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Characterization of Slip Resistance for Metallized-Galvanized Faying Surfaces in Slip-Critical Joints

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Abstract: Exposed structural steel surfaces, particularly in steel girder bridge construction, require coating protection from harsh environmental conditions to preserve structural integrity and provide longevity. Consequently, galvanization and metallization have evolved as effective long-term protection. Practical situations exist where galvanized secondary structural members are joined to primary elements that are metallized in a slip-critical connection. Design provisions for bolted connections in contemporary standards, such as the Canadian Highway Bridge Design Code CAN/CSA S6-06, do not specify slip coefficient for slip-resistant connections with galvanized-metallized faying surfaces (i.e. one connected face metallized and the other face galvanized). Bridge fabricators are thus compelled to mask off connection faying surfaces before applying the protective coatings on structural members. This practice is time-consuming, expensive, and exposes the connection to corrosion before assembling. In this investigation, the resistance of slip-critical joints having metallized-galvanized faying surfaces is characterized in view of the Canadian steel bridge design standard. The mean slip coefficient is determined from compression test regime and for varying parameters of coating thickness, surface conditions, and bolt preload.

1. Introduction

Steel girder bridge members are exposed to damaging atmospheric conditions. Human activities such as the spread of snow/ice salt on road surfaces increase the vulnerability of such structures. Surface coating is used to provide protection against wear and corrosion. This has significant effect on the design life and maintenance costs of the structure. In contemporary practice, two of the most effective and environmentally-friendly surface protection methods are metallization (Gerdeman and Hecht, 1972; Pawlowski, 1995) and galvanization (Birkemoe and Herrschaft, 1970). Metallizing is a common term used to describe thermal sprayed metal coatings; for corrosion control coatings on steel structures, it refers to the thermal spraying of zinc or aluminum alloys as a coating directly onto steel surfaces. It is accomplished by feeding the metal in either wire or powder form to a spray gun where it is melted and sprayed. Once it strikes the steel, it resolidifies almost instantly providing barrier protection between the environment and the steel surface as well as sacrificial protection (Teruo, 1999). Hot-dip galvanizing, on the other hand, is a total immersion process where the steel element is dipped into a bath of molten zinc metal until it comes up to the bath temperature. Unlike metalizing, upon immersion the zinc and steel react metallurgically and becomes a part of the steel surface. The total immersion method imposes size limitations on galvanized structural members. For practical reasons, including cost, primary bridge elements such as plate girders may be metallized and connected to secondary members such as cross frames that are hot-dip galvanized. Essentially, the surface profiles for these two coating protections are non-identical.

Structural steel designers have traditionally been restrained from using any type of protective coating on faying surfaces of bolted slip-resistant joints. Structural bolted joints are designed for either bearing or slip-critical connections. Bearing type connection performance is unaffected by the presence of protective coatings on the contact surfaces as the applied load is transmitted mainly through the bolt to the connected plates. For steel bridges subjected to several cycles of loading during their design life, bolted connection design is generally governed by the slip resistance between the connected parts. The performance of slip-resistant bolted connections depends on the friction that can be developed between the faying surfaces and that in turn depends on the condition and quality of the surface. The friction is developed by the clamping action of high strength bolts. Friction connections that slip turn into bearing connections which are undesirable under certain design conditions.

The resistance to slip in a slip-critical connection is essentially controlled by the total clamping force and the coefficient of slip (or friction) between the connected plates. The slip resistance, V_s, is calculated from:

[1] $$V_s = k_s n_s \sum_{i=1}^{n_b} F_{b,i}$$

where k_s is the coefficient of slip for the faying surfaces, n_s is the number of the slip planes, n_b is the number of bolts, and $F_{b,i}$ is the minimum bolt preload in bolt i, taken as 70% of the tensile strength of the bolt (RCSC, 2009).

