Experimental tests on slip factor in friction joints: comparison between European and American Standards

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ABSTRACT. Friction joints are used in steel structures submitted to cyclic loading such as, for example, in steel and composite bridges, in overhead cranes, and in equipment subjected to fatigue.
Slip-critical steel joints with preloaded bolts are characterized by high rigidity and good performance against fatigue and vibrational phenomena. The most important parameter for the calculation of the bolt number in a friction connection is the slip factor, depending on the treatment of the plane surfaces inside the joint package. The paper focuses on the slip factor values reported in European and North American Specifications, and in literature references. The differences in experimental methods of slip test and evaluation of them for the mentioned standards are discussed. The results from laboratory tests regarding the assessment of the slip factor related to only sandblasted and sandblasted and coated surfaces are reported. Experimental data are compared with other results from the literature review to find the most influent parameters that control the slip factor in friction joint and differences between the slip tests procedures.

KEYWORDS. Bolted joints; Slip resistance; *k*-factor; Slip factor; Surface treatment.

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INTRODUCTION

Eurocode EN 1993-1-8 [1] provides the main recommendations of methods for the effective design of joints using steel grades S235, S275, S355 and S460 and prescribes that only bolt assemblies of classes 8.8 and 10.9, conforming to the requirements of high strength structural bolting for preloading with controlled tightening torque, may be used as preloaded bolts in friction joints. In EN 1090-2 [2] requirements for execution of steel structures (included structural bolting assemblies for preloading), are specified in order to ensure adequate levels of mechanical resistance and stability, serviceability and durability. In particular, it summarizes the steel structures that are designed according to all parts of European standards.

North American RCSC "Specification for structural joints using high-strength bolts" [3] deals principally with the strength grades of HS bolts, ASTM A 325 e ASTM A490 providing guidance for their design, installation and inspection in structural steel joints. ASTM F3125 [4], which replaces the six previous standards, simplifying bolt specification, covers chemical, physical and mechanical requirements for quenched and tempered bolts manufactured from steel and alloy steel, in inch and metric dimensions, in two strength grades. Tab. 1 shows in a benchmarking nominal values of the yield strength f_y and of the ultimate tensile strength f_u for European and American equivalent grades: i.e., respectively, 8.8 and 10.9, A325 and A490.

	EN 1993-1-8		ASTM F3125	
Bolt grade	8.8	10.9	A325	A490
f_{ub} (MPa)	800	1000	830	1040
f_{yb} (MPa)	640	900	660	940

Table 1: Minimum values for yield and ultimate tensile strength of HS bolt material according to European and North American Standards

In a slip-critical joint, the resistance is due to friction forces developed between the faying surfaces depending on the preloaded force of the tightened bolts as well as on surface treatment.

Both American and European Standards require, prior to bolt preloading, the snug-tightening procedure to bring the plies into firm contact and provide four pretensioning methods, without preference:

- Turn-of-Nut Pretensioning;
- Calibrated Wrench Pretensioning;
- Twist-Off-Type Tension-Control Bolt Pretensioning;
- Direct-Tension-Indicator Pretensioning.

According to RCSC [3] the minimum Bolt Pretension for Slip-Critical Joints is equal to 70 percent of the specified minimum tensile strength of bolts multiplied by bolt stress area as prescribed in ASTM Specifications [4].

Similarly, under the provisions of EN 1993-1-8 [1] and EN 1090-2 [2], the nominal minimum preloading force $F_{p,C}$ shall be taken as:

$$F_{p,C} = 0.7 f_{ub} A_{res} \tag{1}$$

where f_{ub} is the nominal ultimate strength of the bolt material and Ares is the stress area of the bolt.

The slip resistant force, governed by preload force $F_{p,C}$, the surfaces-in-contact slip factor μ, the number of plane surfaces in contact n, the safety coefficient γ_{M3}, the hole shape factor k_s, is given by Eqn.(2) in accordance with EN 1993-1-8 [1]:

$$F_{s,Rd} = \frac{k_s n \mu}{\gamma_{M3}} F_{p,C} \tag{2}$$

where $F_{p,C}$ is the preloading force in the elastic field, $k_s = 1$ for normal holes, and γ_{M3} is equal to 1.25 at ultimate limit state and 1.1 at serviceability limit state. For RCSC [3] the values are 1.5 and 1.0, respectively.

The first step in bolted joints is to obtain the snug tightened condition bringing the connected plies into firm contact. To reach the design preload force it is necessary to apply a correct tightening torque M_r; if tightening torque is lower than that necessary to reach the design preload force, the friction joint is not guaranteed and the mechanism is the same as that of shear bolts; on the other hand, overtightening could exceed the yielding point and increase the plasticization of the screw or nut threads and arrive at rupture. The correlation between $F_{P,C}$ and M_r is given by the bolt diameter d and the k-factor k_m.

In terms of preloading force, for the European code EN 14399-2 [5] the tightening torque depends on the surface treatment of bolt that is parameterized by factor k_m.

