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Influence of test speed in slip factor tests

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WP1 – task 1.2

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Abstract

A literature study was conducted to review the test duration of short term slip factor tests in different countries. Short term slip factor tests were carried out using different loading speeds. The test results were used to determine the influence of the test duration on (1) the short term slip factor and (2) the conclusion of creep sensitivity during a creep test.

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List of Symbols & Abbreviations

Symbol	Meaning	Unit
d	bolt diameter	$[\mathrm{L}]$
$\sum t$	clamp length	$[\mathrm{L}]$
$R_{p0.2}$	0,2% proof stress	$[\mathrm{F/L^2}]$
R_m	tensile strength	$[\mathrm{F/L^2}]$
$A5$	strain at failure	$[-]$
R_z	mean roughness depth	$[\mathrm{L}]$
$F_{p,C}$	Nominal preload force	$[\mathrm{F}]$
L	Bolt length	$[\mathrm{L}]$
L_0	Bolt clamp length	$[\mathrm{L}]$
L_1	Bolt clamp length during alternative slip factor test	$[\mathrm{L}]$
DFT	Dry film thickness	$[-]$
μ	Slip factor	$[-]$
μ_{ini} ; $\mu_{ini,mean}$	(Mean) slip factor based on initial preload	$[-]$
μ_{act} ; $\mu_{act,mean}$	(Mean) slip factor based on preload at slip	$[-]$
μ_{nom} ; $\mu_{nom,mean}$	(Mean) slip factor based on nominal preload	$[-]$
COV ; V	Coefficient of variation	$[-]$
F_{Si} ; F_{slip}	Loat at slip	$[\mathrm{F}]$
$F_{p,ini}$	Initial preload force	$[\mathrm{F}]$
$F_{p,slip}$	Preload force at slip	$[\mathrm{F}]$
$F_{p,act}$	Actual preload force	$[\mathrm{F}]$
r	Reduction factor	$[-]$
EA_{eff}	Effective stiffness of the bolt shank	$[\mathrm{F}]$
Δl_{loss}	Loss of bolt elongation	$[\mathrm{L}]$
C_{cl}	Conversion factor	$[-]$
F_{Sm}	Mean slip load	$[\mathrm{F}]$
t	Time / test duration	$[\mathrm{T}]$
E	Young's Modulus	$[\mathrm{F/L^2}]$

Abbreviation	Meaning
st	Static test
ct	Creep test
ZnSM	Zinc Spray Metallized
ASiZn	Alkali Zinc Silicate
GB	Grid Blasted
PE	Plate edge
CBG	Centre Bolt Group
TUD	TU Delft
UDE	University of Duisburg-Essen
LVDT	Linear Variable Differential Transformer

1 Introduction

Slip-resistant bolted connections loaded in shear (High Strength Friction Grip connections) are used in steel structures to reduce deformations and/or to improve the fatigue class of the connected plates. Main fields of application are bridges, cranes, radio masts and tubular towers as well as truss girders for wind turbines. The slip resistance of these connections is determined by the friction of the contact surfaces and the level of preload in the bolts.

The friction of the contact surfaces is described by the slip factor. For frequently used surface treatments of carbon steels the slip factor can be found in EN1090-2 "Execution of steel structures and aluminium structures - Part 2 Technical requirements for steel structures". To use alternative surface treatments in HSFG connections a slip factor test is required, which is described in Annex G of EN 1090-2.

To determine the slip factor according to Annex G, first a series of 4 short term tests are conducted. In these tests the load is gradually increased until a critical value of the slip of the connection is reached. The results of the short term tests are used to define the load level of a creep test. The result of the creep test determines if the coating is sensitive to creep.

The outcome of the creep test is essential in the procedure to determine the slip factor for a coating. If the test passes, the slip factor is calculated based on the combined results of the short term tests and the creep test. If however the creep test fails, time consuming extended creep tests have to be carried out.

The result of a creep test depends on the load level at which the test is performed. This load level is defined as the average of the results of the short term tests. As time is essential for creep effects, the results of the short term tests are potentially influenced by the duration of this test. For this reason time boundaries are specified wherein the short term tests are to be executed. EN1090-2 Annex G currently implements this by the statement: '*tests shall be carried out at normal speed (duration of test approximately 10 min to 15 min)*'. The meaning of 'normal speed' is not further defined. The required speed (either in kN/s or mm/s) depends on the load control method that is used in a laboratory and on the properties of the friction grip assembly to test (hardness/roughness of the faying surfaces, coating system, coating thickness, bolt pretension level, etc.). In practice the specification of the duration of a short term slip test raises questions and leads to confusion:

- The specimens that are to be used for slip factor tests have 2 identical friction grip connections. It is not clear what is exactly meant by the duration of the test; does this refer to the time it takes to load one side of the specimen to the critical slip or to the time it takes to make both connections slip?
- The method to load a specimen is not prescribed, this means the user is free to choose between force and stroke controlled loading. Also a combination of both methods is possible.
- The parameters of the load control method have to be determined by performing initial tests on dummy specimens. Labs will use their expertise with similar coating systems to choose an initial loading speed. This can result in a test duration that complies with the requirements, but most likely will be outside the time frame of 10-15 minutes. The formulation of the test

duration suggests that within the time frame mentioned the influence of the load speed on the slip factor is negligible. It is however not clear on what to do with results of tests that took a few minutes shorter than 10 or longer than 15 minutes.

The lack of clarity in the points mentioned can lead to different interpretations and consequently to differences in the way slip factor tests are executed in practise. This may lead to different conclusions for the slip factor, depending on the laboratory that carried out the tests. It is obvious that the procedure to carry out the slip factor tests should guarantee consistency in the results of tests carried out by different test institutes / labs. For this reason more insight in the influence of the aspects mentioned is desirable.

1.1 Research Objectives

In WP1.2 of the SIROCO project a comparative study has been performed to the influence of the duration of the short term slip factor tests. It was anticipated that the test duration could be of influence on:

1. The slip factor for non-creep sensitive surfaces
2. The outcome of the creep test
3. The spread in the results of the short term slip factor tests

Ad 1 If the load level at which the slip criterion of 0.15 mm is reached is influenced by the duration of the test result, the outcome of the research could be a correction method to be applied on results obtained for durations that fall outside the window of 10-15 minutes.

Ad 2 In the creep test the load level to reach ($0.9.F_{s,m}$) will be obtained after a certain timespan. The current standard does not specify this timespan. To apply the creep loading typically a load controlled method will be used in which the loading speed (kN/s) is determined by the load level that was reached in the short term tests ($F_{s,m}$) and the aimed time to reach 90% of the load. The aimed time is assumed to be in the same order of magnitude as the duration of the 4 short term tests that were carried out on the plates. It must be verified that the outcome of the creep test (indication of creep sensitivity of the coating) is independent of the time in which the creep load is applied.

Ad 3 If the variation in the results of the 4 static slip tests is influenced by the test duration, this affects the characteristic value of the slip factor. The characteristic value (5% fractile value with 75% confidence level) of the slip factor depends on the standard deviation of the individual test results.

2 Literature Research

Other (former) codes state the time constraints presented in Table 1 regarding the minimum and maximum duration of a short term slip test. In contrast to the European Norm (EN 1090-2), the British Standard (BS 4604), the American Research Council on Structural Connections (RCSC), as well as the Australian Standard (AS 4100) do not prescribe a test duration but rather an indication of the speed with which to apply the external load. Moreover, by defining a maximum force increment per unit of time, the codes suggest to use a load controlled loading procedure (except for the RCSC which used a hybrid method).

Table 1 - Rules for short term slip factor tests in other codes

Code	Minimum test duration	Maximum test duration	Rate of load application (for connection with 1 bolt)	Remarks
BS 4604 (1970)	3 minutes	-	Approx. 25 kN/minute	Slip force is the maximum load reached at a minimum slip level of 0,1 mm
RCSC (2014)	-	-	Max. 111 kN/minute Max. 0,00127 mm/s of slip	Slip force is defined at 0,15 mm of slip, or the maximum load reached for any lower slip level
AS 4100 (1998)	-	-	Max. 50 kN/minute	Slower loading rates are preferred Explicit in demanding constant load increase throughout test Slip force is defined at the point at which a sudden increase in slip occurs. If not, then the slip force is the force belonging to a slip level of 0,13 mm.
EN 1090-2 (2008)	10	15	-	Refers to 'normal speed' for load application, but no speeds are explicitly given Slip force is defined at 0,15 mm of slip, or the maximum load reached for any lower slip level

3 Methods and Materials

To answer the research questions, experiments on double lap shear connections cf. Annex G of EN 1090-2 have been carried out using M20 bolts (Figure 4). The steel plates used for all experiments in WP1.2 (and WP2.1) were grade S355J2C+N. All plates were cut from plates from the same batch and individually marked (numbered).

During the production process of the centre plates from the “mother plate”, plates originating from adjacent positions were numbered accordingly. This way the specimens could be assembled using sets of centre plates without thickness variations (Figure 5).

3.1 Material properties

The material properties of the steel plates have been determined and are presented in Table 2.

Table 2 - Material properties steel plates WP1.2

steel grade	specimen part	width	thickness	Rp0.2	Rm	A5	HB
		[mm]	[mm]	[N/mm^2]	[N/mm2]	%	
S355J2C+N	center	100	20	409	538	26%	-
	lap		10	458	597	22%	-

The original test matrix for WP1.2 consisted of only two series of surface preparations: grit blasted (**GB**) and coated with Alkali Zinc Silicate (**ASiZn)**. In the first bilateral meeting of UDE and TUD it was decided to add the series of zinc (Zn) spray metallized specimens (**ZnSM**) to the test matrix. This coating is known to be sensitive to creep. Reason for the expansion of the WP1.2 experiments was the omission in the original test matrix of a series of plates with a coating that is known to be creep sensitive. Especially for creep sensitive coatings it is important to investigate the influence of the test duration on the result of the short term slip test as for these coatings the initial test sequence should guarantee a correct conclusion of the creep test.

The total number of tests to be performed by TUD in WP1.2 increased from 40 to 60. An overview of the test specimen and surface conditions is presented in Table 3. In Figure 26 and Figure 27 the distribution of surface roughness and dry film thickness of the coated specimens can be found.

Table 3 - Test specimens and surface conditions for slip tests in WP1.2

Series ID	Surface preparation		Clamp length Σt [mm]	Clamp length ratio Σt/d$^{1)}$ [-]	Number of tests in WP1.2	
	Coating material	coating thickness $^{2)}$			Static test	Creep test
Grit blasted surfaces Sa 2 ½ (R_z: 80 µm)						
GB	-	-	152	7.5	16	4
Grit-blasted Sa 2 ½ (R_z: 80 µm) + ASiZn coating						
ASiZn	alkali-zinc silicate	60 µm	152	7.5	16	4
Grit-blasted Sa 3 (R_z: 100 µm) + ZnSM coating (R_z: after coating 85 µm)						
ZnSM	Zinc spray metallized	140 µm	152	7.5	16	4
Level of preload $F_{p,C}$ = 172 kN (M20). │ $^{1)}$ d = 20 mm │ $^{2)}$ Nominal dry film thickness (DFT).						

3.2 Test duration

Displacement (stroke) controlled loading was used for all short term slip factor tests that were performed in the SIROCO project. Stroke controlled loading enables registration of the most detailed information on the slip factor of both connections of the specimens. Using load control to execute a slip factor test can cause unreliable results when one connection suddenly ‘slips through’ and is consequently unsuited for these kinds of tests. In all creep tests and extended creep tests the specified load was applied using load control. For these tests load control can be used, as the load level will not cause (sudden large) slip of the connections.

The duration of a test is defined as the time it takes from the starting of the test to load the specimen to the level at which the slip criterion is reached in both connections. Each slip factor test results in 2 test results for the test duration.

To examine the influence of the test duration on the slip factor the three series were tested for 4 test durations of the short term tests, being approximately:

- 5 minutes (loading speed 0,01 mm/s)
- 10 minutes (loading speed 0,005 mm/s)
- 20 minutes (loading speed 0,0025 mm/s)
- 45-60 minutes (loading speed 0,001 mm/s)

The first three durations are chosen in the same order of magnitude as the time frame 1090-2 Annex G prescribes (10 to 15 minutes). The last duration is significantly longer (but still short compared to the duration of a standard 3 h creep test).

3.3 Slip criterion

The slip load (F_{slip}) is defined as the maximum load that can be applied on the specimen or the load when a certain ‘slip’ occurs between the centre and lap plates before the maximum load is reached.

The slip is the displacement between a location on the centre plates and a location on the lap plates. EN1090-2 clearly states that these locations should be the point in between the bolts (at the centre of the bolt group – CBG position) on centre and lap plates.

To study the influence of the test duration on the slip factor in the short term tests the slip criterion as described in EN1090-2 was used:

- 0,15 mm displacement between the centre plates and the lap plates measured at the CBG position

In various other research on the slip factor of steel plates and coatings systems ([1], [2], [10], [11]) not the slip at CBG position is used, but the displacement between the edge of the lap plates and a point on the centre plates (plate edge – PE position). Using the slip at PE position is beneficial from a practical point of view, as only 4 LVDTs are needed to determine the slip where at CBG 8 LVDTs are required.

As the measurement of the displacement at PE also contains the elastic elongation of the part of the centre plate between the CBG position and the reference location on the centre plate, the displacement measured at PE is always larger than at CBG. When the displacement at PE is used to evaluate slip factor tests clearly a larger threshold value than 0.15 mm should be used to get a result that is comparable to the slip factor that results from a CBG based analysis of the same experiment. The differences in evaluation results based on slip at CBG or PE are significant. This is illustrated by Figure 23 and Figure 24 for typical results of slip factor tests of the GB and ASiZN series.

In research [1] and [2] the CBG position was not available, as the specimens had only 1 bolt per connection. The threshold for the slip used in this research was 0.3 mm at PE. In research [10], [11] standard 1090-2 specimen were used. In this research however the threshold for the slip was 0.15 mm at PE, which consequently resulted (in most cases) in conservative slip factors.

In all short term slip factor tests and all creep tests in the Siroco project the slip at both CBG and PE positions were measured to investigate the differences between both approaches. The data gathered can be used in other work packages of the project to define an alternative slip criterion that is to be used when slip measurements are recorded at PE position.

3.4 Measurements of the displacements

To assemble the specimens for the slip tests the centre and lap plates were aligned in lateral direction. After the bolts were placed in the holes, the centre plates were moved as far as possible towards the centre of the specimen. This way the hole clearance of centre and lap plates (in total 4 mm) was available as slip displacement before load transfer by shear of the bolts could occur. See Figure 6, Figure 12, Figure 13.

Each specimen has 2 connections that will be used to determine the slip factor. Technically slipping of the connections is possible in 2 ways (see Figure 11):

A. With increasing load the displacement of the centre plate relative to the lap plates continuously grows for both lap plates. This is observed simultaneously at both connections. One of the connections will reach the maximum load and then ‘slip through’. In this case the load will remain constant (or even drop) until the slip is so large that the bolts start transferring the load by shear force. Now the load can increase further until the other connection also fails. When there is no slipping through but the slip threshold value is reached for one of the connections, the load increases further until the slip threshold is reached for the other connection.
B. For one connection only one of the lap plates slips relative to the centre plate, while the other sticks to the centre plate without slipping. For the other connections the same happens, the lap plate that sticks now is the one that slips on the first connection. In this case both connections reach the critical level (slip through or slip threshold reached) at the same moment

When the surface preparation (blasting, roughness) and the properties of the coating system (dry film thickness) are identical for both sides of the centre plates and constant over the surface of the lap plates the second slip mode will not occur. It is expected that slip mode 2 will not occur in any of the slip factor tests.

Solartron AX/S LVDT’s with a range of ±1 mm and an accuracy of 1 µm were used to measure the displacements. See Figure 7.

3.4.1 CBG position

To measure the displacement at CBG position 2 LVDTs were attached on each edge of the centre plates. To attach the LVDTs special mounting brackets were fixated at CBG position using the M5 holes in the side edges that were made especially for this purpose. After fixation an M4 sharp tip bolt was screwed in the bracket and tightened against the centre plate to prevent rotation of the mounting bracket. The sharp tip screws were tightened only lightly to ensure a clear fixation point of the bracket at CBG position on the centre plate. On the lap plates U- shaped brackets with LVDT reference faces were attached at the CBG position of both connections. The brackets were fixed at CBG position by 2 sharp tip allen screws in the legs of the brackets that were tightened against (and pressed in) the edge of the lap plates. 4 secondary allen screws were used to align the brackets and to prevent rotation. See Figure 7, Figure 9, Figure 10.

The relative displacement of the CBG locations on centre plates and lap plates were measured on both sides of the lap plates. In total 4 LVDTs were used for each connection. The average of all 4 measurements was used to determine the slip of the connection at CBG position.

LVDT numbering:

- Top connection: u_3, u_4, u_5, u_6. CBG $\text{Slip}_{\text{top connection}} = (u_3 + u_4 + u_5 + u_6)/4$
- Lower connection: u_7, u_8, u_9, u_{10}. CBG $\text{Slip}_{\text{lower connection}} = (u_7 + u_8 + u_9 + u_{10})/4$

3.4.2 PE position

To measure the displacement at PE position 2 LVDTs were attached in the centre of the specimen on both side of the centre plates. The LVDT mounting bracket was clamped on to the centre plates at some distance below the edge of the lap plates by tightening 2 M6 allen screws. The clamping force caused 4 sharp tip M4 allen screws that protrude approximately 2 mm above the inner surface of the brackets to be punched into the surface of the centre plate. After fixation the M4 allen screws were used to align the LVDT mounting brackets. A mounting template was used to assure that the clamping position of the brackets was identical for all slip factor tests. See Figure 7, Figure 9, Figure 10. The average of both measurements was used to determine the slip of the connection at PE position.

LVDT numbering:

- Top connection: u_1, u_2. PE $\text{Slip}_{\text{top connection}} = (u_1 + u_2)/2$
- Lower connection: u_{11}, u_{12}. PE $\text{Slip}_{\text{tlower connection}} = (u_{11} + u_{12})/2$

3.5 Slip factors

Due to settling effects and/or creep effects the time to prepare a specimen for a slip factor test and/or the duration of the test could be of influence on the preload in the bolts during the tests. Variations in the preload are of direct influence on the slip load. To be able to analyse these effects the slip factor for each specimen was calculated on 3 different ways (see Figure 16, Figure 18):

1. based on the nominal bolt preload (slip factor according to EN1990-2): $\mu_{\text{nom}} = \dfrac{F_{\text{slip}}}{4.F_{\text{P,C}}}$

2. based on the preload in the bolts at the start of the slip factor test: $\mu_{init} = \dfrac{F_{\text{slip}}}{4.F_{\text{P,init}}}$

3. based on the preload in the bolts when the slip criterion is reached: $\mu_{act} = \dfrac{F_{\text{slip}}}{4.F_{\text{P,slip}}}$

3.6 Bolts

HV bolts M20, class 10.9, were used. For the tests in WP1.2 the preload force in the bolts (M20 x 180) was measured concurrently with implanted strain gauges (produced at UDE) and load cells (produced by TUD, Annex B: Load Cells), see Figure 8. By measuring with both load cells and strain gauges the tests in WP1.2 also gave input to WP1.1 (study to the different methods to measure the preload force during slip factor tests). The preload in each of the bolts was measured continuously from the moment the preload application started to the end of the slip factor test.
Bolt numbering

- Top connection: B_1, B_2
- Lower connection: B_3, B_4

Bolts B_1 and B_4 are external bolts (located closest to the edge of the lap plates).

3.6.1 Preload application

The preload in the bolts was applied using an air driven torque tool. The bolts were initially preloaded to $F_{p,C}$ = 172 kN. The preload was applied in 4 steps of approximately 25% of $F_{P,C}$ in a fixed order B2-B3-B4-B1. The time to reach $F_{P,C,}$ in all 4 bolts was typically 3 minutes. See Figure 6, Figure 14, Figure 17.

3.6.2 Bolt retightening

Coatings or surface treatments can be sensitive to creep. This causes the preload to drop fast during the first minutes after initial application to $F_{P,C}$. From a practical point of view it is impossible to have a guaranteed fixed time span between preload application and the start of the slip factor test. A varying time frame could mean that the preload level at the start of the slip factor test could vary between specimens. To avoid this a waiting period of ≥ 30 minutes between preloading and start of the slip factor test was maintained. When the loss of preload over the waiting period appeared more than 5% of $F_{P,C}$ all bolts of the specimen were retightened. After the waiting time (and the eventual retightening) the slip factor test was started with no further delay (additional losses after retightening were very small). This way of working guaranteed that for all specimens the preload level at the start of the slip factor test ($F_{P,ini}$) was within ±5% of the required preload level $F_{P,C}$. Retightening appeared necessary for all ZnSM specimens. None of the GB and ASiZn specimens needed retightening. See Figure 18.