National standards for structural steel design essentially consider the influence of surface preparations and conditions of the faying surfaces in achieving slip-critical joints using high strength fastener assemblies. The Canadian standard CAN/CSA-S16-09 (CSA 2009) specifies slip coefficients for three faying surface conditions, namely clean mill scale or blast-cleaned with Class A coatings; blast-cleaned or blast-cleaned with Class B coatings, and hot-dip galvanized with wire brushed surfaces. The corresponding design coefficients of slip are given as k_s = 0.33, 0.5 and 0.4 respectively. The AISC Specifications (AISC 2010) on the other hand provide slip coefficients for two steel surface classes, namely unpainted clean mill scale or blast-cleaned with class A coatings (k_s = 0.30) and unpainted blast-cleaned surfaces or blast-cleaned surface with class B coatings (k_s = 0.5). The Research Council on Structural Connections (RCSC 2009) Specifications for Structural Joints include a class C surface consisting of roughened hot-dip galvanized surfaces that provide a slip coefficient of 0.35. For this type of surfaces, Kulak et al. (2001) indicated that the galvanized surface must be carefully and visibly altered without disrupting the continuity of the galvanizing. In general, for coated faying surfaces, the slip resistance is determined by a tested performance of the coating system as meeting Class A, B or C and the steel to be coated must be blast-cleaned in all cases.

In many practical cases, connection faying surfaces are masked off before applying a metallized or galvanized protective coating to structural steel elements (see Figure 1). The masking exercise is highly laborious, time-consuming and costly. Moreover, the unprotected faying surfaces are vulnerable to severe corrosion and consequent separation of the connected parts when faced by aggressive environmental conditions. These issues can be addressed if faying surfaces coated with the same protective treatment as for member surfaces are appropriately characterized as satisfactory in view of prevailing design standards for slip-resistant joints. In other words, large amount of work could be avoided if coated faying surfaces yield a slip coefficient equal to or greater than that of the blast-cleaned uncoated counterpart. This depends on the surface treatment and characteristics, including coating formulation, thickness and method of application on the steel surface. Results of short-term slip tests performed over the years for surfaces having different coating types and thicknesses were collated and reported in the document, Guide to Design Criteria for Bolted and Rivets Joints (Kulak et al. 2001). However, to the best of the authors' knowledge, there is no record of studies that measured the slip coefficient of slip-critical joints having one connected face metallized and the other face galvanized.

