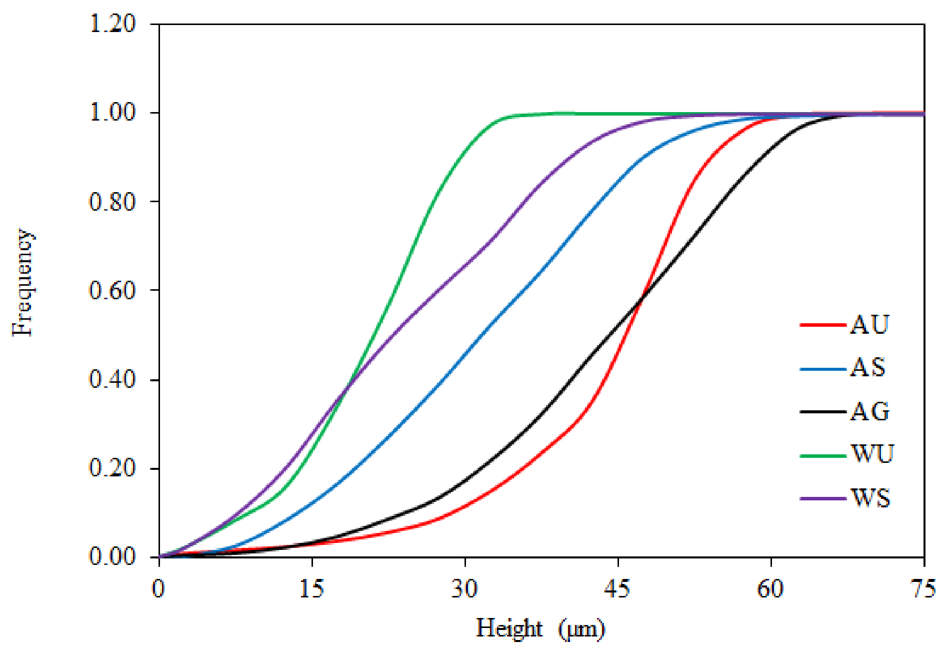

Figure 17. Cumulative Distribution Graphs of Height Data From Selected Faying Surfaces

Table 12. Surface Profile Statistical Parameters for Selected Faying Surface Types

Surface Finish Type	Experimental Slip Coefficient	Maximum Height (µm)	Average Height (µm)	Standard Deviation (µm)	Coefficient of Variation	Root Mean Square (µm)	Skewness	Excess Kurtosis
AU	0.61	74.6	45.8	11.0	0.24	47.1	-1.34	2.29
AS	0.53	76.9	33.8	12.9	0.38	36.2	-0.04	-0.64
AG	0.56	75.8	45.3	13.3	0.29	47.2	-0.55	-0.15
WU	---	43.3	22.7	7.7	0.34	23.9	-0.52	-0.17
WS	0.54	57.6	26.3	12.1	0.46	29.0	0.12	-0.92

AU = 50CR steel unblasted; AS = 50CR steel blasted with steel shot; AG = 50CR steel blasted with garnet; WU = weathering steel unblasted; --- = experimental slip coefficient value was not determined because the design value is already provided in the *AASHTO LRFD Bridge Design Specifications* (American Association of State Highway and Transportation Officials, 2017); WS = weathering steel blasted with steel shot.

The slip coefficient values for each surface finish type in Table 12 are based on the experimental tests of specimens made with matching faying surfaces. For example, the slip coefficient value for the AU surface finish type is the average value obtained from the AU-AU compression tests. This is true for all surface finishes except for WU; an experimental slip coefficient value was not determined in this study because design values are already provided in the AASHTO BDS. However, statistical parameters are shown for WU in the table for informational purposes.

Plots of each line item in Table 12 were constructed to determine if faying surface characteristics were correlated with experimental slip coefficients. The WU design slip coefficient values were not included on the plots or in the analysis because experimental compression tests were not conducted on these specimens since design specifications for this condition already existed. Overall, there were some general trends noted between the statistical parameters and the experimental slip coefficient values.

Figure 18 shows a plot of the slip coefficient vs. maximum height for each surface finish. As shown in the figure, the AS, AG, and AU specimens all have maximum heights near 80 µm and slip coefficients ranging from 0.53 to 0.61. A linear regression was conducted on these data and produced a low R-squared value of approximately 0.08, which could be attributable to the small number of data points. The regression line suggests that the maximum height and experimental slip coefficient move together. However, the range of the four experimental slip coefficient results shown in the figure is quite small, so it is unclear if this relationship is valid for slip coefficient values outside this range.

Figure 19 shows a plot of the experimental slip coefficient vs. average height. A linear regression analysis determined a higher degree of positive correlation between average height and experimental slip coefficient than between maximum height and experimental slip coefficient. Having a greater average height suggests that a surface has more local maximum peaks relative to the mean, whereas a surface with a greater maximum height may have fewer such local maximum peaks Based on the analysis, it appears that a surface with more local maximum peaks relative to the mean correlates with a greater slip coefficient. Since the root mean square is calculated by taking the square root of the mean, nearly identical results were obtained from a linear regression analysis, and therefore the root mean square results are not specifically discussed.

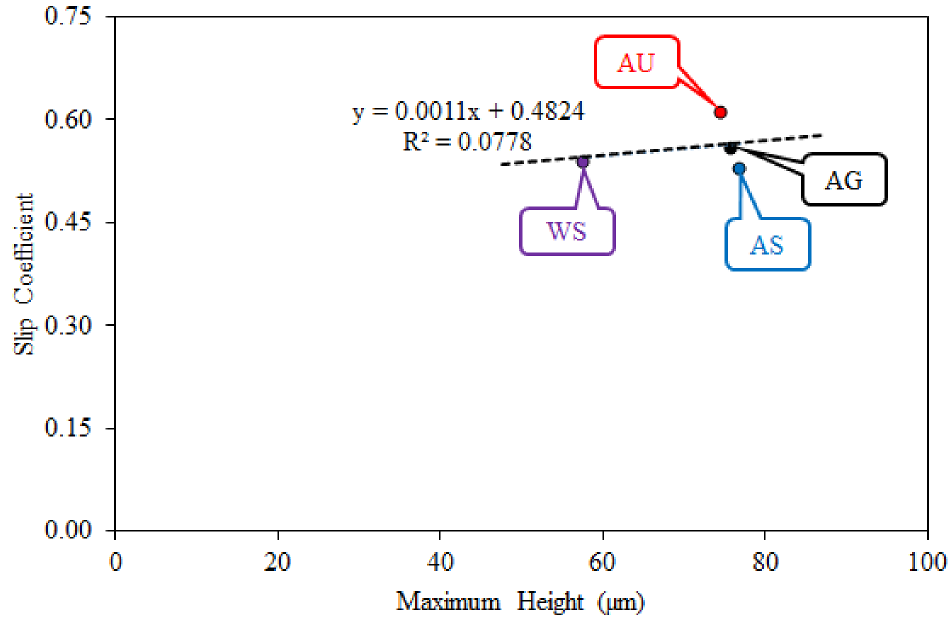

Figure 18. Plot of Experimental Slip Coefficient vs. Maximum Height for Selected Faying Surface Types

