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Preliminary report

Practical issues in slip-resistant bolted connections for steel structures

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ABSTRACT

The application of slip-resistant bolted connections is necessary to prevent the contribution of slippage due to bolt-hole-diameter clearances in the lateral displacements of high-rise steel-braced frames or other high-rise structures. The safety and reliability of these connections rely on the reliable value of the slip factor in calculations. Despite the clear guidelines provided by European standards for connection design and execution, certain issues frequently arise in current construction practices. In this article, the author investigates two cases he found in his practice. For that reason, an experimental campaign with slip determining tests to annex G of EN 1090-2 is conducted at the University of Architecture, Civil Engineering and Geodesy (UACEG). The problems which are pointed out and investigated are: how a lack of knowledge about the k-class K_2 can impact the slip factor test results, and how various surface treatments, such as fabrication errors, impact the slip factor.

1 Introduction

The use of slip-resistant bolted connections is widespread in the design and construction of high-rise steel structures for the industry (Figure 1a, b). Steel or composite bridges also utilize these connections, with fatigue dictating the design (Figure 1c). Their advantages for structures subjected to cyclic loads are well known and reflected in fatigue calculation standards [1], and logically they are the preferred choice of the designers for dynamically or seismically loaded structures. Furthermore, even for relatively tall structures that are primarily subjected to wind (Figure 1a, b), the application of slip-resistant bolted connections is essential for controlling lateral displacement. Such structures, for example, are telecommunication towers, trestle structures for high industrial belt conveyors, towers for power transmission, or process towers (Figure 1a). If the non-preloaded bearing type bolted connections are used within the vertical bracing system (specifically between diagonals and the main frame) at a certain level of lateral load, below the serviceability limit state, slip will occur.

The total elongation of the connection without resistance can reach up to 2 mm, and in the worst case, up to 4 mm. This is due to the standard clearance between the bolt shank and plate hole, which is 2 mm for the most frequently used bolts, M16, M20, and M24 [2]. Experiments [3] reveal that, due to various factors, the theoretical slip of 4 mm never reaches its maximum. However, even if it reaches half or a third of its maximum, the actual horizontal displacements at each storey level significantly increase. This could potentially compromise the structure's serviceability, lead to irreversible horizontal storey drifts, or trigger second-order effects that were not considered in the structural analysis.

At present, slip-resistant bolted connections are well known and often used. They have their technological and market advantages over other alternatives such as injection bolts, fit bolts [2, 4], or field welds. Design guidelines are available in standards [2, 4, 6] or literature [3, 5, 7]. Eurocode 3 [4] classifies bolted connections that transmit shear forces through friction between contact surfaces as either category C or B, based on whether the ultimate or serviceability limit state determines their no-slip response. Eurocode 8 [8] mandates the use of these bolted connection categories in the joints connecting dissipative elements to non-dissipative ones, such as the diagonal connections of Concentrically Braced Frames (CBFs) to columns or beams. Furthermore, as mentioned in [2], the combination of slip-resistant bolted connections and long or short slotted holes provides an excellent combination of liberalized fabrication tolerances, ease of erection, and a clear and reliable force-transmitting path. All this, combined with the significant progress in the field of high-strength bolt fabrication and the development of building chemistry, implies the increasingly widespread use of slip-resistant bolted connections on the steel construction market even within typologies of steel structures outside their traditional fields of application.

Achieving the required bolt preloading and slip factor is crucial for the safety of slip-resistant bolted connections. During the inspection of bolt preloading, the engineer can use either direct or indirect site control methods, such as the torque method, the combined method, direct tension

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b) Belt conveyer with high-rise trestle

a) High-rise industrial steel structure with CBFs

c) Steel road bridge

Figure 1. Steel structures with application of slip-resistant bolted connections

indicators, the HRC method [2] or sensorized structural bolts [9]. When controlling the slip factor, the engineer primarily depends on the technical specifications provided by the vendor for surface preparation and coating application, as well as the alignment between the prescribed actions and their actual execution.

A brief review of the literature highlights the various aspects of research interest in the field of slip-resistant bolted connections. The Bulletin 37 of ECCS [10] is of particular interest to European steel construction. The main results of the study include the analysis of factors related to surface preparation and conservation, correlated to the achieved friction coefficient. The study concludes that blast-cleaning the steel surfaces to a minimum of Sa 2½ degree is necessary. The best slip factors are achieved when a 75- to 100-μm-thick coating is applied.

Since 1951, comprehensive studies that periodically reflect and update design recommendations, has been conducted in North America [5]. As different steel grades with increased strength or improved durability become more widely used, there is a growing interest in studying the methods of cleaning their surfaces, coating them, and exploring the results of their slip factor. The publication [11] addresses this issue by testing S275, S690, and S355 weather-resistant steel and determining their respective slip factors. Following the implementation of EN 1090-2 [12] and, more specifically, Annex G for slip factor determination, several research studies have examined various factors, including test loading speed, slip criteria, preload force determination method, and the location of displacement transducers within the test sample [13, 15]. Researchers draw comparisons between procedures in Europe and North America [14]. Consequently, recommendations were made for improving Annex G.