3.6.3 Preload losses

The preload was recorded from the start of the tightening procedure to the end of the slip factor tests.

3.6.3.1 Initial preload losses

The initial preload losses (the losses directly after the required preload level was reached) are caused by settling of the components of the bolt assembly and the properties of the coating system.
It is expected that the magnitude of the losses is constant for the specimens in each of the series (all components that cause the losses are similar for all specimens).
The initial preload losses were determined for all slip factor specimens. This was done for several reasons:

1. to get insight in the order of magnitude of the initial preload losses,
2. to compare the losses between the 3 WP1.2 series,
3. to compare the properties of the ASiZN and ZnSM coatings of the specimens in WP1.2 and WP2.1,
4. to study the influence of the clamping length of the bolts on the losses,
5. to verify the consistency of the preload application method and preload measuring techniques over time.

To calculate the preload losses the difference in preload that occurs over a certain period of time should be taken into consideration. As the calculated losses are primarily used to compare results in the current research, the definition of initial preload loss is arbitrary. The preload loss immediately after the moment the required preload is reached is relatively large compared to the loss over the rest of the waiting period. These direct initial losses are influenced by the tightening of the surrounding bolts and consequently show relatively high scatter. For this reason for the initial preload losses the preload at 30 seconds after releasing the tightening torque was used as the reference value ($F_{P,init,30}$) to calculate the loss. The second measurement was taken after 15 minutes ($F_{P,init,900}$). The definition of the loss for each bolt is: loss $_{15min}$ = ($F_{P,init,30}$ - $F_{P,init,900}$)/$F_{P,init,30}$. The initial preload losses are reported per connection (average of losses in 2 bolts) of the specimens.
Figure 21 shows the initial losses that were observed in all specimens of WP1.2 and WP2.1. Coating system and clamping length of the bolts are of major influence on the losses. The graph confirms the reproducibility of the measurement system over time.

3.6.3.2 Preload losses during execution of slip factor tests

During execution of the slip factor tests also losses in preload occur. These losses are caused by:

1. elastic lateral contraction of the steel plates (the specimen is loaded in tension)
2. flattening of the asperities of the steel surface during the slip process
3. in specimens with coatings the coating is flattened/compacted by the mutual displacements of centre and lap plates

Figure 19 and Figure 20 are typical examples of the preload losses that occur during a slip factor test on grit blasted and coated specimens. The losses that are caused by the elastic behaviour of the plates (lateral contraction) are an order of magnitude smaller than the losses by other causes.
To calculate the slip factor the nominal value of the preload force is used ($F_{P,C}$), so the losses that occur during a slip factor test are on themselves not relevant for the determination of the slip factor according to EN1990-2. It is however interesting to monitor the losses during the slip factor test for the sake of comparison between series and to:

- gain insight into the magnitude of the various phenomena that cause the loss (lateral contraction, flattening of the asperities)
- investigate the influence of the direction of the load transfer in a connection (tension or compression) on the preload losses (and slip factor)
- investigate if the loss of preload stabilises or progresses, given that the load on the connection will fluctuate in a certain range ($F_{S,min} < F_S(t) < F_{Slip}$) over the lifetime of a structure
- calculate an 'actual slip factor' to define elements that can be used in FEM to model slip of HSFG connections
- validate models to correct the result of slip factor tests that were performed with bolt lengths other than described in the current EN1990-2 (different clamping lengths)

The preload loss during a slip factor test is the difference between the preload at start of the test ($F_{P,init}$) and the preload at the moment the maximum slip load or threshold of the slip at CBG is reached ($F_{P,slip}$). The definition of the preload loss during the slip factor test is: loss $_{test}$ = ($F_{P,init}$ - $F_{P,slip}$)/$F_{P,init}$. Figure 22 shows the losses that were observed in all specimens of WP1.2 and WP2.1. Coating system and clamping length of the bolts are of major influence on the losses. The graph confirms the reproducibility of the measurement system over time.

3.6.4 Clamping length

The clamping length of the bolts in a slip factor test will affect the result of the test. A larger clamp length leads to a reduction of the preload losses during the test and will consequently result in a higher slip factor. The length of the load cells that were used in WP1.2 resulted in a clamp length of the bolts of (4+100+4+40+4=) 152 mm. This is significantly more than the 'standard' clamp length (4 + 40 + 4 = 48 mm) in a 1090-2 Annex G test piece for M20 bolts. This means the slip factors found in the WP1.2 experiments will be higher than when the experiments would have been carried out with standard bolts The research objective of the WP1.2 test program is to determine the influence of the test duration on the result of a slip factor test. For this the ratio's between the slip factors found for the various test durations are of interest. The clamp length is not relevant in this. In *Annex C: Influence of clamping length on the results of slip factor tests'* a method is described to determine a correction factor for slip factors determined by experiments with longer bolts.

3.7 Creep tests

The intention of the creep test is to investigate the creep sensitivity of a coating. The load level for the creep test is set to 90% of the mean value of the short term tests results based on the CBG criteria. For the creep tests load control was used. The loading speed [kN/s] in the creep tests was derived from the loading speed that was achieved in the associated short term tests in the same load duration group. The current version of EN1090-2 Annex G prescribes a test duration of 3 hours for a creep test. All creep tests in the SIROCO project were executed over a time period of at least 12 hours (tests were started at the end of the working day and finished the next morning). The test results (load level-slip-time relation) over this extended time period will be used as input for task 1.4 (in WP1.4 research will be done to formulate alternative criteria to determine the creep sensitivity).

In the creep tests load-control was used to apply the load. Creep tests are carried out at a specific load level. This means the loading speed [kN/s] can be calculated directly by dividing the load level by the time span to reach it in.

3.8 Test rig

All short term slip test and creep tests were carried out on a 600kN Schenck general purpose testing machine with MTS hydraulic clamping devices (Figure 15). Load control was performed by the TUD MP3 [16] system.

3.9 Data acquisition system

The data acquisition system (MP3, [16]) used was developed at TUD. The MP3 system allows data recording at fixed time intervals and/or 'on tripped' recording. 'On tripped' recording means that the data of all instruments are recorded when the change (relative to the last recorded value) in the signal of one of the instruments exceeds its threshold value. Sampling frequency of the MP3 system is typically 300 Hz per channel or higher, so advanced filter techniques can be used on all signals. The high sampling frequency enables accurate and very efficient recording of measurement data, using 'on-tripped' recording of the signals.

Fixed time intervals of data recording: 5 sec
Threshold values for 'on-tripped' recording (resolutions):

- 0.5 kN for the external load
- 1 micron for each of the LVDTs
- 0.1 kN for the preload in the bolts.

3.10 Experiments realised within task1.2

For each of the GB, ASiZn and ZnSM series extra steel plates were produced for 8 extra specimens. A total of 28 (16+4+8) specimens were available for each series. The additional specimens were produced to have spare specimens in case of erroneous tests, to be able to experiment with the slip factor setups and to be able to perform additional tests for verification reasons.

In all other work packages of the SIROCO project the clamp length of the bolts will be 'standard' (48 mm for M20). A limited number of tests (4 for each surface) with HV 10.9 bolts with a clamp length of 48 mm was conducted on the TASK1.2 specimens as reference tests for the experiments in task2.1 (influence of preload level and bolt type on slip factor). From each series (GB, ASiZn and ZnSM) 2 specimens of the task1.2 batch were used in task2.1 as reference tests with HR bolts: HR8.8 and HR10.9.

Some of the extra specimens were used to gain more general insight in the behaviour of HSFG connections. Additional tests were performed on two GB specimen with single bolts using compressive and tensile loading. These tests were conducted to investigate if there is any difference in the results depending of the load orientation. This investigation is motivated by American code (RCSC, 2014) which states that the short term friction coefficient may be determined using compressive rather than tensile external loading. See Annex D: Influence of Compressive vs. Tensile Loading for the results and discussion on this topic. The goal of all additional tests is indicated in the three additional reports where the summary of performed experiments is shown.

Table 4 - Realized experiments within task1.2

CS 1.2		surface treatment / coating		
		Grit Blasted	ASiZn	Zn Spray metallized
		GB	ASiZn	Zn SM
test description/total # specimens:		28	28	28
slip factor tests clamping length = 152 mm	short term	11	12	11
	creep test	3	4	4
	special	-	-	1
	extended creep test	-	1	3
additional tests on series				
clamping length = 152 mm	single bolts in compression	2	-	-
	single bolts in tension	1	-	-
	stepwise compression - tension	2	-	-
clamping length = 48 mm	short term	2	3	2
	SSWLT	1	-	-
	reference tests for task2.1 (HR8.8)	2	2	2
	reference tests for task2.1 (HR10.9)	1	1	2
total # of experiment results		**25**	**23**	**25**
specimen to UDE / FAGP for additional testing		**0**	**3**	**1**
# specimens left		**2**	**0**	**1**
rejected results due to fault during testing		**1**	**2**	**1**
	total	**28**	**28**	**28**

The test results (graphs) of all individual specimens are presented in 3 separate reports (Stevin report 6-18-01 – Addition A, B and C). In these reports a short description is given of the type of test that was performed on each individual specimen. In Annex H: Example of presentation individual test results Additional Stevin Reports, an example of the presentation of each individual test results can be found.

All data files are available in raw and processed formats (Excel files).

4 Results

In Table 5 the results of task1.2 are summarised.

Table 5 - Test program and results task1.2 – influence of the test duration on the slip factor

Speed [mm/s]	Surface preparation: Sa[1] / Rz[2] [µm]	Surface preparation: DFT[3] [µm]	Σt[4] [mm]	Bolt type	Bolt size (Md × L)[5] [mm]	Test duration [min]	Number of tests st/ct[6]	$\mu_{ini,mean}$[7] st/st+ct [-]	$\mu_{act,mean}$[8] st/st+ct [-]	V (μ_{act})[9] st/st+ct [%]
Grit blasted surfaces (GB)										
0.01	Sa 2½ / 80	-	152	HV10.9	M20 × 180	5	8/2	0.72/0.72	0.79/0.80	2/2
0.005			48		M20 × 80	10	4/-	0.67/-	0.81/-	2/-
0.005			152		M20 × 180	11	6/2	0.77/0.78	0.84/0.85	1/2
0.0025			152		M20 × 180	24	4/-	0.79/-	0.85/-	3/-
0.001			152		M20 × 180	64	4/-	0.82/-	0.88/-	1/-
Alkali-zinc silicate coating (ASiZN)										
0.01	Sa 2½ / 80	60	152	HV10.9	M20 × 180	5	6/2	0.70/-	0.76/-	1/-
0.005			48		M20 × 80	9	4/2	0.68/-	0.75/-	1/-
0.005			152		M20 × 180	10	6/2	0.71/-	0.76/-	3/-
0.0025			152		M20 × 180	19	6/-	0.70/-	0.76/-	2/-
0.001			152		M20 × 180	49	6/2	0.72/-	0.78/-	1/-
Zinc spray metalized coating (ZN-SM)										
0.01	Sa 3/ 100	140	152	HV10.9	M20 × 180	6	6/2	0.76/-	0.82/-	2/-
0.005			48		M20 × 80	10	4/-	0.74/-	0.83/-	4/-
0.005			152		M20 × 180	11	6/2	0.76/-	0.83/-	3/-
0.0025			152		M20 × 180	20	4/-	0.72/-	0.78/-	3/-
0.001			152		M20 × 180	45	4/-	0.69/-	0.75/-	2/-
0.0005			152		M20 × 180	95	4/-	0.69/-	0.74/-	1/-

[1] Sa: surface preparation grade | [2] Rz: roughness | [3] DFT: dry film thickness (Coating thickness) | [4] Σt: clamp length [5] d: bolt diameter, l: bolt length | [6] st: static test/ct: creep test | [7] $\mu_{ini,mean}$: calculated slip factors as mean values based on the initial preload w hen the tests started | [8] $\mu_{act,mean}$: calculated slip factors as mean values based on the actual preload at slip (friction coefficients) | [9] V: Coefficient of variation for μ_{act} | * Nominal level of preload: $F_{p,C}$ = 172 kN

Results overview tables and statistical evaluation of the slip tests for all three specimen series per load duration can be found in:

- Annex E: Overview results GB series
- Annex F: Overview results ASiZn series
- Annex G: Overview results ZnSM series

Graphical representations of the results of all slip factor tests can be found in additional Stevin reports (Stevin report 6-18-01 – additon A, B and C).

5 Discussion

5.1 Influence of test duration

From the graphical representation of the results in Figure 1 it can be seen that there is a vague tendency of increase of the slip factor of grid blasted (GB) specimen for longer test durations. For the ASiZn and ZnSM specimen the short term slip factor remains constant or decreases when the test lasts longer. Statistical evaluation of the results show that the difference in slip factor for test durations of 5 (0.01 μm/s) and 60 minutes (0.001 μm/s) is statistically significant for the GB and ZnSM series (result T test with confidence level of 5%). For the ASiZn specimen series the differences are not statistically significant. This conclusion can be drawn for all slip factors, μ_{ini}, μ_{nom} and μ_{act}.

Within the variation of the duration of slip factor tests that can be expected in practice (±5 minutes on the 10 – 15 minute range specified by EN 1090-2 Annex G), the influence of the test duration on the slip factor is very small (negligible). On the bases of linear regression the differences are ±1,5% relative to the slip factor found for test with a load duration of 12,5 minutes.

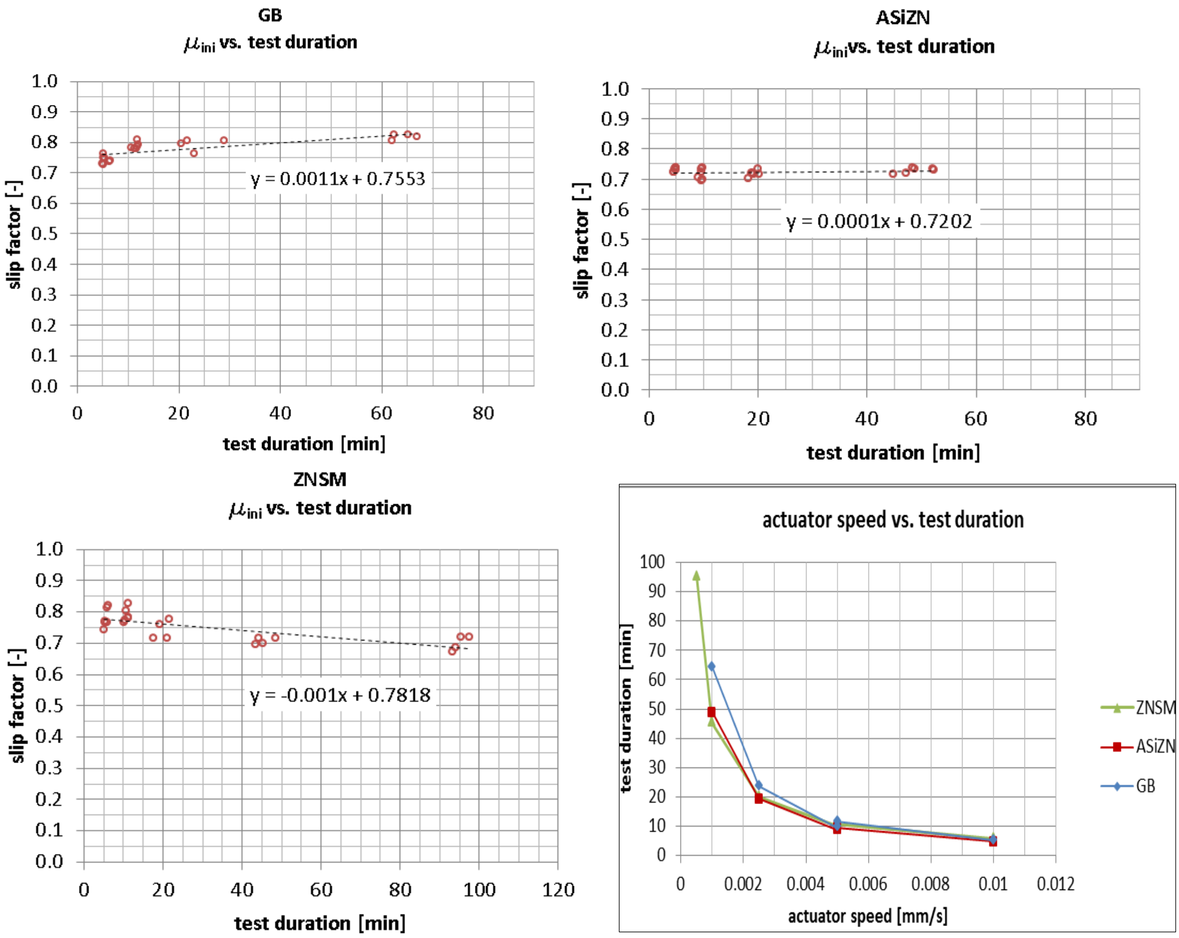

Figure 1 – Short term initial slip factor as a function of test duration. Bottom right: test duration as a function of loading (actuator) speed.

The first specimen of a new surface roughness/coating series of short term slip factor tests is necessary to determine the correct speed of testing. If the load duration of these initial tests is in the range of 5 to 20 minutes (Figure 2), the test results can be used as part of the series of 4 short term tests. If the load duration is outside this time window, the test result can be used to linearly interpolate or extrapolate the required loading speed.

5.2 Comparison to other codes

When the slip loads that were established during the short term tests are calculated back to elapsed time using the loading speeds (kN/min) that are proposed in the codes defined in Table 1, the corresponding loading speed in mm/s can be determined from Figure 2. Since all three coating systems have approximately the same short term slip load (≈500 kN), the corresponding loading speeds are roughly the same. It appears that for the specimens under consideration, the suggested loading speed from the British Standard leads to a test duration (10,6 minutes) that is well in line with the current EN1090-2 requirements. If the maximum loading speeds from the Australian and American codes would have been used, the tests would have lasted only 5 and 2 minutes, respectively.

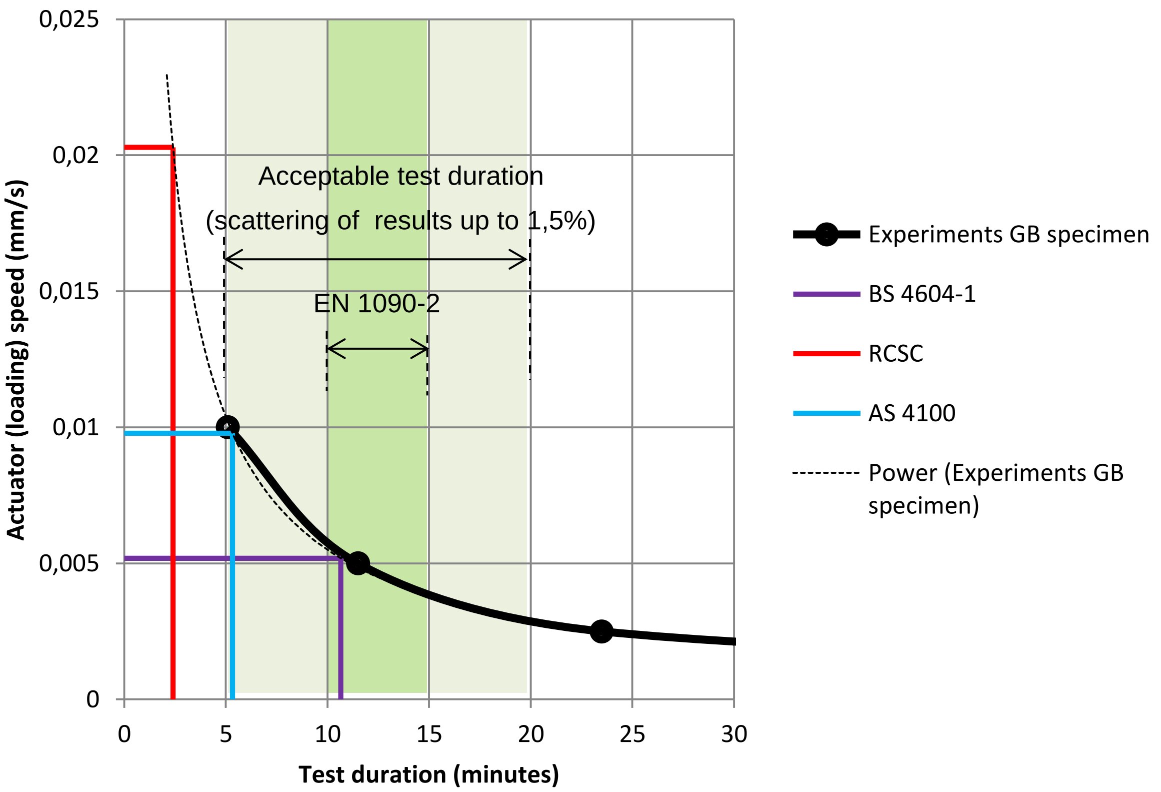

Figure 2 - Test duration based on American, Australian and British Standards for the short term tests (averaged) on grit blasted (GB) specimen.