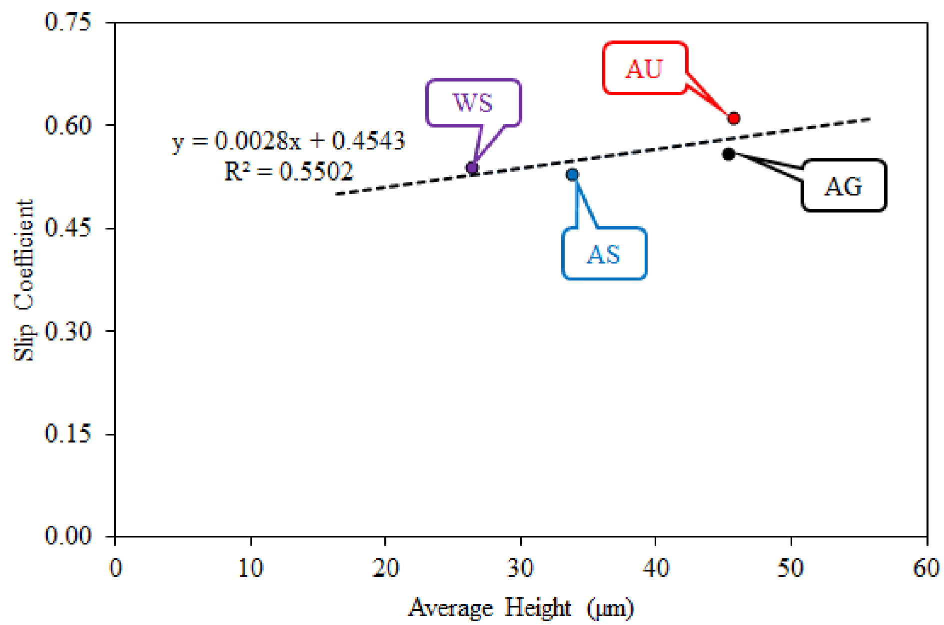

Figure 19. Plot of Experimental Slip Coefficient vs. Average Height for Selected Faying Surface Types

Figure 20 shows a plot of slip coefficient vs. skewness of height data. As discussed previously, skewness refers to the degree of asymmetry of the data, with a skewness value of 0 being a characteristic of a normally distributed dataset, although skewness alone is insufficient to define a normal distribution. The determined values for skewness in Table 12 correlate strongly with the histogram data in Figure 16. In these data shown in Figure 20, negative skewness (i.e., lower tail of height data is relatively extended) correlates strongly with higher experimental slip coefficients, and skewness approaching zero correlates with lower experimental slip coefficients. In other words, surface finish types AS and WS have skewness values near 0 and lower experimental slip coefficients than types AU and AG. When the skewness of only the 50CR steel surface finish types is compared, the skewness values suggest that using steel shot to blast clean 50CR steel (AS) could be associated with a greater symmetry of height values (i.e., skewness near 0) but a lower slip coefficient when compared to both garnet-blasted (AG) and unblasted 50CR steel (AU) surfaces.

As mentioned previously, the average height analysis determined that having a greater number of peaks (i.e., greater heights) in a surface profile correlated with having a greater slip coefficient. When this information and the skewness analysis are combined, it appears that a greater number of valleys (i.e., low heights) relative to the number of peaks is necessary to produce a greater slip coefficient.

Figure 21 shows a plot of slip coefficient vs. excess kurtosis. As mentioned previously, excess kurtosis indicates the degree of peakedness of the data compared to a normal distribution with the same standard deviation. An excess kurtosis value of 0 is a characteristic of a normally distributed dataset. Positive excess kurtosis values indicate higher data peakedness, and negative excess kurtosis values indicate flat-topped data. Similar to the skewness values in Table 12, the excess kurtosis numerical values correlate well with the line histograms. The AS, WS, and AG excess kurtosis values are all between approximately -1 to 0, indicating that these datasets have a slightly wider and flatter histogram compared to a normal distribution. Since all three of these surfaces were blast cleaned, it is likely that the blasting process creates a more evenly distributed height frequency across a wider range of heights.

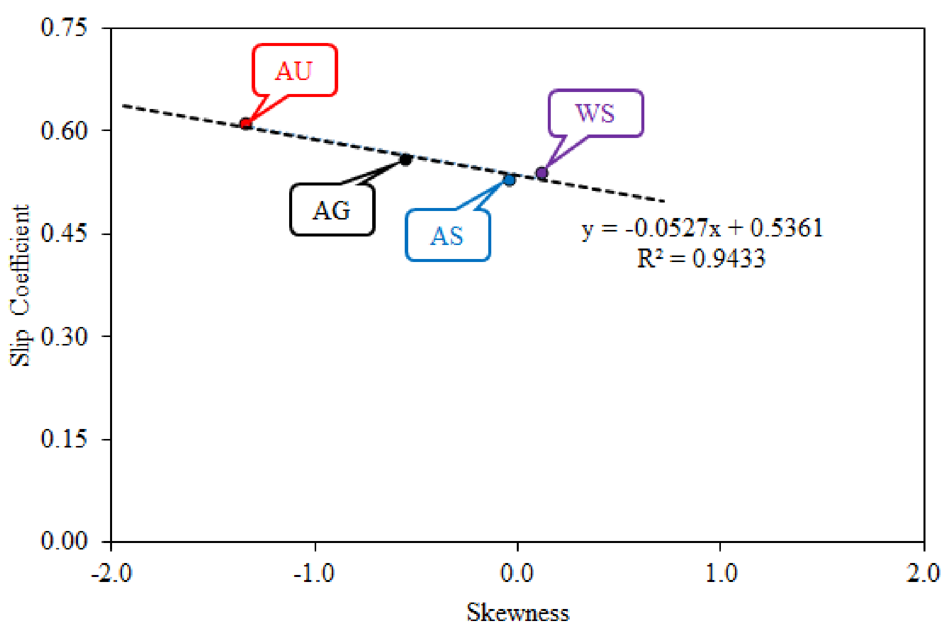

Figure 20. Plot of Experimental Slip Coefficient vs. Skewness of Height Data for Selected Faying Surface Types

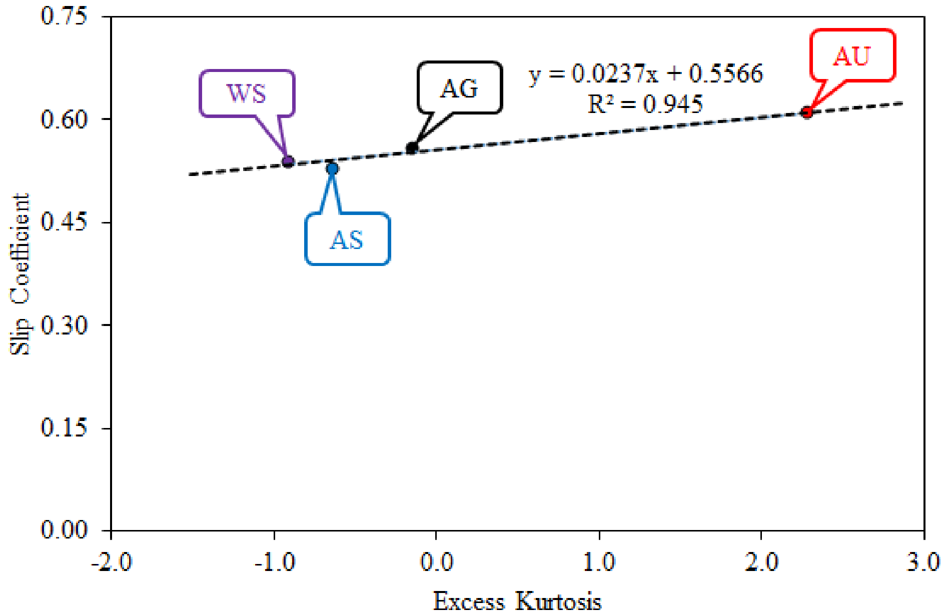

Figure 21. Plot of Experimental Slip Coefficient vs. Excess Kurtosis of Height Data for Selected Faying Surface Types

The AU excess kurtosis value is approximately 2, which means the dataset peaks markedly around a mode value. The linear regression analysis showed that as the excess kurtosis increases, the slip coefficient increases with good correlation. This result suggests that greater frequency of height measurements around a modal value is associated with a higher experimental slip coefficient.

Overall in the surface profile analysis, there was a moderate correlation found between an increase in average height and an increase in slip coefficient. There were also strong correlations found between two relationships: (1) a decrease in skewness and an increase in slip coefficient, and (2) an increase in excess kurtosis and an increase in slip coefficient. Based on the profile measurements and analysis conducted, a height measurement histogram that has the following relative characteristics will have an increased slip coefficient: greater modal value, greater frequency of heights around the modal value, and a long tail of low height values. In terms of a physical profile, this corresponds to a surface with many high peaks (near the maximum height) and a wide range of valleys of varying depth. Since a single 1920 µm x 1200 µm area was analyzed for each selected faying surface, it would be beneficial to analyze additional areas to ensure that the sampled areas were representative of each faying surface.

