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THE EFFECT OF RELAXATION ON THE SLIP RESISTANCE OF METALLIZED FAYING SURFACES IN SLIP-CRITICAL CONNECTIONS

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ABSTRACT

Metallizing has emerged as an effective protective coating for steel bridge members, providing a physical barrier and a galvanic protection. Recent research has shown that metallized faying surfaces used in high strength bolted connections provide higher slip resistance than specified values for uncoated blast-cleaned faying surfaces in North American design standards. As a particularity, relaxation of the clamping force is observed in the slip-critical connections with metallized faying surfaces. In this study, tests were designed to evaluate the effect of relaxation on the slip resistance of metallized faying surfaces in high strength bolted connections. Some design parameters included in this study are the coating thickness, the amount of bolt preload, the type of bolt and the presence of burrs. Test results showed that the relaxation of the clamping force does not adversely affect the slip resistance of connections with metallized faying surfaces.

Keywords: Steel bridge construction. Metallizing. Slip-critical bolted connection. Relaxation. Slip resistance. Design standards.

1. INTRODUCTION

1.1 Context of the study

Steel structures are subjected to aggressive environmental conditions and need to be protected to ensure their longevity and structural integrity. Metallizing, defined as the thermal spraying of zinc or aluminum alloys, has emerged as an effective protective coating for steel bridges in North America (Figure 1), producing a physical barrier and a self-sacrificing protection. The metallized coating emits no volatile organic compounds (Chang et al. 1999) and is recyclable. Some advantages of metallizing are that there no size limitation, reducing the number of field splices compared to galvanized members, and that it is a process requiring no drying time and allowing the handling of the piece almost immediately after application, thereby saving significant amount of time in the shop.

The surface preparation of connection faying surfaces is an important parameter in the evaluation of the slip resistance of high strength bolted connections. Design standards provide slip coefficient for different surface conditions. 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 coatings 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 ($k_s = 0.30$) 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 surface conditions, namely clean mill scale or blast-cleaned with Class A coatings ($k_s = 0.33$), blast-cleaned or blast-cleaned with Class B coatings ($k_s = 0.50$) and hot-dip galvanized surfaces roughened by wire brushing after galvanizing ($k_s = 0.33$).

Recent research have shown that metallized faying surfaces used in high strength bolted connections provide higher slip resistance than specified values for uncoated blast-cleaned Class B surfaces in North American design standards (Chiza et al. 2013; Ampleman et al. 2015). These studies followed the recommended procedure in the Research Council on Structural Connections (RCSC) *Specification for Structural Joints Using High-Strength Bolts* (RCSC 2014), hereafter called the RCSC bolt specification. The tests on the metallized faying surfaces yielded slip coefficients of at least 0.77 in the short-duration slip tests (Chiza et al. 2013) and also presented an acceptable long-term creep performance under the service load associated with a Class B slip coefficient (Ampleman et al. 2015).



Figure 1: Metallized Memorial bridge, Kittery, ME & Portsmouth, NH (Credit: Canam-bridges)

As a particularity, relaxation of the clamping force is observed in high strength bolted connections with metallized faying surfaces. In the present study, tests were designed to evaluate the effect of relaxation on the slip resistance of metallized faying surfaces in slip-critical connections. More precisely, the purpose of this research work is to ensure that the slip resistance of the joint is not adversely affected by the relaxation of the clamping force. Some parameters that represent different practical situations were included in the study, such as the thickness of coating, the clamping force, the presence of burrs and the type of bolt used.

1.2 Nomenclature

Table 1 contains the parameters of the specimens tested. Each specimen has been identified following the variables used in Table 1. For example, specimen M-12m-70-s-A325 refers to a zinc-metallized faying surface with 12 mils thick coating, with a bolt preload equal to 70% of the tension capacity of the A325 bolt used and burrs removed.