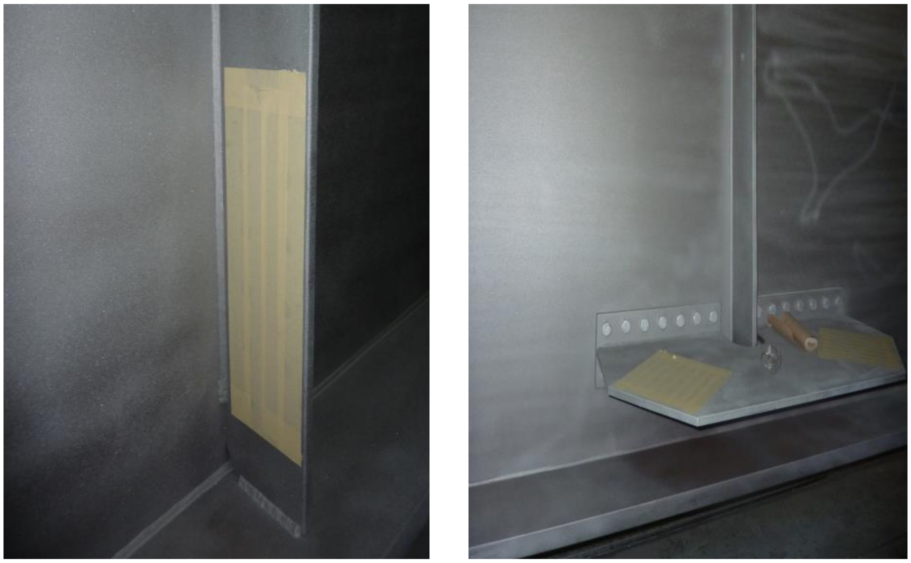


Figure 1: Masked faying surfaces of steel girders before metalizing

In the present study, the slip resistance of slip-critical joints with combined metallized-galvanized faying surfaces are characterized in the light of the CAN/CSA-S6-06 standard. The metallized surface is obtained by thermal spray coating from a zinc wire applied through an electric arc. The steel substrate is prepared according to the Society for Protective Coatings specification SSPC-SP5 (white-metal finish). For the galvanized surface, the coating was applied according to the standard specification for zinc (hot-dip galvanized) coatings on iron and steel products, which was approved by American Society for Testing and Materials (ASTM) in 2011 and known as ASTM A123 (AASHTO M111-11). The mean slip coefficients are determined from compression test regime and for varying parameters of coating thickness, surface conditions, and bolt preload. A number of blast-cleaned uncoated faying surfaces were also tested as 'control specimens' to validate the test set-up and also provide basis for assessing the influence of the metallizing and galvanizing. This paper summarizes the results of the experimental work performed at Laval University, which was supported by Structal-Bridges, a division of the CANAM group.

3. Experimental Program

A series of compression tests was designed to determine the slip coefficient of connected metallized-galvanized faying surfaces under short-term static loading. The overall goal was to determine the slip resistance of slip-critical connections with metallized-galvanized faying surfaces, and to characterise this resistance in view of the Canadian standard, CAN/CSA-S6-06. The design of the test program was guided by the Research Council on Structural Connections Specifications for Structural Joints using ASTM A325 or A490 Bolts (RCSC 2009) with some unique procedure and technique developed to assemble the specimens and monitor the clamping force during testing. Overall, 36 specimens were tested. Table 1 contains the parameters studied.

Each specimen was uniquely identified according to the variables shown in Table 1. For example, specimen MG-6m-90%-A refers to connected metallized-galvanized faying surfaces with metallizing coating thickness of 6 mils and burrs unremoved, which was tested under a bolt pretension equal to 90% of the tensile strength of the bolt. Similarly, SP5-0m-70%-S represents uncoated faying surfaces blast-cleaned to SP5 surface profile with burrs removed, which was tested under a bolt preload of 70% of the bolt capacity in tension. The specimens with the blast-cleaned uncoated faying surfaces were used to control the test as several data on this surface type exists in the literature. The average thickness of the galvanized coating was 19 mils for all test plates.

Table 1: Test Variables

#	Parameters	Variables
1	**Faying surface**	SP6- blast cleaned to SP6 SP5- blast cleaned to SP5 MG- combined metallized-galvanized
2	**Thickness of metallizing coating**	0m-Non-metallized 6m- 6 mils 12m- 12mils
3	**Clamping force**	70% - 70% of bolt tension capacity 90% - 90% of bolt tension capacity
4	**Presence of the burrs**	S- without burrs A- with burrs

3.1 Specimen characteristics and preparation

The test specimens were assembled from steel plates fabricated in a machine shop from a 5/8 inch thick 350AT cat.3 steel. The plate dimensions were in accordance with the RCSC specifications (2009). The specimens consist of three (one middle plate and two splice plates) identical steel plates clamped together using a 7/8 inch diameter ASTM A325 high strength bolts. A 15/16 inch bolt hole diameter allowed for sufficient clearance required for slip to occur during testing. The test plates were fabricated and coated under controlled conditions. Thermal spray coating was applied from a zinc wire through an electric arc. The surface treatment before metallizing was in accordance with the Canadian standard, CAN/CSA-G189. For galvanizing, the specimens were immersed in pickling acid, flux and finally in molten zinc. The galvanizing coating was applied according to ASTM A123 (AASHTO M111-11). The plates were then machined flat at one edge to facilitate compression test set-up and the loading of the specimen.