CONCLUSIONS

- *Based on the sample size tested, unblasted 50CR steel can currently be categorized under the AASHTO Class A surface specifications, having a slip coefficient value of 0.30. Future research could potentially validate unblasted 50CR steel being categorized as a Class B surface with a slip coefficient value of 0.50. Classifying unblasted 50CR as a Class B surface would result in cost savings to VDOT because 50CR steel faying surfaces could be* *designed at a greater slip coefficient without the additional expense of blast cleaning, either with steel shot or garnet media.*

- *Based on the sample size tested, blast-cleaned 50CR steel, blasted with either steel shot or garnet media, can be categorized under the AASHTO Class B surface specifications, having a slip coefficient value of 0.50.*

- *When dissimilar metal connections are made with 50CR steel, the slip coefficient of the connection can be taken to be equal to the smaller of the two slip coefficients being joined.*

- *The surface profile measurements showed that there was a moderate correlation between an increase in average height and an increase in slip coefficient; a strong correlation between a decrease in skewness and an increase in slip coefficient; and a strong correlation between an increase in excess kurtosis and an increase in slip coefficient. In terms of a physical profile, a surface with many high peaks (near the same value as the maximum height) and a wide range of valleys of varying depth is more likely to have a greater slip coefficient. The unblasted 50CR steel surface profile most closely resembled this type of surface.*

RECOMMENDATIONS

1. *VTRC should conduct a technical assistance study to determine the appropriate sample size for slip coefficient tests on 50CR steel and dissimilar metal bolted connections that is necessary to recommend changes to the surface classification and slip coefficient value of 50CR steel in the AASHTO BDS and the VDOT bridge design specifications.*

IMPLEMENTATION AND BENEFITS

Implementation

The implementation of Recommendation 1 will include VTRC initiating a technical assistance study to conduct a statistical analysis on the historical slip coefficient data that were used as the rationale for the *AASHTO LRFD Bridge Design Specifications* on the surface condition classes and slip coefficient values. The statistical analysis will examine the variability of both the material and the laboratory testing. The material variability examination will include variables such as steel heat, steel producer, blasting media used, blasting application, etc. The laboratory variability examination will include the testing facility, loading equipment used, instrumentation accuracy and resolution, etc. The variability of the historical tests used as the rationale for the AASHTO surface condition and slip coefficient values will then be compared to the variability of the results in the current study to determine the appropriate sample size needed for further recommendations. Implementation of Recommendation 1 will occur within 2 years of the publication of this report.

Benefits

The benefit of implementing Recommendation 1 is that a relatively low-cost technical assistance study can be conducted to determine the necessary sample size for slip coefficient tests on 50CR steel. If the proposed technical assistance study concludes that a sufficient number of tests have already been conducted in the current study, then recommendations can be made regarding the surface classification and slip coefficient value of 50CR steel for the AASHTO BDS and the VDOT bridge design specifications. If the proposed technical assistance study concludes that additional slip coefficient testing is necessary, a future VTRC research study can be recommended for further testing. If this is the case, the results of the proposed technical assistance study can be used as a rationale for the scope of testing in the future research study.

ACKNOWLEDGMENTS

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APPENDIX A

COMPRESSION SLIP TEST PLOTS

This appendix contains the remaining compression slip test plots not shown in the body of the report.