5.3 Slip factors, clamp length

The slip factors presented in Table 5 are relatively high compared to values known from literature [1], [2], [10]. This is partly caused by the extended clamp length that was used in the tests in this research (152 mm).

The results on the GB specimens with 48 mm clamp length show a clear reduction of the slip factor μ_{ini}, compared to the results of the tests with the 152 mm clamp length. The results for μ_{act} (the 'actual slip factor' which is based on the actual preload when the slip criterion is reached) that are found for in the experiments with the 48 mm clamp length are well in line with the values that were found in the 152 mm experiments.

In Annex C a method is described to quantify the influence of the clamp length on the slip factor of uncoated surfaces.

5.4 Influence of test duration on scatter

The scatter of the short term results does not appear to be significantly dependent on the loading speed, as can be derived from Figure 3. The coefficient of variation (COV) is in all cases between 1,0% and 3,5% within each subgroup.

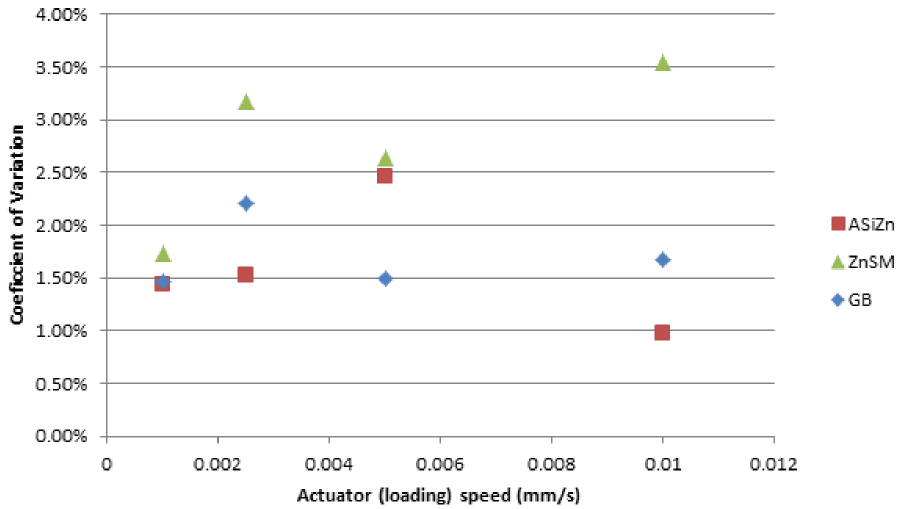

Figure 3 - Coefficient of Variation (COV) as a function of loading speed and specimen coating

5.5 Creep tests

No influence was found of the test duration on the result of the test to determine the sensitivity to creep. The creep tests passed (slip in 3 h < 2μm) for the grit blasted (GB) surfaces. The creep tests on the ASiZn and ZnSM series clearly showed that these coatings are sensitive to creep. This conclusion could be drawn independent of the speed at which the creep load was applied.

6 Conclusions

In task1.2 of the SIROCO project a comparative study has been performed to the influence of the duration of the short term slip factor tests. It was anticipated that the test duration could be of influence on:

- The slip factor for non-creep sensitive surfaces

- The outcome of the creep test
- The scatter in the results of the short term slip factor tests

From the test results the following conclusions can be drawn:

1. When the CBG criterion is used to determine the slip factor, for grit blasted specimens there is a tendency of a slightly higher slip factor for longer test durations. For the zinc spray metalized surfaces the opposite effect was found and for the alkali-zinc coated surfaces no effect of the test duration is found. No general conclusion on the influence of the test duration can be drawn.

2. For variations in the test durations of ±5 minutes compared to the 10-15 minute time frame given by EN 1090-2, the influence of the test duration on the slip factor is ±1,5% compared to the slip factor that is found for a test duration of 12,5 minutes.

3. No influence of the test duration on the scatter in the results of the short term slip factor tests was found.

4. No effect of the loading speed on the result of the test to determine the sensitivity to creep was found.

5. Based on the results obtained within task1.2 the slip factor tests should be determined:
   - Displacement controlled load application
   - Test duration will be “between 10 and 15 minutes”

6. Given the variation in slip factors found in practise, it is impossible to specify a loading speed at which slip factor test should be carried out. When slip factor tests are to be performed on a new coating system or surface treatment, the load head speed of the test rig used must be determined. The correct loading speed (mm/s) of the test equipment has to be estimated by performing an initial test on the coating system. The loading speed used in this initial test can be based on prior knowledge or otherwise estimated. Unless the load duration of the initial test is outside a time frame ranging from 5 to 20 minutes, the results of the initial test can be used as part of the series of 4 short term tests.

7 References

[1] Gruintjes, T.J.J., Bouwman, L.P., Slip factors of structural connections formed with high strength friction grip bolts and with contact surfaces treated in various ways, report 6-84-10 TU Delft, Steven Laboratory – Steel Structures, 1984

[2] Kulak, L. et al, Guide to Design Criteria for Bolted and Riveted Joints, AISC, 2001

[3] EN 1090-2:2008, Execution of steel structures and aluminium structures – Part 2: Technical requirements for steel structures

[4] EN 1993-1-4:2006 – Eurocode 3: Design of steel structures - Part 1-4: General rules - Supplementary rules for stainless steels

[5] EN 1993-1-8:2005 - Eurocode 3: Design of steel structures – Part 1-8: Design of joints

[6] EN 14399-2:2005, High-strength structural bolting assemblies for preloading – Part 2: Suitability test for preloading

[7] EN 14399-3:2005, High-strength structural bolting assemblies for preloading – Part 3: System HR – Hexagon bolt and nut assemblies

[8] EN 14399-4: High-strength structural bolting assemblies for preloading – Part 4: System HV – Hexagon bolt and nut assemblies

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[17] Vries, P.A. de. Results of slip factor tests on Grit Blasted steel plates. Delft university of Technology, report 6-18-01 – addition A

[18] Vries, P.A. de. Results of slip factor tests on Alkali Silicate Zinc coated steel plates. Delft university of Technology, report 6-18-01 – addition B

[19] Vries, P.A. de. Results of slip factor tests on Zinc spray metallized steel plates. Delft university of Technology, report 6-18-01 – addition C

8 Annex A: Experimental set-up of HSFG connections

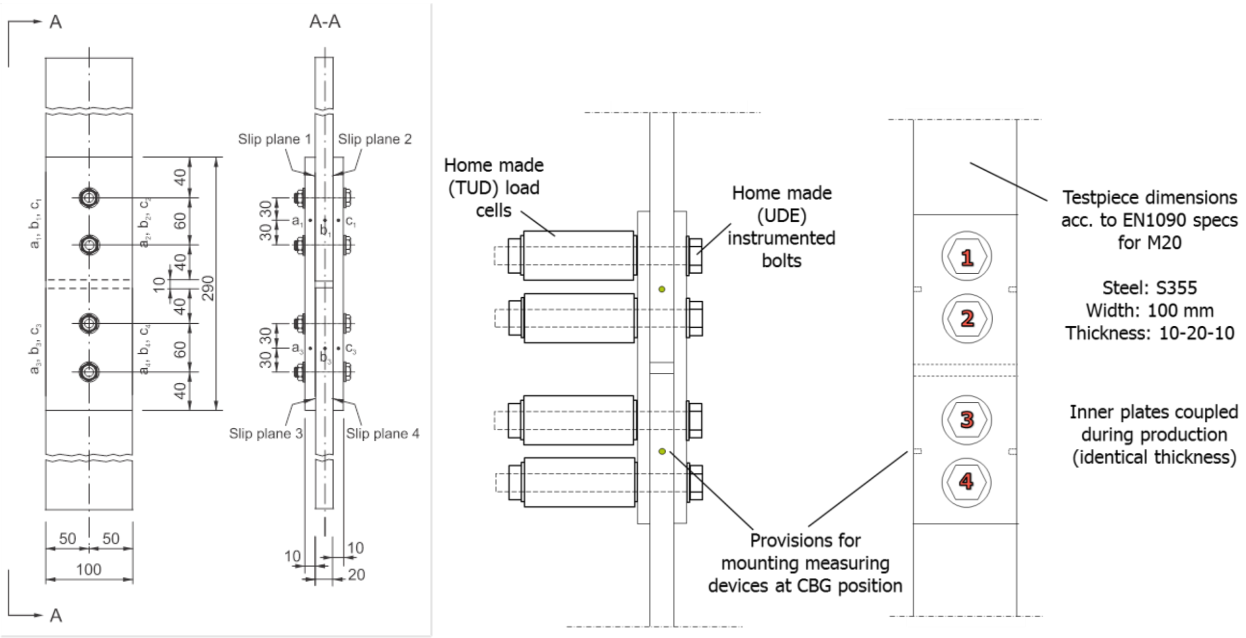


Figure 4 - Specimen dimensions

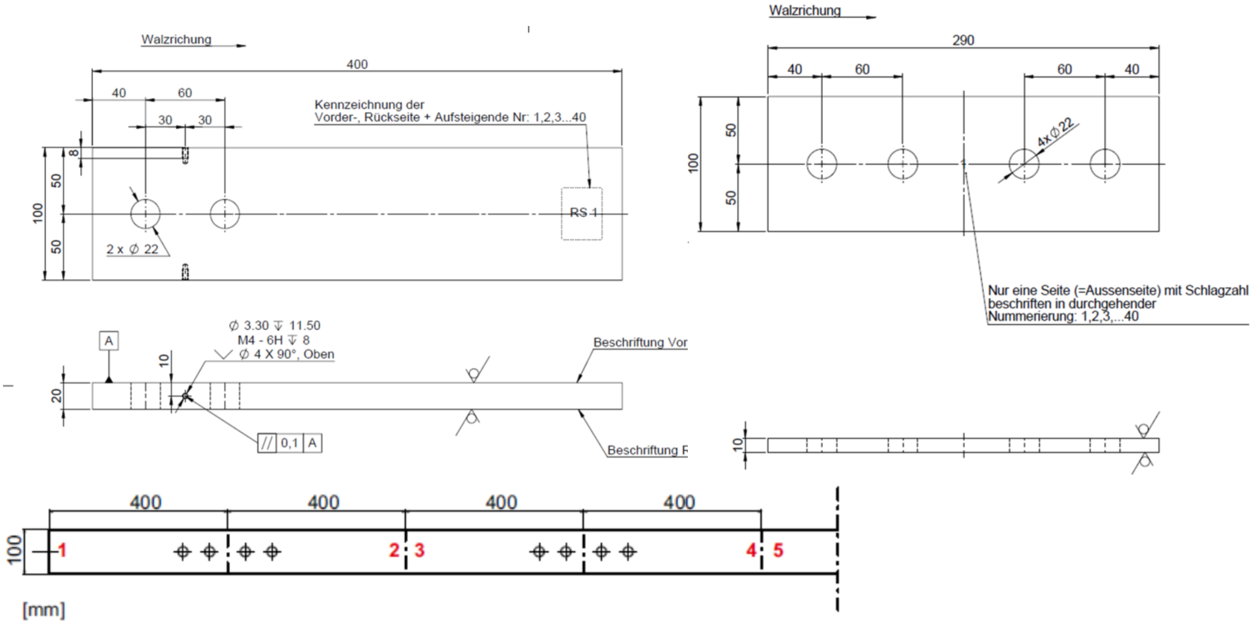


Figure 5 - Specimen dimensions

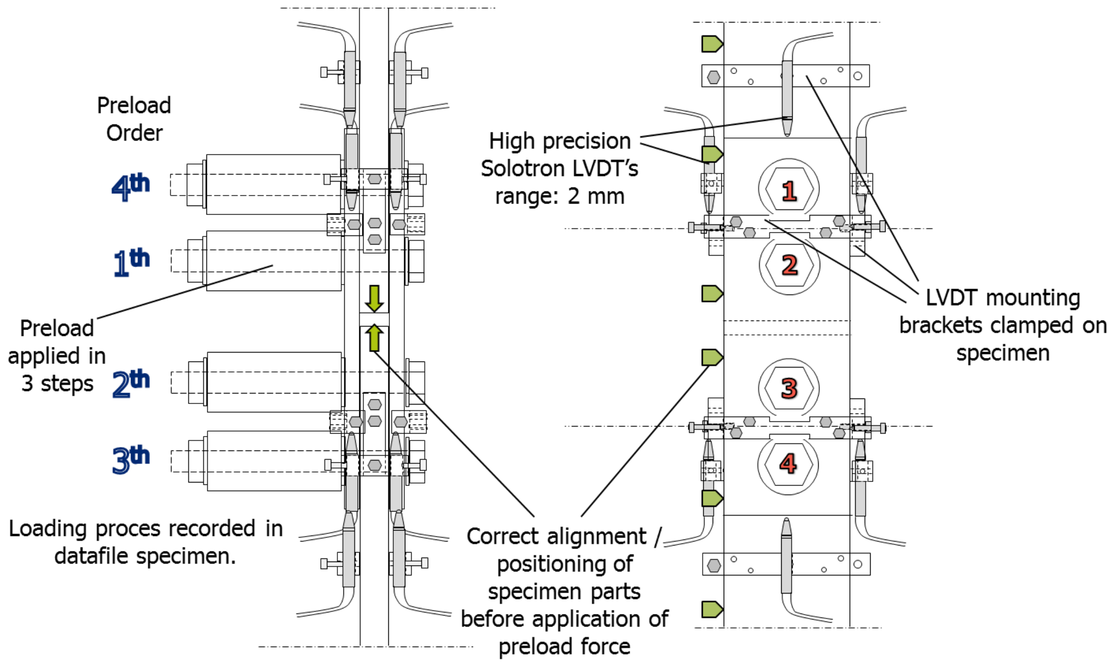


Figure 6 - Order of preload application, mounting brackets LVDT's, bolt numbering

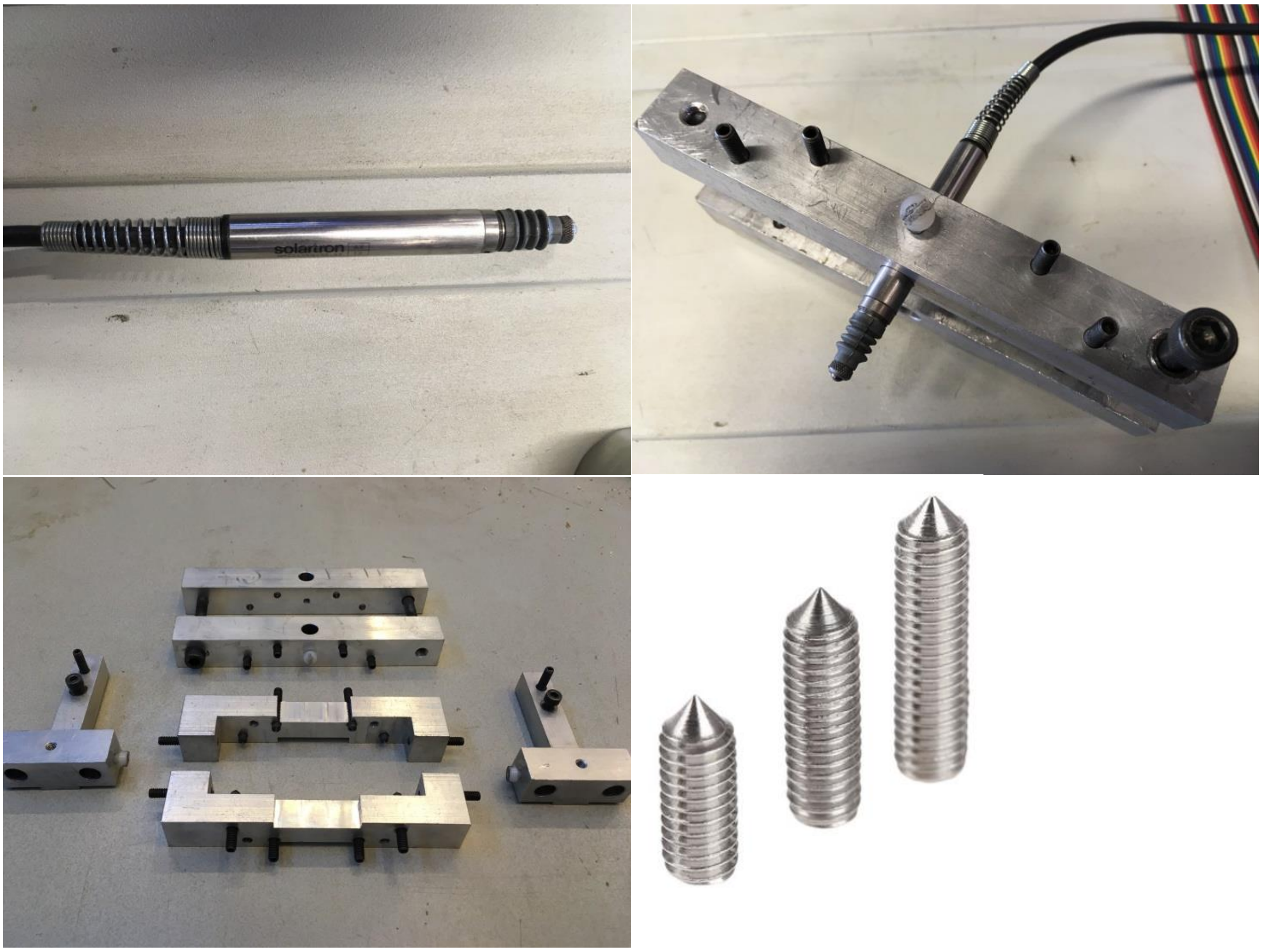


Figure 7 - Solartron AX 1.0 LVDT used for all slip measurements, various mounting brackets LVDT's. Lower right picture: Sharp tip allen screws were used to clamp/fixate mounting brackets to centre and lap plates

Figure 8 - Instrumented bolts M20,class10.9, TUD home made load cell (L=100mm); fully instrumented 'top connection' of a specimen