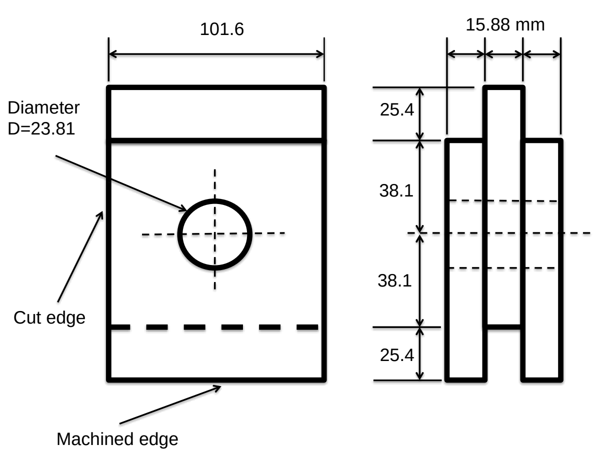
The angular profile for each test plate after blast cleaning was measured in the shop to certify the standard requirement for steel substrate of metallized surfaces. Table 2 shows the average angular profile (in mils) for each specimen type tested. The profile for the blast-cleaned uncoated specimens indicates the surface profile of the metallized plates. For all metallized plates, before the test plates were assembled and tested, a Positector magnetic gage was used to measure the coating thickness on each test plate. Readings 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 for metallized specimens, and the average thickness determined. The average thickness of galvanized plates was confirmed by the same procedure. An independent professional body was tasked with these measurements, which were carried out in the testing laboratory at Laval University. The galvanized plates were tested in as-received condition, without any roughening.

Table 2: Specimen's type

Specimen type	Surface preparation		Nominal coating thickness [mils]
	SSPC-specification	Average angular profile [mils]	
Blast-cleaned to SP6	SP6	2.6	0
Blast-cleaned to SP5	SP5	4.5	0
Metallized 12 mils	SP5	4.5	12
Metallized 6 mils	SP5	4.5	6
Galvanized	SP8	2.6	19

3.2 Specimen assembly and testing

The assembly of the plates to form specimens for testing is shown schematically in Fig. 2a. The specimen consists of a double lap joint with a bolt hole in each of the three identical sized plates. The middle plate is galvanized on both sides, and only one connected face of the two splice plates is metallized. Fig. 2b shows a special device fabricated to facilitate and standardize the assembling of the plates before testing, which also insures the creation of sufficient clearance in the bolt hole to permit a maximum slip of 1/16 inch to occur.



(a)

(b)

Figure 2: Test specimen and plate assembly

It is essential to measure and monitor the amount of clamping force as slip results are heavily influenced by the clamping effect. Different techniques with different degrees of accuracy exist for controlling the clamping force. In this research, the bolt preload was applied manually using a hand-held ratchet to recapture field practice. However, the bolt pre-tensioning force was monitored from assembly through testing by a carefully calibrated 500 kN Omega washer-type load cell installed in series with the clamped test plate assembly. The calibration was made in accordance with the manufacturer's specification using the same MTS machine used for the testing. A special washer was fabricated and used in series with the plate assembly to simulate the pressure transmitted on the test plates with a structural washer. A spherical head on the test machine ensured uniform compression along the machined edge of the middle plate.

The slip tests were performed on a 1500 kN MTS hydraulic Universal Testing Machine as shown in Fig. 3. The specimen was carefully mounted on the testing machine in a way that permits aligning the specimen in 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 plate (galvanized plate) and the two rigid base splice plates (metallized plates) was measured using two LVDT transducers. The mean value of the two displacement readings was calculated. This gives a measure of the slip amount in the connection. A data acquisition system was used to monitor and record the applied loading and the associated slip. It also served to monitor the amount of the clamping force during the test. The slip displacement was monitored on an X-Y plotter. The test was terminated when a significant amount of slip was reached, typically greater than 1.5 mm.