The presented brief literature review indicates that the primary focus of research is on the impact of factors such as surface preparation, steel grades, coating type, and testing procedures on the slip factor. Researchers focus on this classic set of topics to some extent. This article takes a different approach. The article identifies and discusses two common issues faced by practitioners. There is no table in EN 1090-2 [2, 12] with prescribed values for tightening moments in the torque method. Only k-class K_2 permits this tightening procedure in Europe. Therefore, the engineer must calculate the torque moment separately for each bolt batch. Nevertheless, engineers often encounter surprises within the execution phase due to the lack of information for the value of K_2. This could be attributed to the manufacturer's longer delivery terms for bolts with a k-class K_2 specification, or it could simply be the result of routine practices from earlier times (before EN 1090-2 [12]). In such a situation, under the pressure of deadlines and circumstances, designers and supervisors are forced to work only with the k-class K_1, where its range is from 0.10 to 0.16 wide [16]. This is the first problem that the author encountered in his practice, and which is discussed in this article.

The second practical problem addressed is the following. It is a matter of interest to explore how a possible error in the coating technology affects the coefficient of friction. Most often, this can happen when the surfaces with the already applied conservation primer (Figure 2) are painted by mistake with the anti-corrosion coating for the structure. This is not a rare thing to happen, according to the author's practice, because the corrosion protection is applied mostly manually. In addition, the worker's body is covered with a protective suit and face mask. Seeing is tough and high personal concentration is required in a dirty work environment. In such a case, after painting by mistake, the flying surfaces for the slip-resistant bolted connection must be cleaned locally and the conservation primer applied again.

The formulated practical problems necessitate further investigation through an experimental campaign. It is conducted by the Research Laboratory of the department of “Steel, timber and plastic structures” of UACEG. The main goals of this campaign are (a) to find out the real coefficients of friction that are achieved by using the same vendor product to preserve the surface and k-class K_1 as per [2, 12] for torque moment calibration; (b) to see how using different ways to prepare the surfaces of contact plates affects the real coefficients of friction; and (c) to obtain a force-displacement diagram for the pre-slip and post-slip connection response as a starting point for more research.

2 Experimental setup and experimental specimens

The experimental set-up used is entirely dictated by the recommendations and requirements of Annex G of [2]. The test is carried out using a universal testing machine type UMM-50 which has a force range of 500 kN. The components for the test specimens are fabricated and the surfaces coated in a professional workshop under strict quality control of the author and an independent specialized laboratory. They are assembled in the workshop, while the bolts are preloaded by the lab staff. About 15 days pass between the bolt preloading and the testing day, achieving the expected initial relaxation. Only short-time tests are conducted while a creep test was not planned. The specimens are being loaded in tension with a force that increases smoothly with a speed of 0,20 kN/sec for specimens with bolts M16 and 0,50-0,60 kN/sec for specimens with bolts M20. The value of the applied force is measured by a sensor connected to the measuring mechanism of the testing machine (force sensor #0). Four displacement transducers (DT) with a range of 0-10 mm are mounted on both sides of each of the cover plates of the test specimen, along the longitudinal axis. They measure the mutual slippage between the inner plate and fixed angle to the cover plates. In this way, four relative displacement values between the cover plates and the inner plates are measured from each specimen, two on the left and two on the right (Figure 3, indicated as 1, 2, 3 and 4). Figure 3 illustrates the geometry and type of test specimens, while Table 1 and Table 2 provide the dimensions for Groups 1 and 2, respectively. The lab staff measures only the dimension L_1 for the test specimens of Group 1 while the rest of the dimensions are assumed to be equal to the nominal. All dimensions for the test specimens of Group 2 are measured by the lab staff, Table 2.

a) Flying surface in hot-rolled profile b) Flying surface in gusset plate

Figure 2. Flying surface coated by conservation coat for slip-resistant bolted connections

Table 1. Geometric dimensions of the specimens, Group 1

Specimen (group-series-specimen #) / bolt diameter	L, mm	L_1, mm	a, mm	b_1, mm	c_1, mm	t_1, mm	t_2, mm
Specimen 01-01-01 / M16	700	250	80	35	50	16	8
Specimen 01-01-02 / M16	700	250	80	35	50	16	8
Specimen 01-01-03 / M16	700	248	80	35	50	16	8
Specimen 01-02-01 / M20	780	289	100	40	60	20	10
Specimen 01-02-02 / M20	780	288	100	40	60	20	10
Specimen 01-02-03 / M20	780	287	100	40	60	20	10
Specimen 01-03-01 / M20	780	288	100	40	60	20	10
Specimen 01-03-02 / M20	780	289	100	40	60	20	10
Specimen 01-03-03 / M20	780	287	100	40	60	20	10

Table 2. Geometric dimensions of the specimens, Group 2

Specimen (group-series-specimen #) / bolt diameter	L, mm	L_1, mm	a, mm	b_1, mm	c_1, mm	t_1, mm	t_2, mm
Specimen 02-01-01 / M16	792	293	100.8	39.6	61.5	20.2	10.5
Specimen 02-01-02 / M20	786	293	100.0	39.2	60.9	20.4	10.6
Specimen 02-01-03 / M20	788	290	100.8	37.8	60.8	20.1	10.4
Specimen 02-02-01 / M20	786	290	100.4	38.0	61.5	20.1	10.1
Specimen 02-02-02 / M20	786	290	100.8	37.4	62.0	20.0	10.4
Specimen 02-02-03 / M20	783	292	100.4	39.6	62.1	20.1	10.3
Specimen 02-03-01 / M20	788	292	100.0	38.2	61.5	20.1	10.3
Specimen 02-03-02 / M20	789	293	100.6	38.5	60.9	20.4	10.3
Specimen 02-03-03 / M20	788	290	99.7	37.9	61.3	20.2	10.3