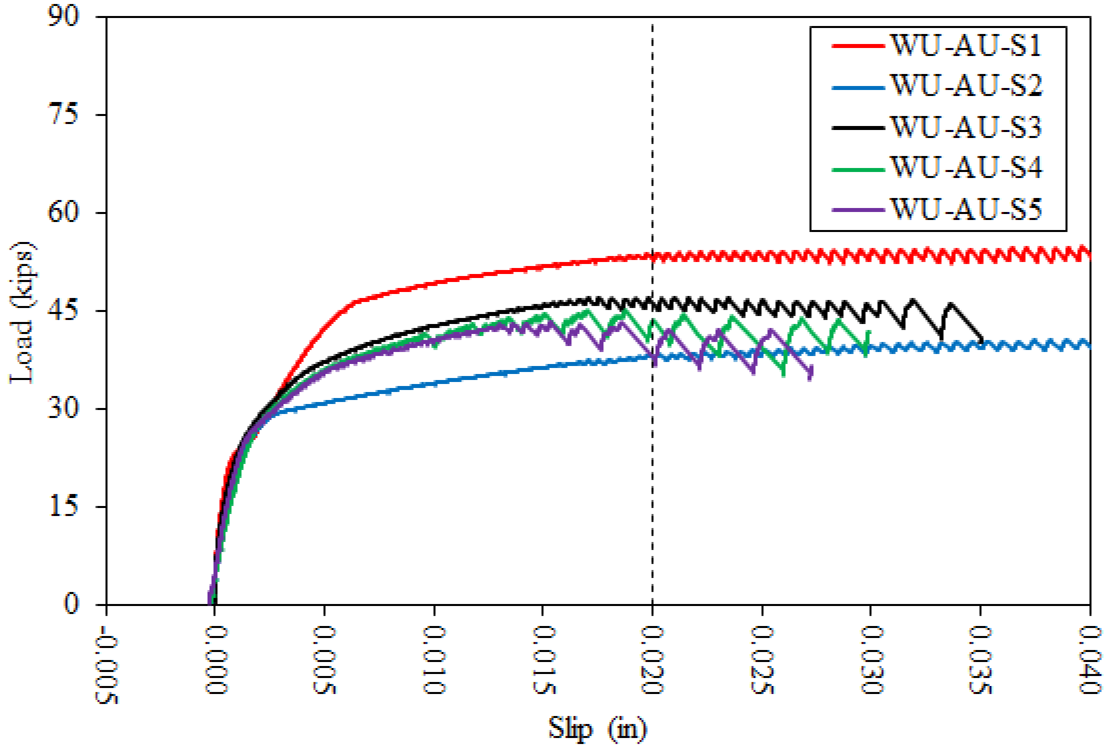

Figure A1. Plot of Compression Slip Test Data for WU-AU Specimens

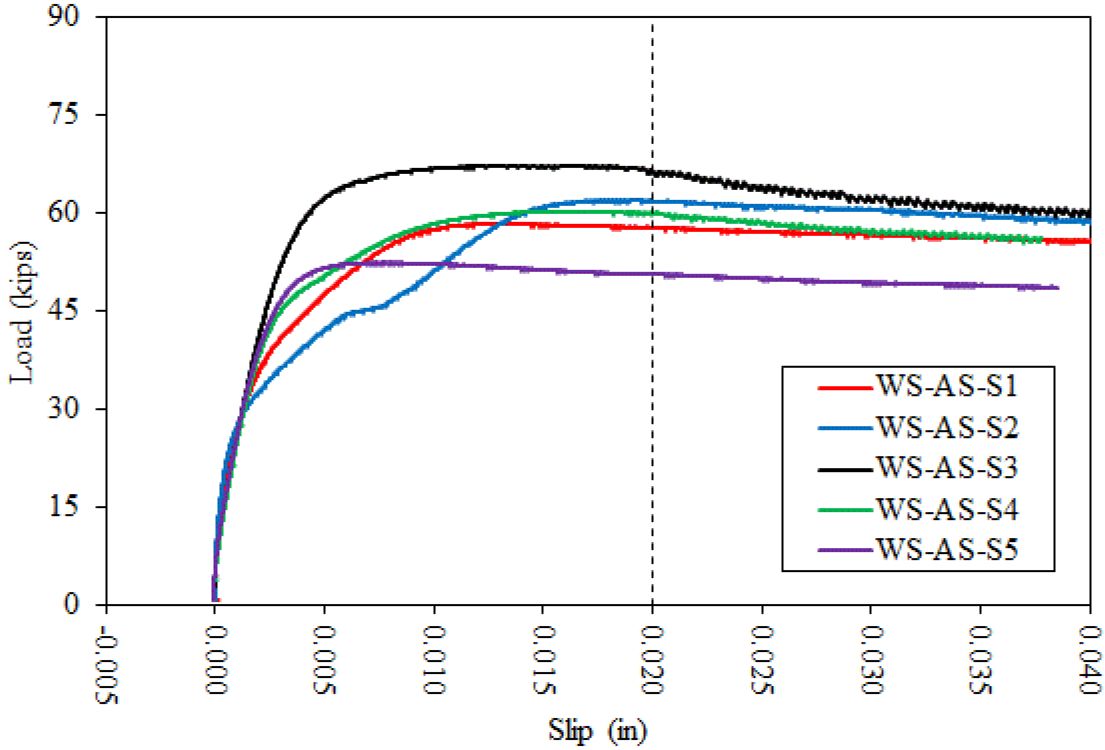

Figure A2. Plot of Compression Slip Test Data for WS-AS Specimens

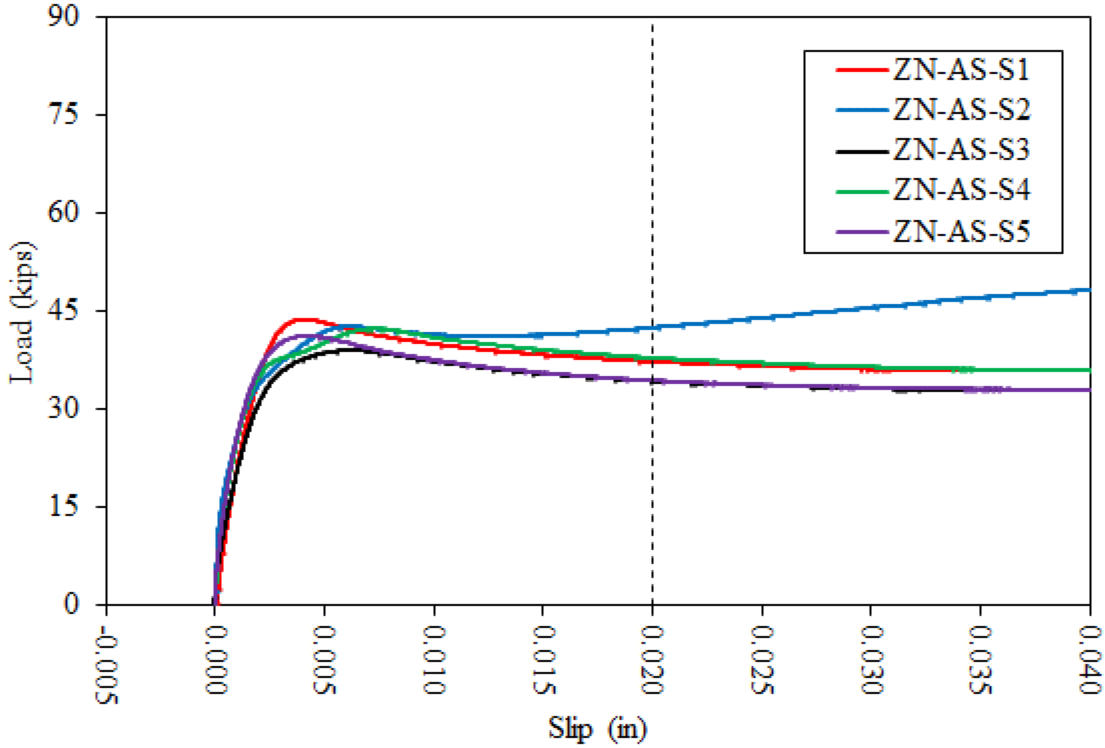

Figure A3. Plot of Compression Slip Test Data for ZN-AS Specimens

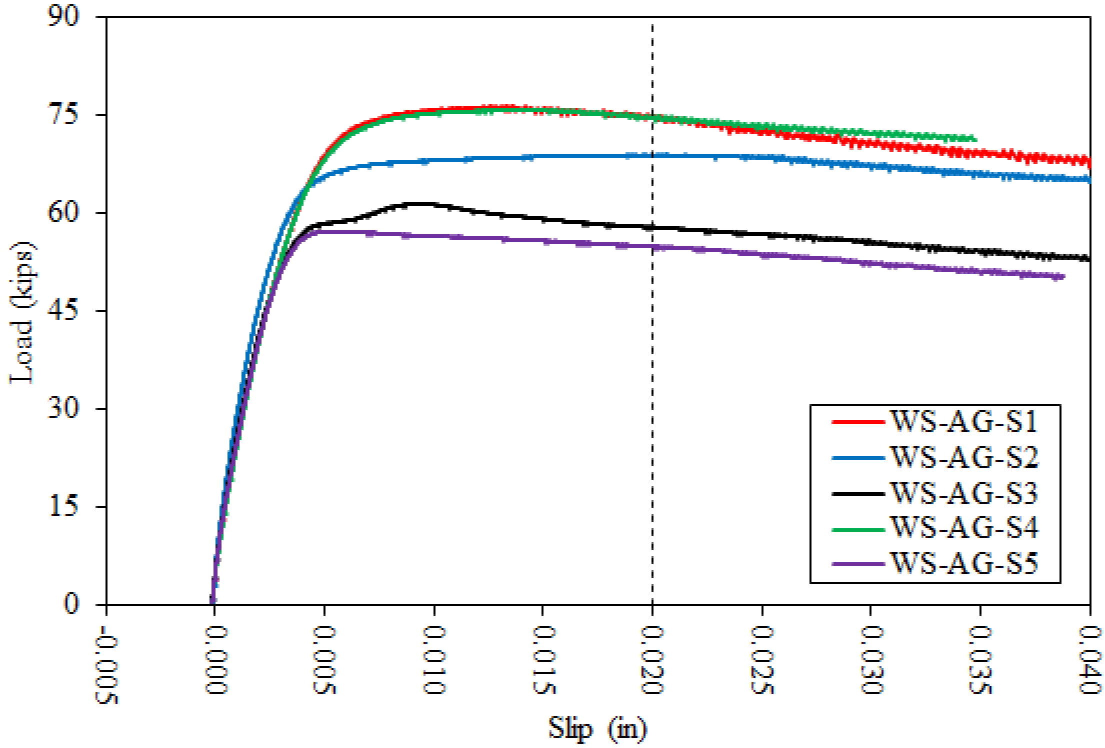

Figure A4. Plot of Compression Slip Test Data for WS-AG Specimens