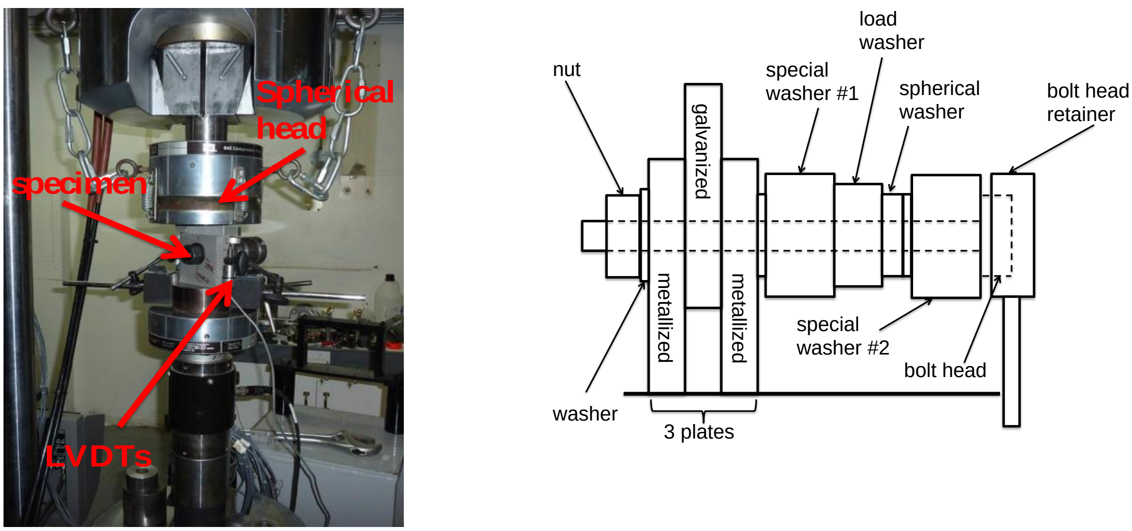


Figure 3: Test set-up

4. Results and Discussions

Thirty-six (36) short-term slip tests were performed in this study. For each variable studied, five identical specimens were tested except for the uncoated specimens where three identical tests were carried out for each surface profile.

By continuously monitoring the bolt clamping or pre-tension force during the test, it was possible to evaluate the short-term clamping relaxation and assess the effect of the variation in the clamping force on the slip resistance. Table 3 shows the average amount of short-term relaxation (expressed as a percentage of the initial bolt preload) observed during the test for each faying surface type studied. In general, the blast-cleaned uncoated surfaces fell within 1.0% reduction in clamping force, as recommended by Yura and Frank (1985). In other words, it was possible to maintain the applied clamping force within -1.7 kN (for 70% bolt preload) during the test until slip occurred. In the case of the connected metallized-galvanized faying surfaces, clamping force reduction was greater, up to -3.7 % of the initial bolt preload for the 12 mils thick metallized coating. It was slightly less for the 6 mils thick metallized coating, and in general about twice as higher for the 90% clamping force than for the 70%. It is noted that this might not necessarily be the case for varying thicknesses of galvanized protection treatment.

The presence of burrs appears to affect the amount of clamping force reduction, with an increase over surfaces with the burrs removed. In order to fully understand the relaxation phenomenon (under service loading) and its effect on the connection slip resistance, long term sustained loading tests would be useful.

Table 3: Short-term Reduction of Clamping Force

Specimen I.D.	Mean test relaxation [%]
SP6-0m-70%-S	0.88
SP5-0m-70%-S	0.82
MG-6m-70%-S	1.11
MG-12m-70%-S	1.27
MG-6m-90%-S	2.37
MG-12m-90%-S	3.71
MG-6m-70%-A	1.95
MG-12m-70%-A	2.63

The slip coefficient for a single specimen is obtained as:

[2] $$slip\ coefficient, k_s = \frac{slip\ load}{clamping\ force \times number\ of\ slip\ planes}$$

where the number of slip planes equals 2 and the clamping force is equal to 174 kN for 70% of the tension capacity of the bolt (7/8" A325) and equal to 224 kN for 90% (7/8" A325). The initial clamping force was used in equation (2), as it provides conservative slip coefficient values.