The equation that gives the relationship between tightening torque and preload force is

$$M_r = (1 + 1.65v_k)k_m F_{p,C} d \tag{3}$$

Approximated with:

$$M_r = 1.10 k_m F_{p,C} d \tag{4}$$

SLIP FACTOR

The decisive parameter for the operation of the friction mechanism in the bolted joint is the slip factor μ which depends on the roughness of the plate, which is associated with the surface treatment of plates impacted by the bolted joints.

However, the surfaces of the steel components should be protected, as all the other surfaces, to avoid the development of corrosion phenomena between the manufacturing and the erection phase, but also to guarantee the greatest possible friction. In general, the surfaces are cleaned, blasted, followed by the application of inorganic zinc. The grade of sandblasting is usually Sa2½ as described in international standard ISO 8501-1 [6].

In practical applications, the slip factor for short-time loads may be necessary to sustain dynamic loads. For example, Fig. 1 shows a steel bridge girder where the bolted joints surfaces are specifically prepared for friction connections.

Figure 1: Painted beam with inorganic zinc coated surfaces for friction joints.

The slip factor tends to decrease with time due to the creep phenomena in coated surfaces. Several studies have been developed to establish adequate slip factors for different conditions; these studies are in general very time consuming due to the wide range of parameters involved. In this context, reference should be made, for example, to the studies reported in the publication n.37 of ECCS [7]. Also, the results of an extensive research work are collected in Kulak *et al.* [8]. Tab. 2 shows the slip factor value assumed with different surface treatment as in EN 1090-2 [2] while, for an useful comparison, Tab. 3 shows the prescription in prEN 1090-2 (*draft European Standard new version of EN 1090-2*). In practical applications, the slip factor for short-time loads may be necessary to sustain dynamic loads. For example, Fig. 1 shows a steel bridge girder where the bolted joints surfaces are specifically prepared for friction connections.

In other international standards, different systems of friction classes are specified; for instance, in "Specification for structural joints using high-strength bolts" RCSC [3] used in North America, three surface classes are established (Tab. 4).

A comparison among European, American, Australian, Japanese, Italian and British Standards for design of bolted joints in steel bridges is reported in Maiorana and Pellegrino [9].

Surface treatment	Class	Slip factor μ
Surfaces blasted with shot or grit with loose rust removed, not pitted.	A	0.50
Surfaces blasted with shot or grit; a) spray-metallized with aluminum or zinc based product b) with alkali-zinc silicate paint with a thickness of 50 μm to 80 μm	B	0.40
Surfaces cleaned by wire brush or flame cleaning, with loose rust removed	C	0.30
Surfaces as rolled	D	0.20

Table 2: Classifications that may be assumed for friction surfaces according to EN 1090-2 [2].

Surface treatment	Class	Slip factor μ
Surfaces blasted with shot or grit with loose rust removed, not pitted.	A	0.50
Surfaces hot dip galvanized to EN ISO 1461 and flash (sweep) blasted and with alkali-zinc silicate paint with a nominal thickness of 40 μm to 80 μm	B	0.40
Surfaces blasted with shot or grit: a) coated with alkali-zinc silicate paint with a nominal thickness of 40 μm to 80 μm; b) thermally sprayed with aluminium or zinc or a combination of both to a nominal thickness not exceeding 80 μm	B	0.40
Surfaces hot dip galvanized to EN ISO 1461 and flash (sweep) blasted (or equivalent abrasion method)	C	0.35
Surfaces cleaned by wire-brushing or flame cleaning, with loose rust removed	C	0.30

Table 3: Classifications that may be assumed for friction surfaces according to prEN 1090-2.

Surface treatment	Class	Slip factor μ
Uncoated clean mill scale steel surfaces or surfaces with class A coatings on blast-cleaned steel	A	0.30
Uncoated blasted and cleaned steel surfaces or surfaces with class B coatings on blasted and cleaned steel	B	0.50
Roughened hot-dip galvanized surfaces	C	0.30

Table 4: Classifications that may be assumed for friction surfaces (RCSC [3]).

Cruz *et al.* [10] obtained slip factors with values of 0.50 only with blasted surfaces, without any additional surface treatment. In blasted surfaces, spray metalized with zinc or hot-dip galvanized ones, the slip factor easily reaches values above 0.40. For blasted surfaces, with a painted coating of zinc ethyl-silicate, in Cruz *et al.* [10] a characteristic value of 0.40 was obtained with a small margin. For blasted surfaces, with a painted coating of zinc epoxy, the lowest slip factor values, no higher than 0.30, were obtained. Concerning the specimens in S355 weathering steel, it was verified that the value of the slip factor increased with the duration of environmental exposure, from 0.502 to 0.560. Cruz *et al.* [10] conclude that the slip factor is strongly influenced by the surface treatment and weakly by the steel grade. In fact, in specimens of S275 steel and S690 high strength steel, with equivalent surface treatment, similar values for the slip factor were obtained. Therefore, it seems that the classification system predicted in EN 1090-2 [2] remains valid for use in slip resistant joints with high strength steel.