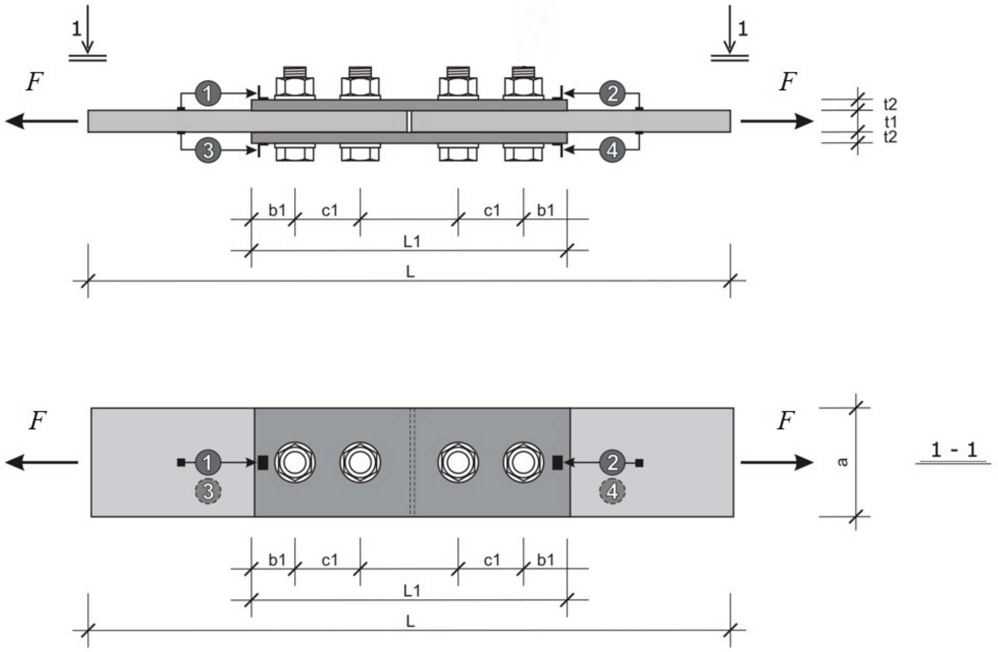


Figure 3. Test specimens' geometrical parameters and DTs location and numbering

The time for testing one specimen with bolts M16 is about 20 minutes, while for specimens with bolts M20, it is about 10 minutes. A computer-aided system records data readings every second (Figure 4).

The specimens are made of steel grade S235JR in accordance with the EN 10025-2 [17]. All bolts are HV type grade 10.9, according to EN 14399-4 [18] having an oxidized surface (no hot deep galvanizing). All bolts and nuts are supplied in the lab with an applied lubricant.