#	Parameters	Variables
1	Condition of surfaces	SP5 - Prepared SSPC SP 5 M - Metallized
2	Thickness of coating	0m - Not coated 6m - 6 mils 12m - 12 mils
3	Clamping force	70 - 70% of bolt capacity 90 - 90% of bolt capacity
4	Presence of burrs	s - With burrs removed a - With burrs left in place
5	Bolt	A325 - A325 bolt A490 - A490 bolt

1.3 Short-term slip tests

Chiza et al. (2013) evaluated the short-duration slip resistance of metallized slip-critical connections clamped with A325 bolts without relaxation time. For each set of parameters, five replicates tests were conducted. Control specimens with non-metallized blast cleaned faying surfaces were also tested to validate the experimental set-up. Table 2 shows the mean slip coefficient obtained for different specimens with their associated standard deviation. These slip coefficient, hereafter called theoretical values, will serve as reference values for evaluating the effect of relaxation on the slip resistance.

Table 2: Slip coefficient (Chiza et al. 2013)

Specimen	Mean slip coefficient	σ
SP5-0m-70-s	0.53	0.03
M-6m-70-s	0.82	0.04
M-12m-70-s	0.85	0.09
M-12m-90-s	0.91	0.06
M-12m-70-a	0.86	0.08

2. EXPERIMENTAL PROGRAM

2.1 Specimen characteristics and preparation

Test assemblies were machined from 5/8 inch thick steel plates, grade 350AT. Plate dimensions (Figure 2) were chosen in accordance with that prescribed by the RCSC bolt specification (RCSC 2014) for the short-term slip test. An assembly consists of three identical steel plates (a middle and two lap plates) clamped together using a 7/8 inch diameter high strength bolt. A 1-inch bolt-hole diameter is used to allow sufficient clearance required for slip to occur during the compression slip testing. Burrs produced by drilling of bolt holes were removed or left in place, depending on the parameters tested.

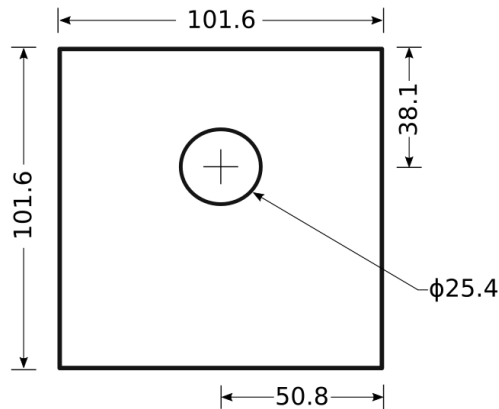


Figure 2: Plate dimensions, mm

Thermal spray coating was applied from a zinc wire through an electric arc in accordance with SSPC-CS 23.00/AWS C2.23M/NACE No. 12 (SSPC/AWS/NACE 2003). The steel substrate for each plate was prepared to white metal finish SSPC-SP 5 and the angular profile depth was measured to ensure compliance. All plates were coated on both sides. Thus, there are six layers of coating between the bolt head and the nut in each assembly. This allows for the maximal relaxation of the clamping force. The thickness of the coating was measured with a Positector magnetic gage on each test plate in order to mate plates with similar average coating thickness. Five different readings were taken on each plate faying surface in accordance with the Society for Protective Coatings SSPC-PA 2 (SSPC 2012) standard and the average thickness was determined.

The test matrix included a combination of parameters with surfaces that were non-metallized and prepared to SSPC-SP 5, in order to compare the relaxation and the post-relaxation slip performance of non-coated blast-cleaned

surfaces with metallized surfaces. For each combination of parameters, three replicate specimens was fabricated and subjected to the relaxation test.

2.2 Relaxation tests

Each specimen consists of a double lap joint. Figure 3 shows a special device fabricated to facilitate the assembling of the plates. The device permits the creation of the necessary clearance in the bolt hole to permit a maximum slip to occur in the post-relaxation slip test.



Figure 3: Assembly of a specimen

The applied clamping force needs to be known since it is an important parameter in the evaluation of the slip resistance of the joint. In this research work, the bolt preload was manually applied using a hand-held ratchet to reproduce field practice. 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. The load cell was calibrated in accordance with the manufacturer's specification using a 1500 kN MTS hydraulic Universal Testing Machine. A special washer was designed and used in series with the plate assembly to simulate the pressure transmitted on the test plates with a structural washer. Two types of high strength bolts, A325 or A490, were used in order to evaluate the effect of the bolt type on the relaxation of the bolt preload.