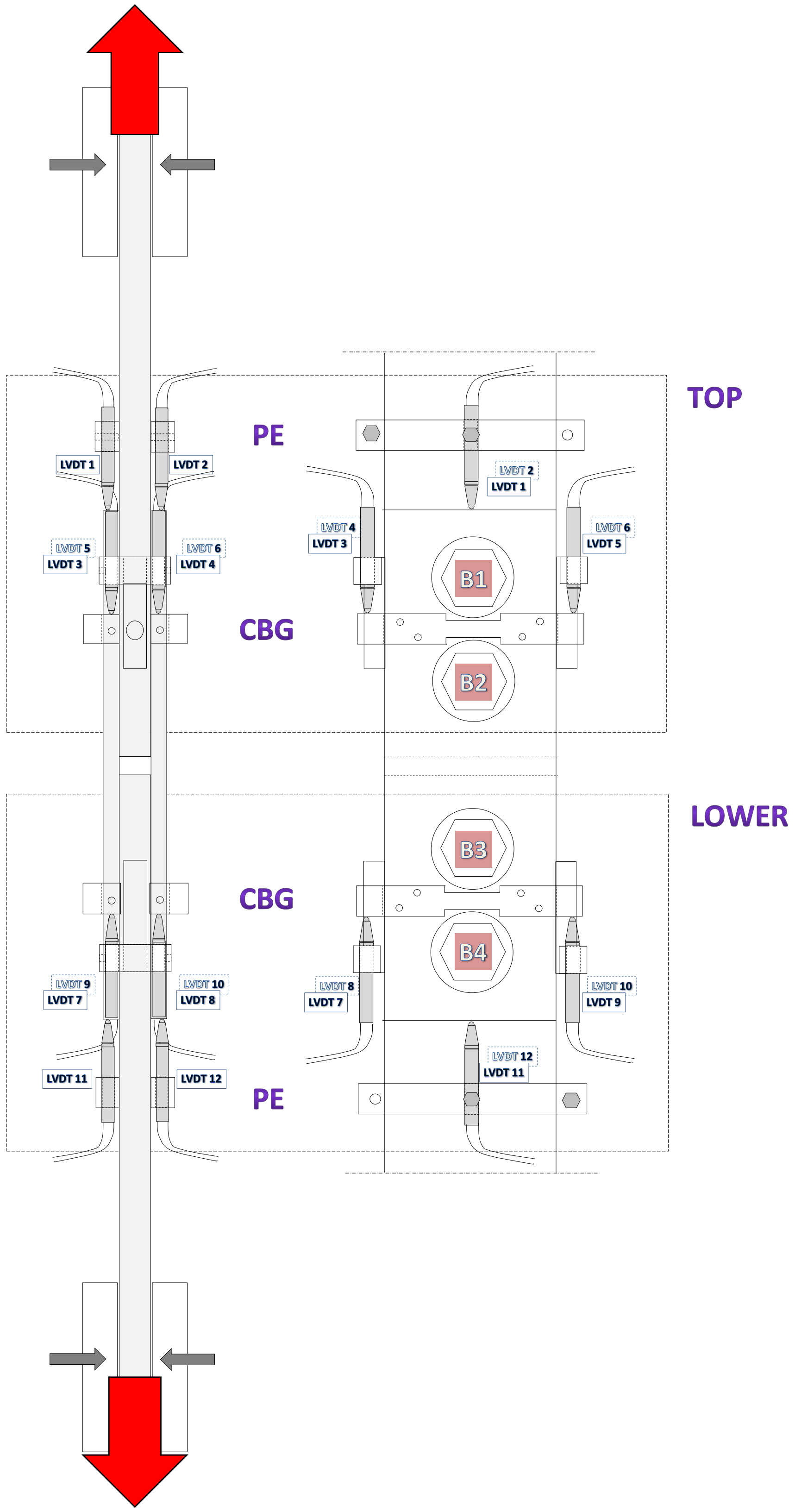


Figure 9 - Top / Lower connection, slip measurement positions: PE (Plate Edge) and CBG (Centre Bolt Group)

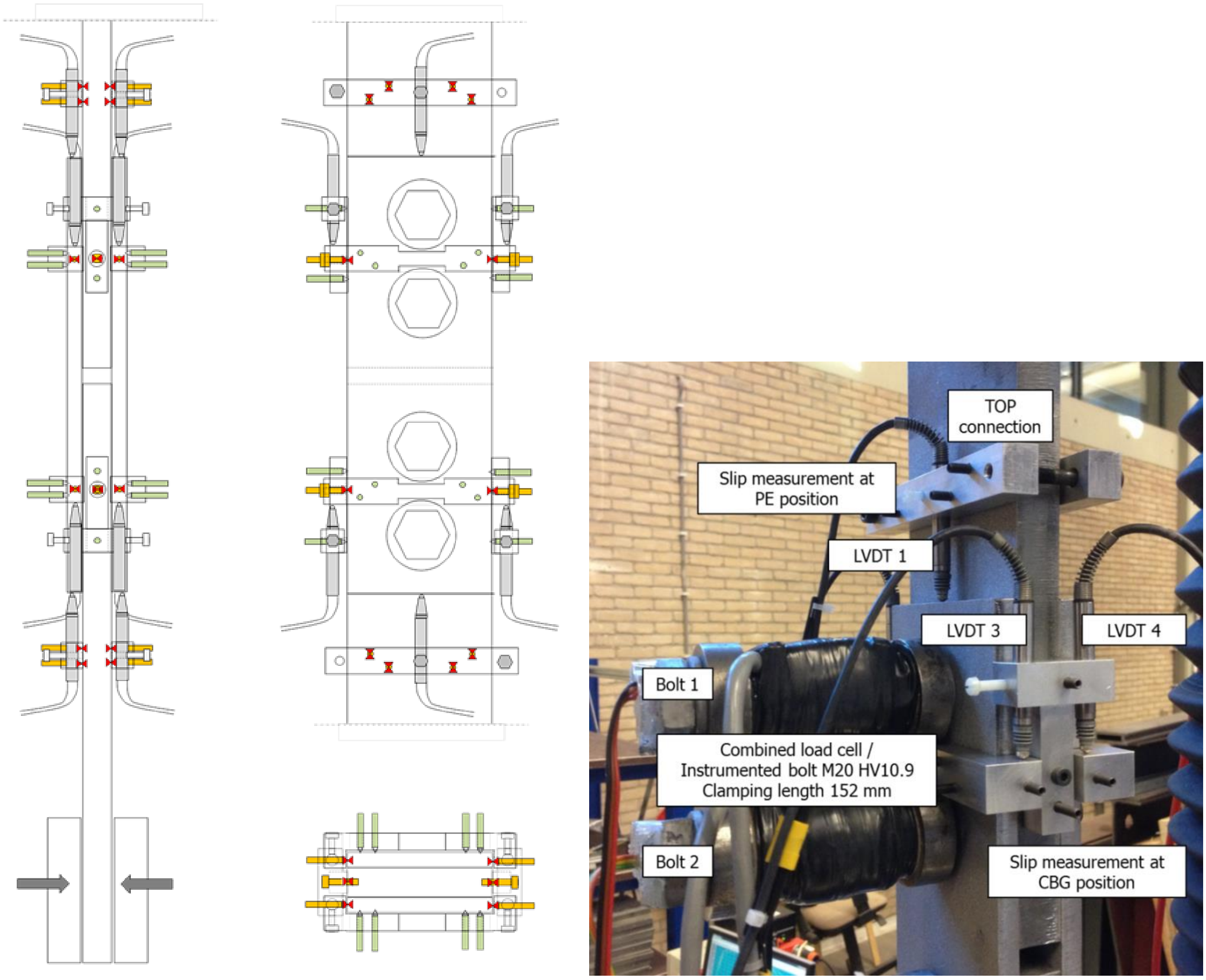


Figure 10 – Left: Marked red: fixation points mounting brackets; Right: Numbering of LVDT's at PE and CBG locations on 'top connections';

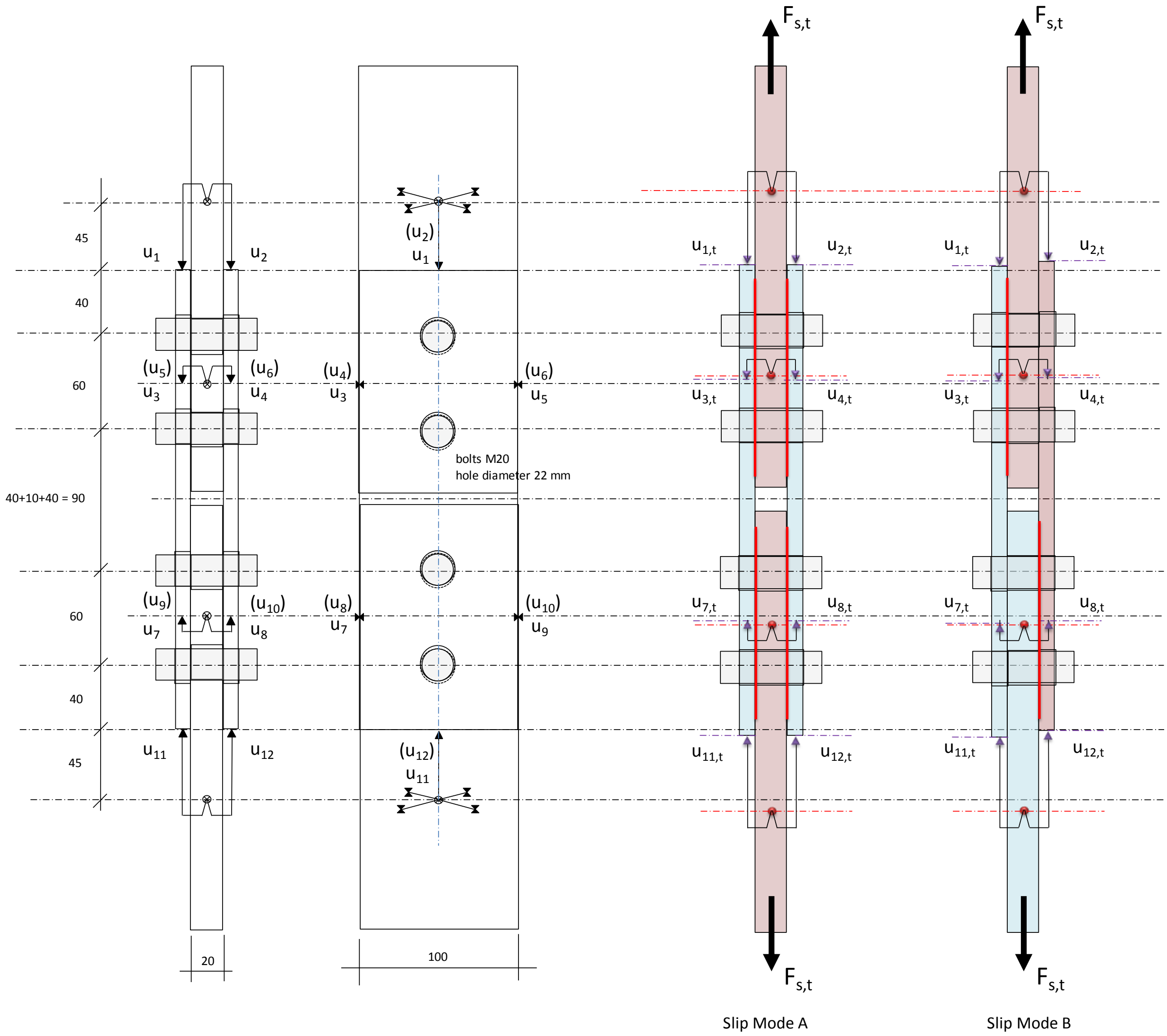


Figure 11 - Fixation points / numbering of LVDT's / technical possible slip modes	**Left: Slip mode A, equal slip at both plate interfaces.** **Right: Slip mode B, severely unequal slip at both interfaces. Did not occur in any of the tests.**

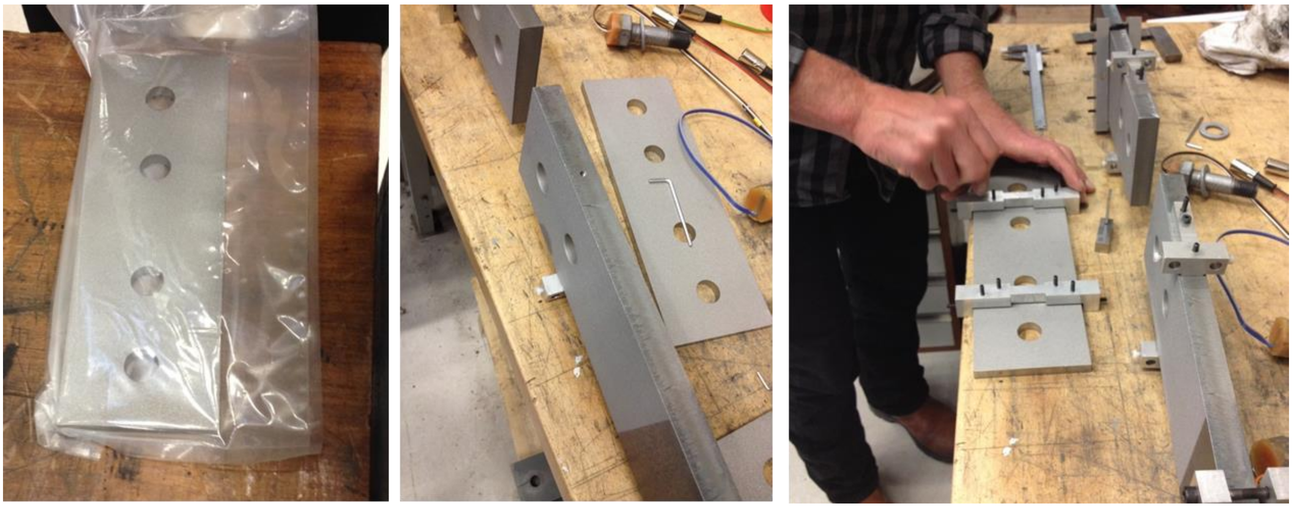


Figure 12 - Specimen assembly, mounting LVDT brackets

Figure 13 - Specimen assembly: alignment of centre / lap plates prior to pre-tensioning

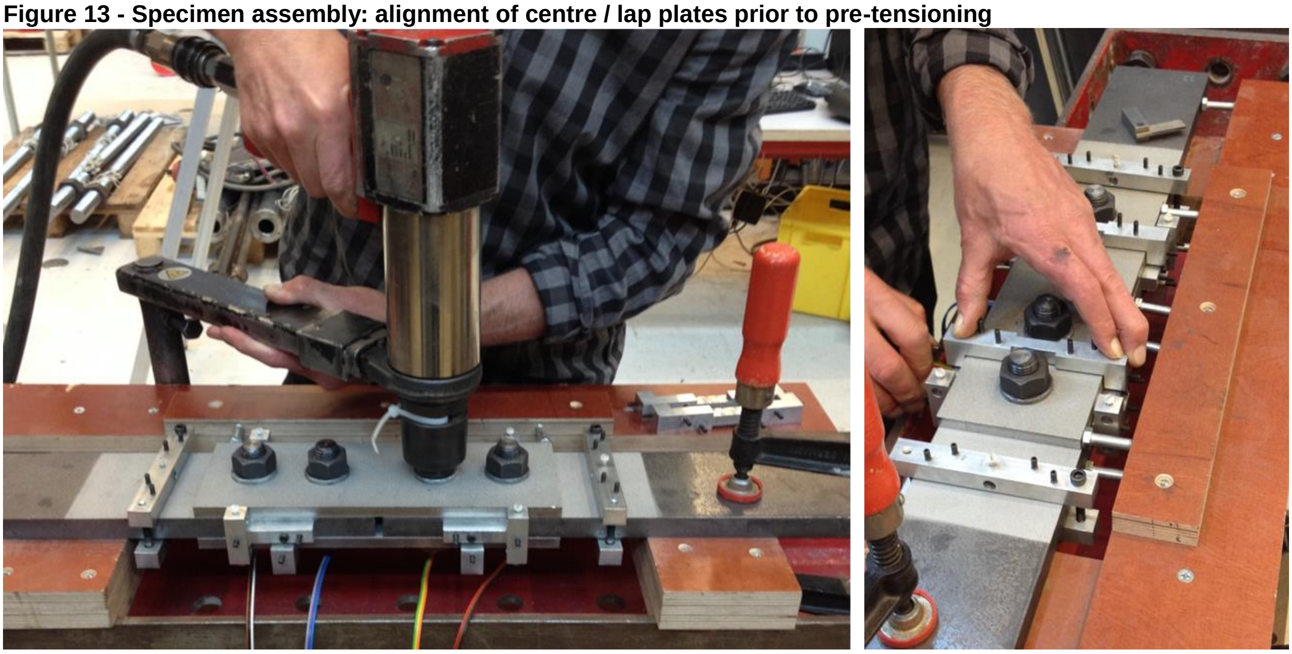


Figure 14 - Application of pretension using air driven torque tool; mounting of LVDT brackets on lap plates

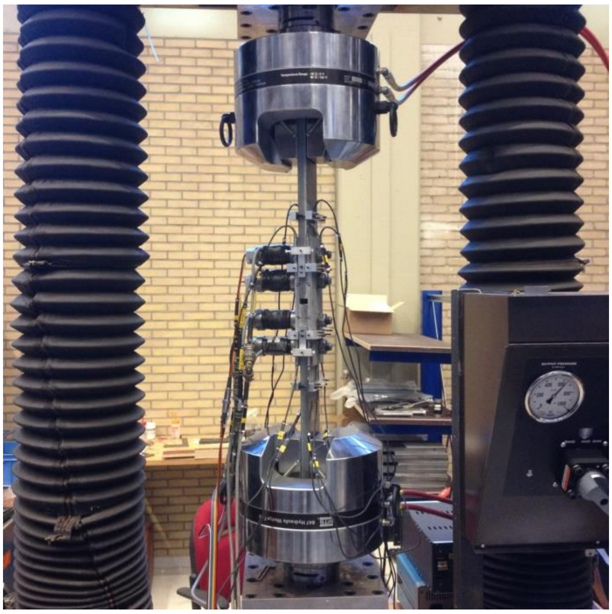
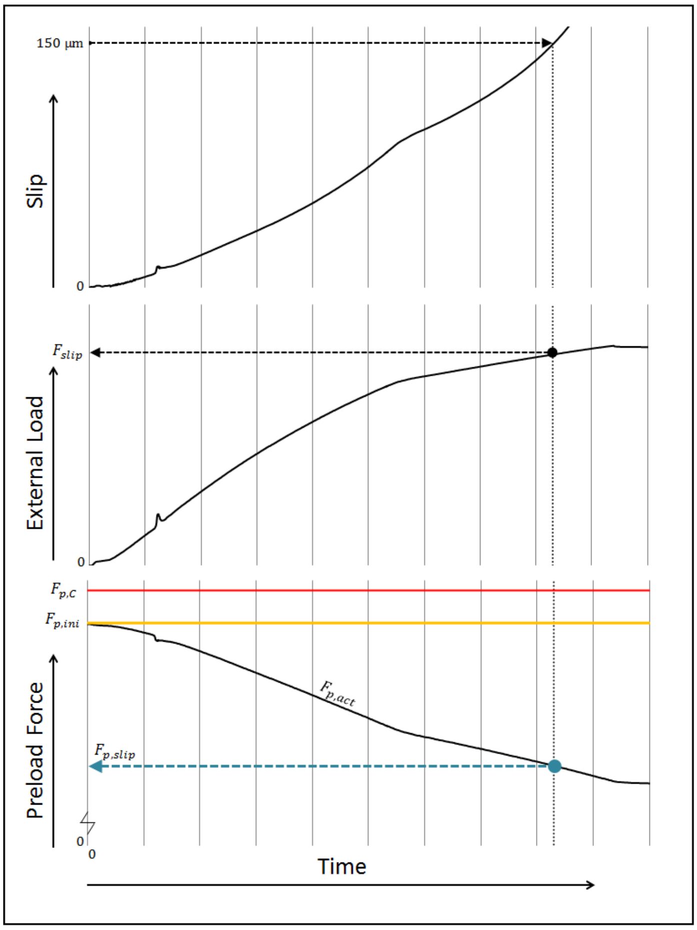


Figure 15 - Overview of test setup (600kN Schenck general purpose testing machine with MTS hydraulic clamping devices). Slip factor test specimen ready for testing.



$$\mu_{nom} = \frac{F_{slip}}{4 \cdot F_{p,C}}$$

$$\mu_{ini} = \frac{F_{slip}}{4 \cdot F_{p,init}}$$

$$\mu_{act} = \frac{F_{slip}}{4 \cdot F_{p,slip}}$$

Figure 16 - Overview of determination of different slip factors. The slip load is defined at 0,15 mm (150 µm) of CBG slip.

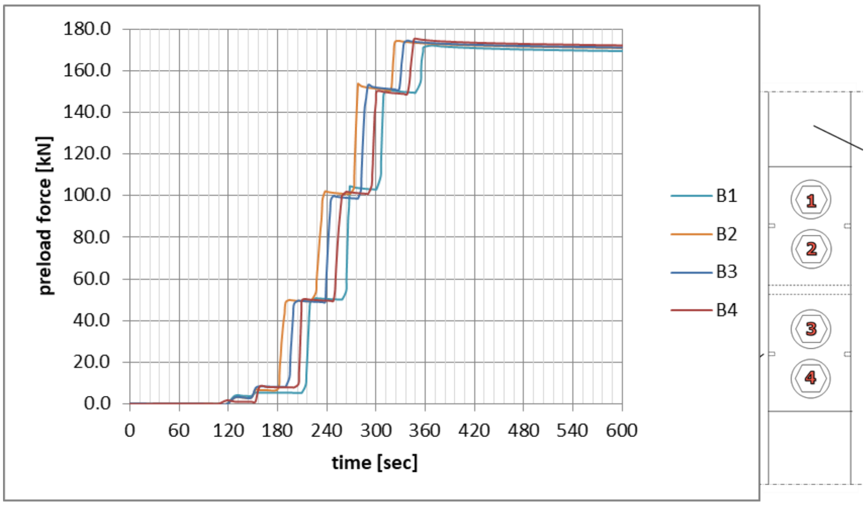


Figure 17 - Typical example of preload application process. Load was applied in 4 steps from 0 to $F_{P,C}$. Order: B2-B3-B4-B1. Typical time frame in which the preload was applied: 3 minutes.

