Slip Characteristics of Combined Metallized/Galvanized Faying Surfaces in Slip-Critical Bolted Connections

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Abstract

Steel bridge elements may be exposed to aggressive conditions from ambient environment and human activities such as the spread of de-icing salt on roadways. In order to increase the service life of these members and reduce maintenance costs, two coating solutions - metallizing and galvanizing – have evolved as effective and widely used in providing a physical barrier and a sacrificial protection against corrosion. In some practical situations, secondary elements of steel bridge structures are galvanized and are connected to primary elements that are metallized in slip-critical joints. North American bridge design codes, such as the Canadian CSA-S6, the AISC specifications - 360 and the AASHTO LRFD, do not prescribe slip coefficient values for high strength bolted connections that are metallized on one connection surface and galvanized on the other. Bridge fabricators are then compelled to mask off connection faying surfaces before coating. This exercise increases the cost of and delays fabrication in the shop. In order to eliminate the need of masking off of these connection faying surfaces, it is important to characterize the slip resistance of high strength bolted connections having combined metallized-galvanized faying surfaces in light of prevailing bridge design codes. The slip resistance of these combined faying surfaces is determined in this research from both short-duration slip tests and long-term sustained tension creep tests.

1. Introduction

Bolted joints may be designed as either bearing-type or slip-critical. In bearing-type bolted connections, the applied load is transferred through the bolt shank to the connected steel member. The design must be done at the ultimate limit state and may be governed by bearing of the connected material or by shear in the fastener. Consequently, the surface condition of the contact areas of the connected members does not affect the resistance of the joint. However, when the connection is subjected to load reversals, cyclic or impact loading as in bridges, slip-critical connections are required. In this type of joint, the load is transferred by friction through the contact area of the connected material, also known as faying surfaces, and slip in the joint is prohibited at the serviceability limit state. The friction is developed by the clamping action of the bolts on the connected members. Thus, the surface preparation is a critical parameter for the resistance of the joint. If the slip resistance is reached, the joint slips into bearing. So, the connection is also designed as a bearing-type in order to resist the load applied at the ultimate limit state. The slip resistance of slip-critical joint (V_s) can be calculated as follow:

$$V_s = \mu n_s \sum_{i=1}^{n_b} F_{b,i}$$

where μ is the slip coefficient for the connection faying surfaces, n_s is the number of slip planes, n_b is the number of bolts, and $F_{b,i}$ is the minimum bolt preload in bolt i. The magnitude of the bolt preload is required to evaluate the slip resistance. According to the Specification on Structural Joints using High-Strength Bolts, published by the Research Council on Structural Connections (RCSC 2014), hereafter named the RCSC bolt specification, the minimal bolt preload must be equal to 70% of the tensile capacity of the bolt used.

The slip coefficient, μ, is a critical parameter in the evaluation of the slip resistance. The higher the slip coefficient value, the lower the number of bolts needed to prevent slippage. The Canadian standard CAN/CSA S6-14 (CSA 2014) specifies slip coefficients for two faying surface conditions, namely clean mill scale or blast-cleaned with Class A coating and blast-cleaned or blast-cleaned with Class B coatings. The corresponding slip coefficients are given as 0.30 and 0.52, respectively. Also, a Class A slip performance ($\mu = 0.30$) is prescribed for hot-dip galvanized surfaces roughened by wire brushing. On the other hand, the American standard AASHTO LRFD bridge design code (AASHTO 2014) provide slip coefficient for three faying surfaces conditions, namely clean mill scale or blast-cleaned with Class A coatings ($\mu = 0.33$), blast-cleaned or blast-cleaned with Class B coatings ($\mu = 0.50$) and hot-dip galvanized surface roughened by wire brushing ($\mu = 0.33$).

Exposed elements in steel bridges are subjected to severe environmental conditions. Surface coatings are used to protect these members against wear and corrosion, increasing the service life of the structure. In bridges, two of the most effective surface