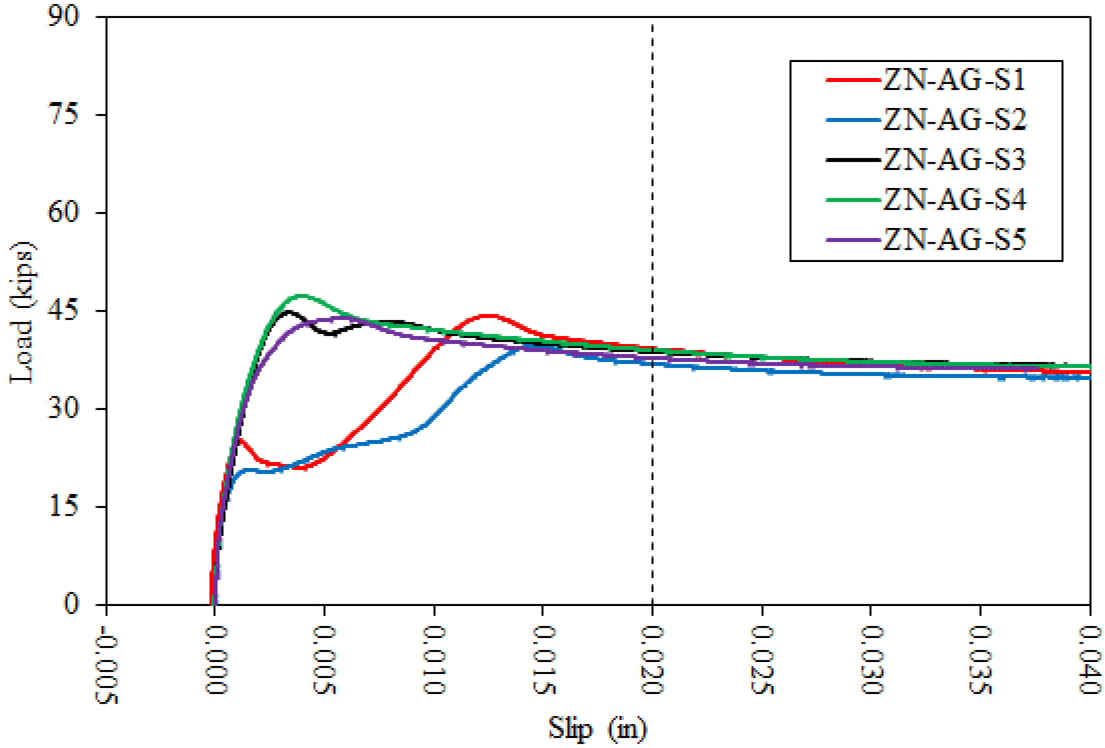

Figure A5. Plot of Compression Slip Test Data for ZN-AG Specimens

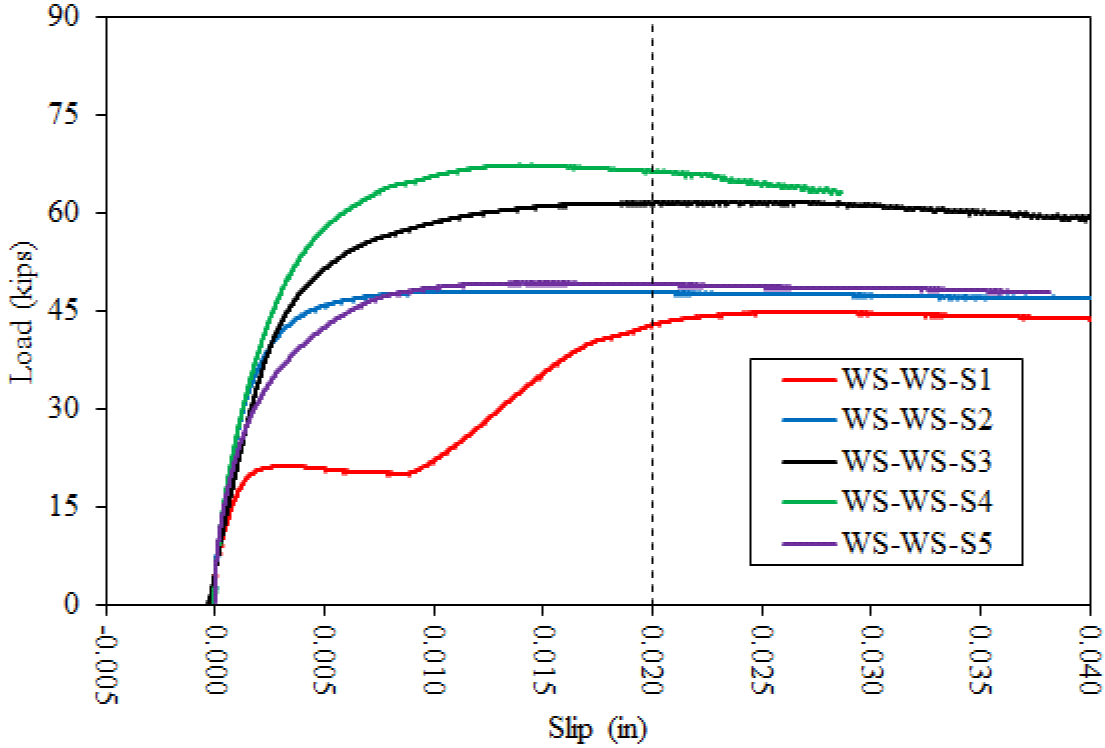

Figure A6. Plot of Compression Slip Test Data for WS-WS Specimens

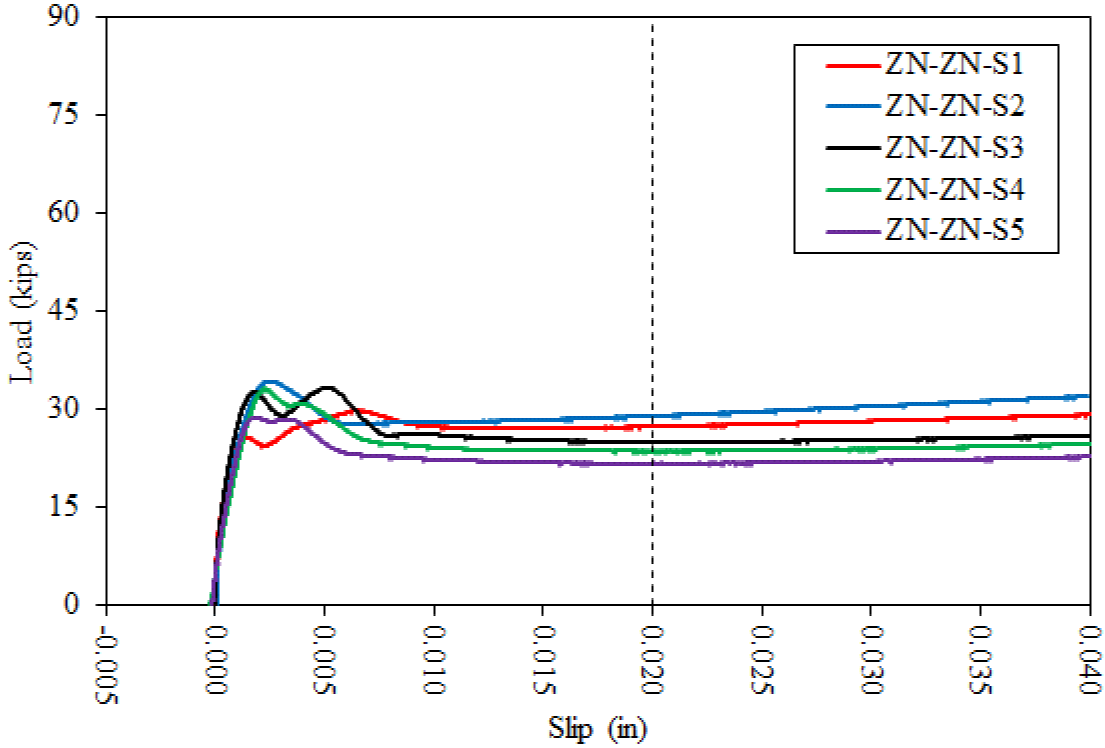

Figure A7. Plot of Compression Slip Test Data for ZN-ZN Specimens

APPENDIX B

TENSION CREEP TEST PLOTS

This appendix contains the remaining tension creep test plots not shown in the body of the report.

