RESISTANCE OF CORROSION-RESISTANT METALIZED FAYING SURFACES USED WITH SLIP-CRITICAL BOLTED CONNECTIONS

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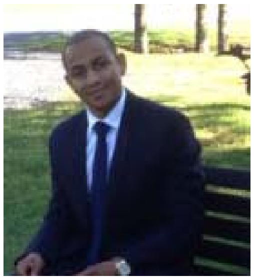

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BIOGRAPHY

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SUMMARY

Metalizing is becoming a commonly used corrosion protection solution for steel bridges, and designers need to know the slip resistance of metalized faying surfaces in order to eliminate the currently costly and time-consuming practice of masking off connection faying surfaces before metalizing. Will research indicating significant slip resistance influence future code revisions and impact steel bridge fabrication in North America?

The present study is part of an extensive research program to evaluate the resistance of metalized faying surfaces used with slip-critical connections.

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Abstract

Structural steel elements, particularly in steel bridge construction, that are exposed to severe environmental conditions require surface protection coating to preserve structural integrity and provide longevity. Metalizing is becoming a commonly used corrosion protection solution, providing physical barrier as well as sacrificial protection. Bridge design codes, such as the American Institute of Steel Construction (AISC) specifications ANSI-AISC 360-2010 and the Canadian Highway Bridge Design Code CAN/CSA S6-06, however do not specify slip coefficients for metalized faying surfaces used with slip-critical bolted connections. In practice, therefore, many steel bridge fabricators are compelled to mask off all connection faying surfaces before applying the metalized coating on the structural elements. This exercise is time consuming, labour-intensive and costly. In this study, the slip resistance for metallized faying surfaces in slip-critical bolted joints are determined from a short-duration tension test regime and for varying parameters of plate thickness, coating thickness, and bolt preload. The research indicates significant slip resistance for metalized faying surfaces compared with the uncoated faying surfaces. The results show potential to influence future code revisions and may impact steel bridge fabrication in North America.

Keywords: Metalizing, steel bridge construction, slip-critical bolted connections, design standards

Introduction

High strength bolted connections in structures under significant load reversal or fatigue-type loading are designed as slip-critical. Slip-critical connections possess a low probability of intolerable slip at any time during the life of the structure. The resistance to slip depends on friction between the planes of contact of the joint plies, also known as the faying surfaces, developed by the clamping action of the pretensioned bolts. Thus, the slip resistance is governed by the bolt preload and the coefficient of slip at the faying surfaces, and it is expressed mathematically as

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

where V_s is the slip resistance, μ is the slip coefficient for the faying surface, n_s is the number of the slip surfaces involved in the joint, n_b is the number of bolts, and $F_{b,i}$ is the minimum bolt pretension in bolt *i*. The bolt preload results from the nut being tightened against the resistance of the material to be connected. The specified minimum bolt pretension for high strength bolts is equal to 70 percent of the specified minimum tensile strength of the bolt [1].

The coefficient of slip, μ, is a function of the surface condition of the connected parts. The Research Council on Structural Connections (RCSC) Specifications for Structural Joints using ASTM A325 or A490 [1] defines three classes of surface preparation: unpainted clean mill scale steel faying surfaces (or surfaces with Class A coatings on blast-cleaned steel) as Class A surfaces with $\mu = 0.33$; unpainted blast-cleaned faying surfaces (or surfaces with Class B coating on blast-cleaned steel) as Class B with $\mu = 0.50$; and hot-dip galvanized and roughened surfaces as Class C surfaces with $\mu = 0.35$. The Canadian standard CAN/CSA-S16-09 [2] specifies the same three faying surface conditions as in the RCSC, but with a higher slip coefficient for Class C of $\mu = 0.40$. The American Institute of Steel Construction (AISC) specifications ANSI-AISC 360-2010 [3] on the other hand specifies slip coefficients for two faying surface classes, namely unpainted clean mill scale or surfaces with Class A coatings on blast-cleaned steel or hot-dipped galvanized and roughened surfaces ($\mu = 0.30$); and unpainted blast-cleaned surfaces or surfaces with class B coatings on blast-cleaned steel ($\mu = 0.50$). Essentially, the higher the slip coefficient, the lower the number of bolts needed to prevent slippage.