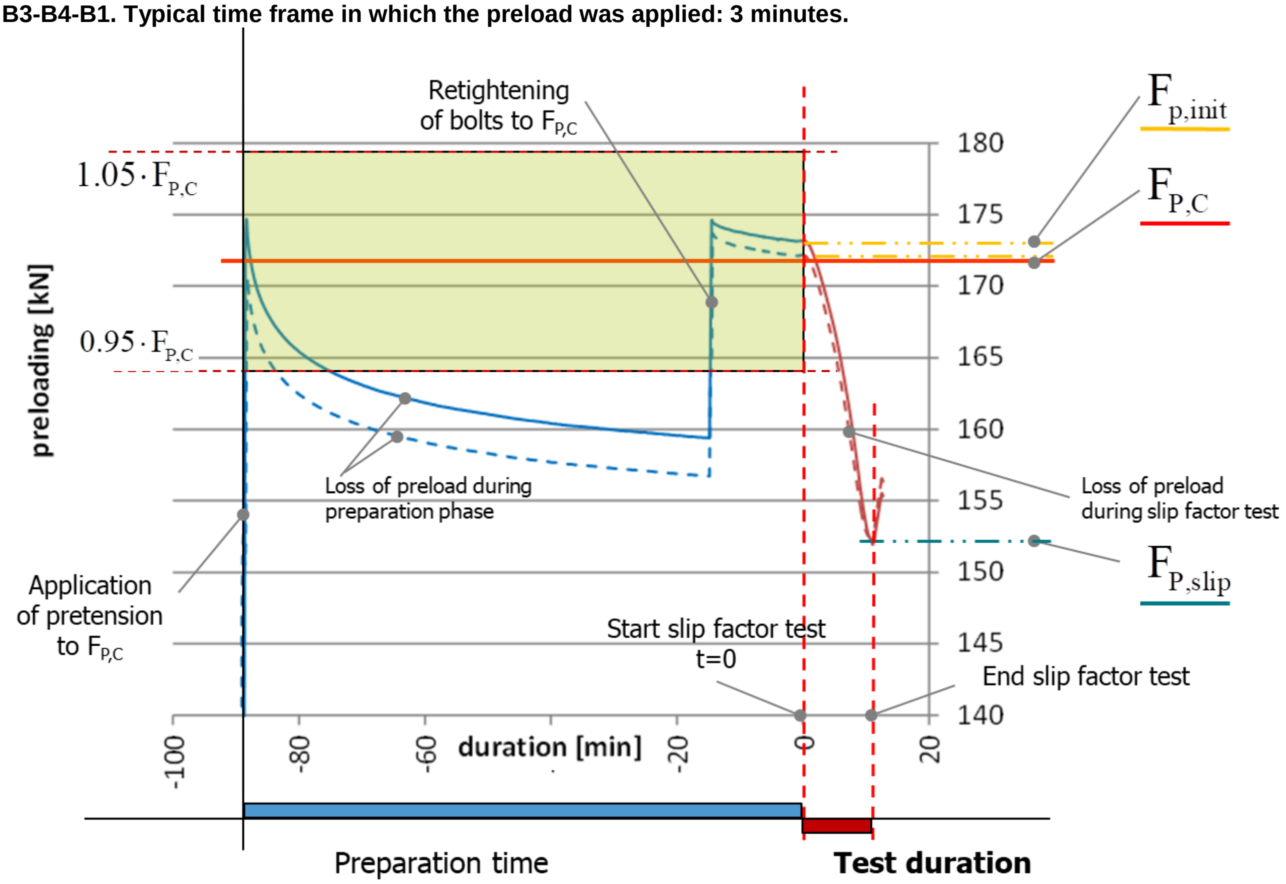


Figure 18 - Test protocol: application of preload, preparation time (waiting period >= 30 min), retightening (only when preload drops below $0.95F_{P,C}$ during waiting period), execution of slip factor test.
Preload losses are observed directly after application of preload (bolt settling, creep of coating) and during execution of slip factor test.

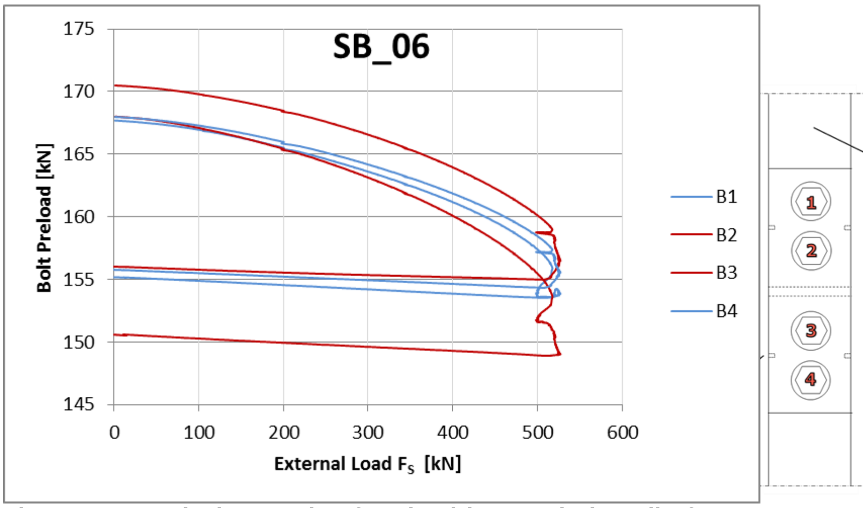


Figure 19 - Typical example of preload losses during slip factor test on GB specimens with long bolts (clamp length 180 mm). At the start of the test (F_S=0 kN) the preload in all bolts is between 168 kN and 171 kN. When the maximum external loading is reached (F_S=520 kN) preload losses in the external bolts (B1 and B4) and internal (B2 and B3) are approximately 6% and 7% respectively (Annex E: Overview results GB series). The elastic recovery of the preload that results from the release of the external load (effect of inverse lateral contraction) is very small (<1%). Specimen ID: SB_06.

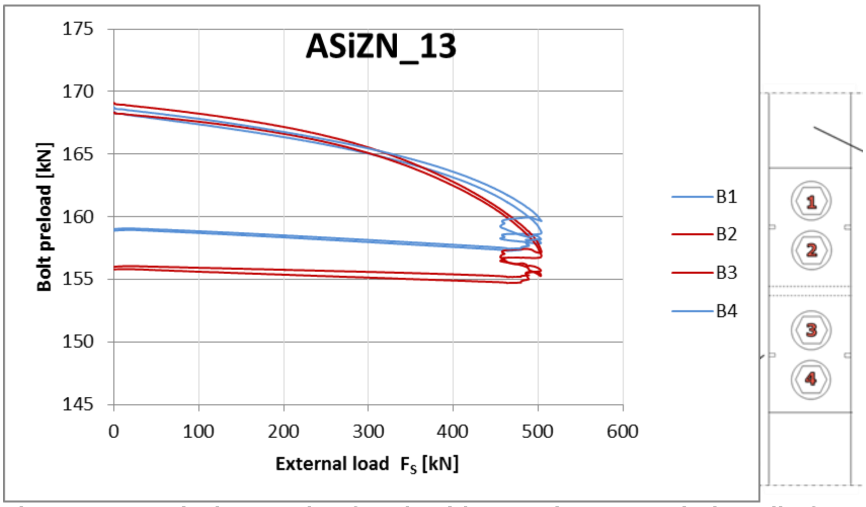


Figure 20 - Typical example of preload losses that occur during slip factor test on ASiZN specimens with long bolts (clamp length 180 mm). At the start of the test (F_S=0 kN) the preload in all bolts is approximately 168 kN. When the maximum external loading is reached (F_S=500 kN) preload losses in the external bolts (B1 and B4) and internal (B2 and B3) are approximately 5% and 6% respectively (Annex F: Overview results ASiZn series). The elastic recovery of the preload that results from the release of the external load (effect of inverse lateral contraction) is very small (<1%). Specimen ID: ASiZN_13.

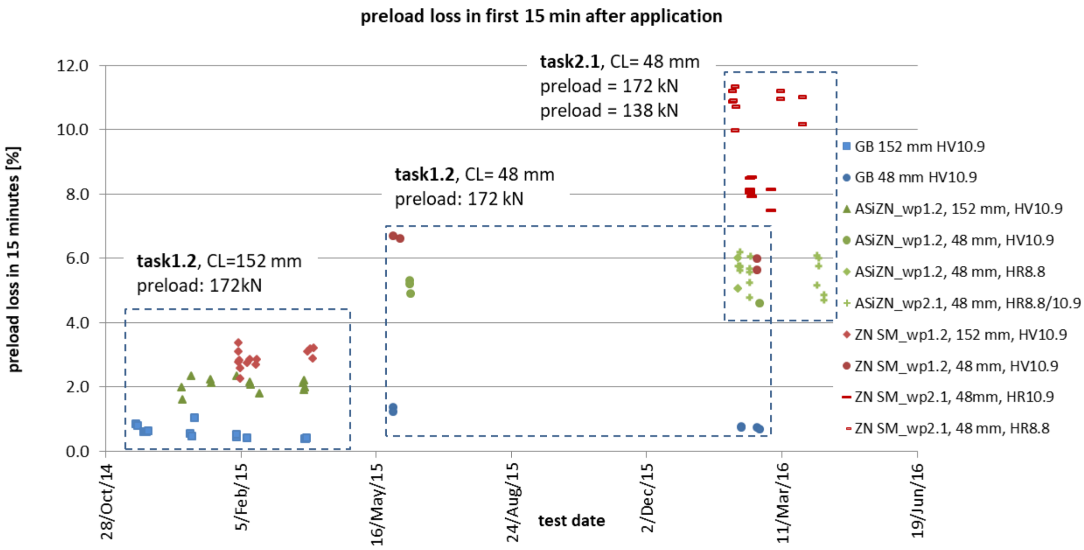


Figure 21 - Initial preload losses. Loss of preload 15 minutes after preloading to $F_{P,C}$. Illustration of influence of clamp length (152 mm vs 48 mm) on initial preload losses. Illustration of influence of preload level (172 kN vs 138 kN) on initial preload loss.

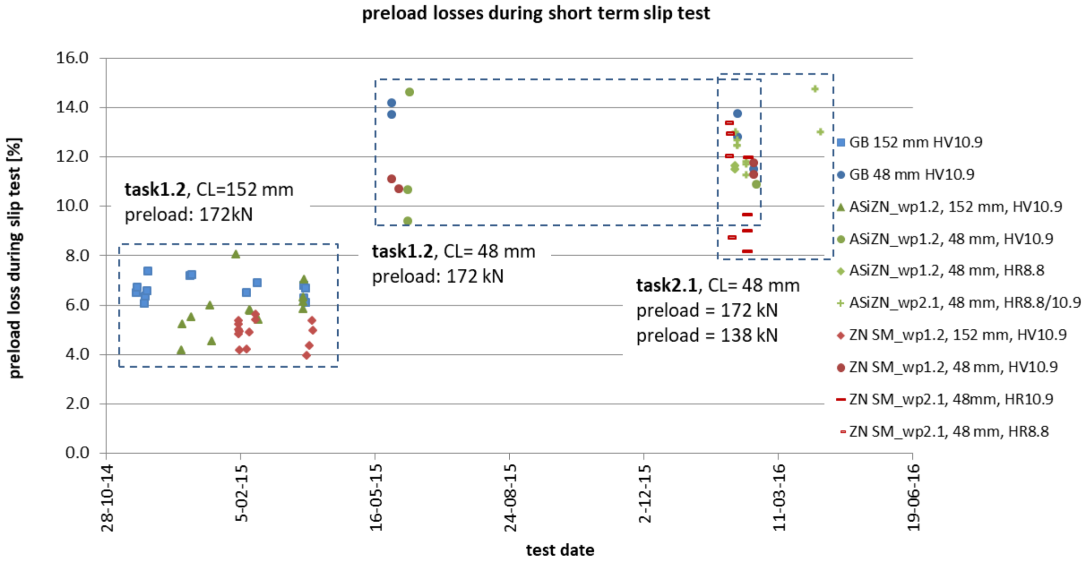


Figure 22 - Preload losses during execution of slip factor test. Illustration of influence of clamp length (152 mm vs. 48 mm) on preload losses. Illustration of influence of preload level (172 kN vs 138 kN) on losses during execution of slip factor test.

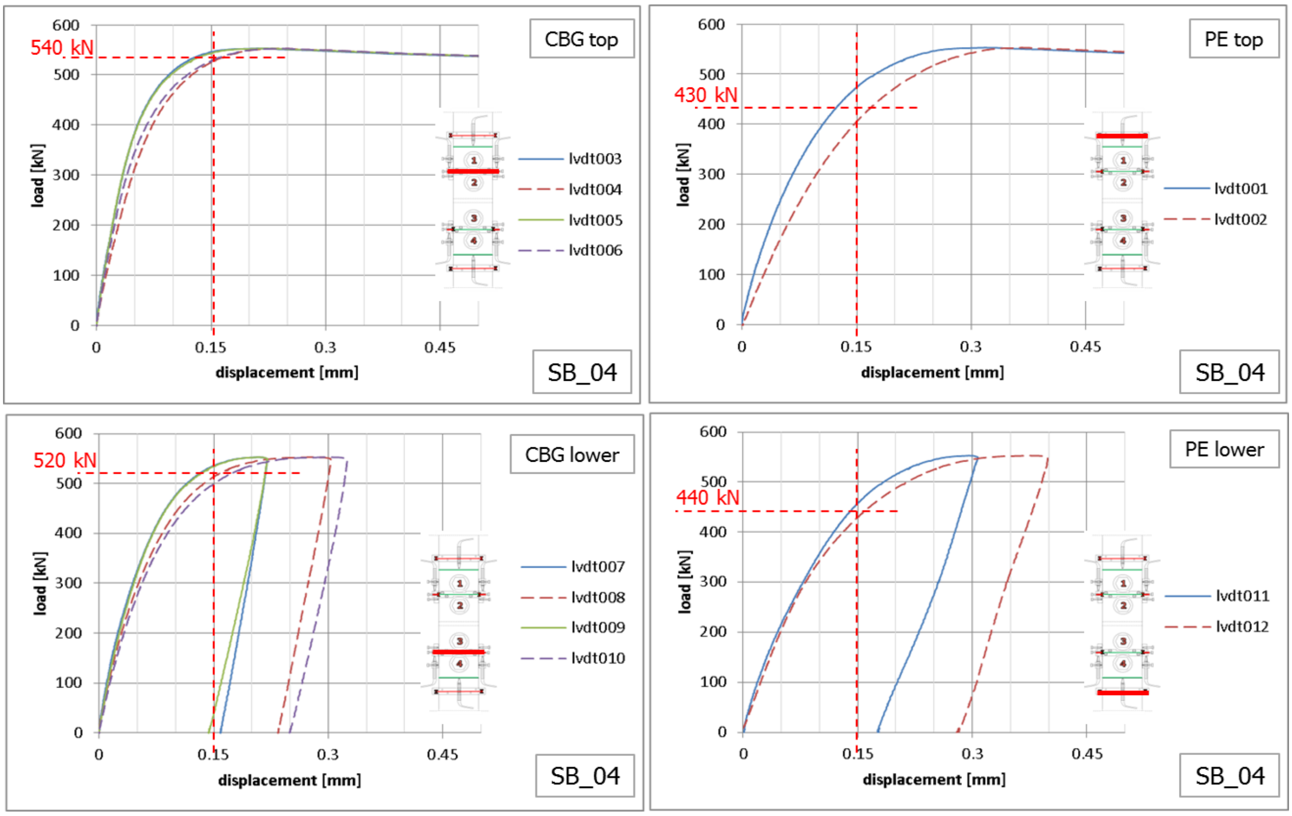


Figure 23 - Illustration of difference between evaluation of slip factor test based on CBG and PE slip measurements. Grit blasted specimen. For GB series the CBG based evaluation results in approx. 20% higher slip factor.

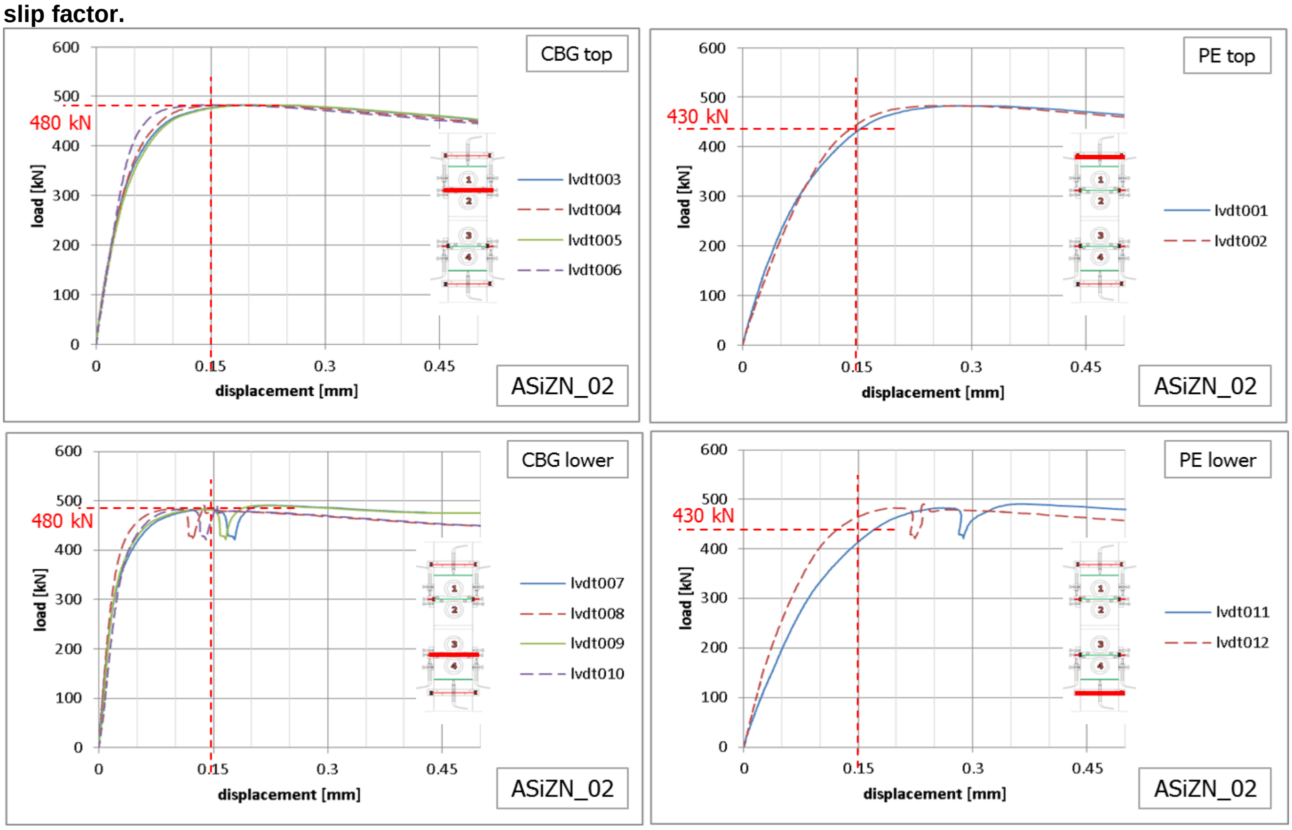


Figure 24 - Illustration of difference between evaluation of slip factor test based on CBG and PE slip measurements. AlcaliSilica Zinc coated specimen. For ASiZn series the CBG based evaluation results in approx. 10% higher slip factor.

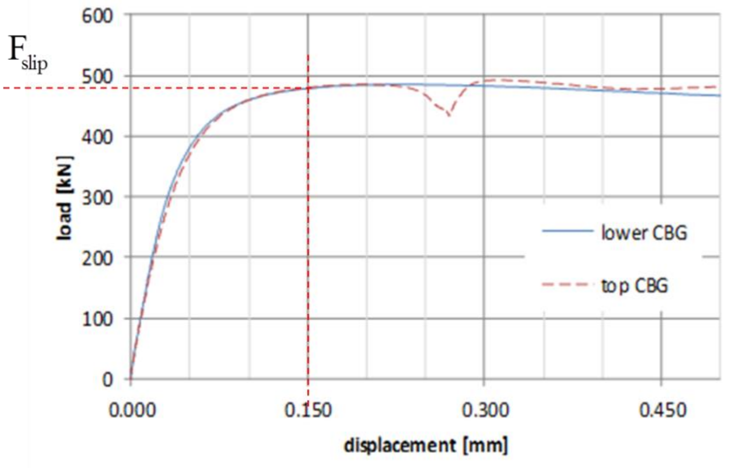


Figure 25 - Load-slip diagram indicating the slip load based on the 0,15 mm displacement criterion at CBG.