Heistermann *et al.* [11] studied the slip resistance in lap joints with long open slotted holes while Annan and Chiza [12] presented a work about the characterization of slip resistance of high strength bolted connections with zinc-based metallized faying surfaces and Annan and Chiza [13] the slip resistance of metalized-galvanized faying surfaces in steel bridge construction.

Latour *et al.* [14] made an experimental analysis on friction materials for supplemental damping devices while Pavlović *et al.* [15] presented friction connection vs. ring flange connection in steel towers for wind converters. Ferrante Cavallaro *et al.* [16] presented the experimental behavior of innovative thermal spray coating materials for FREEDAM joints while Li *et al.* [17] the slipping coefficient study of frictional high strength bolt joint.

Through Finite Element Analysis and experimental study, in Huang *et al.* [18] the mechanical behavior including slip vs. load ratio, load transfer factors, stress state, and friction stress distribution of this type of joints was studied in detail. Both FEA results and experimental ones show that the loads resisted by bolts in the edge rows are, as expected, larger than the ones by bolts in the middle rows.

A report of the Federal Highway Administration [19] has shown that ambiguities within the test method might increase the variability of reported friction coefficients. The report outlines that:

- variability of slip coefficients attained for the same coatings were noted by coating manufacturers despite no change in formulation. The most common approach is to use a multilayer paint system with a zinc-rich primer;
- labs following the same RCSC [3] procedure were sometimes reporting very different slip coefficients for identical coatings;
- the major finding was the manner in which each lab measured slip displacement which contributed to the greatest variability in frictional coefficient results.

So, the aim and the main contribution of this work is not only to collect and evaluate the slip factor for different surfaces treatments, through an extensive product comparison and testing but also compare the European and American method for the friction coefficient determination.

EXPERIMENTAL TEST METHODS FOR THE DETERMINATION OF THE SLIP FACTOR

For the European Code, the procedure for the determination of the characteristic value μ_k of the slip factor was found testing a series of five specimens as descripted in Annex G of the EN 1090- 2 [2] "Slip test".

For each series, firstly four models are tested applying an incremental tensile load with a velocity of about 0.4 kN/s, to obtain a test duration between 10 and 15 min; in a second stage, the 5th test was performed to evaluate long-term effects.

In the first four tests (short-time tests), the slip loads F_{Si} are recorded when a slip of 0.15 mm occurs. The 5th model (long-term test) is loaded with 90% of the mean slip loads reached in the previous four tests, during 3 h to assess the behavior under sustained loads. If the difference between the slip measured at the end of 5 min and 3 h after the load application does not exceed 2 μm, the test is valid and the slip load shall be determined as for the previous four tests. If this condition is not verified, a minimum of three extended creep tests should be performed. The validity of the 5th test still depends on an additional condition: the standard deviation S_{Fs} of the slip loads obtained in the five tests, i.e. ten values, cannot exceed 8%.

The slip factor is calculated with Eq. (5):

$$\mu_k = \mu_m - 2.05 s_\mu \tag{5}$$

For the American Standard, the procedure for the determination of the mean value μ_m of the slip factor derives directly from a series of results found testing five specimens as described in Appendix A of the RCSC [3].

It is important to note that for RCSC [3], testing setup to determine the slip factor is different respect European standard and the single value μ_i per specimen is

$$\mu_i = \frac{F_{si}}{2F_{p,C}} \tag{6}$$

where the slip load is the load corresponding to a deformation of 0.02 in., that is 0.5 mm.

Tab. 5 shows the list of specimen series, surface treatment and the reference standard.

As many products report results for the slip coefficient found following the procedure of the Italian former standard CNR UNI 10011 [20], for a comparation also these results are reported.
According to CNR UNI 10011 [20], the preload was found by $F_{C,P} = 0.8\ f_{k,N}\ Ares$ where $f_{k,N} = min\{0.7\ f_{u,b};\ f_{y,b}\}$; for example, for bolts M20 class 10.9 $f_{k,N} = 700\ N/mm^2$ and $A_{res} = 245\ mm^2$ so $F_{P,C} = 137\ kN$ (25% less European code) and the corresponding tightening torque $M_r = k\ F_{P,C}\ d$ that is 550 Nm. Note that CNR UNI 10011 [20] gave a fixed value $k = 0.2$ and the partial safety factor γ_M in formula of resistance force was the same as in EN 1993-1-8 [1] at ultimate state limit.