In many practical cases, faying surfaces are cleaned and masked off before applying a corrosion protection coating on structural steel elements (see Figure 1). This exercise is labour-intensive, time-consuming and costly, and can be avoided if designers know the slip resistance of faying surfaces coated with the same corrosion protection used on the steel element. The characteristics of the coating technology, including its formulation, thickness and workmanship may significantly influence the slip resistance. Kulak and his colleagues [4], in the Guide to Design Criteria for Bolted and Rivets Joints, collated results of slip tests performed over the years for faying surfaces with different coating types and thicknesses. There have been new and improved developments in the science and technology of metal surface protection after the publication of this Guide. In the present paper, a summary of short-duration tension tests and results for the slip coefficient of metalized faying surfaces is presented. A number of connection and coating parameters such as coating thickness, plate thickness, and bolt preload were investigated. Also, a number of uncoated blast-cleaned faying surfaces were tested to validate the test set-up.

Metalizing Steel Bridge Elements

Thermal spray coatings are a versatile and established technology for protecting metal surfaces in a variety of environments [5, 6]. Metalizing, which describes the thermal spray of zinc, aluminum or both on steel surfaces, is becoming a commonly used corrosion protection solution in the North American bridge industry due to its effectiveness as a protective coating and inorganic character [7, 8, 9]. The coating provides protection from corrosion related problems to the steel substrate by sacrificial and barrier protection [10]. Metalized coatings bond almost instantly with the steel member with no drying time, and are known to have no significant effect on its metallurgical structure [6, 11]. Moreover, the metalized substrate is known to be compatible with many different sealer types; sealing is recommended by many existing guidelines in the United States as it tends to increase coating longevity and improve aesthetics.

The metalizing process begins with a proper surface preparation. Here, the surface profile required is a white-metal blast finish according to the Society for Protective Coatings specification SSPC-SP 5/NACE No. 1, or near-white-metal finish (SSPC-SP 10) as a minimum. Essentially, the merits of metalized coating systems for corrosion protection of steel bridge components depend on such factors as the surface preparation, coating thickness, coating type, workmanship and environmental conditions. It is worthy of note that there is no limit to the size of structural elements that can be metallized, unlike in the case of hot-dipped galvanizing where the size of the bath containing the molten zinc imposes size limitations on the structural elements that can be galvanized.

The present research involves the use of a thermal spray coating from a zinc wire applied through an electric arc. The steel substrate for all specimens was prepared according to the SSPC-SP 5 (white-metal blast-cleaned surface finish).

Test Design

A series of tension tests was designed to evaluate the slip coefficient of metalized faying surfaces under short-duration static loading. The design was guided by the Research Council on Structural Connections Specifications for Structural Joints using ASTM A325 or A490 Bolts [1] with some unique additional techniques developed to facilitate the assembling of the specimens and monitoring of the clamping force during testing. Overall, 31 specimens were tested. Table 1 shows the parameters studied in the work presented herein.

Each specimen was uniquely identified according to the variables shown in Table 1. For example, specimen 5/8-M-6m-90% refers to 5/8 in. thick plates metalized with a coating thickness of 6 mils and tested under a bolt pretension equal to 90% of the tension capacity of the bolt. Similarly, 1/2-BC-0m-70% is a 1/2 in. thick test plates with non-metalized blast-cleaned faying surface of an average angular surface profile of 2.6 mils and tested under a bolt pretension equal to 70% of the bolt tension capacity. In each test plate, the surface preparation included removal of burrs around bolt holes.