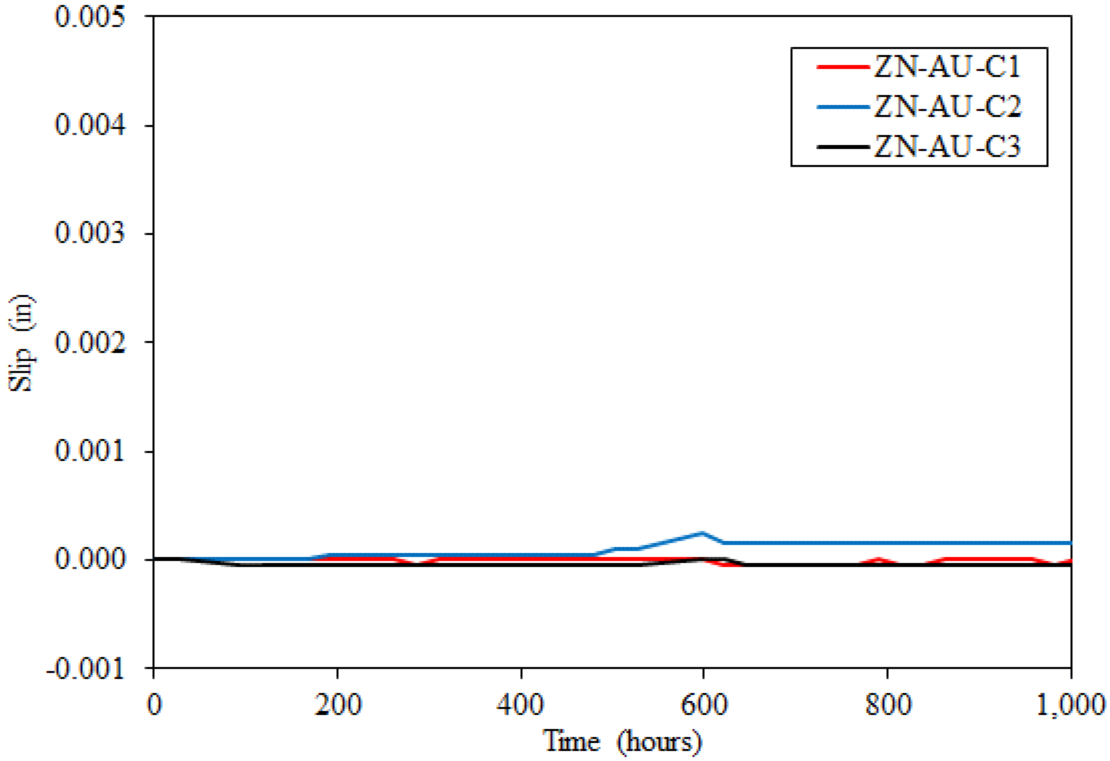

Figure B1. Plot of Tension Creep Test Data for ZN-AU Specimens

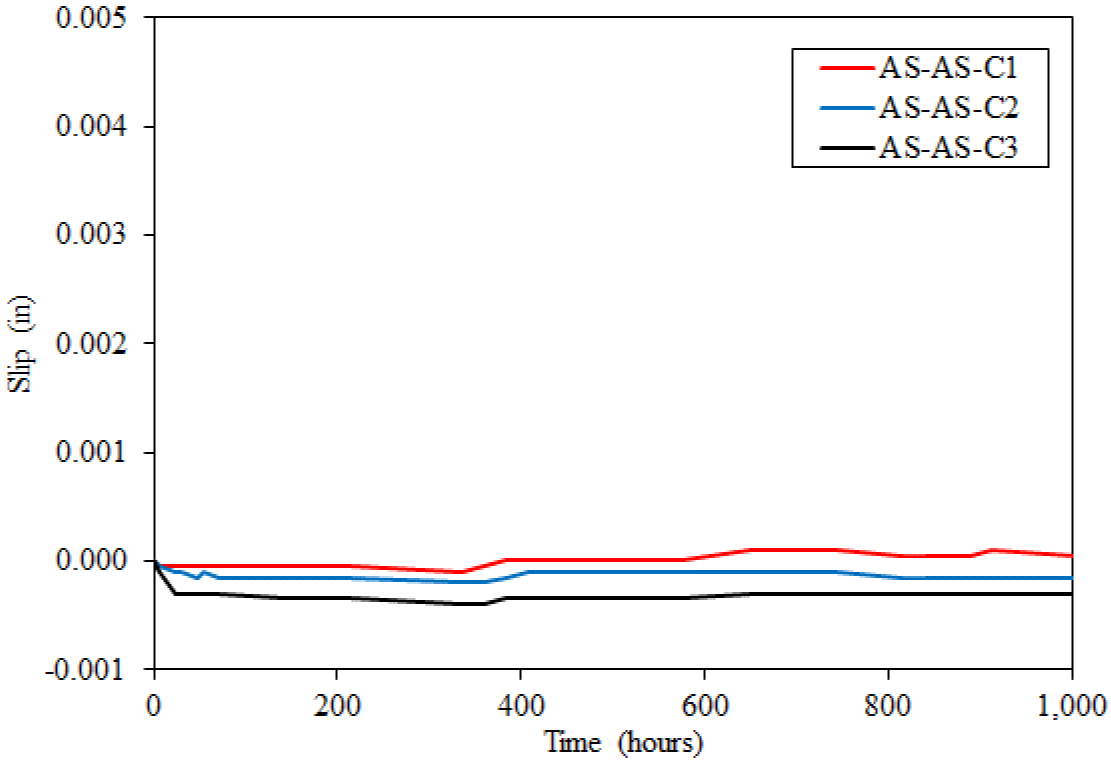

Figure B2. Plot of Tension Creep Test Data for AS-AS Specimens

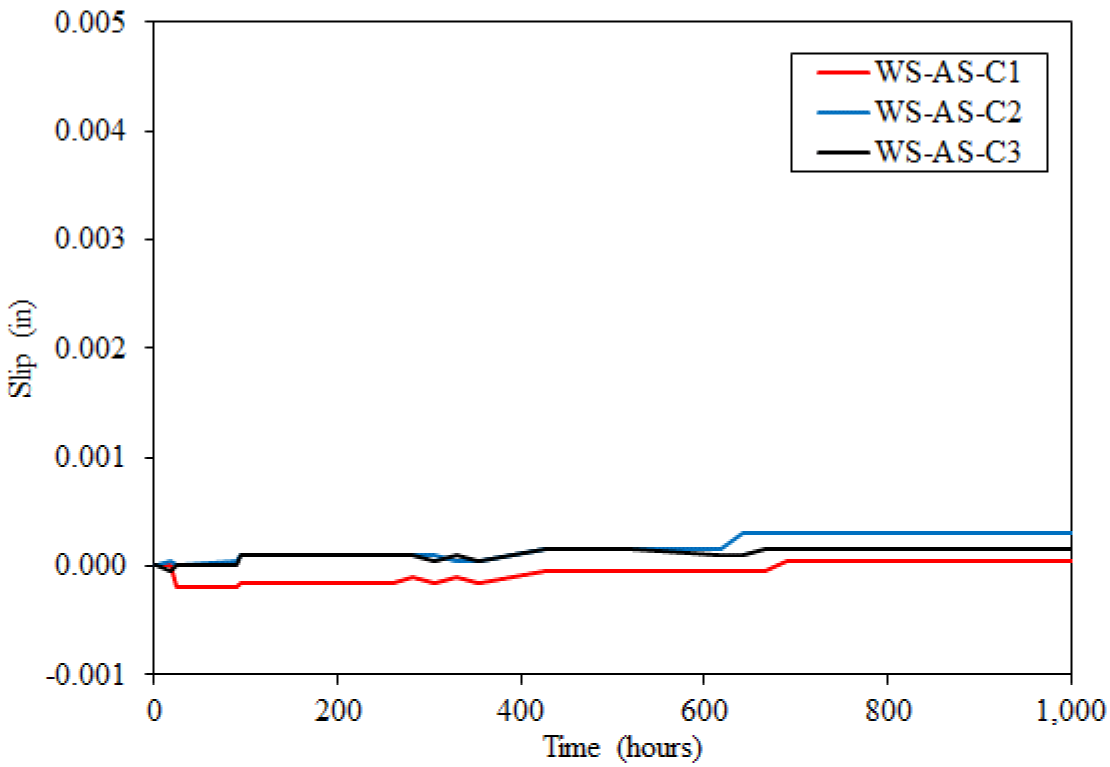

Figure B3. Plot of Tension Creep Test Data for WS-AS Specimens