Series	Product n. Coating	Bolts (diam. and grade)	Standard	Slip force F_{Si} [kN]	Slip coeff. μ_m	Slip coeff. μ_k
1	-	M20 10.9	EN 1090-2	353	0.52	**0.45**
2	-	M20 10.9	EN 1090-2	340	0.50	**0.45**
3	1 [1]	M20 10.9	CNR UNI 10011	227	**0.42**	0.38
4	2 [2]	Ø20 ASTM A490	RCSC	278	**0.64**	0.47
5	3 [2]	Ø20 ASTM A490	RCSC	223	**0.51**	0.28
6	4 [3]	M20 10.9	EN 1090-2	263	0.39	**0.34**
7	5 [3]	M16 10.9	CNR UNI 10011	220	**0.62**	0.58
8	5 [3]	M16 10.9	EN 1090-2	311	0.45	**0.41**
9	6 [4]	Ø20 ASTM A490	RCSC	152	**0.34**	0.29
10	7 [1]	Ø20 ASTM A490	RCSC	243	**0.56**	0.45
11	7 [1]	M20 10.9	EN 1090-2	354	0.51	**0.43**
12	8 [3]	M20 10.9	EN 1090-2	230	0.34	**0.29**

Chemical composition: [1] inorganic zinc ethyl silicate bicomponent; [2] inorganic zinc-rich bicomponent; [3] inorganic zinc polyethylene silicate bicomponent; [4] inorganic zinc silicate bicomponent

Table 5: Series of tests with different coating products (final value of μ in bold font)

Series n.1. Slip test on only blasted surfaces

The material of the specimens was weathering steel with characteristics as in EN 10025-5 [21] S355J0W. Fig. 2 shows the geometry of the samples.

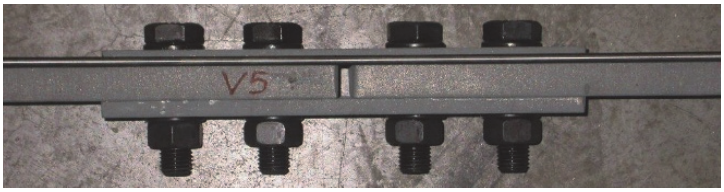

Figure 2: Geometry of the specimen

Surfaces were cleaned at grade Sa2½, i.e. surfaces sandblasted as white metal surface; mean profile roughness was about 100 μm. The bolts used to assembly the specimens were HV M20 grade 10.9.
To reach the preload force the bolts, as in the Combined method, were subjected to a tightening torque of 334 Nm, that is 75%M_r, plus a rotation angle A = 90°, corresponding to a final tightening torque of about 520 Nm.
The instrument utilized for measuring the relative displacements of the plates in the connection is formed by four transducers of inductive displacement (LVDT) useful to find displacements δ in the order of 10^{-3} mm.
The tensile force applied was measured with a load cell installed in a universal test machine MetroCom of 500 kN as in Fig. 3.
The specimen number five (S5), as reported in Annex G of EN 1090-2 [2], was loaded with a force equal to 90% of the mean value of the sliding forces F_{Si} found for the other previous four specimens, for a period of three hours. Over this time the displacement recorded was under the limit of the standard, 0.002 mm, so five tests were sufficient for the statistic evaluation of the slip factor (Fig. 4) and from each specimen, two values S_i were found.

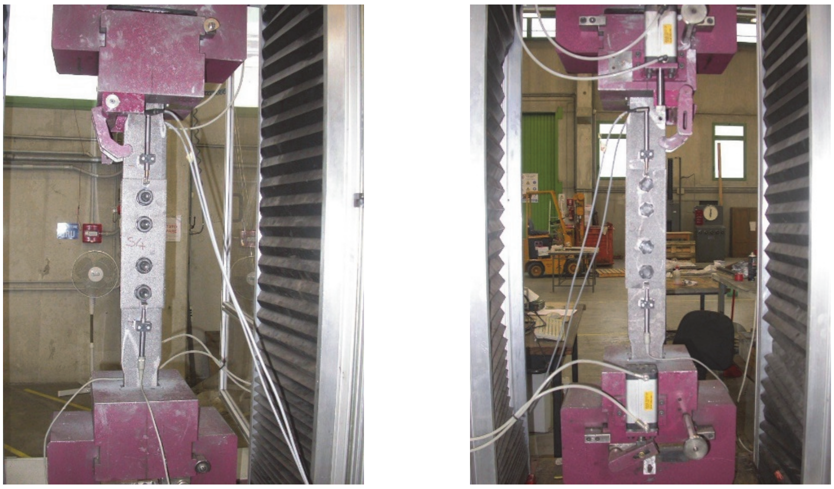

Figure 3: Test of the blasted specimen.