Figure 1: Masking of connection faying surfaces (courtesy of Structal-Bridges, Québec)

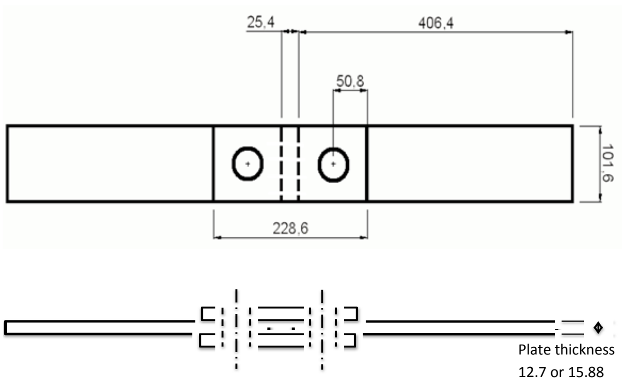
Table 1: Test variables

#	Parameters	Variables
1	**Faying surface**	BC- commercial blast cleaned
		M- metalized
2	**Thickness of coating**	0m- uncoated
		6m- 6 mils
		12m- 12mils
3	**Clamping force**	70% - 70% of bolt tension capacity
		90% - 90% of bolt tension capacity
4	**Plate thickness**	1/2- 1/2 in. thick plate
		5/8- 5/8 in. thick plate

Specimen Design

The specimens for the tests were assembled from steel plates prepared in a fabrication shop from 1/2 in. and 5/8 in. thick Canadian CAN/CSA G40.21 350AT cat.3 steel (popularly known as corten steel). Each specimen consists of two pairs of identical plates; 4 in. x 9 in. exterior plates bolted to two identical 4 in. x 16 in. interior plates (Figure 2) by two 7/8 in. diameter ASTM A325 high strength bolts. Each bolt hole measures 15/16 in. in diameter allowing for a maximum slip of 1/16 in. to occur during testing. The contact surface area per bolt of the test specimen is 4 in. x 3 in. (Figure 2). The metalized coatings were applied in the fabrication painting shop using techniques similar to the routine practice. Metalizing was applied from a zinc wire through an electric arc. The surfaces were all solvent cleaned to remove any oil or fabrication lubricant before preparation and treatment. Plates with any surface defects were removed from the test matrix.

The angular profile for each test plate after surface preparation was measured in the fabrication shop to assure the requirement for surface profile for metalizing are met. Table 2 shows the average angular profile (in mils) for each faying surface type tested, including the uncoated blast-cleaned-surface specimens. For all metalized plates, before the test plates were assembled and tested, a Positector Magnetic Gage was used to measure the coating thickness (Figure 3). This was to ensure that plates with similar average coating thickness were mated and tested. Measurements were taken at five different spots on each plate faying surface in accordance with the requirements of the Society for Protective Coatings SSPC-PA 2 standard [12] for metalized specimens, and the average thickness determined. The measurements were carried out at the testing laboratory.



All dimensions are in mm

Figure 2: Test plate dimensions

Specimen Assembly and Testing

The test plates were assembled into specimens using a specially fabricated device shown in Figure 4. This was to facilitate the plate assembling before testing and also aid in the clamping force application. The device allowed the creation of a negative bearing in the bolt hole to permit a maximum slip to occur.

Table 2: Specimens type and surface profile

Specimen type	**Surface preparation**		**Nominal coating thickness [mils]**
	SSPC-specification-	**Average angular profile [mils]**	
Uncoated blast-cleaned	SP6	2.6	0
Metalized 12 mils	SP5	4.5	12
Metalized 6 mils	SP5	4.5	6

It was essential to monitor the level of clamping force during the duration of each test as it has significant influence on the slip resistance. Some common techniques for controlling the bolt preload include the bolt calibration method, use of a hydraulic jack device, and the use of bolts with strain gages. In this research, the bolt pretension force was monitored from the time of assembly through to the end of testing by a calibrated 500 kN Omega washer-type load cell installed in series with the clamped test plate assembly.