protection solutions are metallizing and galvanizing. Metallizing, defined as the thermal spraying of molted zinc or/and aluminum alloys, produces a physical barrier and a self-sacrificing protection of the steel element. This is accomplished by feeding the metal in either wire or powder form to a spray gun where it is melted and sprayed. Upon the deposition on the steel substrate, the coating cools and solidifies almost instantly, interlocking into the surface angular profile. Since it is a mechanical bond, the angularity of the profile is a critical parameter in the adherence of the coating. According to the Specification for the application of thermal spray coating SSPC-CS 23.00/AWS C.2.23M/NACE No. 12 (2003), the surface preparation must be a white-metal blast finish or, at a minimum, a near-white-metal blast finish. Alternatively, hot-dip galvanizing is a total immersion process where the steel member is dipped into a bath of molten zinc until it comes to the bath temperature. Like metallizing, it provides a barrier and a self-sacrificing protection. However, unlike metallizing, the coating bonds metallurgically to the steel substrate. The total immersion process and the size of the zinc bath impose size limitations on structural elements that can be galvanized. Thus, for practical reasons, primary bridge elements such as main girders are often metallized and connected to secondary components such a cross frames that are hot-dip galvanized.

To date, design standards do not specify slip coefficient values for combined metallized-galvanized faying surfaces. Thus, bridge fabricators are compelled to mask off all faying surfaces (Figure 1) in slip-critical connection before metallizing the steel elements . This process is time consuming, labour intensive and generally expensive, in terms of fabrication costs. The work of masking can be eliminated if the slip resistance of the combined metallized-galvanized faying surface is appropriately characterized in light of the prevailing design standard. The RCSC bolt specification (RCSC 2014) provides, in Appendix A, a methodology to evaluate the slip resistance of a coated faying surface. Two sets of test are required to characterize the slip resistance of a coated surface: the first is a short-duration static test to evaluate the mean slip coefficient. If the mean slip coefficient is found to be satisfactory, a long-term sustained tension creep test is carried out to ensure that the coating will not undergo significant creep and that creep will not adversely affect the long term slip resistance in the connection.

Figure 1: Masked off faying surface in shop

This paper presents results from research work carried out at Université Laval in collaboration with Canam-Bridges, Canada, on the slip characteristics of combined metallized-galvanized connection faying surfaces.

2. Plates preparation and test matrix

Test plates were machined from steel grade 350AT. Zinc-metallization was applied in the shop under controlled environmental conditions. Thermal spray coating was applied from a 99.9% zinc wire through an electric arc in accordance with SSPC-CS 23.00/AWS C2.23M/NACE No. 12 (2003). The steel substrate for each plate to be metallized was prepared to white metal finish SSPC-SP 5 and the angular profile depth was measured in the shop per standard requirements. For the plate to be hot-dip galvanized, the zinc-coating was applied by a local galvanizer, near Quebec City. The thickness of both coatings were measured using a Positector magnetic gage on each test plate in order to mate plates with similar average coating thicknesses. In accordance with the Society for Protective Coatings SSPC-PA 2 (SSPC 2012) standard, five different readings were taken on each plate faying surface and the average thickness was determined. In the short-term slip tests, the middle plate was galvanized on both sides, and the inside faces for the two splice plates were prepared and metallized. However, in the long-term creep tests, since the thickness of the coating is probably the most important parameter that has an effect on relaxation of the bolt clamping force, the galvanized middle plate and the metallized splice plates were all coated on both sides. Thus, there were six layer of coating between the head of the bolt and the nut.

In some of the cases tested, small burrs produced by the drilling of bolt holes in test plates were left in place. However, all burrs were within the limit imposed by RCSC bolt specification (RCSC 2014), since their depths were less than 1/16 in. Bolt clamping force on the metallized plates were also part of the study. Table 1 contains the parameters of the specimens tested at the laboratory of Université Laval. Each specimen has been identified following the variables used in Table 1.

Table 1: Parameters tested

#	Parameters	Variables
1	Thickness of metallized coating	6m – 6 mils 12m – 12 mils
2	Clamping Force	70 – 70% of bolt capacity 90 – 90% of bolt capacity
3	Presence of burrs	S – burrs cleaned A – burrs left in place

For example, specimen 12m-70-S refers to a faying surface with a 12 mils thick metallized coating, tested under a bolt preload equal to 70% of the tension capacity of

the bolt and where small burrs produced by drilling are removed. For the short-duration slip tests, the average thickness of galvanized coating was measured as 19 mils, and the actual thicknesses of this coating on the specimen for the long-term creep tests are shown in Table 3.