Figure 4 and 5 show typical load-slip displacement curves for each of the faying surfaces investigated and for specimens with burrs and with burrs removed. In almost all cases, 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. Table 4 contains a summary of the slip coefficient values (columns 2-6) for the various tests carried out. The arithmetic mean for each faying surface type and the associated standard deviations are also shown in the table, in column 7 and column 8 respectively. Figure 6 shows a comparison of slip coefficients between the various parameters investigated, i.e. the metallized coating thickness, the bolt preload and the effect of burrs. Once again, it is noted that the same average thickness of the galvanized coating on each faying surface was maintained. These were measured at different spots on the plate surface before the tests.

Table 4: Slip Coefficient Values

Specimen I.D.	k_{s1}	k_{s2}	k_{s3}	k_{s4}	k_{s5}	$k_{average}$	S.D.
SP6-70%-0m-S	0.39	0.35	0.41			0.38	0.03
SP5-70%-0m-S	0.51	0.55	0.52			0.53	0.02
MG-70%-6m-S	0.57	0.62	0.59	0.63	0.55	0.59	0.04
MG-70%-12m-S	0.64	0.62	0.71	0.71	0.57	0.65	0.06
MG-90%-6m-S	0.48	0.49	0.47	0.51	0.49	0.49	0.01
MG-90%-12m-S	0.58	0.60	0.61	0.60	0.57	0.59	0.02
MG-70%-6m-A	0.60	0.62	0.68	0.65	0.58	0.62	0.04
MG-70%-12m-A	0.65	0.77	0.65	0.64	0.69	0.68	0.06

The average slip coefficients for the uncoated faying surfaces (blast-cleaned to SP 6 and SP 5) were obtained as 0.38 (from a range of 0.35 to 0.41) and 0.53 (from a range of 0.51 to 0.55) respectively. According to the Canadian standard, CAN/CSA-S6-06, these slip coefficients can be classified as class A and class B faying surfaces respectively. Also, reported coefficient values available in the literature (Kulak et al., 2001) for similar surface conditions agree well with the values observed in the present study.

The combined metallized-galvanized coated faying surfaces yielded higher mean slip factors than the class B faying surface based on the Canadian standard specifications, except for one specimen type where the mean slip coefficient was slightly lower, an average of 0.49 and a standard deviation of 0.01. This represents the 6 mils thick metallized face coating with burrs removed and under a clamping force equal to 90% of the bolt tensile capacity. With the clamping force reduced to 70% of the tensile strength of the bolt, there was a significant increase in the mean slip coefficient to 0.59, at a standard deviation of 0.04. This effect of increasing slip resistance with a reduction in the bolt preload or clamping force was also evident for the specimen with one connected face metallized to 12 mils coating thickness and the other face galvanized. The slip coefficient increased from 0.59 to 0.65, with corresponding standard deviations of 0.02 and 0.06 respectively. The thickness of the metallized coating also played a significant role in slip resistance. Increasing thickness from 6 mils to 12 mils resulted in an increase in slip factor from 0.59 to 0.65 for the 70% bolt preload, and from 0.49 to 0.59 for the 90% bolt preload. The presence of burrs slightly improved the slip resistance for both the 6 mils and 12 mils metallized coated face specimens, with slip coefficients of 0.62 and 0.68 respectively and corresponding standard deviations of 0.04 and 0.06. A similar effect of burr presence has been reported elsewhere for uncoated faying surfaces (Polyzois and Yura, 1985). The improved slip resistance effect with increasing metallized coating thickness was also observed for specimens with unremoved burrs.

In general, hot-dip galvanized faying surfaces in slip-critical connections are considered inferior to uncoated blast-cleaned steels and are classified as Class C by the Canadian standard CAN/CSA-S6-06, with slip coefficient of 0.4. Moreover, they are required to be wire-brushed or roughened to qualify for this class as it has been observed that this additional treatment improved slip resistance significantly. Metallized faying surfaces are not covered by the standard, although some studies have revealed improved slip resistance over the uncoated blast-cleaned surfaces (Class B). It can be inferred from the present study that slip-critical connections with one connected face metallized and the other hot-dip galvanized develops slip resistance greater than the typical Class C surface (roughened hot-dip galvanized structural joint) and in most cases, greater than the typical Class B faying surfaces. It is worth mentioning that the hot-dip galvanized surfaces used in the present study were not roughened or wire-brushed, which would normally lead to a much lower slip coefficient than a Class C surface.