Figure 3: Coating thickness measurement using a PosiTector Magnetic Gage

The calibration was made in accordance with the manufacturer's specification using the same MTS machine used for testing and under a set-up identical to the test set-up. A special washer was fabricated and used in series with the plate assembly to simulate the pressure transmitted on connection plates with a structural washer.

Figure 4: Test plate assembly device

The slip tests were performed on a 1500 kN MTS hydraulic Universal Testing Machine as shown in Figure 5. The specimen was carefully mounted on the testing machine to minimize any eccentric loading or slip. The applied loading rate was 100 kN/minute. The relative displacement between the loaded middle plates and the two side plates was measured using LVDT displacement transducers. This gives a measure of the slip displacement in the connection. A data acquisition system was used to record the applied loading and the associated slip. It also monitored the clamping force in real time during the test. The slip displacement was monitored on an X-Y plotter. The test was terminated after a significant amount of slip occurred, typically greater than 1.5 mm.

Results and Discussion

Results of a total of 31 short-duration slip tests in tension are presented in this paper. For each set of variables, studied, five identical specimens were tested [1], except for the uncoated blast-cleaned faying surfaces where three identical specimens were tested.

As previously indicated, the slip resistance is a function of the clamping force developed by the bolt pretension. Significant reduction of the clamping

Figure 5: Test set-up

force is likely to compromise the slip resistance of the connection. Table 3 shows the average amount of short-duration clamping force relaxation observed for each faying surface profile studies. The relaxation is expressed as a percentage of the initial bolt preload and represents the difference between the clamping force at the time of slip and the initial clamping force at the start of loading.

For the uncoated blast-cleaned faying surfaces, the relaxation in the clamping force was generally low, less than 1.0% of the initial clamping force. In other words, for the case of 70% bolt pretension say, it was possible to maintain the applied clamping force within -1.7 kN during the test until slip occurred. This was not the case for the metalized faying surfaces; clamping force relaxation was much higher, up to -3.7 % of the initial bolt preload. In general, it was higher for the 12 mils thick metalized coating than for the 6 mils, and also higher for the 90% clamping force than the 70% in the same plate thickness. The 1/2 in. thick test plates also exhibited higher relaxation of the metalized coating than the 5/8 in. thick plates for the same coating thickness and bolt pretension.

The slip coefficient for a tested faying surface is obtained from:

$$slip\ coefficient, \mu = \frac{slip\ load}{clamping\ force \times number\ of\ slip\ planes} \qquad (2)$$

Table 3: Short-term reduction of clamping force

Specimen I.D.	**Mean test relaxation [%]**
5/8-BC-0m-70%	0.75
5/8-BC-0m-90%	0.85
5/8-M-6m-70%	1.72
5/8-M-12m-70%	1.97
5/8-M-6m-90%	1.91
5/8-M-12m-90%	2.77
1/2-M-12m-70%	3.77

where the number of slip planes equals 2 in the present investigation and the clamping force equals 174 kN for 70% of the tension capacity of the bolt (7/8” A325) and equals 224 kN for 90% (7/8” A325) [13]. The initial clamping force was used in the slip coefficient evaluation as it gives the most conservative slip coefficient value.

Table 4 contains a summary of the slip coefficient values (columns 2-6) evaluated using Equation (2) above. The arithmetic mean for each faying surface type and the associated standard deviations are also shown in this table, in column 7 and column 8 respectively. Figure 6 shows typical load versus slip displacement curves for each of the faying surfaces investigated. In the majority of the slip test, the maximum slip load occurred before a slip displacement of 0.5 mm was attained. The slip coefficient was evaluated based on the maximum slip load.