3. Slip and creep testing: methodology and instrumentation

3.1 Short-term compression slip tests

The mean slip coefficient of the combined metallized-galvanized faying surfaces is evaluated by compression slip tests, in accordance to RCSC specification (RCSC 2014). In those tests, assemblies were made from three identical 5/8 inch thick steel plate, each measuring 4 in. by 4 in. Tests plates were mechanically assembled together and the middle plate was loaded in compression while the two exterior plates sat solidly on their flat edge. The clamping load of the bolt and the slip in the joint are monitored and recorded throughout the test. The slip coefficient (μ) is calculated as follow:

$$\mu = \frac{F_s}{F_b \text{ x } n_s} \qquad (1)$$

where F_s is the slip load, F_b is the clamping force and n_s is the number of slip planes (equals 2). The slip load is determined as either the peak load that occurs before a slip of 0.5 mm (0.02 in.) on the load-slip curve or the load corresponding to a slip of 0.5 mm (0.02 in.), according to the RCSC specification (RCSC 2014).

For each set of test parameters, five replicate specimens were tested, and the mean slip coefficient was evaluated. Additional guidance on loading and instrumentation are provided in the RCSC Specification (2014).

In this study, the compression slip tests were performed on a 1500 kN MTS hydraulic Universal Testing machine (Figure 2). The applied loading rate was 100 kN/minute. The clamping load was applied using a 7/8 inch diameter ASTM A325 bolt preloaded to a minimum of 70% of its tension capacity. The pre-tensioned force was monitored using a carefully calibrated washer-type Omega load cell of 500 kN installed in series with the clamped test plate assembly from time of assembly to the end of the test. The relative displacement between the loaded middle plate and the two side plates is found to be the slip displacement and was measured using LVDT displacement transducers. A data acquisition system was used to monitor and record the applied loading and the associated slip. It also served to monitor the clamping force during the test.

Figure 2: Short-term slip test

2.2 Long-term tension creep tests

Tension creep tests are conducted to ensure the coating will not undergo significant creep deformation under service load (Yura & Frank 1985). A test consisted of a set of three specimens assembled in series by ASTM A490 bolts. The bolts connecting different specimens were left loose, and plates making up individual specimens were clamped by pretensioned A490 bolts to obtain the slip critical connection. The test chain was loaded in sustained tension for 1000 hours. The sustained tension load applied during the test corresponds to the serviceability load level according to the RCSC bolt specification (2014). Creep deformation was obtained as the deformation that occured between 30 minutes and 1000 hours of sustained tension loading. The creep deformation for each specimen is deemed satisfactory if it is less or equal to 0.127 mm (0.005 inch). In that case, the assembly is further loaded in tension up to the design slip load, equal to the real average clamping load times the design slip coefficient times the number of slip planes (= 2). This post-creep slip test is carried out in order to ensure that the loss of clamping force in the bolt does not reduce the slip load below that associated with the design slip coefficient. If the average post-creep slip deformation that occurs at this load level is less than 0.381 mm (0.015 inch) for the three identical specimens, the coated faying surface tested is considered to meet the requirements for the design slip coefficient tested. If any of the above-mentioned creep and post-creep slip requirements is not respected, the coating is considered to have failed for the design slip coefficient and a new creep test is required with a lesser design slip resistance. In the present test set-up, two different sets of specimens were tested in a single creep test set-up. Thus, 6 specimens were mounted in a chain, as shown in Figure 3.
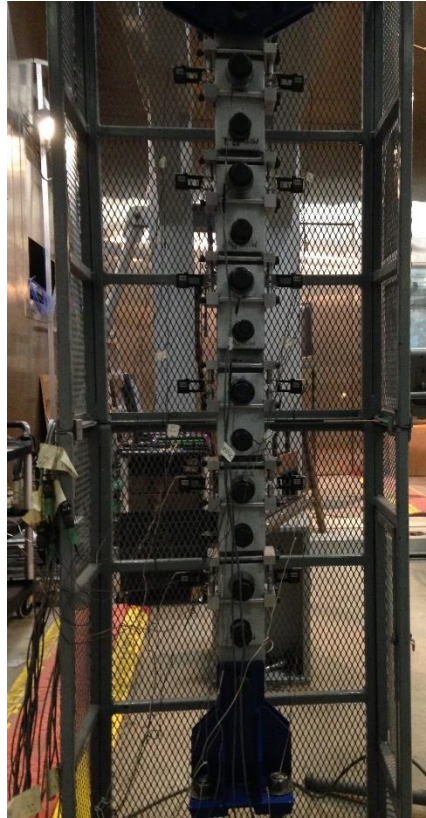
Figure 3: Tension creep test set-up