In the relaxation test, three identical plates were clamped and set aside for one week (168 hours) while recording continuously the clamping force. The clamping force monitored by the load cell was recorded using a DataTaker. A preliminary test of several weeks of relaxation showed that nearly 95% of the relaxation of the bolt preload was attained after one week. So, a week of relaxation was selected for the present study.

After one week of relaxation, the three specimens were subjected to a post-relaxation compression slip test (Figure 4) in order to evaluate the effect of the relaxation of the clamping force on the slip resistance. All tests were performed on a 1500 kN MTS hydraulic Universal Testing Machine as shown in Figure 5. The compression load was applied at a rate of 100 kN/minute. For each specimen, the relative displacement between the middle plate and the two lap plates was measured using two LVDT, one on each side of the assembly. The displacement recorded is the average of the two measurements, and the slip is defined as a relative displacement of 0.50 mm (0.02 inch). The compression load and the relative displacement were monitored continuously during the test.

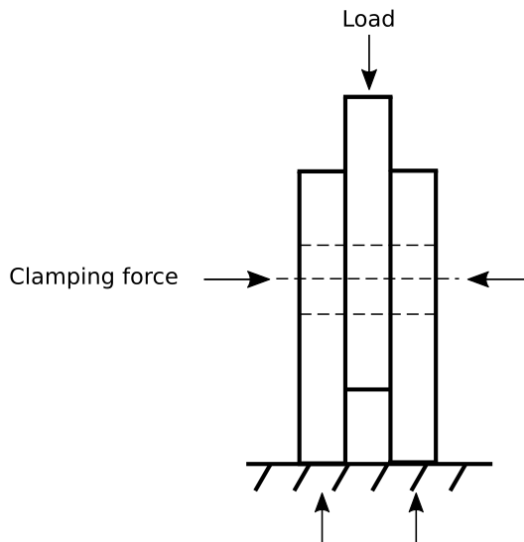


Figure 4: Assembly subjected to compression slip test



Figure 5: Compression slip test setup

3. RESULTS AND DISCUSSION

A total of 18 relaxation and consequent short-duration slip tests were performed in this study. For each set of variable studied, three identical specimens were tested. As discussed previously, the bolt clamping force was monitored during one week (168 hours) in order to quantify the loss of bolt preload, also known as relaxation.

Figure 6 presents the average amount of relaxation over time, expressed as a percentage of the initial-maximum preload. Clearly, it is seen that the major part of the relaxation occurred in the first 48 hours. Blast-cleaned uncoated surfaces yielded an average relaxation of 4.8% after one week. That means the clamping load was almost entirely maintained over the period. However, in the case of the metallized faying surfaces, the relaxation recorded was clearly superior. The 12 mils thick metallized specimens, with burrs removed and with a clamping force equal to 70% of the tension capacity of the A325 bolt used, showed an average relaxation of up to 30.6%. The presence of burrs appeared to have increased the amount of relaxation, as an average loss of preload of 37.0% was recorded for the same set of parameters but with burrs left in place. The loss of clamping force was expectedly higher for 12 mils thick metallized coating than for 6 mils. The 6 mils thick metallized coating assemblies yielded a mean relaxation of about 21.1% after one week, an observation consistent with earlier studies reported in the literature (Yura & Frank, 1985). The results also indicated that the amount of preload (70 or 90%) and the type of bolt used (A325 or A490) do not have a significant effect on the amount of relaxation.

With the considerable loss of preload observed during the relaxation week for metallized specimens, the post-relaxation slip test was designed to verify if the relaxation reduces the slip load under the design slip load. Figure 7 presents typical load-slip curves obtained in the post-relaxation slip test for different sets of parameter. The slip load is recorded as the maximum load reached before a slip of 0.50 mm or the load that corresponds to a slip of 0.50 mm. In the majority of cases, metallized connection surfaces yielded a higher slip load than uncoated blast-cleaned surfaces prepared to SSPC-SP 5, although the former are characterized by a significant loss of clamping force.