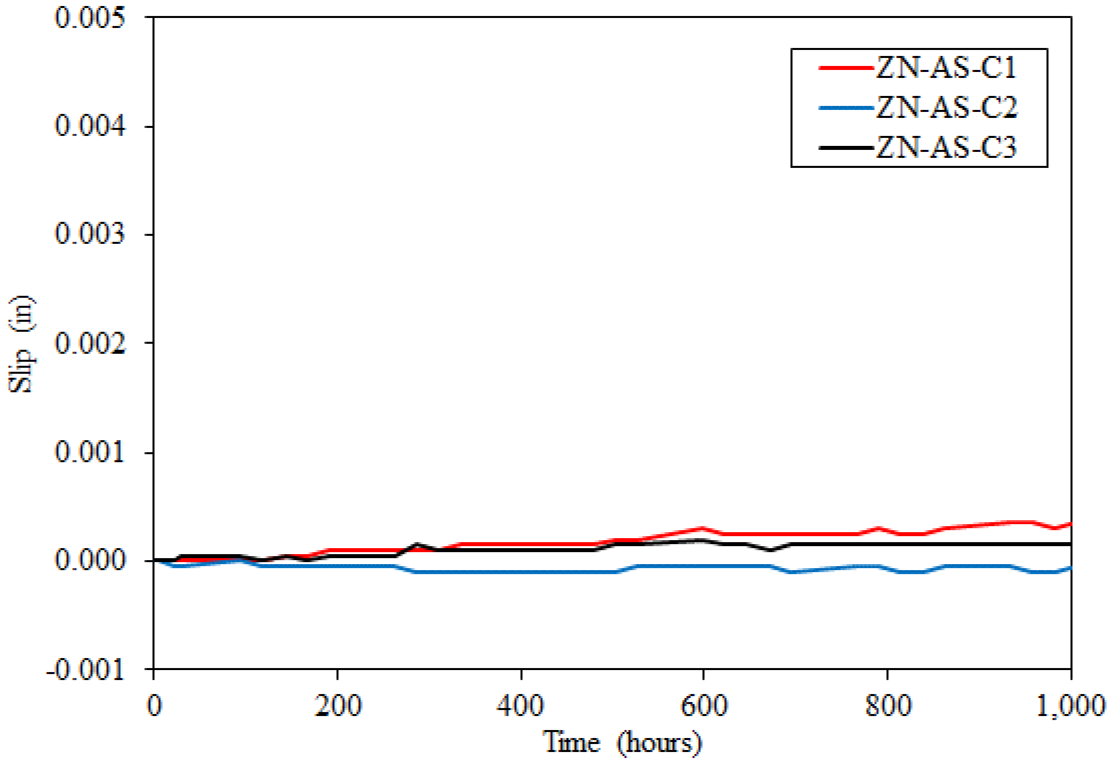

Figure B4. Plot of Tension Creep Test Data for ZN-AS Specimens

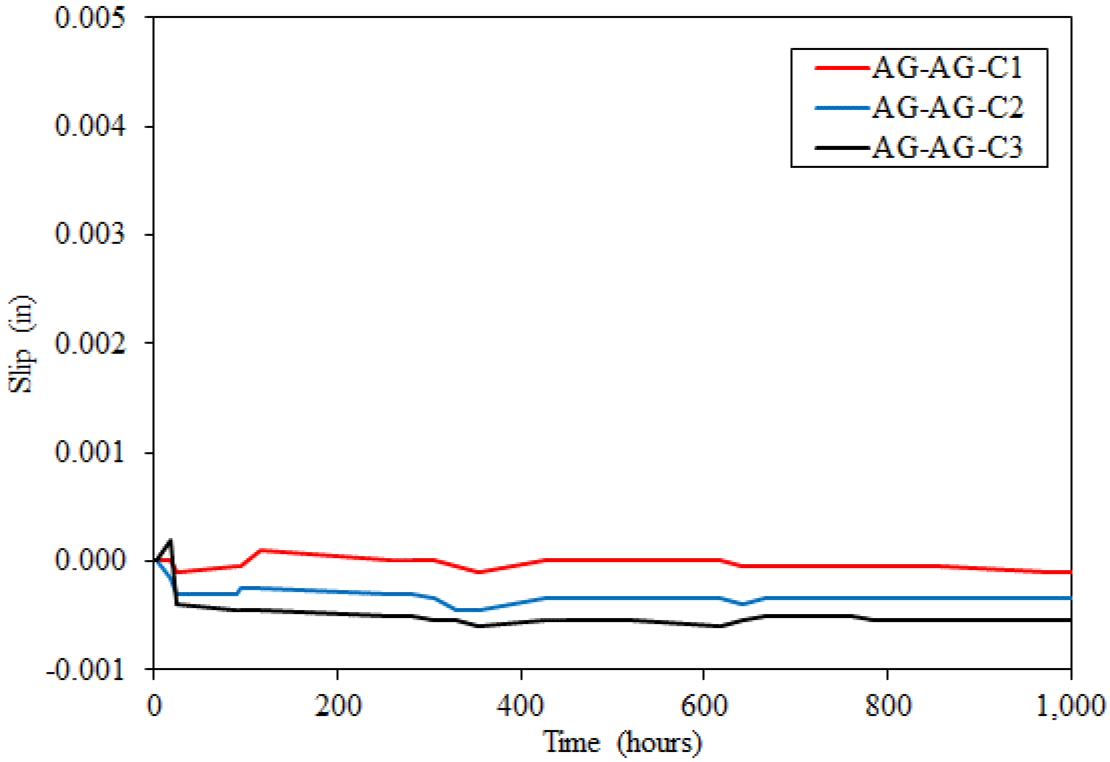

Figure B5. Plot of Tension Creep Test Data for AG-AG Specimens

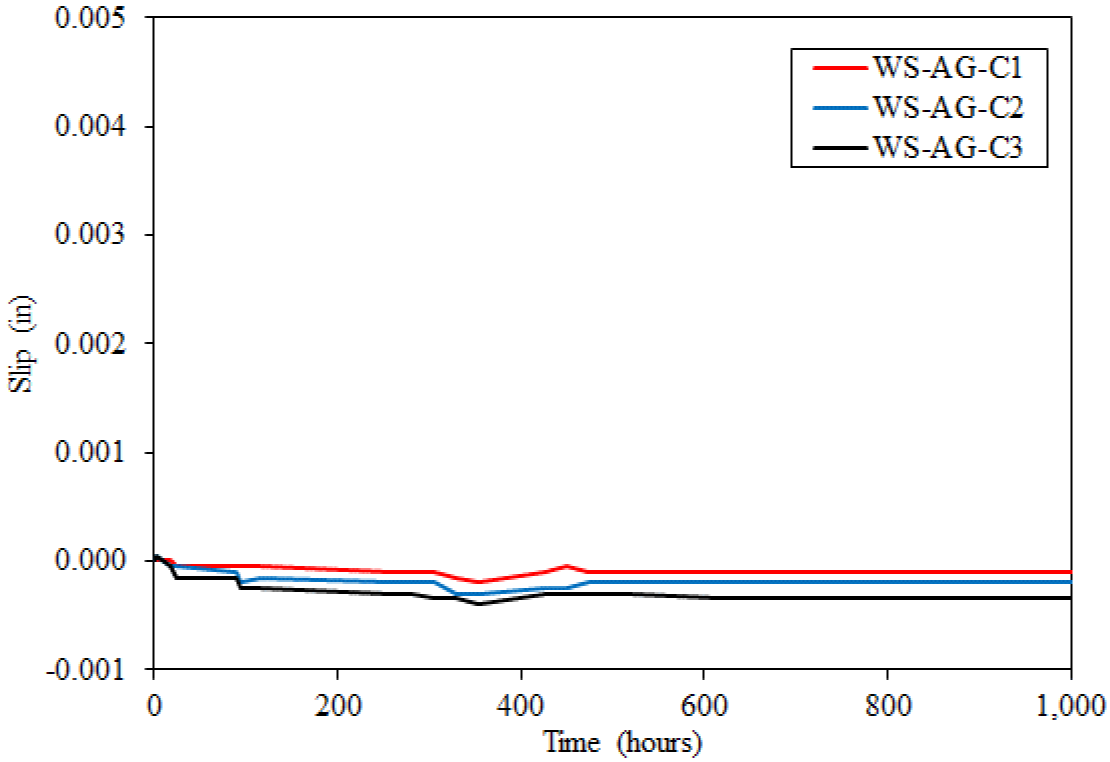

Figure B6. Plot of Tension Creep Test Data for WS-AG Specimens