Figure 4. Experimental set-up and data recording system

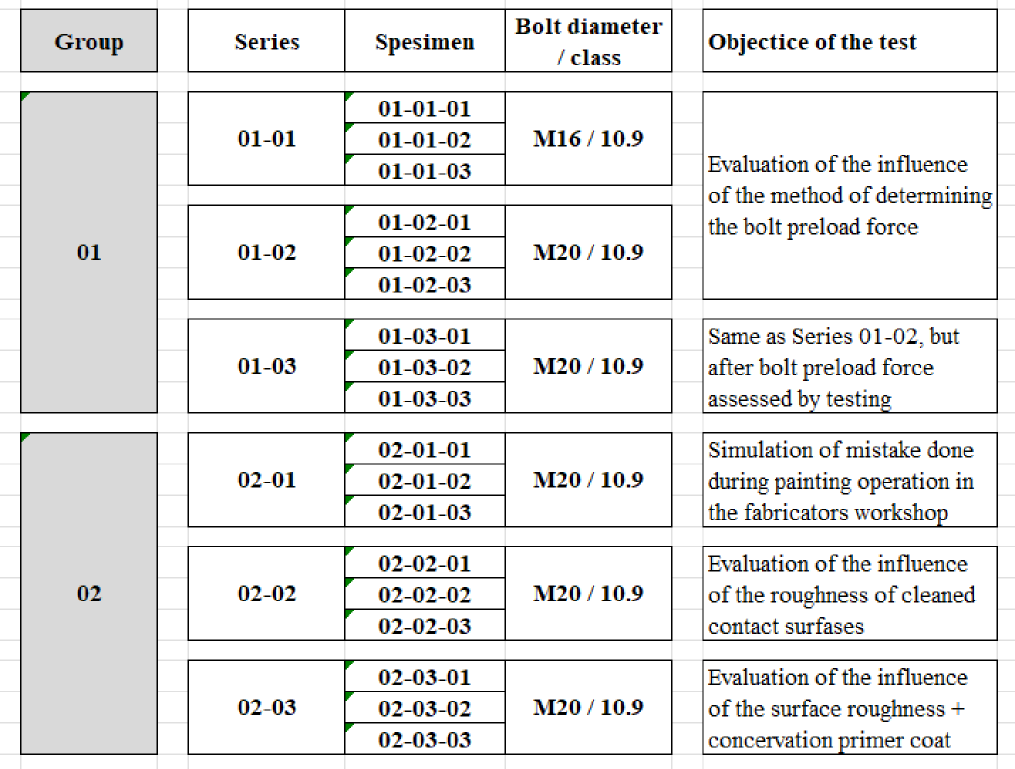
3 Experimental campaign

Two groups of tests, named Group 1 and Group 2, are conducted within the experimental campaign, Figure 5. Group 1 involves the execution of three series of experimental specimens. The first three with bolts M16-10.9 are named Series 1-1, and the second and third with bolts M20-10.9 are named Series 1-2 and Series 1-3. The samples' surfaces are grit-blasted to grade Sa 2½, which is medium roughness (G), according to ISO 8503-1 [19]. They are then covered with a zinc silicate primer that is about 80 µm thick. The first objective of the tests in Group 1 is to obtain the value of the coefficient of friction. The second objective is to investigate whether k-class K_1 (Series 1-2) and k-class K_2 (Series 1-3) can determine the preloading force and produce reliable slip factor results. The workshop fabricates all experimental specimens of Group 1 using the same technology, and prepares the steel plates of all six specimens in an almost identical manner. The conservation primer is a two-component zinc silicate coat, which falls into the friction coefficient class B according to EN 1090-2 Appendix G.

Testing Group 2 comprises nine tests, arranged in three series (Figure 5), each of which includes three standard specimens (Figure 7), namely Series 2-1, Series 2-2, and Series 2-3. All 9 tests use bolts M20-10.9, fabricated by the same (European) manufacturer from a single delivery batch. The objective of testing Group 2 is to investigate how the surface preparation affects the slip factor. For this purpose, the specimens of Series 2-1 are grit blasted to Sa $2^{1/2}$ grade and then coated with an anti-corrosion primer. The primer is then cleaned using a mechanical wire brush, Bristle Blaster (Figure 6, b), again to grade Sa $2^{1/2}$ and medium roughness (G) according to ISO 8503-1 [19]. After that, a conservation coat is put on the contact surfaces. This is a one-component zinc dust paint based on ethyl silicate (the primer is tested and approved in accordance with EN 1090-2 appendix G for friction coefficient class B, vendor datasheet). The layer should be up to 80 µm thick. The purpose of the steps prior to the testing of Series 2-1 is to simulate an error in the fabricator's painting workshop regarding the treatment of the friction surfaces (see Figure 6) and the subsequent application of cleaning and coating manipulation. It should be emphasized that only the side plates of 10 mm thickness were subjected to these manipulations, and not the inner plates of 20 mm. This implies that only 50% of the flying surface is cleaned and repainted.

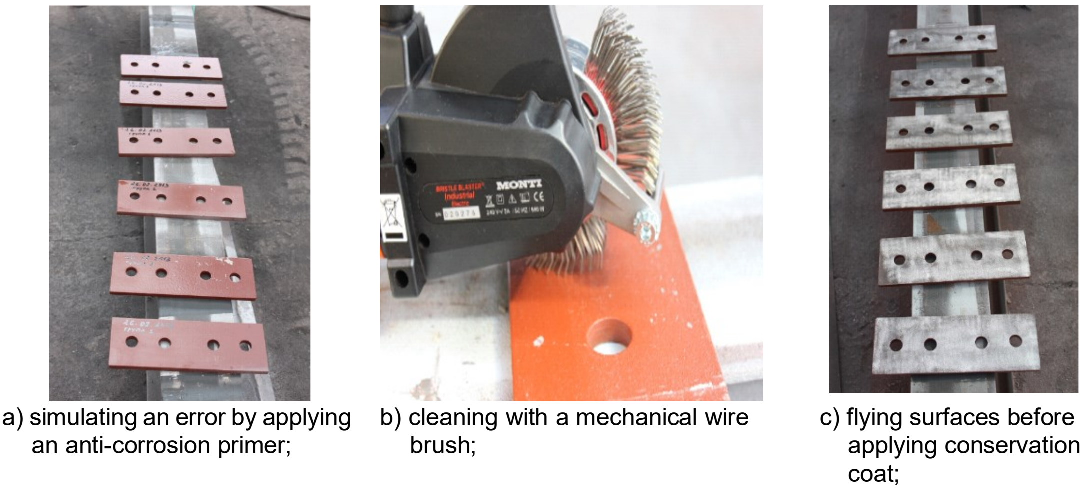
Series 2-2 specimens are grit blasted to Sa 2½ and medium roughness (G) according to [19]. After cleaning, the plates are assembled in the specimen. The contact surfaces remain uncoated (Figure 7, b). The purpose of Series 2-2 is to determine the coefficient of friction, which solely depends on the level of cleaning. Here it is relevant to clarify that from the time of cleaning to the time of assembly, the steel plates were in a room with a relatively dry environment, and therefore no intensive rust should be expected on the contact surfaces.

Series 2-3 specimens were grit blasted to Sa 2½ grade and medium roughness (G) according to ISO 8503-1 [19]. The specimens receive a conservation coating (one-component zinc-based metallizing primer) after cleaning, with a nominal layer thickness of up to 80 m. The purpose of Series 2-3 is to obtain the slip factor (coefficient of friction) after following the technical specifications of the manufacturer of the conservation coat.