The average slip coefficient for the uncoated blast-cleaned faying surfaces (with an average angular profile of 2.6 mils) was obtained as 0.36 (from a range of 0.33 to 0.39) for both the 70% and 90% bolt pretension on a 5/8 in. thick test plates. This implies that for the uncoated faying surface tested, the level of bolt preload above the specified minimum of 70% has no influence on the short-duration slip resistance. The mean coefficient evaluated for this surface angular profile corresponds to a Class A faying surface according to both the Canadian and American standard specifications. This coefficient value is also well within observed values available in the literature.

Table 4: Slip Coefficients Values

Specimen I.D.	μ_1	μ_2	μ_3	μ_4	μ_5	$\mu_{average}$	**S.D.**
5/8-BC-0m-70%	0.37	0.36	0.33			0.36	0.02
5/8-BC-0m-90%	0.34	0.39	0.36			0.36	0.02
5/8-M-6m-70%	0.77	0.81	0.76	0.77	0.82	0.79	0.03
5/8-M-12m-70%	0.98	0.93	0.93	0.99	0.89	0.94	0.04
5/8-M-6m-90%	0.79	0.84	0.70	0.77	0.74	0.77	0.05
5/8-M-12m-90%	0.99	1.01	0.93	0.94	1.01	0.97	0.04
1/2-M-12m-70%	0.98	0.98	0.99	1.01	0.96	0.98	0.02

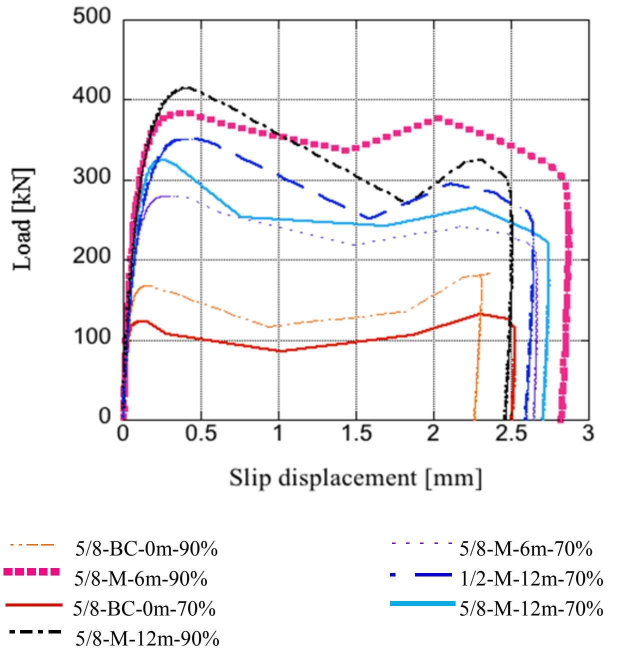


Figure 6: Typical load versus slip displacement for surfaces

The metalized coated faying surfaces yielded much higher slip coefficient values than the standard specifications for a Class B surface finish. The least mean slip coefficient was evaluated as 0.77 representing the 6 mils thick metalized coating on a 5/8 in. test plates and under a clamping force equal to 90% of the bolt capacity in tension. For the same coating thickness, a reduced level of bolt preload (70%) yielded similar slip resistance (coefficient = 0.79). The same trend was also observed for the 12 mils thick metalized coating, where the slip coefficients under 70% and 90% were evaluated as 0.94 and 0.97, respectively. The corresponding standard deviation values for the evaluated mean coefficients are very low, indicating that the data points are very close to the mean values.

The metalized coating thickness was observed to have a significant effect on the short-duration slip resistance. For a 70% bolt preload, the slip coefficient increased from 0.79 for the 6 mils thick coating to 0.94 for the 12 mils thick metalized coating. The increase was from 0.77 to 0.97 for the 90% bolt preload. Again, the standard deviation values were very low. Figure 7 shows a graphical effect of the influence of metalized coating thickness on the slip resistance.