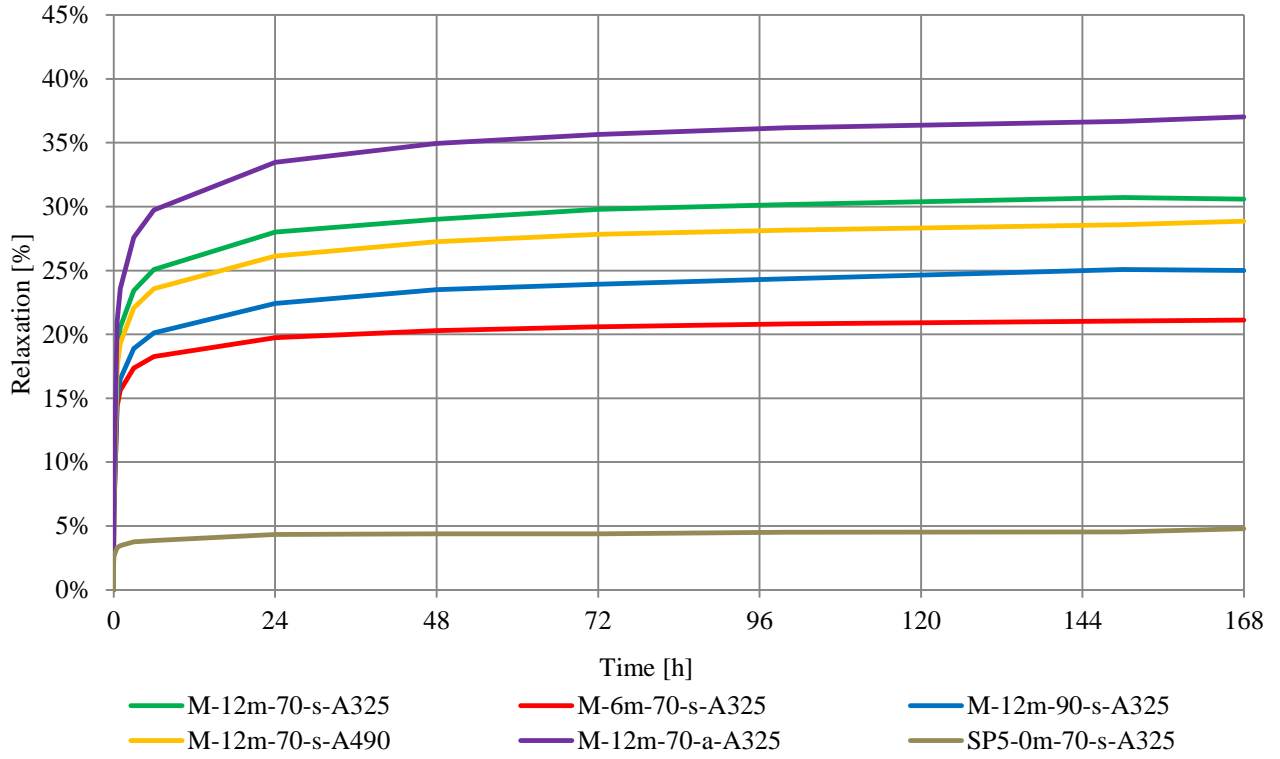


Figure 6: Average relaxation over time

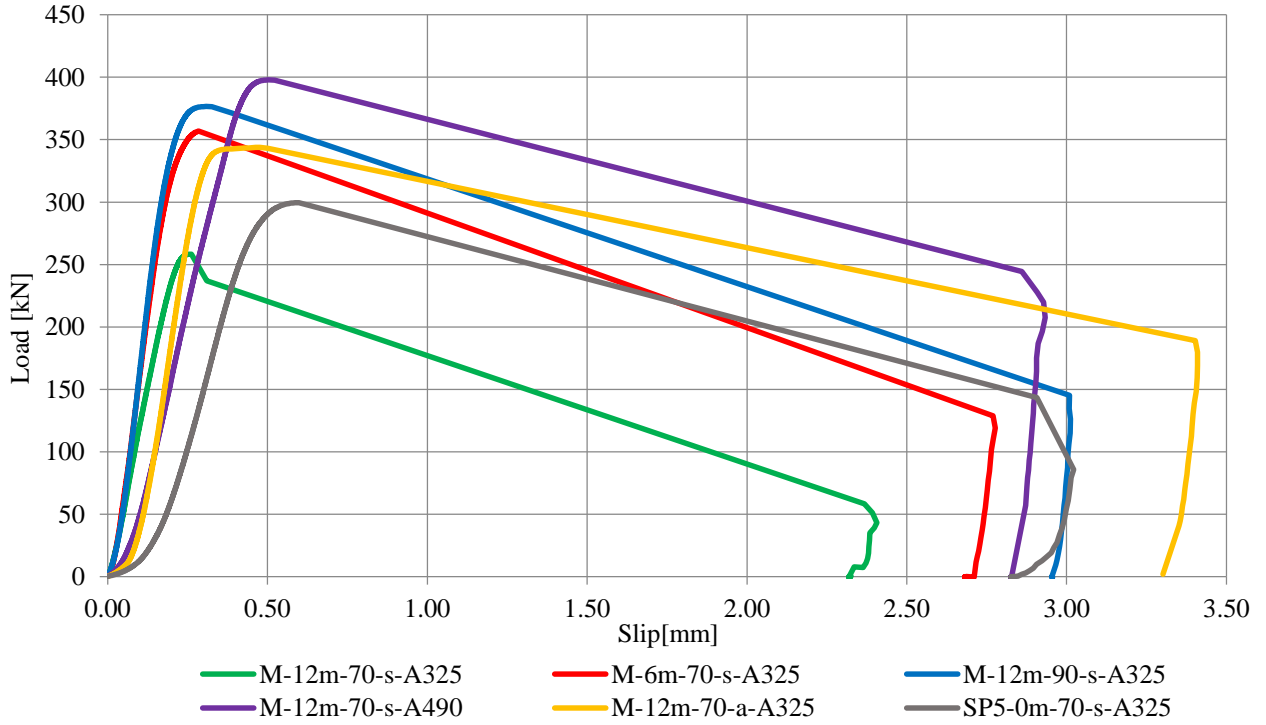


Figure 7: Typical slip-load curves

Table 3 contains a summary of results obtained for each set of parameters. The first column contains the specimen identification. The second column presents the design slip coefficient targeted for the metallized faying surfaces (that is a Class B). Note that for specimen SP5-0m-70-s-A325, a Class B slip coefficient of 0.52 is prescribed by the Canadian bridge design code. This combination of parameters serves as a reference value. The third column contains the average loss in clamping force that occurred during the 1-week relaxation time. Columns 4, 5 and 6 present respectively the theoretical slip load, the design slip load and the mean slip load after 1-week relaxation. Theoretical slip load value is calculated based on the theoretical slip coefficient presented in Table 2 with the average of the real maximum-initial clamping load induced in specimens subjected to the relaxation test. So, it represents the real slip resistance that that we should obtain right after the clamping of the connection. The design slip load is calculated based on the same clamping load, but with the design slip coefficient as reference, which is presented in the second column of Table 3. Thus, it would be the unfactored design slip resistance calculated by an engineer. Finally, the mean slip load obtained after relaxation is the real average slip load obtained in this present study. In practice, it represents the slip resistance of the metallized joint during its service life. Comparison of theoretical slip load and mean slip load after relaxation is presented in Figure 7, while comparison of design slip load and mean slip load after relaxation is presented in Figure 8.