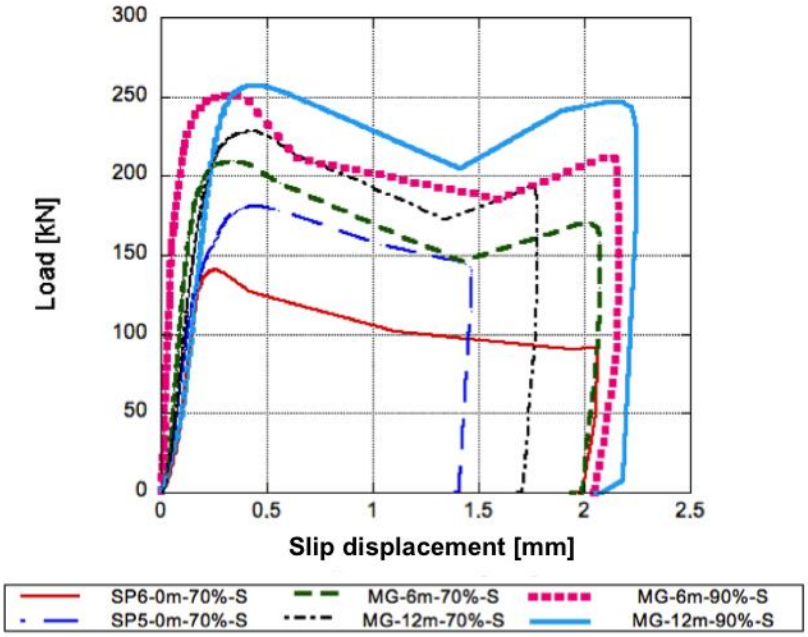


Figure 4: Typical load-slip displacement for different surfaces with burrs removed