The tension creep tests were performed on a 500 kN MTS hydraulic Universal Testing machine. For each specimen, the relative displacement between the galvanized middle plate and the two metallized lap plates was measured using two MTS extensometers, on each side of the assembly. The displacement recorded for each assembly is the average of the two measurements. The bolt preload was manually applied by using the turn-of-nut-method with a hand-held ratchet. This was continuously monitored from the time of assembly through to the end of testing by using a washer-type Omega load cell of 500 kN installed in series with the clamped test plate assembly. ASTM A490 high strength bolts were used as prescribed by the RCSC specification (RCSC 2014). A data acquisition system was used to monitor and record the applied loading, the extensometers measurements and the load cells measurements. For creep tests, a design slip coefficient must be chosen in order to calculate the tension service load and to verify the creep performance under that load associated to that slip coefficient. A parameter was thus added to each specimen notation to represent the assessed design slip coefficient.

3.2 Short-term slip tests: results

Table 2 presents individual specimen results of the short-term slip tests conducted by Annan & Chiza (2014). The mean slip coefficient and the standard deviation are also shown for each set of parameters. The minimum mean slip coefficient of 0.49 was

obtained for the 6 mils combined metallized-galvanized coating thickness, with a clamping load equals to 90% of the bolt capacity, with burrs removed. When small burrs within the limit imposed by RCSC specification (RCSC 2014) are left in place, the mean slip coefficient observed was 0.62 for the 6 mils zinc-metallized coating thickness clamped to 70% of the bolt capacity. For the 12 mils metallized-galvanized coating surface, with a preload of 70% of the bolt capacity, with burrs removed and with burrs left in place, the slip coefficients were obtained as 0.65 and 0.68, respectively.

Table 2: Slip results

Specimen	k_1	k_2	k_3	k_4	k_5	$k_{average}$	Standard deviation
6m-70-S	0.57	0.62	0.59	0.63	0.55	0.59	0.04
12m-70-S	0.64	0.62	0.71	0.71	0.57	0.65	0.06
6m-90-S	0.48	0.49	0.47	0.51	0.49	0.49	0.01
12m-90-S	0.58	0.60	0.61	0.60	0.57	0.59	0.02
6m-70-A	0.60	0.62	0.68	0.65	0.58	0.62	0.04
12m-70-A	0.65	0.77	0.65	0.64	0.69	0.68	0.06

Extracted from Annan & Chiza (2014).