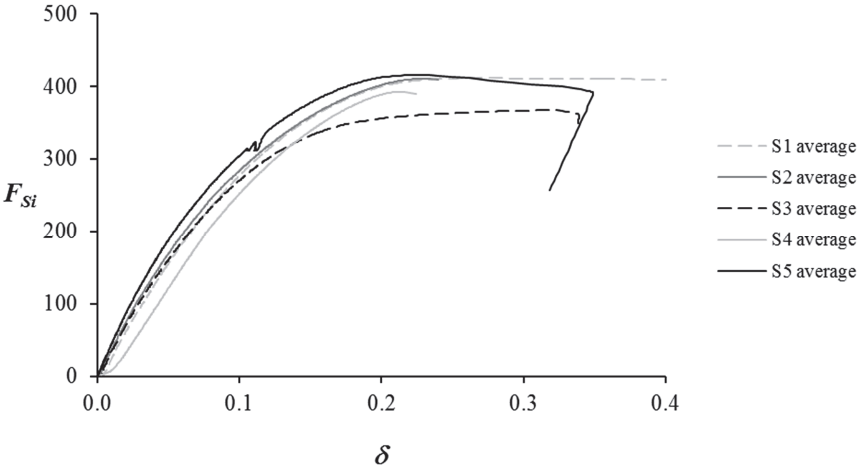

Figure 4: F_{Si} [kN] vs. δ [mm] relationship.

From the ten values obtained by the tests, the mean value of the slip factor was calculated $\mu_m = 0.519$ with the standard deviation $s_\mu = 0.030$, finally a characteristic value $\mu_k = 0.454$ was achieved. Fig. 5 shows the test results.

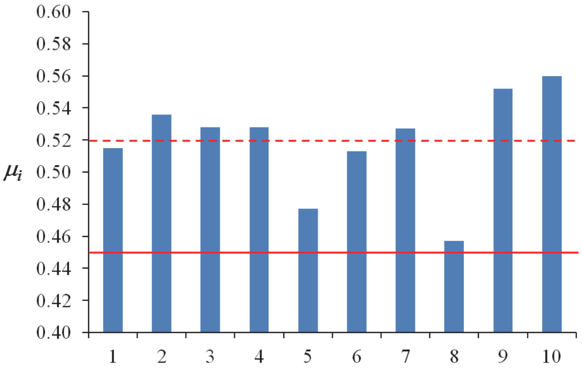

Figure 5: Blasted and close specimens. Dashed line: mean value of μ_m; continuous line : μ_k.

Series n.2. Slip tests on specimens blasted and rusted in a saline atmosphere

A set of blasted specimens, material EN 10025-2 [21] S355J2+N, was exposed for one week above a box with saline water (H2O con 3% of NaCl). Fig. 6 shows the final surface aspect of the specimens. The surfaces in contact were brushed and the connection was closed. The tightening torque applied was 545 Nm.

Figure 6: Blasted and rusted specimens.

The specimen number five (S5), as reported in the code, was loaded with a force equal to 90% of the mean value of the sliding forces found for the other four specimens, for a period of three hours. Over this time the displacement recorded was under the limit of the norm, 0.002 mm, therefore five tests are sufficient for the statistic evaluation of the slip factor.

The values obtained by the tests were reworked, obtaining the mean value of the slip factor μ_m = 0.500, a standard deviation s_μ = 0.023, thus a characteristic value μ_k = 0.453 is achieved. Fig. 7 shows the test results.

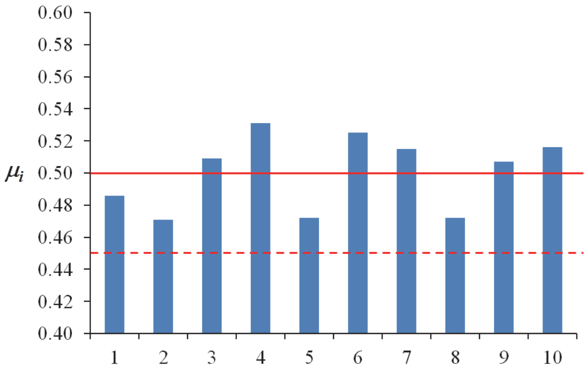

Figure 7: Blasted and rusted specimens. Dashed line: mean value μ_m; continuous line: μ_k.

Slip tests on blasted and coated surfaces

Fig. 8 shows the specimens of series n.6 under test.

For specimen number five (V5), the displacement recorded was 0.0280 mm for the upper limit and 0.0335 mm for the lower limit, thus above the limit of the standard, so five tests are not sufficient for the statistical evaluation of the slip factor and an extended creep test procedure should be necessary.

Otherwise, apart from the delayed slip of the fifth test, the values obtained by the tests were processed obtaining the mean value of the slip factor μ_m = 0.387, a standard deviation s_μ = 0.022, thus a characteristic value μ_k = 0.343 is achieved. Fig. 9 shows the test results.

Since the characteristic value for the slip factor using specimens painted with product n.4 was very low compared to the previous results, the authors thought that the problem was both the thickness of the paint (for thicknesses greater than 100 μm the cracking of the film may occur), and the product itself, therefore inorganic zinc-rich primer with a 5% higher weight was used, i.e. product n.5.

Fig. 10 shows the specimens of series n.8 under test. It is product n.5 tested following EN 1090-2 [2].

Using the data of the first four slip test specimens, the mean value μ_m = 0.45 and a characteristic value μ_k = 0.41 were achieved, but the creep test, on the fifth specimen, failed with relative displacements of 0.0245 mm and 0.012 mm that were observed after half an hour, instead of the maximum 0.002 mm over three hours.