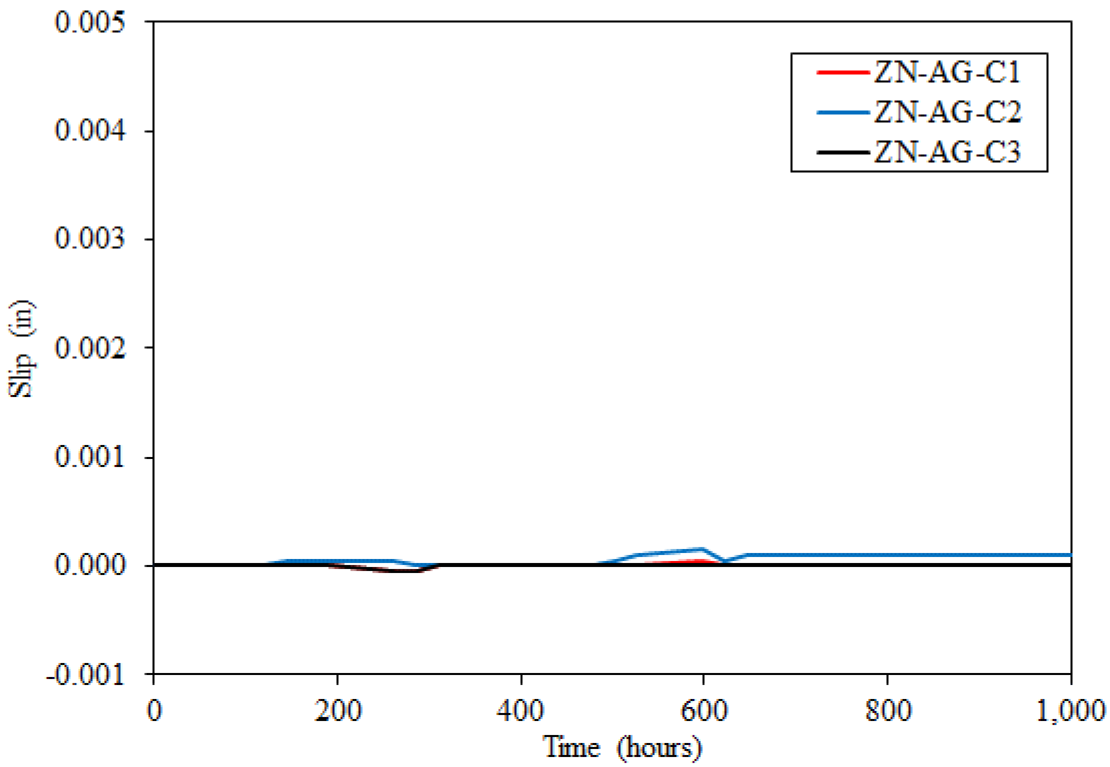

Figure B7. Plot of Tension Creep Test Data for ZN-AG Specimens

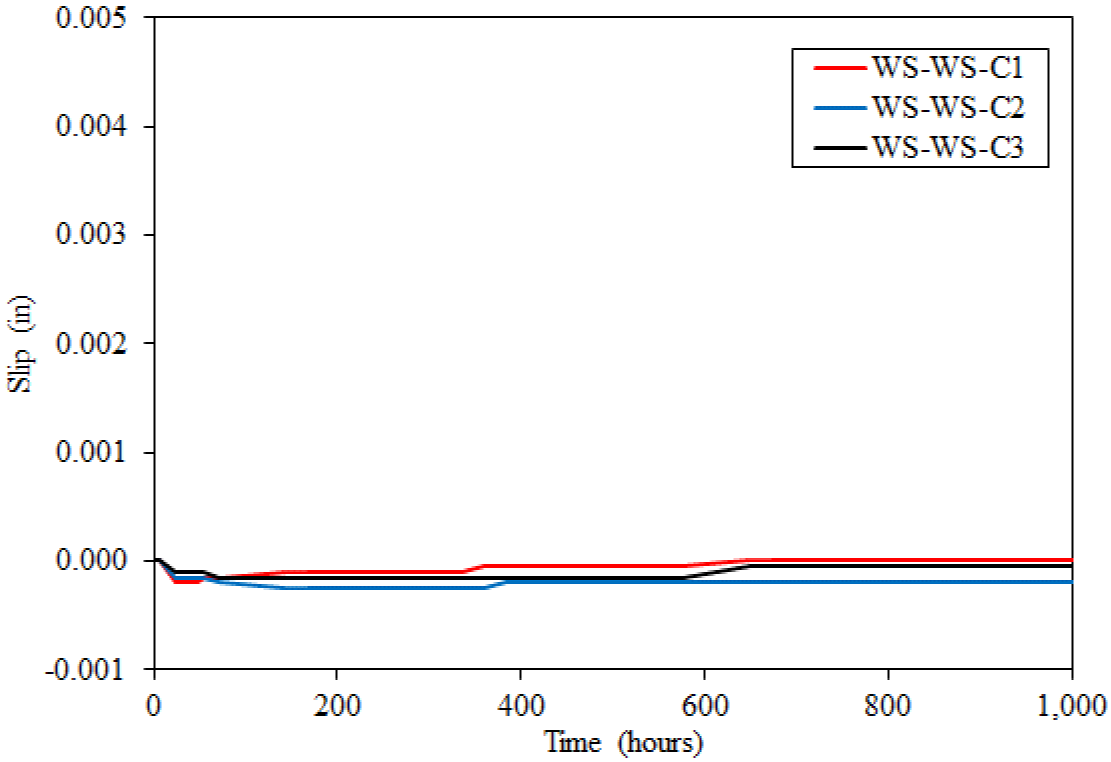

Figure B8. Plot of Tension Creep Test Data for WS-WS Specimens

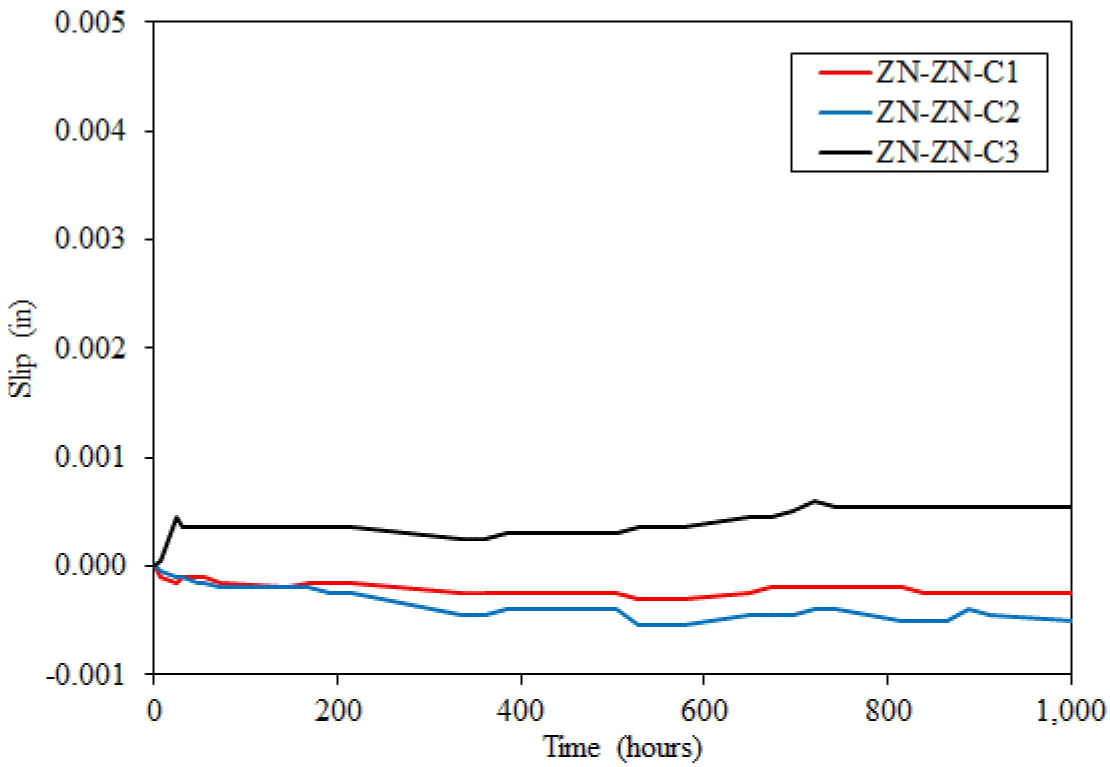

Figure B9. Plot of Tension Creep Test Data for ZN-ZN Specimens