Table 3: Relaxation results

Specimen	Design slip coefficient targeted	Mean loss in clamping force (%)	Slip load		
			Theoretical (kN)	Design (kN)	Mean after relaxation (kN)
SP5-0m-70-s-A325	0.52	4.8	203.8	199.9	266.9
M-6m-70-s-A325	0.52	21.1	314.4	199.4	329.4
M-12m-70-s-A325	0.52	30.6	330.1	202.0	269.5
M-12m-90-s-A325	0.52	25.0	430.6	246.1	383.6
M-12m-70-s-A490	0.52	28.9	434.8	266.0	403.6
M-12m-70-a-A325	0.52	37.0	326.3	197.3	357.0

The average slip load after relaxation for uncoated blast-cleaned faying surfaces was obtained as 266.9 kN. This value is superior to the design slip load of 199.9 kN, which confirms that even after relaxation, the Class B slip coefficient requirement in the Canadian standard CAN/CSA S6-14 is satisfied.

According to Figure 8, the effect of relaxation on the slip resistance of metallized faying surfaces appears not to be significant. In fact, even with a loss of clamping force between 21 and 37%, the slip load obtained after relaxation were either greater or smaller than theoretical slip load. For example, the 6 mils thick metallized specimens, with burrs removed and with a clamping force equal to 70% of the tension capacity of the A325 bolt used, yielded a mean slip load after relaxation of 329.4 kN while the theoretical slip load was 314.4 kN. However, the 12 mils thick metallized specimens, with burrs removed and with a clamping force equal to 70% of the tension capacity of the A325 bolt used, presented a mean slip load after relaxation of 269.5 kN while the theoretical value was 330.1 kN. Thus, according to the results obtained, it is not possible to say that relaxation of bolt preload has a detrimental effect on the slip resistance of metallized connections.

On the other hand, metallized faying surfaces yielded a much higher slip loads than Class B-design slip loads for each set of parameters after relaxation (Figure 9). The least difference was a slip load after relaxation 33.4% superior to the design slip load, representing the 12 mils thick metallized coating with burrs removed under a clamping force equals to 70% of the A325 bolt tension capacity. Every other set of parameters presented a slip load after relaxation greater than 33.4% superior to the design slip load.