Figure 8: Test of the blasted and coated specimen.

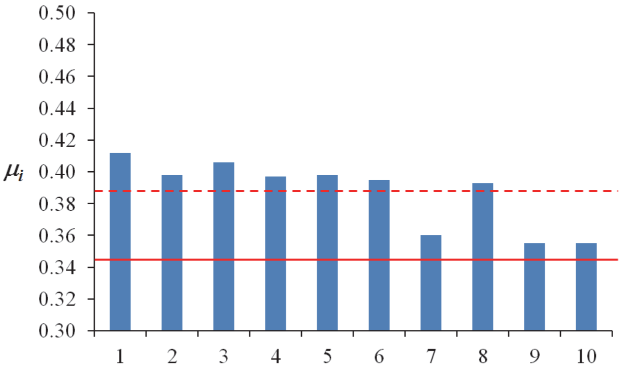

Figure 9: Blasted, painted with product n.4. Dashed line: mean value of μ_m; continuous line: μ_k

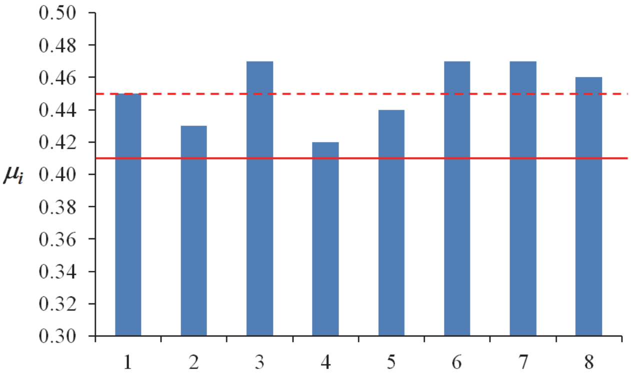

Figure 10: Blasted, painted with product n.5. Dashed line: mean value μ_m; continuous line: μ_k

To increase the slip factor as much as possible, an applicative relationship was found in order created to check the effective correlation between the preload and the tightening torque because of the potentially great variability of the friction coefficient k.

Since $F_{p,C}$ = 172 kN, the tightening torque to be applied is found by reading the Voltage, V = 172.000 / 92162 = 1.8663 V; 10 kN correspond to 0.108 V.

Three tests were performed, and it was found that although the box of the bolts was closed and correctly stocked, in respect of the data reported in the box regarding the k_{max}, an increase of k_i was observed.

So for the following slip tests on blasted and painted specimens the tightening torque was 545 Nm, assuming k_i = 0.16, maximum value of k_i according to the code. An increase in the case of the normal speed tests was observed but in two cases the creep test failed again since relative displacements of 0.02 mm and 0.015 mm were observed after half an hour instead a maximum of 0.002 mm over three hours. The results of the third specimen in the static force test show a slight increase in the slip factor values to 0.47.

A last set of specimens, series n.12, material EN 10025-2 [21] S355J2+N, was prepared connecting a central blasted and coated plate, using product n.8, with two cover only blasted plates. Fig. 11 shows an image of the set of specimens.

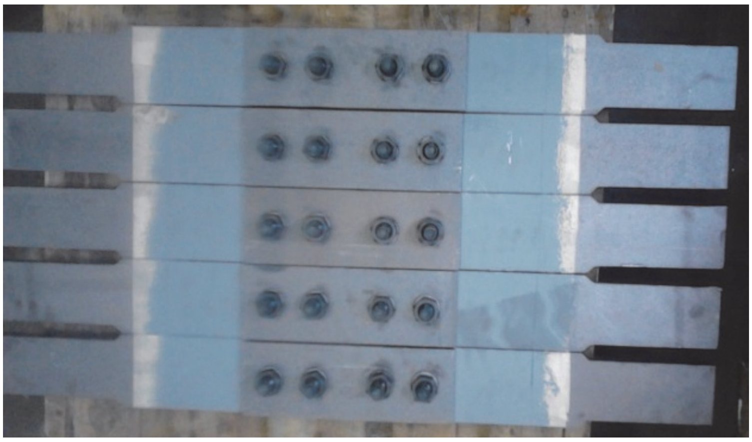

Figure 11: Blasted and half-coated specimens.

For this set, bolts M20 class 10.8 with k_m = 0.13 and v_k = 0.06 were used. The grease was applied between the screw and the nut. Since the manufacturer declares that the standard production guarantees $f_{tb,min}$ = 1040 N/mm^2, and EN 1090-2 [2] suggests for the tightening torque method a final torque of $1.1M_s$, the final tightening torque was M_s = 545 Nm. This result is equal to the previous one using k_m = 0.16 but since the grease was applied, it was necessary to respect the manufacturer's indication. This last procedure to find the tightening torque was discussed with the manufacturer and approved.

For specimen number five (V5), the displacement recorded was 0.0400 mm for the upper and 0.0360 mm for the lower limit, thus above the limit of the standard, therefore five tests are not sufficient for the statistic evaluation of the slip factor and an extended creep test procedure should be necessary.