3.3 Long-term creep tests: results

A total of 2 creep tests, consisting of 6 metallized specimens, were conducted in this study. Only a nominal thickness of metallized coating of 12 mils has been presented here, as it is the most critical (Yura & Frank, 1985). considered in this study. The difference between the two set of parameters studied is that one was with burrs removed, and the other with burrs left in place. However, every burr left in place was less than 1/16 inch in height, which is the limit tolerated by RCSC (2014). For both set of parameters studied, three identical specimens were tested. By continuously monitoring the bolt-clamping load in each assembly from the clamping of the plates to the post-creep slip test, it was possible to evaluate the long-term relaxation of the coating. Figure 4 shows the average relaxation which occurred during the creep test for both set of parameters studied. Specimens with 12 mils thick metallized coating, with a bolt preload of 70% of bolt tension capacity and with burrs removed underwent a mean relaxation of 11.52%. Specimen with burrs left in place presented a mean relaxation of 13.95%.
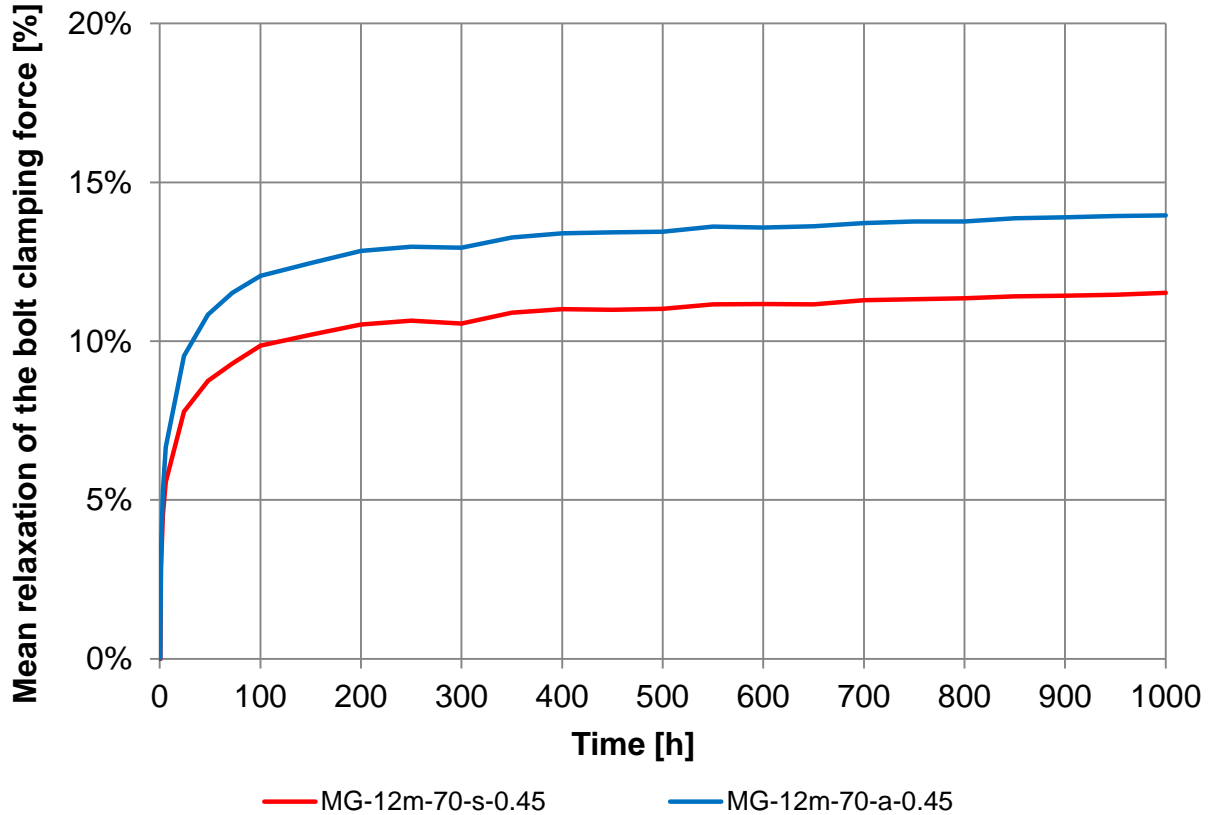
Figure 4: Mean relaxation of the bolt clamping force during the creep test

As the minimum mean slip coefficient found in the short term slip test was 0.49, the creep performance was evaluated at a slip coefficient value of 0.45 for the combined metallized-galvanized faying surface. Figure 5 shows the average connection slip between 30 minutes and 1000 hours of sustained loading, also referred to as creep deformation. Also shown on this figure is the creep deformation limit specified by RCSC bolt specification (RCSC 2014). Clearly, 12 mils thick metallized-galvanized faying surfaces passed the creep test.