Group	Series	Spesimen	Bolt diameter / class	Objectice of the test
01	01-01	01-01-01	M16 / 10.9	Evaluation of the influence of the method of determining the bolt preload force
		01-01-02		
		01-01-03		
	01-02	01-02-01	M20 / 10.9	
		01-02-02		
		01-02-03		
	01-03	01-03-01	M20 / 10.9	Same as Series 01-02, but after bolt preload force assessed by testing
		01-03-02		
		01-03-03		
02	02-01	02-01-01	M20 / 10.9	Simulation of mistake done during painting operation in the fabricators workshop
		02-01-02		
		02-01-03		
	02-02	02-02-01	M20 / 10.9	Evaluation of the influence of the roughness of cleaned contact surfases
		02-02-02		
		02-02-03		
	02-03	02-03-01	M20 / 10.9	Evaluation of the influence of the surface roughness + concervation primer coat
		02-03-02		
		02-03-03		

Figure 5. Flow chart of the conducted experimental campaign

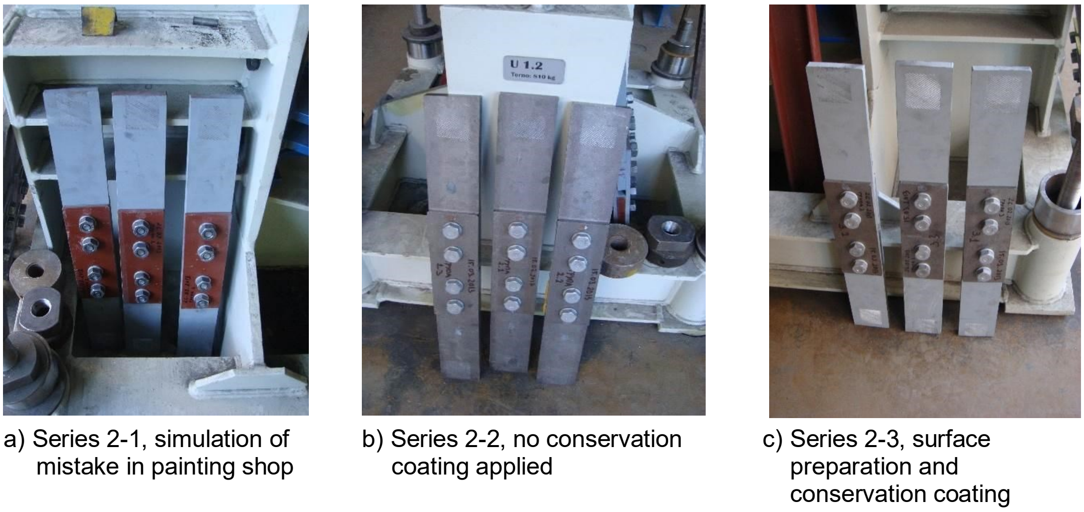


a) simulating an error by applying an anti-corrosion primer;

b) cleaning with a mechanical wire brush;

c) flying surfaces before applying conservation coat;

Figure 6. Steps for processing the Series 2-1 specimen



a) Series 2-1, simulation of mistake in painting shop

b) Series 2-2, no conservation coating applied

c) Series 2-3, surface preparation and conservation coating

Figure 7. Specimens of Group 2

4 The data elaboration methodology and experimental results

Each of the eighteen tests directly yields the slip force F_S [kN]. The tensile force F (Figure 3) is constantly measured throughout the whole test, by force sensor #0 connected to the measuring mechanism of the testing machine and the recording system controlled by software (Figure 4). The value assigned as F_S is that corresponding to a recorded slip of 0.15 mm or for a very close smaller value between the side plate and the inner plate in each of the four DTs (Figure 3). Tables 3 and 5 present the average values of the forces Fs for sensors #1 and #3 and correspondingly for sensors #2 and #4. The final average value of Fs is from the readings of all DTs.

The two parameters the slip force FS depends on are the contact pressure (preloading) and the coefficient of friction between the slipping surfaces. Each bolt's contact pressure equals the preload force $F_{p,C}$. This implies that this force must be defined precisely. Regardless for the *Series 1-1* and *Series 1-2* tests the preload force is calculated by formula (1), based on k-class $K1$. The value of 0,16 is selected according to the practice before EN 1090-2 [12]. The value K_1=0.16 is applied to the two bolt sizes, M16 and M20, resulting in tightening moments of 280 Nm and 550 Nm, respectively. The value of the tightening moment, $M_{r,2}$ [Nm], is measured by a calibrated dynamometric wrench. Despite its widespread use in real construction, this approach lacks precision and is prohibited by [2, 12]. For this reason, it is one of the subjects of research in this article.

$$F_{p,C} = \frac{M_{r,2}}{d \cdot K_1} \tag{1}$$

where d is the diameter of the bolts in meters.

K-class K_2 having a value of 0,17 obtained through testing, is used to achieve the preloading in the Series 1-3 and to compare the results with Series 1-2.

The preload force based on k-class K_2 only is used for all the tests belonging to Group 2. For this purpose, the K_2 factor for specimens in Group 2 is obtained after testing.

It is also assumed that the preload force $F_{p,C}$ within all four bolts of an experimental specimen is the same since they are tightened with the same torque moment and wrench. Therefore, formulas (2) and (3) yield the mean value of the coefficient of friction μ_m.

$$\mu_i = \frac{F_{s,i}}{4 \cdot F_{p,C}} \tag{2}$$

where μ_i is the coefficient of friction obtained by testing the *i*-th specimen.

$$\mu_m = \frac{\Sigma \mu_i}{n} \tag{3}$$

where μ_m *is* the mean value of the coefficient of friction for each series and *n* is the number of values obtained through testing. Formulas (4) and (5) calculate the standard deviation S_μ and the coefficient of variation V, respectively.

$$S_\mu = \sqrt{\frac{\Sigma(\mu_i - \mu_m)^2}{n-1}} \tag{4}$$

$$V = \frac{S_\mu}{\mu_m} \tag{5}$$

The characteristic value of the coefficient of friction μ_{car} is obtained as the 5% fractile value with a confidence level of 75%, through calculation by equation (6) [2, 11].

$$\mu_{car} = \mu_m - 2.05 \cdot S_\mu \tag{6}$$

After following the methodology thus described, the elaborated data for slip factor values are obtained. The results of the conducted experiments from Group 1 are summarized in Tables 3 and 4, while the results of the conducted experiments from Group 2 are summarized in Tables 5 and 6.