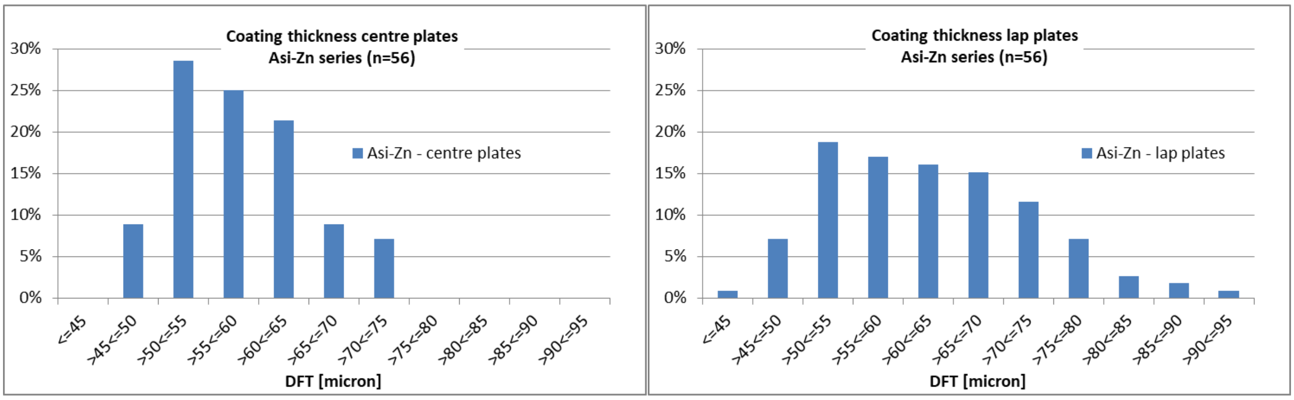


Figure 26 - Dry Film Thickness Alkali Zinc Silicate specimens (task1.2 ASiZN series).
Left centre plates, right lap plates.
Coating thickness centre plates average: 61 μm, stdev: 9 μm.
Coating thickness lap plates average: 63 μm, stdev 11 μm

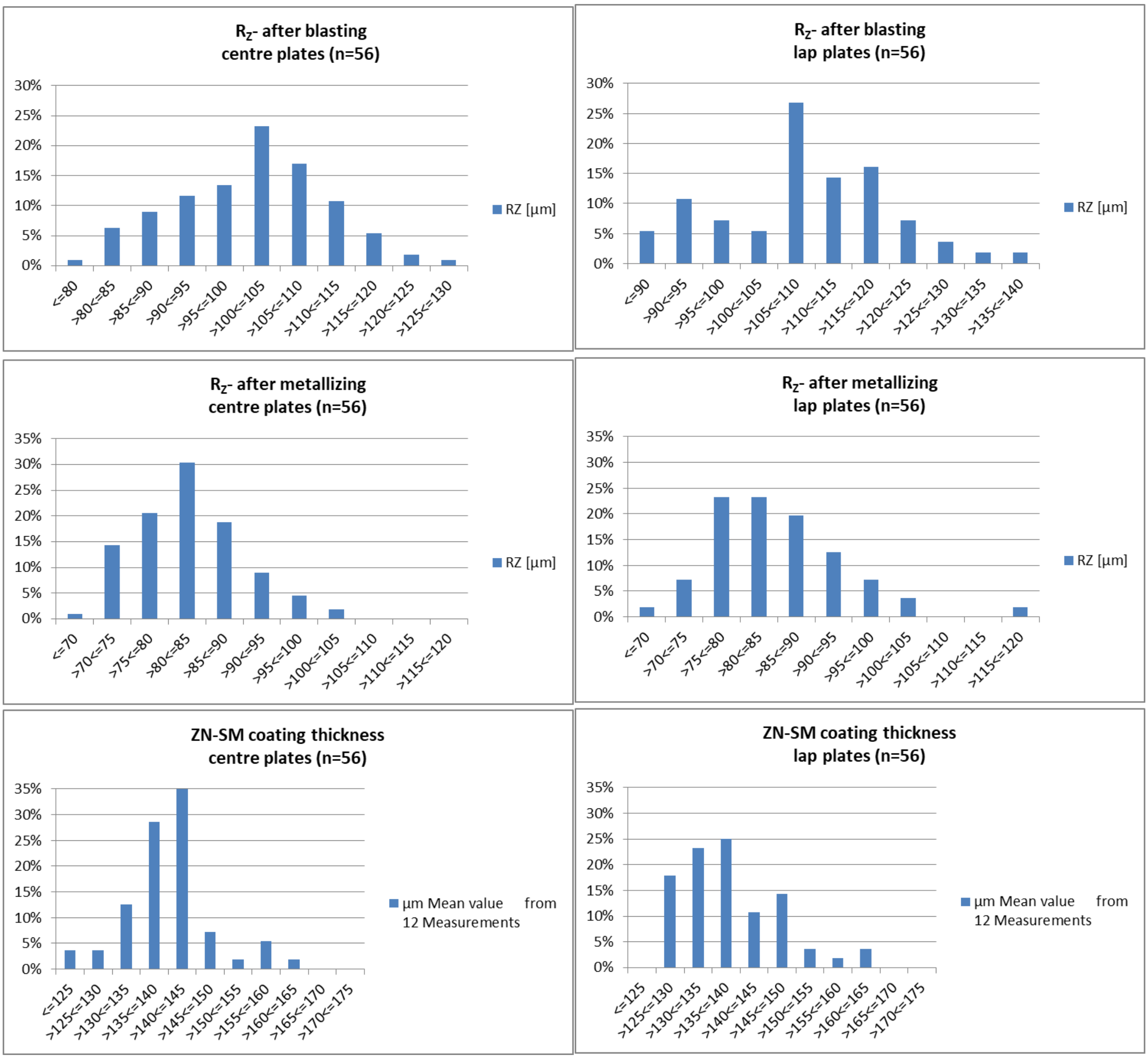


Figure 27 - Surface roughness and coating thickness Zinc Spray Metallized specimens (task1.2 ZN-SM series). Diagrams on the left: centre plates, on the right: lap plates.
Surface roughness after blasting: centre plates: average Rz: 101 µm ,stdev 10 µm ,lap plates: 109, stdev 11.
Surface roughness after metallizing: centre plates: average Rz 83 µm,stdev 7 µm, lap plates: 85, stdev 9.
Coating thickness: centre plates: average 140 µm,stdev 8 µm, lap plates: 138, stdev 8.

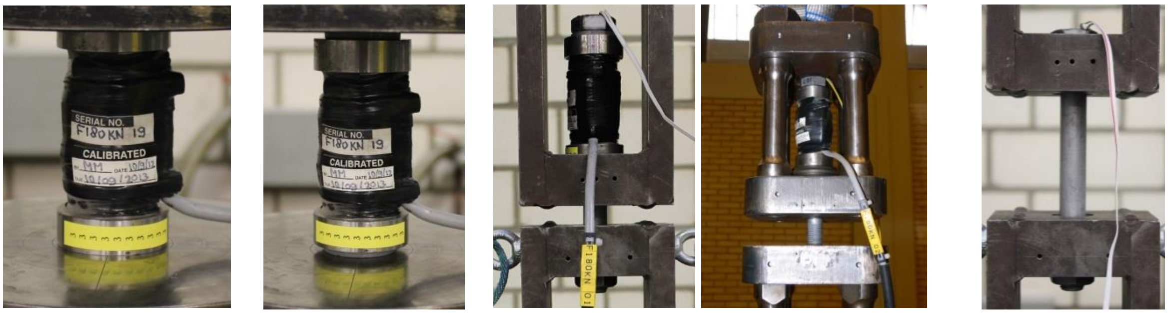
9 Annex B: Load Cells

The accuracy of load cells that are used to measure bolt forces heavily depends on the effect of eccentricities between the bolt axis and the axis of the load cell. This eccentricity leads to bending strains in the load cell that are difficult to compensate for. Especially when the measurement body of the load cell (the area of the load cell with the strain gauges) is short. The load cells that are used in task1.2 are 'home-made' instruments by TUD that are relatively long (100 mm), compared to the standard load cells that can be purchased on the market. As an additional measure to restrict eccentricities, the internal diameter of the home-made load cells is only 0.1 mm larger than the diameter of the bolts. The capacity of the especially produced load cells is 180 kN. The strain gauges used in the load cells are of type XY11-6/120 (produced by HBM, see Fig. 4. Around the circumference of the measurement body of the load cells four XY11-6/120 gauges are placed, arranged at a 90° degree offset from each other. The four gauges are combined to a full bridge strain gauge configuration, which is fully compensated for temperature variations. After production, the load cells were calibrated in a certified calibration test rig in the Stevin lab of TU Delft. The calibration was carried out by loading the load cells on such a way that the loading of the cells during the slip factor tests is matched as much as possible. To achieve this, a long M20 bolt was placed into the load cell. Thereafter, the bolt was loaded in tension by the calibration test rig and the calibration factor for the load cell was determined. The calibration procedure confirmed the expected robustness and accuracy of the instruments (error <1% of the full scale), used in combination with M20 bolts.

Figure 28 - Various phases of the production process of the load cells used in SIROCO (TUD)

The UDE bolts with implanted strain gauges as well as the TUD load cells have been independently pre-checked at both testing laboratories at UDE and TUD to verify 'common ground' between UDE and TUD labs with respect to the accuracy of the measured bolt forces, see figure. This was done by applying the calibration load to the load cells using the instrumented bolts. By doing so, both instruments were calibrated in once. The differences between the calibration factor of the instrumented bolts determined in UDE and the results of the TUD calibration of the bolts was less than 3%.

In the calibration process the force in a bolt is applied by the test rig. In practise, during the tests to determine the slip factor, the bolt force is applied by turning of the nut until the specified level of preloading is reached. Unlike during the calibration process, this practical method of applying the bolt force introduces a torsional moment in the load cells. To investigate the influence of torsion related strains on the accuracy of the load cell measurements, additional calibration procedures were conducted. For this part of the calibration procedure, the instrumented bolts produced were used to measure the actual bolt force (as the strain gauges in the instrumented bolts are in the centre line of the bolts, these are not influenced by eventual torsional deformations of the bolt shaft). From this investigation it can be concluded that when standard hardened washers are used and when the thread of a bolt is unharmed and lubricated, the influence on the accuracy of the measurement of the bolt force of the torsion caused by the tightening of the bolt up to the maximum capacity of the load cells is negligible. This even holds when the nut is tightened from the load cell side (which is not the case during the tests).



a) Compression test – load cell only **b) Compression test – load cell with HV-washers** **c) Tension test – load cell with bolt calibrated at UDE (left) and TUD (right)** **d) Tension test – bolt only (UDE)**

Figure 29 - Calibration setups of load cell and instrumented bolts

10 Annex C: Influence of clamping length on the results of slip factor tests

In this chapter a theory is described to compensate for the influence of the clamp length of the bolts on the results of slip factor tests. Starting point for the method is that the preload in the bolts is continuously measured during the slip factor test.

In engineering practise the slip factor is used to calculate the resistance of a friction grip connection, based on a prescribed minimal preload level in the bolts. If and how the preload in the bolts is influenced by the shear load on the connection normally is not an issue for the engineer. Therefore in the definition of the slip factor the loss of pretension that is associated with slipping of the connection is not explicitly considered, EN1090-2 Annex G defines the slip factor μ as:

$$\mu = \frac{F_{slip}}{4 \cdot F_{p,init}} \qquad \text{(C-1)}$$

where:

- F_{slip} is the load at which the slip criterion reached in a slip factor test (maximum load or load at 0.15 mm slip if this is reached before the maximum load) is
- $F_{p,init}$ is the initial (or nominal) pretension in the bolts.

During a slip factor test losses in the pretension of the bolts are observed. These losses are the result of a gradual reduction of the thickness of the clamped plate package during the test. This reduction is caused by lateral contraction of the plates and plastic deformations in the faying surfaces caused by the slipping process (flattening of the surface asperities or coating system). The magnitude of the reduction is depending on the properties of the faying surfaces (e.g. roughness, coating system). The influence of the reduction on the loss of pretension depends on the clamp length of the bolts. Larger the clamp length, result in smaller pretension loss.

Provided that in a practical application the ratio between the clamped length (L) and the bolt diameter (D) is larger or equal to the L/D ratio during the slip test, the preload loss in practise will be less or equal to the loss during the test. Consequently in practise the slip factor will be equal or higher than the result of the test.

The current EN1090-2 Annex G is not explicit with respect to the clamp length of the bolts (L/D ratio) used in slip factor tests. This implies that users of the standard have freedom to choose the clamp length of the bolts. Standard bolts with implanted strain gauges can be used, but also elongated bolts in which the preload is measured by a load cell. In experiments in which load cells are used the L/D ratio of the bolts can be significantly higher than in practise. The results of these tests overestimate the slip factor. Therefore the results of these tests should be corrected to safely use them in practical applications where bolts with normal length (complying with the EN14399 regulations with respect to the clamped length) are used.

This correction can be carried out by using the measured preload losses that occur during the slip factor test with elongated bolts[1.]

For this we introduce the 'actual slip factor' μ_a of a preloaded assembly as the ratio of the slip load to the pretension in the bolts at the moment the slip criterion is reached. The actual slip factor (the 'friction coefficient' of the assembly) is a property of the preloaded assembly (determined by bolt geometry, surface roughness, coating) when the slip condition is reached. The actual slip factor is defined as:

$$\mu_a = \frac{F_{slip,0}}{4 \cdot F_{p,slip,0}} \tag{C-2}$$

Where:

- $F_{p,slip,0}$ is the pretension in the bolts when $F_{slip,0}$ (the load at 0.15 mm slip or maximum load when this is reached at lower slip) is reached in the experiment with the elongated bolts.

The loss of pretension during the slip test ($F_{p,loss,0} = F_{p,init,0} - F_{p,slip,0}$) can be expressed as a reduction factor r on the initial pretension in the bolts:

$$r = \frac{F_{p,loss,0}}{F_{p,init,0}} = \frac{\left(F_{p,init,0} - F_{p,slip,0}\right)}{F_{p,init,0}} \tag{C-3}$$

The actual friction coefficient μ_a can now be rewritten as:

$$\mu_a = \frac{F_{slip,0}}{4 \cdot F_{p,init,0} \cdot (1-r)} \tag{C-4}$$

The loss of pretension that occurs during a slip factor test is caused by the reduction of the thickness of the clamped package ($\Delta\ell_{cp}$) when a friction grip connection is loaded to slip. Like the actual friction coefficient $\Delta\ell_{cp}$ is a property of the preloaded assembly. Its magnitude is independent of the length of the bolts that are used in the slip test.

The reduction of the thickness of the clamped package $\Delta\ell_{cp}$ results in 1) a reduction of the stretch of the bolt ($\Delta\ell_{loss,b}$) and 2) a reduction of the inclination of the clamped package ($\Delta\ell_{loss,cp}$):

$$\Delta\ell_{cp} = \Delta\ell_{loss,b} + \Delta\ell_{loss,cp} \tag{C-5}$$

How $\Delta\ell_{cp}$ is distributed over bolt and clamped package depends on the stiffness of both components. When we denote the stiffness of the clamped package as k_{cp} and the stiffness of the bolt as k_b we can write: $k_{cp} = \alpha \cdot k_b$ and consequently $\Delta\ell_{loss,cp} = \frac{1}{\alpha}\Delta\ell_{loss,b}$.

This results in:

$$\Delta\ell_{loss,b} = \frac{\alpha}{\alpha+1}\Delta\ell_{cp} \tag{C-6}$$

1 Subscript index 0 refers to slip test with elongated bolts, index 1 to test with standard bolt length

The loss of preload in the experiment with the shorter bolts will be larger than the loss with the elongated bolts. This means the force at which the slip criterion is reached is also lower for the experiment with the shorter bolts. Part of the reduction of the thickness of the clamped package is caused by lateral contraction of the plates, so $\Delta\ell_{cp}$ will be smaller for the experiment with the shorter bolts. The part of the preload loss that is caused by the lateral contraction is small compared to the loss caused by the damaging of the faying surfaces. In the following it is assumed that the total reduction of the thickness of the clamped package that is caused by the slipping is not influenced by the bolt length. This is a conservative assumption.

In slip factors tests in which elongated bolts and load cells are used, the ratio between the resilience of the bolts and the resilience of the clamped package is smaller compared to the setup with standard length bolts. This is caused by the relatively low stiffness of the load cell, compared to the stiffness of the clamped plates. Effectively this means that for the elongated bolts the factor α is lower than when standard bolts would have been used.

This means the reduction of the stretching of the bolts: $\Delta\ell_{loss,b,0} = \frac{\alpha_0}{\alpha_0 + 1}\Delta\ell_{cp}$ is larger for the experiment with the shorter bolts. The reduction of the bolt stretch in the experiment with the short bolts: $\Delta\ell_{loss,b,1} = \frac{\alpha_1}{\alpha_1 + 1}\Delta\ell_{cp}$ can be expressed as:

$$\Delta\ell_{loss,b,1} = R_\alpha \cdot \Delta\ell_{loss,b,0}$$
$$\text{where: } R_\alpha = \frac{\alpha_1}{\alpha_1 + 1} \cdot \frac{\alpha_0 + 1}{\alpha_0} \qquad \text{(C-7)}$$

The measured loss of preload during the experiment with the elongated bolts is used to calculate the shortening of the stressed length of the bolt during the slip test:

$$\frac{\mathrm{F_{p,loss,0}}}{\mathrm{A_{eff,L0}}} = \mathrm{E} \cdot \varepsilon_{loss,b,0}$$
$$\frac{r \cdot \mathrm{F_{p,init,0}}}{\mathrm{A_{eff,L0}}} = \mathrm{E} \cdot \frac{\Delta\ell_{loss,b,0}}{\mathrm{L_0}} \qquad \text{(C-8)}$$
$$\Delta\ell_{loss,b,0} = \frac{r \cdot \mathrm{F_{p,init,0}} \cdot \mathrm{L_0}}{\mathrm{EA_{eff,L0}}}$$

where:

- $\Delta\ell_{loss,b,0}$ = reduction of the shortening of the bolt
- L_0 = stressed length of the elongated bolts
- $E_{Aeff,L0}$ = effective stiffness of the bolt shank for clamped length L_0

Using equation (C-7) we can calculate the loss of preload at $F_{slip,1}$ in the experiment with the standard bolts length:

$$\frac{\Delta\ell_{loss,b,1}}{\mathrm{L_1}} \cdot \mathrm{EA_{eff,L1}} = \frac{R_\alpha \cdot \Delta\ell_{loss,b,0}}{\mathrm{L_1}} \cdot \mathrm{EA_{eff,L1}} \qquad \text{(C-9)}$$

where:

- L_1 = clamp length for standard bolt length

- $E_{Aeff,L1}$ = effective stiffness of the bolt shank for clamped length L_1

Using (C-5) this can be rewritten to:

$$\frac{R_\alpha \cdot \Delta\ell_{loss,b,0}}{L_1} \cdot EA_{eff,L1} = \frac{R_\alpha \cdot \left(\frac{r \cdot F_{p,init,0} \cdot L_0}{EA_{eff,L0}}\right) \cdot EA_{eff,L1}}{L_1} = R \cdot F_{p,init,0} \qquad \text{(C-10)}$$

$$\text{where}: R = r \cdot R_\alpha \cdot \frac{A_{eff,L1} \cdot L_0}{A_{eff,L0} \cdot L_1}$$

The initial preload in the bolts is approximately the same in both experiments (max difference 5%), so we assume $F_{p,init,1}$ = $F_{p,init,0}$. This means that when the slip condition (F = $F_{slip,1}$) is reached in the experiment with the short bolts, the preload in the bolts is reduced to:

$$F_{p,slip,1} = F_{p,init,1} \cdot (1 - R) \qquad \text{(C-11)}$$

Using the actual slip factor μ_a we can now calculate (as a good estimation) the force at which slip will occur in the experiment with the short bolts:

$$F_{slip,1} = \mu_a \cdot F_{p,slip,1}, \quad \text{with } \mu_a = \frac{F_{slip,0}}{4 \cdot F_{p,init,0}(1-r)}$$

$$F_{slip,1} = \frac{(1-R)}{(1-r)} \cdot F_{slip,0} \qquad \text{(C-12)}$$

This means the following factor can be used to correct for the influence of the clamp length on the slip factor:

$$\mu_1 = \frac{F_{slip,1}}{4 \cdot F_{p,init,1}} = \frac{\frac{(1-R)}{(1-r)} \cdot F_{slip,0}}{4 \cdot F_{p,init,0}} = \frac{(1-R)}{(1-r)} \cdot \mu_0 \qquad \text{(C-13)}$$

$$\text{Conversion factor } C_{cl} = \frac{(1-R)}{(1-r)} \qquad \text{(C-14)}$$

Verification to test results

To verify the correctness of the conversion factor the test results obtained with 152 mm and 48 mm clamp length on the task1.2 specimens were compared.