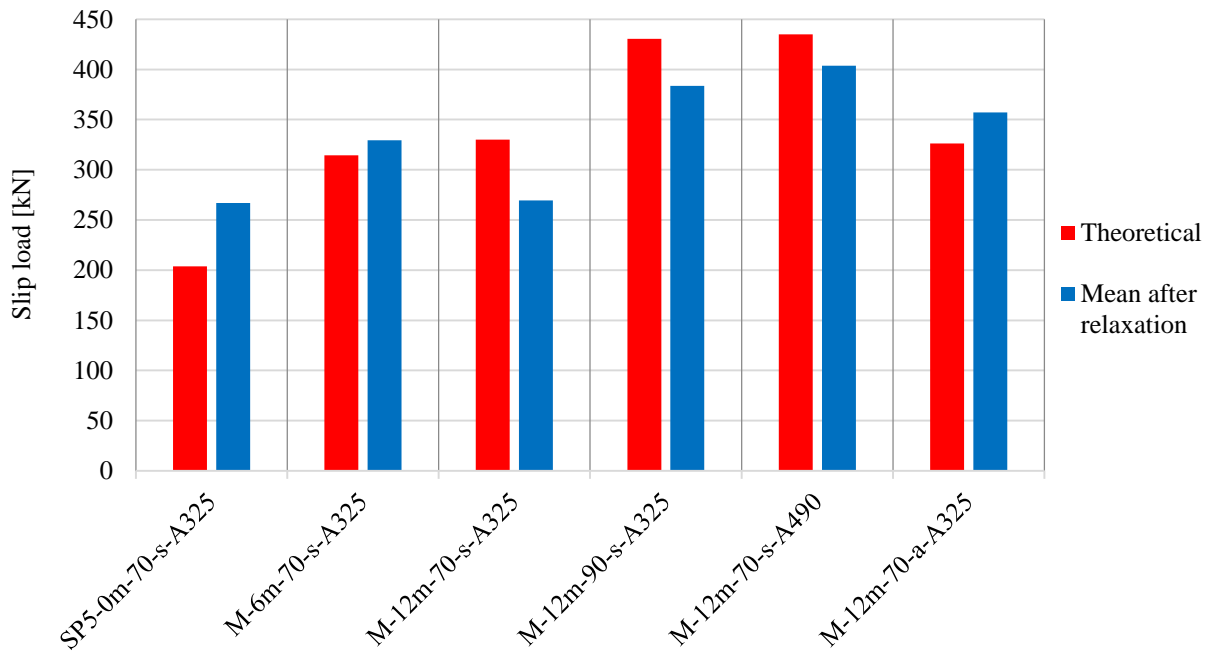


Figure 8: Theoretical slip load vs mean slip load after relaxation

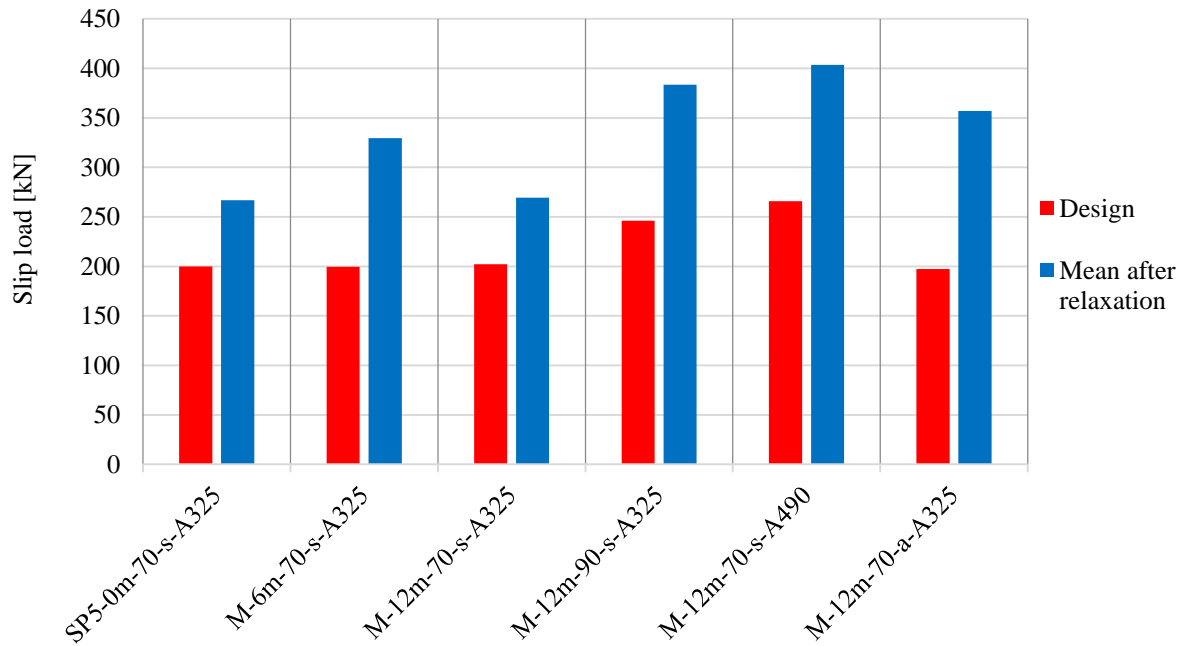


Figure 9: Design slip load vs mean slip load after relaxation

4. CONCLUSIONS

Metallizing has emerged as an effective protective coating for steel bridge. Studies revealed that metallized faying surfaces can achieve a Class B slip performance in light of the North American design standards. Relaxation of the clamping force is, however, observed to be significant in slip-critical connections with metallized faying surfaces. The present research work investigated the effect of relaxation on the performance of metallized slip-critical connections. Overall, test results showed a better slip performance after relaxation of clamping force than uncoated blast-cleaned Class B faying surfaces. More specific conclusions are summarised as follows:

1. Metallized faying surfaces exhibited very good slip performance after one week of relaxation of the clamping force. Class B slip performance requirements can easily be achieved after relaxation.
2. The loss of clamping force in metallized assemblies does not have a direct correlation with the slip load.
3. Relaxation of the bolt clamping force increases with increasing coating thickness.
4. Relaxation of the bolt clamping force occurred mainly in the first 48 hours. After that, the clamping force is nearly stable.

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