After processing the data from Table 3, the calculated parameters presenting the coefficient of friction for series belonging to Group 1 are summarized in Table 4.

As can be seen from Table 4, there is a significant scatter in the obtained values and the coefficient of variation is high (*V*=13,36%) for Series 1-2 compared to Series 1-1. Not surprisingly, the characteristic value for the coefficient of friction obtained for Series 1-2 is lower and differs significantly from that obtained from Series 1-1. It is worth

Table 3. Group 1, testing results

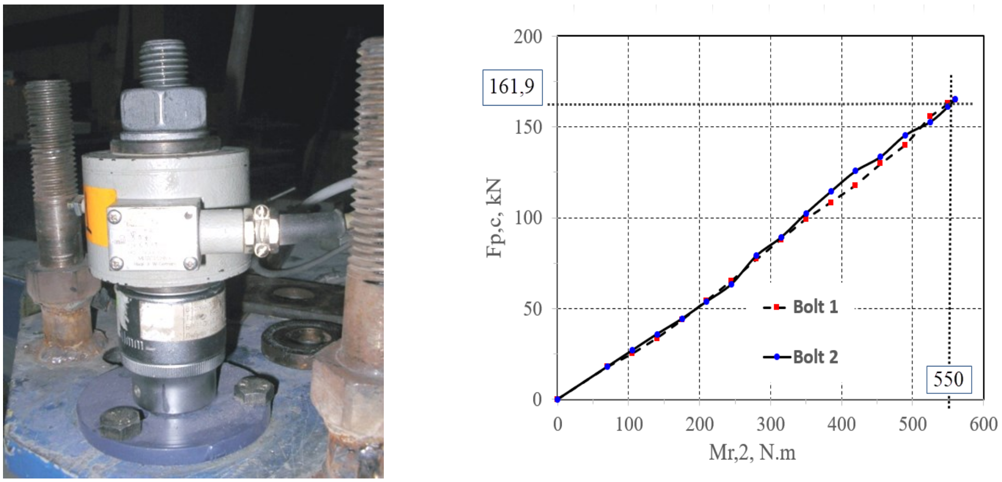
Series number	**Specimen (group-series-specimen) / bolt diameter**	**Slip Force F_S, [kN]**	**Coefficient of friction, μ_i**
1-1	Specimen 01-01-01 / M16	205,90	0,4705
		201,7	0,4609
	Specimen 01-01-02 / M16	211,3	0,4829
		217,3	0,4966
	Specimen 01-01-03 / M16	193,3	0,4417
		200,5	0,4582
1-2	Specimen 01-02-01 / M20	237,0	0,3447
		238,2	0,3465
	Specimen 01-02-02 / M20	301,1	0,4380
		265,8	0,3866
	Specimen 01-02-03 / M20	315,4	0,4588
		318,4	0,4632
1-3 (conducted after measurement of preload force)	Specimen 01-03-01 / M20	278,0	0,4293
		287,7	0,4443
	Specimen 01-03-02 / M20	282,7	0,4365
		302,6	0,4673
	Specimen 01-03-03 / M20	284,9	0,4399
		273,3	0,4220

Table 4. Group 1, elaborated data

Series	**Mean slip force, F_{sm}, kN**	**Mean Coefficient of friction, μ_m**	**Standard deviation, S_μ**	**Coefficient of Variation, (V%)**	**Characteristic Coefficient of friction, μ_{car}**
1-1	205,0	0,4685	0,0194	4,138	0,4287
1-2	279,3	0,4063	0,0543	13,360	0,2950
1-3	284,9	0,4399	0,0156	3,539	0,4080

reminding that the surfaces of the steel plates of Series 1-1 and 1-2 were cleaned in an identical manner and the same conservation coat was applied identically. There should be no physical reason for such a large difference in the results for the coefficient of friction. In searching for an answer to these deviations, it is concluded that applying the same K_1 factor for bolts M16 and M20 is misleading. That is why the last three specimens in *Series* 1-3 are tested after the preload force is obtained by k-class K_2. The execution of specimens is done by the same fabricator, using the same dimensions as for specimens from Series 1-2. The bolt preload force is obtained by measurements in a similar manner to the set-up used in [20]. Since the publication [20] is in Bulgarian only, the experimental setup will be presented very briefly hereafter. The bolt is placed on a specially designed stand so that its head is stationary. A cylindrical compression force gauge (measuring device) with a central hole is put and the bolt body stays in the hole. Washers are placed between the bolt head, the force gauge, and the nut (Figure 8a). The bolt nut is tightened with a torque wrench, with steps of 35 Nm increasing tightening torque. The force gauge provides information about the compressive force obtained in it, which is assumed to be equal to the preload force in the bolt. In addition to the tightening torque at each step, the angle of rotation of the torque wrench is also measured and reported [20]. An illustration of the results of the measurements are presented in Figure 8b.