Table 6 - Summary of results short term slip factor tests for clamp length 152 and 48 mm (n=4 for all series)

	parameters		slip factor			$loss_{test}$
	clamp length	$F_{p,init}$ / COV	μ_{act} / COV	μ_{ini} / COV	μ_{nom} / COV	av. B1-4 / COV
	[mm]	[kN] / %	[-] / %	[-] / %	[-] / %	% / %
GB	152	169 / 2	0.83 / 5	0.79 / 4	0.76 / 5	7 / 9
	48	167 / 1	0.80 / 2	0.69 / 2	0.67 / 2	14 / 2
ASiZN	152	168 / 2	0.76 / 2	0.72 / 2	0.71 / 2	5 / 13
	48	172 / 1	0.75 / 1	0.68 / 1	0.68 / 1	10 / 6
ZNSM	152	167 / 2	0.80 / 5	0.76 / 5	0.74 / 5	5 / 10
	48	173 / 2	0.83 / 2	0.74 / 2	0. 74 / 4	11 / 4

Figure 30 shows the test setup of the slip tests executed with the elongated bolts (load cell 100 mm, 3 x washer 4 mm, plates 40 mm = 152 mm) and the tests with 'normal' clamp length of bolts M20 (2 x washer 4mm, plates 40 mm). In Table 6 the results of the slip factor tests are summarised.

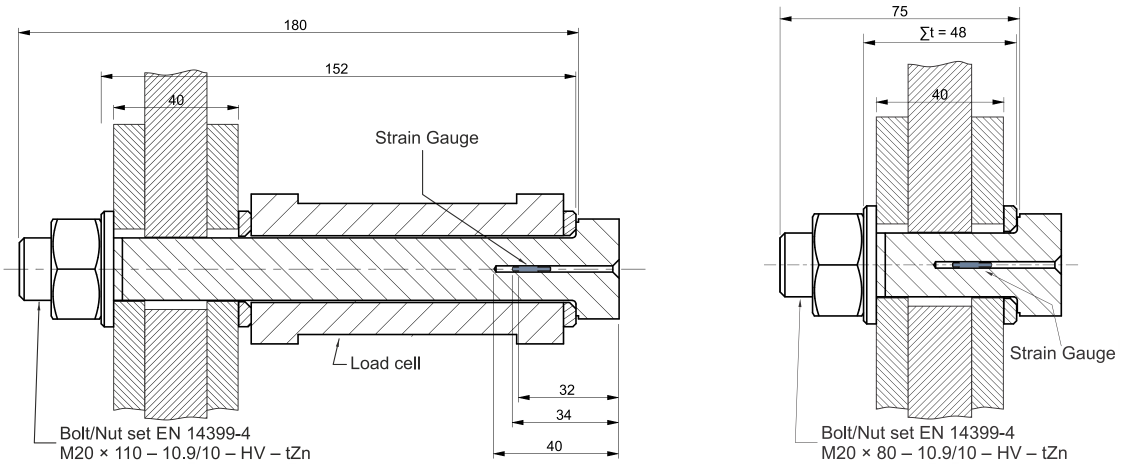


Figure 30 - slip test setup with elongated bolts and load cells – clamp length 152 mm (left) and standard bolt length – clamp length 48 mm (right)

The stiffness of both bolt and clamped part can be determined based on VDI2230.

For elongated bolts M20 (L/D ≈ 8, see Figure C-1-1) and a load cell (L=100 mm, D_{out}=37 mm, D_{in}=20.1 mm) we find $\alpha_0 \approx 3.4$, while for standard bolt length for M20 (L/D ≈ 2.5) we find $\alpha_1 \approx 5$ (for uncoated surfaces).

This means for the elongated bolts this is $\frac{3.4}{3.4+1} \approx 78\%$ of the reduction of the thickness of the clamped plates is accounted for by the bolts, for short bolts this is $\frac{5}{5+1} \approx 83\%$.

$$R = r \cdot R_\alpha \cdot \frac{\mathrm{A}_{\mathrm{eff,L1}} \cdot \mathrm{L}_0}{\mathrm{A}_{\mathrm{eff,L0}} \cdot \mathrm{L}_1}$$

$$R_\alpha = \frac{\alpha_1}{\alpha_1+1}\cdot\frac{\alpha_0+1}{\alpha_0} = \frac{5}{5+1}\cdot\frac{3.4+1}{3.4} = 1.08$$

$$\frac{\mathrm{A_{eff,L1}}\cdot \mathrm{L_0}}{\mathrm{A_{eff,L0}}\cdot \mathrm{L_1}} = \frac{0.59}{0.27} = 2.1$$

$$R = r\cdot R_\alpha \cdot \frac{\mathrm{A_{eff,L1}}\cdot \mathrm{L_0}}{\mathrm{A_{eff,L0}}\cdot \mathrm{L_1}} = r\cdot 1.08\cdot 2.1 = r\cdot 2.3$$

$$\text{conversion factor } \mathrm{C_{cl}} = \frac{(1-R)}{(1-r)} = \frac{(1-2.3r)}{(1-r)}$$

Table 7 - result of conversion

	r [1)]	C_{cl} [2)]	$\mu_{ini,0}$ [3)]	$\mu_{ini,corr}$ [4)]	$\mu_{ini,1}$ [5)]	Error [6)]
	[%]	[-]	[-]	[-]	[-]	[%]
GB	6.5	0.91	0.76	0.69	0.69	0
ASiZn	5.4	0.93	0.71	0.66	0.68	-3
ZnSM	5.2	0.93	0.74	0.69	0.74	-7

1): preload loss during slip test with long bolts (clamp length 152mm); 2) Correction factor; 3) result slip factor test with long bolts; 4) corrected slip factor; 5) result slip factor test standard bolts (48 mm); 6) difference between calculated value and test result ((4 – 5))/5)

Table 7 shows that application of the correction factor gives good results for the Grit blasted surfaces. The correction gives conservative results for the coated surfaces. This is line with the expectation, as the assumptions that were made in the deduction of the correction factor result in a conservative correction.

One of the assumptions is that the initial preload is equal in both experiments. This assumption was met in the grit blasted surfaces. For the coated surfaces the initial preload force in the experiment with the shorter bolts was higher (see Table 6). When the differences in initial preload are incorporated in the correction function, the correction result improves:

$$\text{ASiZn: } \frac{\mathrm{F_{p,init,1}}}{\mathrm{F_{p,init,0}}} = \frac{172}{168} = 1.024 \quad \Rightarrow \quad \mu_{ini,corr} = 0.67 \text{ , error = -1\%}$$

$$\text{ZnSM: } \frac{\mathrm{F_{p,init,1}}}{\mathrm{F_{p,init,0}}} = \frac{173}{167} = 1.036 \quad \Rightarrow \quad \mu_{ini,corr} = 0.71 \text{ , error = -4\%}$$

In the calculation of the correction factor the influence of the coating on the stiffness of the clamped part is not taken into account. The total thickness of the specimens with the ASiZn coating was (table 3): 4*60 = 240 μm, of the ZnSM specimens: 4*140 = 560 μm. As there is no information available on the stiffness of the coatings the effect of the coating on the quality of the correction cannot be verified in this study. The influence of the coating further reduces the stiffness of the clamped part, this means implementing the effect of the coating in the correction factor will further improve the result of the conversion.

11 Annex D: Influence of Compressive vs. Tensile Loading

Apart from the planned tests, it was chosen to additionally test two specimen with single bolts using compressive and tensile loading, in order to investigate if there is any difference between the short term slip coefficients. This investigation is mainly based on the fact that American code (RCSC, 2014) states that the short term friction coefficient may be determined using compressive rather than tensile external loading. Theoretically, the short term friction coefficient determined in the American way will be higher, given that the plate package will contract rather than expand and hence the preload will increase.

Table 8 lists the short term friction coefficients found using external tensile and compressive loading. Statistical evaluation of the results shows that there is no significant difference between the short term slip factors of tests carried out using external tensile or compressive loading. However, given the small number of test results this does not necessarily mean that there is no effect at all.

Table 8 - Short term slip factors for specimen with a single bolt , externally loaded in compression and tension

Compressive external loading		Tensile external loading	
Specimen ID	Short term slip factor	Specimen ID	Short term slip factor
SB-11-1	0,81	SB-12-1	0,89
SB-11-2	0,91	SB-12-2	0,91
SB-13-1	0,90		
SB-13-2	0,93		

Figure 31 illustrates the relationship between actual preload force and external load for a specimen tested in tension and compression. As opposed to the expectations from theory, the preload decreases under (absolutely) increasing external load. Only initially (indicated in the dotted circle) the preload slightly increases. These results show that the effect of lateral expansion of the plate package is smaller than the effect as a result of slipping (e.g. flattening of surface asperities) on the bolt preload. Hence, it is expected that any additional testing will statistically confirm the that there is no difference in the short term slip factor for specimen loaded in compression or tension.

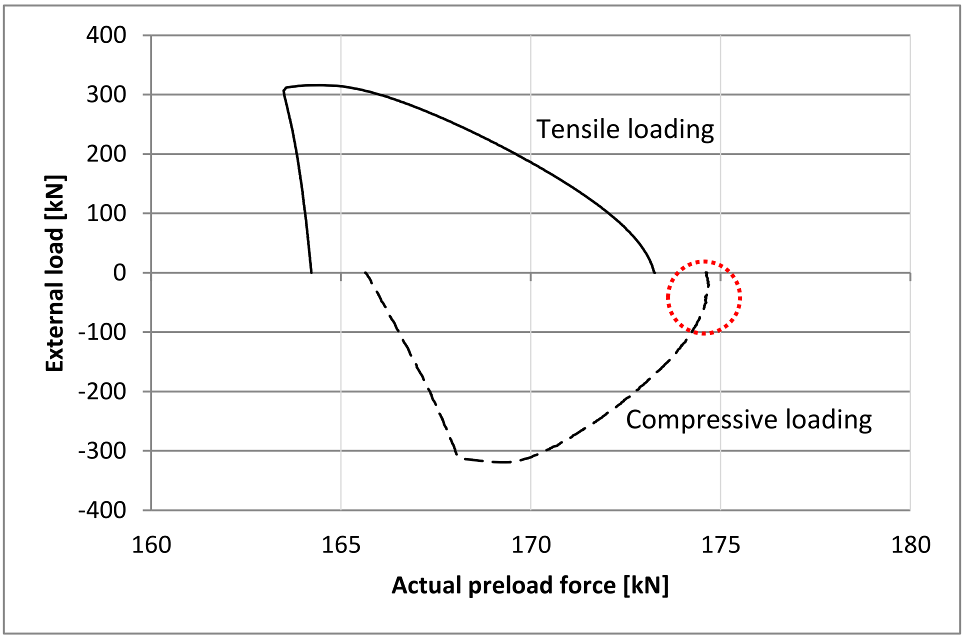


Figure 31 - External load vs. actual preload force for connection with single bolt subjected to tensile and compressive loading

12 Annex E: Overview results GB series

For all individual short term slip factor results see additional Stevin report:

- **Stevin report 6-18-01 – additon A: Test results Grit Blasted,**

Slip criterion used: slip at CBG: 0.15 mm

- Short term tests
- Creep tests

Clamp length	Speed
[mm]	[mm/s]
152	0.01
152	0.005
48	0.005
152	0.0025
152	0.001

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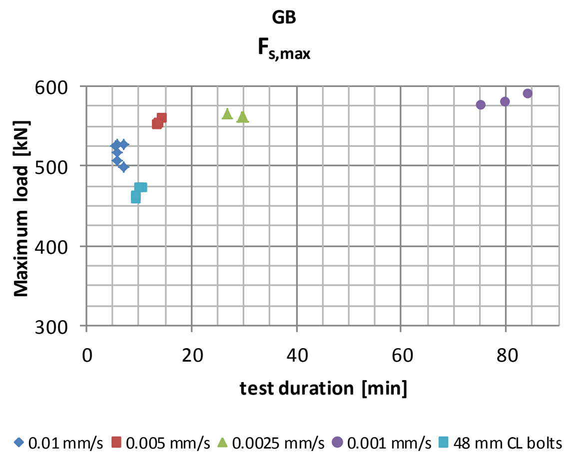
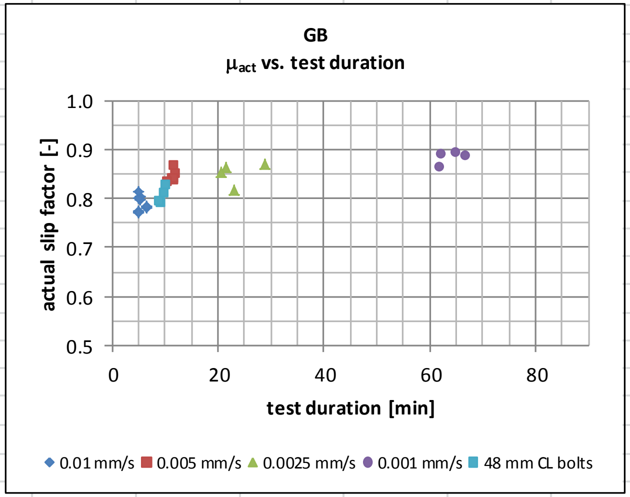
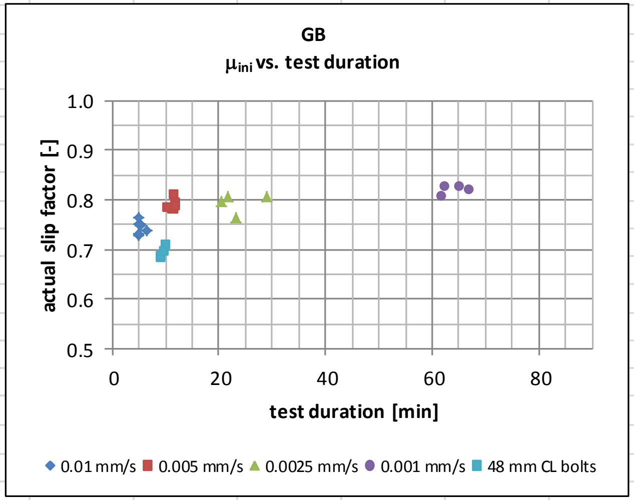
15-02-17

GB — Results overview table

GB																	
	speed	# tests				test results short term tests						test results including creep test				characteristic value acc. to Annex G	
CL		task 1.2 test matrix		realisation		test duration [min]		μ_{act}		μ_{ini}		μ_{act}		μ_{ini}		μ_k	
[mm]	mm/s	short term	creep	short term	creep	mean	COV	mean	COV	mean	COV	mean	COV	mean	COV	actual	Fp,init
152	0.01	8	2	8	2	5	3%	0.79	2%	0.72	2%	0.80	2%	0.72	2%	0.76	0.69
152	0.005	8	2	6	2	11	4%	0.84	1%	0.77	1%	0.85	2%	0.78	2%	0.81	0.74
48	0.005	-	-	4	0	10	6%	0.81	2%	0.67	2%	-	-	-	-	-	-
152	0.0025	8	2	4	0	24	16%	0.85	3%	0.79	2%	-	-	-	-	-	-
152	0.001	8	2	4	0	64	4%	0.88	1%	0.82	1%	-	-	-	-	-	-

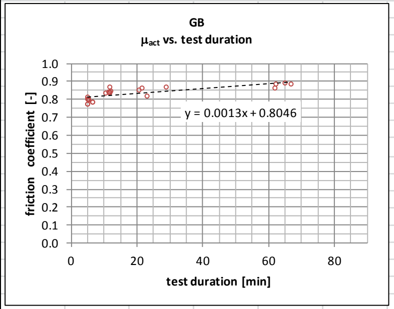






GB			friction coefficient			$loss_{test}$						
speed	clamping length	$F_{p,init}$	μ_{act}	μ_{ini}	μ_{nom}	group	outer bolt	inner bolt	sample iD	t_{test}	t_{prep}	loss $_{15\ min}$
[mm/s]	[mm]	[kN]	[-]	[-]	[-]	%	%	%		[min]	[min]	%
0.01	152	164	0.78	0.74	0.70	6%	5%	6%	SB_01	6.4	no data	no data
		165	0.78	0.74	0.71	6%	6%	6%		6.5		
		166	0.80	0.75	0.73	7%	6%	7%	SB_02	5.3	77	0.8
		166	0.80	0.75	0.72	6%	6%	7%		5.2		
		168	0.80	0.75	0.73	6%	6%	7%	SB_05	5.1	43	0.6
		167	0.81	0.76	0.74	6%	6%	7%		5.1		
		168	0.78	0.73	0.71	6%	6%	7%	SB_06	5.1	130	0.6
		169	0.77	0.73	0.72	5%	5%	5%		4.9		
0.005	152	169	0.84	0.78	0.77	7%	6%	7%	SB_07	12	18	0.6
		171	0.84	0.78	0.78	7%	7%	7%		11		
		169	0.85	0.79	0.78	7%	6%	8%	SB_03	12	186	0.8
		168	0.84	0.79	0.77	6%	6%	7%		12		
		166	0.87	0.81	0.78	7%	8%	6%	SB_04	12	no data	no data
		166	0.83	0.78	0.76	6%	7%	5%		11		
0.0025	152	173	0.82	0.76	0.77	6%	5%	7%	SB_16	23	13	no data
		173	0.87	0.80	0.81	7%	7%	8%		29		
		169	0.86	0.81	0.79	7%	6%	7%	SB_18	22	16	0.4
		168	0.85	0.80	0.78	7%	6%	7%		21		
0.001	152	170	0.89	0.83	0.82	7%	7%	7%	SB_15	62	50	0.3
		172	0.89	0.82	0.82	8%	7%	9%		65		
		172	0.86	0.81	0.81	7%	6%	7%	SB_17	62	16	0.4
		173	0.89	0.82	0.82	7%	7%	8%		67		
	mean	**169**	**0.83**	**0.78**	**0.76**	**7%**	**6%**	**7%**			mean	**0.6**
	stdev	2.8	0.04	0.03	0.04	0.01	0.01	0.01			stdev	0.2
	COV	2%	5%	4%	5%	9%	11%	12%			COV	35%