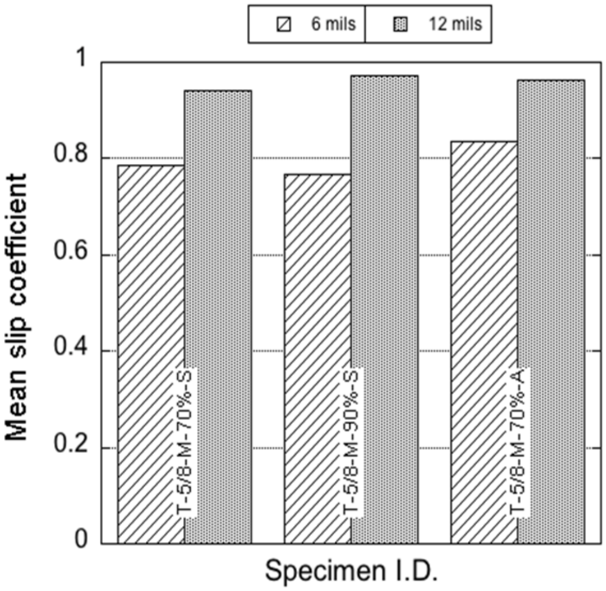


Figure7: Influence of metalized coating thickness on mean slip coefficients

The 1/2 in. thick test plates provided the greatest slip coefficient of 0.98 for a 12 mils coating thickness and a 70% bolt preload. However, a careful observation reveals that the thickness of the test plate does not have significant effect on the slip resistance. The corresponding 5/8 in. thick test plates exhibited a similar slip resistance (coefficient = 0.94).

Figure 8 shows the conditions of both the metalized faying surface and the uncoated surface after the tests.

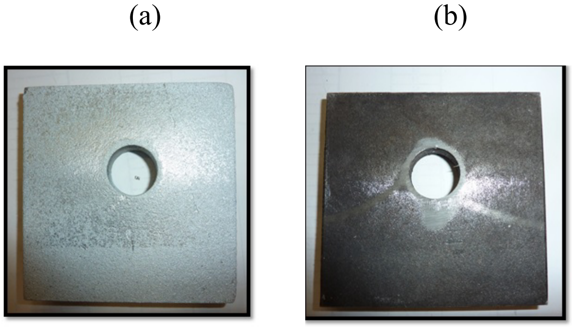


Figure 8: Conditions of (a) metalized (b) uncoated faying surfaces after slip tests

Conclusions

In a slip-critical connection, the pretensioned bolts create resistance to slip through the friction on the faying surface between the connected parts. Thus, the slip resistance is a function of the faying surface condition, expressed as the coefficient of slip. Metalizing is becoming a commonly used corrosion protection solution for steel bridges and designers need to know the slip resistance of metalized faying surfaces in order to eliminate the currently expensive practice of masking off faying surfaces before metalizing.

In the current study, the slip resistance of metalized faying surfaces used with slip-critical connections is evaluated through a series of tension tests. The results clearly indicate a much improved slip resistance over the uncoated blast-cleaned surfaces. However, the full merit of these test results can be established only after long-duration tension creep tests under sustained loading have yielded satisfactory results. Specific observations made in the study are summarised in the following.

1. A bolt preload over the standard specified minimum of 70% of the bolt tension capacity does not have any significant influence on both the uncoated blast-cleaned surfaces and the metalized faying surfaces.
2. Metalized faying surfaces yielded much higher slip resistance than the uncoated surfaces with mean slip coefficient values ranging from 0.77 to 0.98 and standard deviations from 0.02 to 0.05. Increase in metalized coating thickness from 6 mils to 12 mils resulted in improved slip resistance. The test plate thickness does not have significant effect on the slip resistance.
3. Compared with the uncoated blast-cleaned faying surfaces, the metalized coating surfaces yielded significant clamping force reduction during the test, with the 12 mils thick coating on the 1/2 in. thick test plates giving the maximum effect. A creep test under sustained tension is ongoing to understand the full effect of the relaxation on the slip resistance.

Acknowledgments

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