Table 5 presents the testing results of the specimens from Group 2, while Table 6 presents the elaborated data. Recall that the preload force is obtained from measurements, following the same process as Series 1-3. Its value is 161 kN related to a torque moment 450 Nm.



a) Setup for preload forcemeasurements

b) Relation preload force – torque moment

Figure 8. Testing for preload force determining for the bolts in Series 1-3

Table 5. Group 2, testing results

Series number	**Specimen (group-series-specimen) / bolt diameter**	**Slip Force F_S, [kN]**	**Coefficient of friction, μ_i**
2-1	Specimen 02-01-01 / M20	263,6	0,4093
		261,0	0,4053
	Specimen 02-01-02 / M20	270,9	0,4207
		269,6	0,4186
	Specimen 02-01-03 / M20	267,2	0,4149
		262,7	0,4079
2-2	Specimen 02-02-01 / M20	274,2	0,4258
		292,8	0,4547
	Specimen 02-02-02 / M20	332,2	0,5160
		347,8	0,5401
	Specimen 02-02-03 / M20	356,7	0,5539
		328,3	0,5098
2-3	Specimen 02-03-01 / M20	312,8	0,4857
		297,1	0,4613
	Specimen 02-03-02 / M20	331,2	0,5143
		322,6	0,5009
	Specimen 02-03-03 / M20	304,3	0,4725
		309,4	0,4804

Table 6. Group 2, elaborated data

Series	**Mean slip force, F_{sm}, kN**	**Mean Coefficient of friction, μ_m**	**Standard deviation, S_μ**	**Coefficient of Variation, (V%)**	**Characteristic Coefficient of friction, μ_{car}**
2-1	265,8	0,4128	0,0062	1,504	0,4001
2-2	322,0	0,5000	0,0498	9,969	0,3978
2-3	312,9	0,4859	0,0192	3,953	0,4465

Another important aspect of the behaviour of these bolted connections is the force-displacement diagram that clearly indicates the pre-slip and post-slip connection behaviour. The experiments carried out made it possible to record both values namely connection tensile force *F* and relative displacements in DTs #1, #2, #3 or #4. Graphical illustration of one these records is presented in Figure 9. which shows expected behaviour of bolts in preloaded shear connections (category *B* or *C*) according to Eurocode 3 [4]. After reaching the slipping force Fs the connection slips without resisting until some clearances are exhausted. The connection starts working as category *A* until bolt shear failure or steel net section capacity is reached.

Some observations can be outlined from the graph from Figure 9. The following three specific stages are recognized in the relation force-displacement. They are distinguished by the points 0, 1, 2 and 3 in Figure 10. The phase of elastic and rigid response is between points 0 and 1. The displacements are due only to the elastic elongations in the connected plates. When the force F reaches the value of Fs, then the friction is overcome, and the connection elongates without resisting. This stage can be named "*major slip*" [3], and it is characterized by an almost constant value of the force and with the margin of the elongation D_{MS}. The conducted tests clearly show that the magnitude of D_{MS} is smaller than the theoretical value of the clearances between the bolt body and the diameter of the hole. Other researchers have also noted and reported on that specialty [3].This can be attributed to the fact that geometric imperfections in the fabrication and erection and the unavoidable small misalignments of the elements cause some bolts to come close to the steel surfaces of the holes. Thus, a given bolt meets the surface of the steel in the hole and begins to work on the bearing and shear. From this moment (after point 2), the connection enters the post-slip phase and begins to resist but also to elongate. The behaviour of the bolted connection after point 2 towards point 3 is of interest. The tests conducted had another purpose. With the sensors used and the experimental setup, a realistic picture of the force-displacement relationship in the branch 2-3 cannot be presented. This should be a question for future research. Of interest will be the tangential stiffness (whether there is a hardening branch or a softening branch). Of interest is also what criteria for the ultimate displacement and corresponding force will be found in the state of connection failure or the structural ultimate limit state.

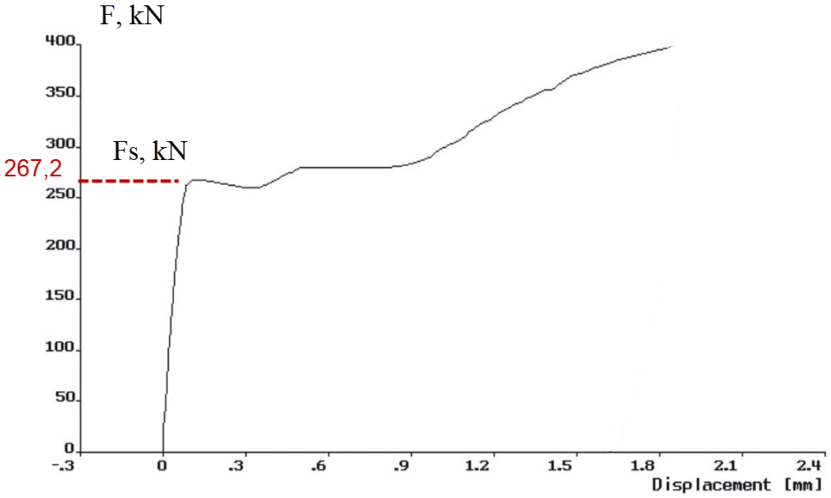


Figure 9. Relation tensile force F – relative displacement between side and inner plate. Raw data from DTs #1, Specimen 02-01-03