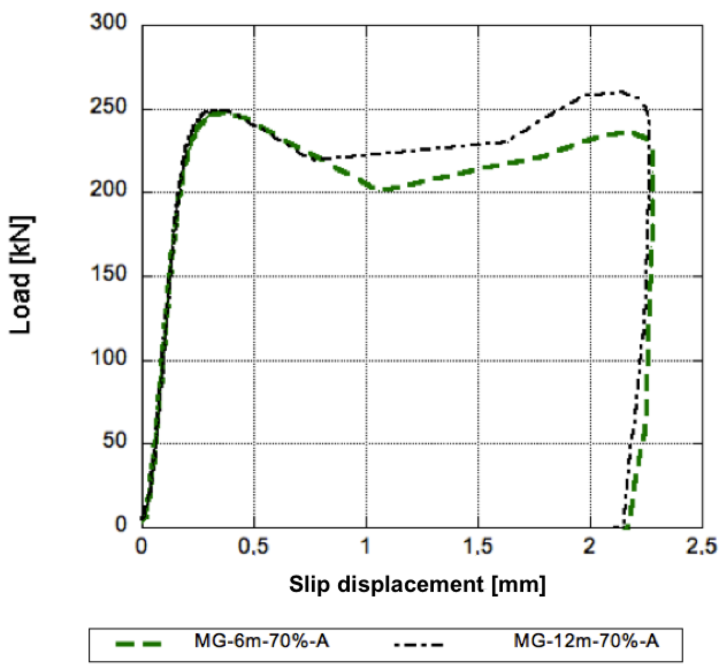


Figure 5: Typical load-slip displacement for different surfaces with burrs

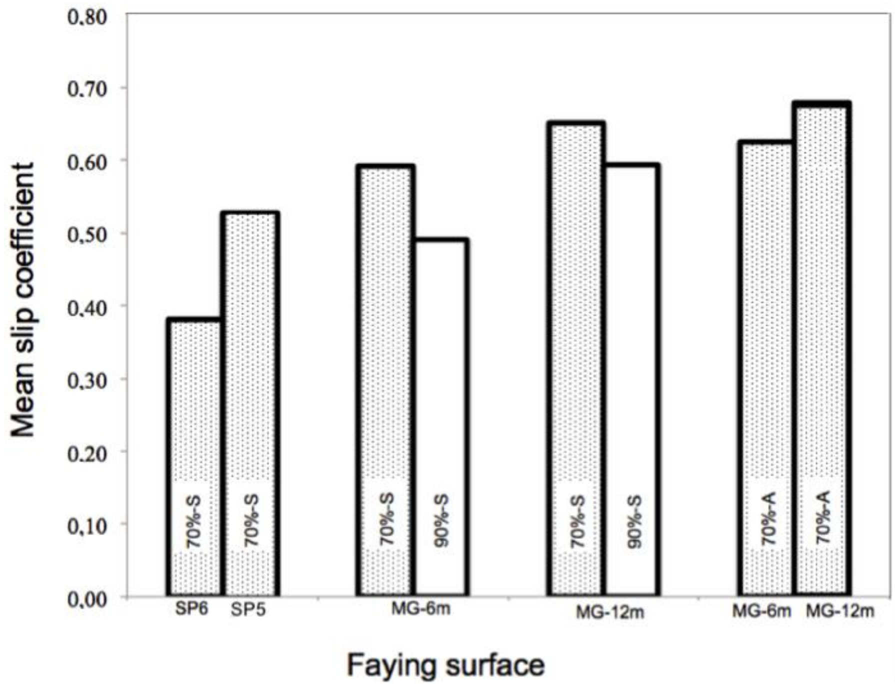


Figure 6: Comparison of slip coefficients for different faying surfaces

5. Conclusion

The slip resistance is a critical factor influencing bolted joint behaviour in steel structures under repeated loading. The surface condition of the connected steel components, also known as the faying surface, controls the level of the slip resistance. Design standards specify desired surface conditions and associated slip coefficients for slip-critical connections. In general, the standards prohibit coating of faying surfaces, although protective surface coating is essential for the steel elements. It is expensive and labour-intensive to mask off faying surfaces before steel member coating, and moreover the uncoated connected parts are exposed to damaging environmental conditions. In this study, the resistance of slip-critical joints with one connected part metallized and the other part hot-dip galvanized has been investigated and characterized in the light of the Canadian standard for steel bridge design. The following observations are made in the study.

1. Practical situations exist where primary bridge elements that are metallized are connected to secondary elements that are hot-dip galvanized. If reliable testing can establish satisfactory slip resistance based on prevailing design standards, then masking of faying surfaces in slip-critical connections and subsequent re-touching could be avoided before surface protection coating.
2. The blast-cleaned uncoated surfaces cleaned to SSPC specifications for SP 6 and SP 5 falls respectively into Classes A and B faying surfaces based on both the Canadian standard and the AISC Specifications, with mean slip coefficients of 0.38 and 0.53 and corresponding standard deviations of 0.03 and 0.02.
3. Slip-critical connections with one connected face metallized and the other face hot-dip galvanized develops slip resistance greater than the typical Class C surface (roughened or wire-brushed hot-dip galvanized structural joint) and in most cases, greater than the typical Class B faying surfaces.
4. Slip resistance for slip-critical connections with one connected face metallized and the other face hot-dip galvanized improved with a reduction in the bolt preload from 90% to 70%. Increasing thickness of the metallized coating from 6 mils to 12 mils resulted in an increase in slip coefficient

for both the 70% and 90% bolt preload. The presence of burrs slightly improved the slip resistance for both the 6 mils and 12 mils metallized connected parts.

5. Compared with the blast-cleaned uncoated surfaces, the specimens with one connected face metallized and the other face hot-dip galvanized yielded an increased clamping force reduction during the test. The relaxation phenomenon can be fully understood by a long term sustained loading tests.

Acknowledgements

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