Otherwise, apart from the delayed slip of the fifth test, the values obtained by the tests were processed obtaining the mean value of the slip factor μ_m = 0.338, a standard deviation s_μ = 0.024, thus a characteristic value μ_k = 0.289 is achieved. Fig. 12 shows the test results.

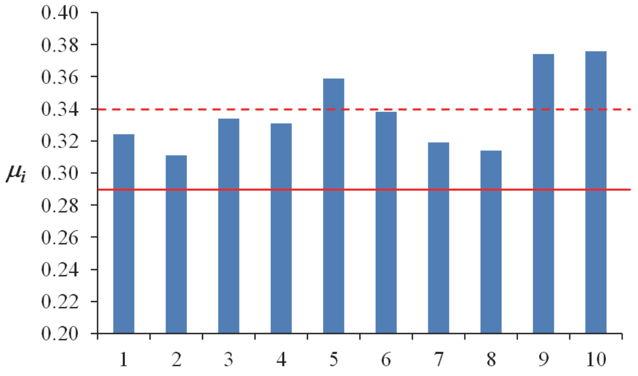

Figure 12: Blasted, half-coated with product n.8. Dashed line: mean value of μ_m; continuous line: μ_k.

DISCUSSION

In recent experiments of Cruz *et al.* [10] and in experiments conducted by the authors following the EN standard, the values of the coefficient of friction peaks have been obtained with samples blasted, with Sa2½, brushed, closed and tested.

In the case of the use of weathering steel where the sandblasted surface was left unprotected prior to closure, the friction coefficient increased. On the contrary, in the case of carbon steel, to ensure a high friction coefficient of the surface covered by the bolted joint package and simultaneously having a guaranteed corrosion protection before the tightening torque, the alternatives are two. The first is to blast the surfaces and protect them until the closure, possibly treating the surfaces themselves by brushing before applying tightening torque; the second is to use a paint with effective corrosion resistance and adequate roughness after coating.

Commercially, products for the protection of surfaces joined by bolted joint packets working with friction mechanism are available. Some products marketed in Italy were tested according to the directions of the previous legal framework, CNR UNI 10011 [20], which was based on earlier standards applicable to the manufacture of bolts and other products were classified according to other standards such as RCSC [3]. Given the current regulatory scenario of reference in Europe and in Italy, DM 14.01.08 [22], which includes the verification procedures according to EN 1993-1-8 [1] and other related European standards, it was necessary to carry out the experimental tests to obtain the friction coefficients in the manner described in EN 1090-2 [2]. Such redevelopment, that would take into account the congruence of the results for the friction conforms to the values that can actually be achieved by preloading and tightening torque bolts manufactured and supplied in accordance with applicable European standards.

An important observation should be made regarding the values of k_{min} and k_{max} given by the manufacturer that controlled the production by lot, while by [5], as already mentioned, for K_1, values of k should be inside the range $0.10 \leq k_i \leq 0.16$, thus the value for k_m has a relevant oscillation. In the tests performed on the specimens painted with product n.1, the tightening torque value was 520 Nm, that is $k_m = 0.1505$. In the tests performed on the specimens painted with product n.2, the tightening torque value was 520 Nm for the first three specimens and 545 Nm for the fourth, that is $k_m = 0.16$. An increase in the μ_i value was observed with the percent of zinc in the coating component. Alternatively, using grease between the screw and the nut, to consider a lower k_i, is suggested, in fact rather the kmax suggested by the manufacturer, and the application of a torque of $1.1M_s$.

Fig. 13 shows synthetically all the results found of μ in terms of comparison of: factor k_m, surface treatment, paints, standards applied (EN [2], RCSC [3] and CNR [20]). In terms of preload force, the European code permits raising by 25% CNR [20] and 10% RCSC [3]. On the other hand, considering the test for the determination of slip factor, contrary to CNR [20] and RCSC [3], which assumes a value μ_m from four tests, EN [2] adopts the characteristic value $\mu_k = \mu_m - 2.05 s_\mu$ taking into account the standard deviation within the tests, and in conclusion the mean value μ_m is reduced by about 10%.

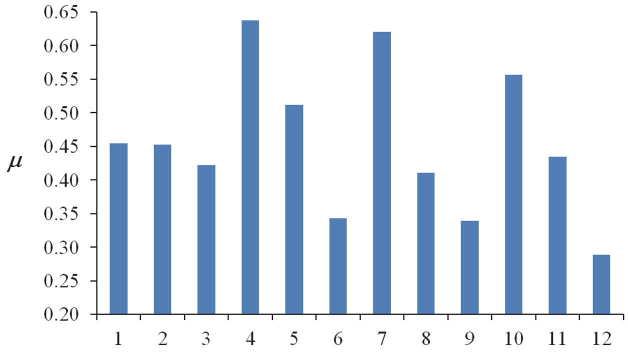

Figure 13: Comparison of all results μ. 1-blasted surfaces EN [2]; 2-Rusted EN [2]; 3-paint n.1 CNR [20]; 4-paint n.2 RCSC [3]; 5-paint n.3 RCSC [3]; 6-paint n.4 EN [2]; 7-paint n.5 CNR [3]; 8-paint n.6 EN [2]; 9-paint n.7 RCSC [3]; 10-paint n.8 RCSC [3]; 11-paint n.9 EN [2]; 12-Half coated EN [2]