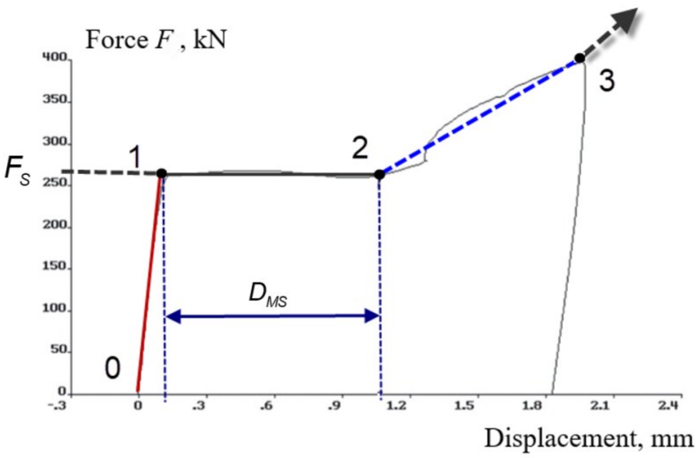


Figure 10. Characteristic phases in the behavior of a slip-resistant bolted connection

5 Conclusions

From the nine tests conducted in Group 1, it was clearly seen that when one of the governing parameters, namely the preload force in the bolt, is assumed theoretically, based on k-class K_1 , the results are not reliable. The differences in the obtained characteristic values of the slip factor between Series 1-1 and Series 1-2 and the improvement achieved after testing Series 1-3 prove this thesis. Testing is necessary to determine both the sliding force (F_S) and the preload force ($F_{p,C}$) in the bolts, ensuring a reliable determination of the coefficient of friction for a specific prepared conservation coat.

In practice, we must avoid determining torque moments based on theoretical data (k-class K_1), even from authoritative product-oriented sources like [21]. When using the tightening method, it is strictly mandatory to work with k-class K_2 [2]. In such cases, one must obtain K_2 factors either from the bolt kit manufacturer's certificates or after testing some bolt assemblies from delivered batches.

Testing Group 2 aims to investigate the technological aspects of conservation coating application. Based on the elaborated data and results presented in Table 6, it can be concluded that the highest average value of the coefficient of friction appears in Series 2-2, at which no conservation coating is applied. Conversely, the largest variation of the reported results is observed in this series. In the end, the characteristic value of the coefficient of friction is lower than that of Series 2-1 and Series 2-3. The occurrence of some corrosion between the time of cleaning the steel plates and the connection assembly can explain this controversial result. The use of cleaned and uncoated surfaces for such bolted joints is assumed and allowed in [2, 12], but the engineer should bear the following in mind. Using friction surface class *A* of the standard [2, 12] for slip-resistant connection design means that the organized execution process must ensure the absence of rust between the friction surfaces. Only a strict and rigorous site-oriented organization for cleaning and assembly can accomplish this. Such a strict organization of work is difficult, and therefore the engineer should take advantage of this option only when he is convinced that it is technologically and managerially feasible.

Comparing the results of Series 2-1 and Series 2-3 is of particular interest for the practice. This comparison focuses on the correct application of surface treatment and coating, which Series 2-3 simulates, and how Series 2-1 simulates a fabrication error and the subsequent repair of that error. Testing determines the preload force for both series, and the bolts originate from the same manufacturing batch. This implies that the sole distinction between the two series lies in the treatment of the plates' friction surfaces.

Workshop painting errors are a common occurrence in professional practice. In the author's engineering practice, workshop painting errors have frequently occurred in structures fabricated in Europe, specifically in Bulgaria, Slovenia, or the Czech Republic, by fabricators with high reputations, a strong technological culture, and EXC3 certificates in accordance with EN 1090-2 [2, 12]. One should prepare for such an unexpected situation in any design project that uses a slip-resistant bolted connection.

Comparing the results of Series 2-1 and Series 2-3 (Table 6) shows that the mean value of the slip factor is 17.7% lower for Series 2-1. The difference in characteristic values is 11.6%. These findings need the following comment. Only the side plates, which account for half of the contacting surfaces in Series 2-1, simulate fabrication error. Should the error encompass all surfaces, we anticipate a more significant reduction. This reduction is explained by the fact that cleaning with a mobile brush does not provide the surface roughness required for this conservation coat.

Formulating the following design recommendations is possible. In case of a mistake in applying the primers, it is best to repeat the cleaning technology using a grit blasting machine. This is not always possible for scheduling or technological reasons. In case of using a mobile mechanical brush for cleaning, the engineer should anticipate a reduction of 25% in the coefficient of friction for 100% affected contact surfaces and 15% for 50% affected. To achieve more accurate results, more experimental investigations similar to those presented in this article should be conducted.

Investigating the post-slip behavior of the slip-resistant bolted connections requires a constitutive behavior model. The proposed model, according to Figure 10, is an approximation but still not sufficient. It can be interpreted as an initial framework for further refinement. Future research should focus on conducting experiments with an advanced test setup to track the force-displacement relationship after the major slip and establish failure criteria. We can successfully apply these bolted connection models to a wide variety of structural archetypes and various limit states. These include, for instance, seismic analysis for significant damages or near-collapse limit states (seismic analysis), key structural element loss scenarios (robustness of structures), fire design situations (fire engineering), and other similar scenarios.

CRediT authorship contribution statement

Tzvetan Georgiev: Conceptualization, Formal analysis, Investigation, Methodology, Supervision, Validation, Visualization, Writing.

Declaration of competing interest

As the sole and corresponding author, I declare that I have no financial or personal relationships with other people or organizations that could inappropriately influence my work related to this research. I declare that I have no potential conflicts of interest related to consultations, stock ownership, honoraria, paid expert testimony, patent applications/registrations, and grants or other funding that may be relevant to the research presented in the manuscript.

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