Table 3 presents individual specimen dry film thicknesses and results obtained in the creep tests. All of the creep displacements were less than 0.127 mm (0.005 inch) after 1000-h for both specimens with and without burrs. Each chain slipped less than 0.381 mm (0.015 inch) after 1000 hours when the load was increased to the design slip load. So, each of the two set of parameters tested respected the requirement of the RCSC bolt specification (RCSC 2014) for a design slip coefficient of 0.45. The presence of small burrs doesn't seem to have any significant effect on the creep performance, since the mean creep deformation was 0.0525 mm for specimens with burrs removed and was 0.0591 mm for specimens with burrs left in place.
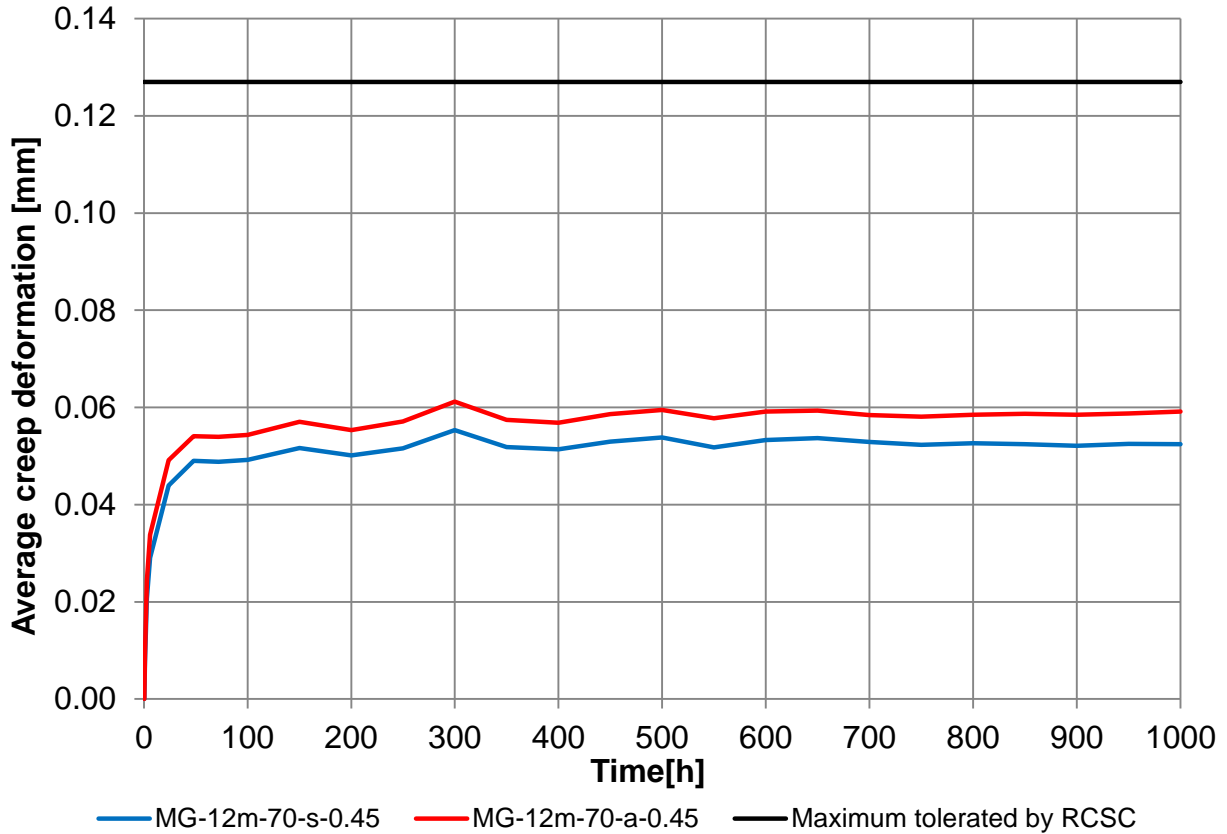
Figure 5: Average creep deformation

Tableau 3: Specimen dry film thickness and creep results

Specimen	Assembly	Left Outer Panel	Middle Plate*, Left Face	Middle Plate*, Right Face	Right Outer Panel	1000-h Creep displacement
		mils	mils	mils	mils	mm
12m-70-S-0.45	1	12.5	13.3	14.7	12.5	0.0558[a]
	2	12.7	14.2	14.4	12.8	0.0456[a]
	3	12.7	14.3	14.4	12.7	0.0560[a]
12m-70-A-0.45	1	12.5	14.9	13.3	12.5	0.0583[b]
	2	13.2	13.6	14.4	13.2	0.0356[b]
	3	13.0	13.0	12.9	13.0	0.0835[b]

* Galvanized plate
[a] Chain of three specimens slipped 0.0728 mm when loading to the design load.
[b] Chain of three specimens slipped 0.0844 mm when loading to the design load.

6. Conclusions

Slip-critical connections are required when the structure is subjected to repeated or reversal of loads. In some practical cases, primary bridge elements such as main girders are metallized and connected to secondary components such a cross frames that are hot-dip galvanized. Thus, designers need to know the slip coefficient of combined metallized-galvanized faying surfaces to be used. In this study, short-term slip coefficient and long-term creep deformation are evaluated following Appendix A of the RCSC bolt specification (RCSC 2014). Overall, the test results showed a good creep performance of the combined metallized-galvanized faying surfaces for a slip coefficient of 0.45. More specific conclusions are presented as follows:

1. The combined metallized-galvanized faying surfaces exhibited very good creep performance for 12 mils metallized coating thickness for a design slip coefficient of 0.45.
2. Creep performance was similar for the specimens with burrs left in place and with burrs removed.
3. Relaxation of the bolt clamping force of combined metallized-galvanized faying surfaces reached 13.95%.
4. Relaxation of the bolt clamping force and creep deformation occurred in the first 100 hours; thereafter, no significant creep deformation was observed.

Acknowledgements

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