Fig. 14 shows test results showing a comparison between RCSC [3] and EN [2] in terms of the ratio of F_{Si} vs. μ. For both American and European standards μ_k increases F_{Si}, but with RCSC [3] a greater value of μ than that of EN [2] is observed.

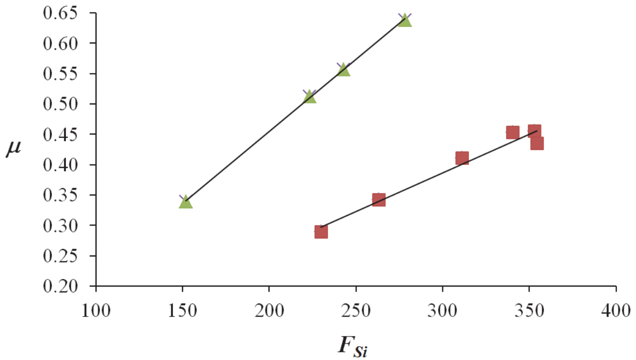

Figure 14: F_{Si} [kN] vs. μ Comparison between RCSC [3] (▲) and EN [2] (🟥).

Results of series from CNR [20] are not included in the diagram. The trend of the curve shows an increase of μ with F_{Si} and considering the slip coefficient from tests by EN [2], if the results of μ_m are multiplied by 1.5, the obtained valued are in line with the coefficient by RCSC [3]. Fig. 15 shows all the single results with the test method as in EN [2]. The higher values were found maximizing the roughness of the surfaces and the tightening torque.

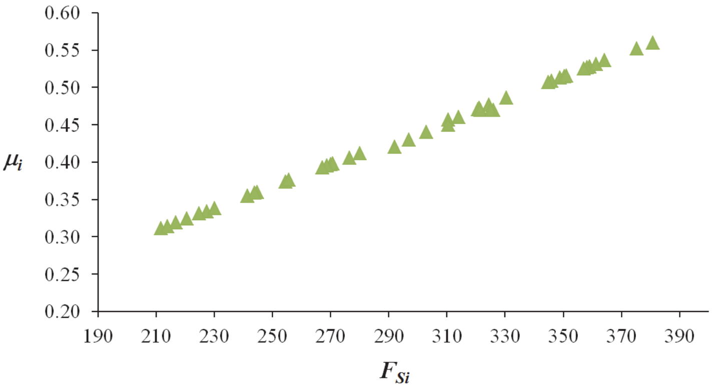

Figure 15: F_{Si} [kN] vs. μ_i for the EN [2] method.

CONCLUSION

The results of comparison and experimental tests on coating products regarding the evaluation of the slip factor for only sandblasted and sandblasted-coated surfaces are reported.

In terms of preload force, EN 1090-2 [2] permits an 10% increase on RCSC [3], with a lower tightening torque of k_m achieved by a bolt surface treatment.

Considering test for the determination of the slip factor, EN [2], contrary to RCSC [3] which assume a value $\mu = \mu_m$, adopts the characteristic value μ_k taking into account the standard deviation within the tests and in conclusion the mean value μ_m is reduced by about 10% also considering that the partial safety factor applied to the design slip resistance is 1.25; 1.5 for RCSC [3].

The improvement regards the following aspects:

- An increase in the μ_i value was observed with the percentage of zinc in the coating component, but an increase was obtained applying a greater tightening torque that is, on the other hand, considering in the calculation a greater k-factor. Alternatively, using grease between the screw and the nut, to consider a tightening force $1.1M_s$ is suggested.
- Making a comparison between RCSC [3] and EN [2] in terms of experimental applied force F_{Si} vs. μ, for both American and European standards, μ increases F_{Si}, but with RCSC [3] a greater value of μ is observed than that of EN, of about 10%, because test setup and the method to calculate μ are different. In term of μ the ratio is 1.5.
- The trend of F_{Si} respect μ_i shows an increase in the slip factor with the applied force, thus to obtain a greater slip factor it is necessary to increase the roughness of the surfaces and the tightening torque.

- As observed in the previous point, to evaluate exactly the ultimate strength of the bolt and to establish an admissible standard deviation on the same is suggested, reducing the admissible standard deviation of the *k*-factor and the safety coefficient on prealoading force.
- Finally, the discussion underlines the necessity to increase the applied force, to harmonize the safety coefficients and to review the design rules, justifying the adoption of a slip factor value in the calculation depending by the allowable displacement of the bolt inside the hole.

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