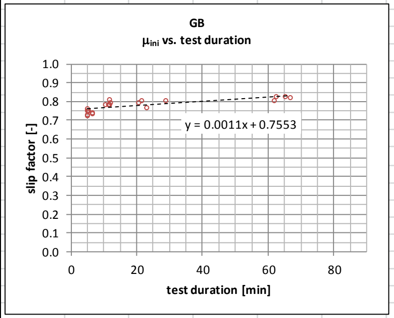
GB			friction coefficient			$loss_{test}$						
speed	clamping length	$F_{p,init}$	μ_{act}	μ_{ini}	μ_{nom}	group	outer bolt	inner bolt	sample iD	t_{test}	t_{prep}	loss $_{15\ min}$
[mm/s]	[mm]	[kN]	[-]	[-]	[-]	%	%	%		[min]	[min]	%
0.005	48	166	0.83	0.71	0.68	14%	13%	15%	SB_20	10.2	45	1.3
		167	0.79	0.68	0.66	14%	12%	15%		9.2		
		167	0.79	0.68	0.67	14%	13%	15%	SB_21	9.1	21	1.2
		169	0.81	0.70	0.68	14%	13%	15%		9.9		
	mean	**167**	**0.81**	**0.69**	**0.67**	**14%**	**13%**	**15%**			mean	**1.3**
	stdev	1.4	0.02	0.01	0.01	0.00	0.00	0.00			stdev	0.1
	COV	1%	2%	2%	2%	2%	4%	1%			COV	6%



trend line	0.805	0.0013

test duration

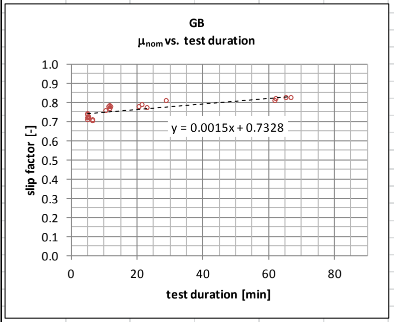
[min]	μ_{act}	diff
5	0.81	**-1.2%**
12.5	**0.82**	-
20	0.83	**1.2%**



trend line	0.755	0.0011

test duration

[min]	μ_{ini}	diff
5	0.76	**-1.1%**
12.5	**0.77**	-
20	0.78	**1.1%**



trend line	0.733	0.0015

test duration

[min]	μ_{nom}	diff
5	0.74	**-1.5%**
12.5	**0.75**	-
20	0.76	**1.5%**

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GB	0.01	CBG

Test protocol

15-02-17

basics slip fator experiment		
	Tested according to	EN 1090-2:2011-10 – Annex G **slip criterion used**: 0.15 mm at Centre Bolt Group
	Test date	
	test performed by	P.A. de Vries, F. Schilperoord
	Steel	S355JR +N (hot rolled)
	Coating	–
	Coating composition	–
	Surface treatment	Grit Blasted Rz = 80 mm
	Maximum coating thickness	–
	Curing procedure	–
	Duration of curing	–
	Time between application coating and testing	–
	Specimen	Standard test piece M20 (EN 1090-2, drawing Annex G.1 b)
	Bolt class, bolt type	10.9 (EN 14399-4 – HV – M20 x 180 – 10.9/10 – tZn)
	Nominal Preload level	172 kN = $F_{p,C}$
	Measuring of the preload level	Load cells, continuously measured, bolt length Σt = 152 mm
	load head speed	0,010 mm/sec

	specimen mark	plate ID's	slip (average at CBG) u_i [mm]	Slip load F_{Si} [kN]	Pre loading at start test (initial pre load): outer Bolt $F_{bi,o,ini}$ [kN]	average mean $F_{bi,ini}$ [kN]	inner Bolt $F_{bi,i,ini}$ [kN]	slip factor based on initial preload $\mu_{i,ini}$ [–]	based on nominal preload $F_{p,C}$ [kN] 172 $\mu_i = \mu_{i,nom}$ [–]	based on preload at reaching slip criterion $\mu_{i,act}$ [–]	Preload at reaching slip criterion: outer bolt $F_{bi,o,act}$ [kN]	average mean $F_{bi,act}$ [kN]	inner bolt $F_{bi,i,act}$ [kN]	test duration t [min]	comment Equations from EN 1090-2 annex G	test date start test
Static load	SB_01	0	0.150	483	163	164	165	0.74	0.70	0.78	155	154	154	6.4	0.00	05-11-14 14:11
		0	0.150	487	164	165	165	0.74	0.71	0.78	155	155	155	6.5	0.00	
	SB_02	0	0.150	500	165	166	167	0.75	0.73	0.80	156	156	155	5.3	0.00	19-11-14 11:48
		0	0.150	496	165	166	166	0.75	0.72	0.80	156	156	155	5.2	0.00	
	SB_05	0	0.150	505	168	168	168	0.75	0.73	0.80	159	158	157	5.1	0.00	25-11-14 15:05
		0	0.150	508	167	167	166	0.76	0.74	0.81	157	156	154	5.1	0.00	
	SB_06	0	0.150	488	168	168	168	0.73	0.71	0.78	158	157	156	5.1	0.00	26-11-14 14:44
		0	0.150	495	168	169	170	0.73	0.72	0.77	159	160	161	4.9	0.00	
	Statistics (4 specimen, 8 test results)	n=8	number of tests													
		max	Maximum	508				0.76	0.74	0.81				5.3		
		min	Minimum	483				0.73	0.70	0.77				4.9		
		mean	Average F_{Sm} | μ_m	**495**				**0.74**	**0.72**	**0.79**				**5.1**	Eq. (2), Eq. (4)	
		R	spread	25.2				0.04	0.04	0.04				0.4	*R = max – min*	
		s	standard deviation	9.0				0.012	0.013	0.015				0.1	Eq. (3), Eq. (5)	
		V	coefficient of variation	1.8%				1.6%	1.8%	1.9%				3%	*V = s / mean*	
	creep test	**0,9 F_{Sm}**		**446**										slip [μm]	Load level creep test [kN]	
	SB_08		0.150	517	167	168	168	0.77	0.75	0.83	154	155	156	1.5	**468**	28-11-14 15:25
			0.150	508	169	168	167	0.75	0.74	0.81	158	157	156	1.6		
	Statistics (5 specimen, 10 test results)	n=10	number of tests											**result**		
		max	Maximum	517				0.77	0.75	0.83				passed	Δ slip < 2 μm in 3 h.	
		min	Minimum	483				0.73	0.70	0.77						
		mean	Average F_{Sm} | μ_m	499				0.75	0.72	0.80					Eq. (2), Eq. (4)	
		R	spread	33.5				0.04	0.05	0.06					*R = max – min*	
		s	standard deviation	10.9				0.014	0.016	0.019					Eq. (3), Eq. (5)	
		V	coefficient of variation	**2.2%**				**1.9%**	**2.2%**	**2.4%**					*V = s / mean* $\leq$ 8%	
		0,9 F_{Sm}		449												
	μ_k	Characteristic value slip factor						0.72	0.69	0.76					Eq. (6)	

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GB	0.005	CBG

Test protocol

15-02-17

basics slip fator experiment		
	Tested according to	EN 1090-2:2011-10 – Annex G **slip criterion used**: 0.15 mm at Centre Bolt Group
	Test date	
	test performed by	P.A. de Vries
	Steel	S355JR +N (hot rolled)
	Coating	–
	Coating composition	–
	Surface treatment	Grit Blasted Rz = 80 mm
	Maximum coating thickness	–
	Curing procedure	–
	Duration of curing	–
	Time between application coating and testing	–
	Specimen	Standard test piece M20 (EN 1090-2, drawing Annex G.1 b)
	Bolt class, bolt type	10.9 (EN 14399-4 – HV – M20 x 80 – 10.9/10 – tZn)
	Nominal Preload level	172 kN = $F_{p,C}$
	Measuring of the preload level	Instrumented bolts, continuously measured, clamping length St = 52 mm
	load head speed	0,005 mm/sec

	specimen mark	plate ID's	**slip** (average at CBG)	**Slip load**	**Pre loading** at start test (initial pre load) outer Bolt	average	inner Bolt	**slip factor** based on initial preload	based on nominal preload $F_{p,C}$ [kN] 172	based on preload at reaching slip criterion	**Preload** at reaching slip criterion outer bolt	average	inner bolt	**test duration**	**comment** Equations from EN 1090-2 annex G	**test date** start test
			u_i [mm]	F_{Si} [kN]	$F_{bi,o,ini}$ [kN]	mean $F_{bi,ini}$ [kN]	$F_{bi,i,ini}$ [kN]	$\mu_{i,ini}$ [–]	$\mu_i = \mu_{i,nom}$ [–]	$\mu_{i,act}$ [–]	$F_{bi,o,act}$ [kN]	mean $F_{bi,act}$ [kN]	$F_{bi,i,act}$ [kN]	t [min]		
Static load	**SB_20**	0	0.150	470	164	166	168	0.71	0.68	0.83	143	142	142	10.2	0.00	28-05-15 17:23
		0	0.150	454	167	167	167	0.68	0.66	0.79	146	144	141	9.2	0.00	
	SB_21	0	0.150	458	167	167	168	0.68	0.67	0.79	146	144	143	9.1	0.00	29-05-15 9:48
		0	0.150	470	170	169	168	0.70	0.68	0.81	147	145	142	9.9	0.00	
	Statistics (2 specimen, 4 test results)	n=4	number of tests													
		max	Maximum	470				0.71	0.68	0.83				10.2		
		min	Minimum	454				0.68	0.66	0.79				9.1		
		mean	Average F_{Sm} | μ_m	**463**				**0.69**	**0.67**	**0.81**				**9.6**	Eq. (2), Eq. (4)	
		R	spread	16.6				0.03	0.02	0.04				1.1	*R = max – min*	
		s	standard deviation	8.5				0.013	0.012	0.017				0.5	Eq. (3), Eq. (5)	
		V	coefficient of variation	1.8%				1.8%	1.8%	2.1%				6%	*V = s / mean*	
	creep test	**0,9 F_{Sm}**		**417**										slip [μm]	Load level creep test [kN]	
	Statistics (2 specimen, 4 test results)	n=4	number of tests											**result**		
		max	Maximum	470				0.71	0.68	0.83				failed	Δ slip < 2 μm in 3 h.	
		min	Minimum	454				0.68	0.66	0.79						
		mean	Average F_{Sm} | μ_m	463				0.69	0.67	0.81					Eq. (2), Eq. (4)	
		R	spread	16.6				0.03	0.02	0.04					*R = max – min*	
		s	standard deviation	8.5				0.013	0.012	0.017					Eq. (3), Eq. (5)	
		V	coefficient of variation	**1.8%**				**1.8%**	**1.8%**	**2.1%**					*V = s / mean* $\leq$ 8%	
		0,9 F_{Sm}		417												
	μ_k	Characteristic value slip factor						-	-	-					Eq. (6)	

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GB	0.005	CBG

Test protocol

15-02-17

basics slip fator experiment		
	Tested according to	EN 1090-2:2011-10 – Annex G **slip criterion used**: 0.15 mm at Centre Bolt Group
	Test date	
	test performed by	P.A. de Vries, F. Schilperoord
	Steel	S355JR +N (hot rolled)
	Coating	–
	Coating composition	–
	Surface treatment	Grit Blasted Rz = 80 mm
	Maximum coating thickness	–
	Curing procedure	–
	Duration of curing	–
	Time between application coating and testing	–
	Specimen	Standard test piece M20 (EN 1090-2, drawing Annex G.1 b)
	Bolt class, bolt type	10.9 (EN 14399-4 – HV – M20 x 180 – 10.9/10 – tZn)
	Nominal Preload level	172 kN = $F_{p,C}$
	Measuring of the preload level	Load cells, continuously measured, bolt length Σt = 152 mm
	load head speed	0,005 mm/sec

	specimen mark	plate ID's	slip (average at CBG) u_i [mm]	Slip load F_{Si} [kN]	Pre loading at start test (initial pre load): outer Bolt $F_{bi,o,ini}$ [kN]	average mean $F_{bi,ini}$ [kN]	inner Bolt $F_{bi,i,ini}$ [kN]	slip factor based on initial preload $\mu_{i,ini}$ [–]	based on nominal preload $F_{p,C}$ [kN] 172 $\mu_i = \mu_{i,nom}$ [–]	based on preload at reaching slip criterion $\mu_{i,act}$ [–]	Preload at reaching slip criterion: outer bolt $F_{bi,o,act}$ [kN]	average mean $F_{bi,act}$ [kN]	inner bolt $F_{bi,i,act}$ [kN]	test duration t [min]	comment Equations from EN 1090-2 annex G	test date start test
Static load	SB_07	0	0.150	528	168	169	170	0.78	0.77	0.84	157	158	159	11.6	0.00	27-11-14 17:19
		0	0.150	534	170	171	171	0.78	0.78	0.84	159	159	159	11.3	0.00	
	SB_03	0	0.150	536	170	169	169	0.79	0.78	0.85	160	158	156	11.9	0.00	20-11-14 15:30
		0	0.150	529	170	168	167	0.79	0.77	0.84	160	157	155	11.8	0.00	
	SB_04	0	0.150	536	165	166	166	0.81	0.78	0.87	153	155	157	11.7	0.00	21-11-14 13:27
		0	0.150	521	166	166	166	0.78	0.76	0.83	155	156	157	10.5	0.00	
	Statistics (3 specimen, 6 test results)	n=6	number of tests													
		max	Maximum	536				0.81	0.78	0.87				11.9		
		min	Minimum	521				0.78	0.76	0.83				10.5		
		mean	Average F_{Sm} | μ_m	**531**				**0.79**	**0.77**	**0.84**				**11.5**	Eq. (2), Eq. (4)	
		R	spread	15.2				0.03	0.02	0.03				1.4	*R = max – min*	
		s	standard deviation	5.9				0.010	0.009	0.012				0.5	Eq. (3), Eq. (5)	
		V	coefficient of variation	1.1%				1.3%	1.1%	1.4%				4%	*V = s / mean*	
	creep test	**0,9 F_{Sm}**		478										slip [μm]	Load level creep test [kN]	
	SB_14		0.150	526	170	171	171	0.77	0.76	0.82	160	160	159	1.7	**498**	09-02-15 15:03
			0.150	564	172	172	172	0.82	0.82	0.88	160	160	159	1.6		
	Statistics (4 specimen, 8 test results)	n=8	number of tests											**result**		
		max	Maximum	564				0.82	0.82	0.88				passed	Δ slip < 2 μm in 3 h.	
		min	Minimum	521				0.77	0.76	0.82						
		mean	Average F_{Sm} | μ_m	534				0.79	0.78	0.85					Eq. (2), Eq. (4)	
		R	spread	42.5				0.05	0.06	0.06					*R = max – min*	
		s	standard deviation	13.0				0.016	0.019	0.019					Eq. (3), Eq. (5)	
		V	coefficient of variation	**2.4%**				**2.0%**	**2.4%**	**2.2%**					*V = s / mean* ≤ 8%	
		0,9 F_{Sm}		481												
	μ_k	Characteristic value slip factor						0.76	0.74	0.81					Eq. (6)	

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GB | **0.0025** | **CBG**

Test protocol

15-02-17

basics slip fator experiment		
	Tested according to	EN 1090-2:2011-10 – Annex G **slip criterion used**: 0.15 mm at Centre Bolt Group
	Test date	
	test performed by	P.A. de Vries, F. Schilperoord
	Steel	S355JR +N (hot rolled)
	Coating	–
	Coating composition	–
	Surface treatment	Grit Blasted Rz = 80 mm
	Maximum coating thickness	–
	Curing procedure	–
	Duration of curing	–
	Time between application coating and testing	–
	Specimen	Standard test piece M20 (EN 1090-2, drawing Annex G.1 b)
	Bolt class, bolt type	10.9 (EN 14399-4 – HV – M20 x 180 – 10.9/10 – tZn)
	Nominal Preload level	172 kN = $F_{p,C}$
	Measuring of the preload level	Load cells, continuously measured, bolt length Σt = 152 mm
	load head speed	0,0025 mm/sec

	specimen mark	plate ID's	slip (average at CBG) u_i [mm]	Slip load F_{Si} [kN]	Pre loading at start test (initial pre load): outer Bolt $F_{bl,o,ini}$ [kN]	average mean $F_{bl,ini}$ [kN]	inner Bolt $F_{bl,i,ini}$ [kN]	slip factor: based on initial preload $\mu_{i,ini}$ [–]	based on nominal preload $F_{p,C}$ [kN] 172 $\mu_i = \mu_{i,nom}$ [–]	based on preload at reaching slip criterion $\mu_{i,act}$ [–]	Preload at reaching slip criterion: outer bolt $F_{bl,o,act}$ [kN]	average mean $F_{bl,act}$ [kN]	inner bolt $F_{bl,i,act}$ [kN]	test duration t [min]	comment Equations from EN 1090-2 annex G	test date start test
Static load	**SB_16**	0	0.150	530	173	173	173	0.76	0.77	0.82	164	162	161	23.1	0.00	24-03-15 12:05
		0	0.150	558	173	173	173	0.80	0.81	0.87	162	160	159	28.9	0.00	
	SB_18	0	0.150	543	169	169	168	0.81	0.79	0.86	159	157	156	21.7	0.00	25-03-15 10:18
		0	0.150	535	168	168	168	0.80	0.78	0.85	158	157	156	20.5	0.00	
	Statistics (2 specimen, 4 test results)	n=4	number of tests													
		max	Maximum	558				0.81	0.81	0.87				28.9		
		min	Minimum	530				0.76	0.77	0.82				20.5		
		mean	Average F_{Sm} | μ_m	**542**				**0.79**	**0.79**	**0.85**				**23.5**	Eq. (2), Eq. (4)	
		R	spread	28.0				0.04	0.04	0.05				8.4	*R = max – min*	
		s	standard deviation	12.2				0.019	0.018	0.024				3.7	Eq. (3), Eq. (5)	
		V	coefficient of variation	2.2%				2.4%	2.2%	2.8%				16%	*V = s / mean*	
	creep test	0,9 F_{Sm}		487										slip [mm]	Load level creep test [kN]	
														result		
	Statistics (2 specimen, 4 test results)	n=4	number of tests											failed	D slip < 2 mm in 3 h.	
		max	Maximum	558				0.81	0.81	0.87						
		min	Minimum	530				0.76	0.77	0.82						
		mean	Average F_{Sm} | μ_m	542				0.79	0.79	0.85					Eq. (2), Eq. (4)	
		R	spread	28.0				0.04	0.04	0.05					*R = max – min*	
		s	standard deviation	12.2				0.019	0.018	0.024					Eq. (3), Eq. (5)	
		V	coefficient of variation	**2.2%**				**2.4%**	**2.2%**	**2.8%**					*V = s / mean* ≤ 8%	
		0,9 F_{Sm}		487												
	μ_k	Characteristic value slip factor						-	-	-					Eq. (6)	

GB	0.001	CBG	**Test protocol**	15-02-17

basics slip fator experiment

Tested according to	EN 1090-2:2011-10 – Annex G **slip criterion used**: 0.15 mm at Centre Bolt Group
Test date	
test performed by	P.A. de Vries, F. Schilperoord
Steel	S355JR +N (hot rolled)
Coating	**–**
Coating composition	–
Surface treatment	Grit Blasted Rz = 80 mm
Maximum coating thickness	–
Curing procedure	–
Duration of curing	–
Time between application coating and testing	–
Specimen	Standard test piece M20 (EN 1090-2, drawing Annex G.1 b)
Bolt class, bolt type	10.9 (EN 14399-4 – HV – M20 x 180 – 10.9/10 – tZn)
Nominal Preload level	172 kN = $F_{p,C}$
Measuring of the preload level	Load cells, continuously measured, bolt length Σt = 152 mm
load head speed	0,001 mm/sec

Static load

specimen mark	plate ID's	slip (average at CBG) u_i [mm]	Slip load F_{Si} [kN]	Pre loading at start test (initial pre load): outer Bolt $F_{bi,o,ini}$ [kN]	average mean $F_{bi,ini}$ [kN]	inner Bolt $F_{bi,i,ini}$ [kN]	slip factor based on initial preload $\mu_{i,ini}$ [–]	based on nominal preload $F_{p,C}$ [kN] 172 $\mu_i = \mu_{i,nom}$ [–]	based on preload at reaching slip criterion $\mu_{i,act}$ [–]	Preload at reaching slip criterion: outer bolt $F_{bi,o,act}$ [kN]	average mean $F_{bi,act}$ [kN]	inner bolt $F_{bi,i,act}$ [kN]	test duration t [min]	comment Equations from EN 1090-2 annex G	test date start test
SB_15	0	0.150	564	170	170	171	0.83	0.82	0.89	159	159	159	62.4	0.00	17-02-15 12:19
	0	0.150	566	172	172	171	0.82	0.82	0.89	160	158	157	65.1	0.00	
SB_17	0	0.150	555	171	172	174	0.81	0.81	0.86	160	161	161	62.0	0.00	24-03-15 13:57
	0	0.150	567	172	173	174	0.82	0.82	0.89	161	160	159	66.9	0.00	
Statistics (2 specimen, 4 test results)	n=4	number of tests													
	max	Maximum	567				0.83	0.82	0.89				66.9		
	min	Minimum	555				0.81	0.81	0.86				62.0		
	mean	Average F_{Sm} | μ_m	**563**				**0.82**	**0.82**	**0.88**				**64.1**	Eq. (2), Eq. (4)	
	R	spread	12.2				0.02	0.02	0.03				4.9	*R = max – min*	
	s	standard deviation	5.4				0.010	0.008	0.013				2.3	Eq. (3), Eq. (5)	
	V	coefficient of variation	1.0%				1.2%	1.0%	1.5%				4%	*V = s / mean*	
creep test	0,9 F_{Sm}		**507**										slip [μm]	Load level creep test [kN]	
Statistics (2 specimen, 4 test results)	n=4	number of tests											**result**		
	max	Maximum	567				0.83	0.82	0.89				failed	Δ slip < 2 μm in 3 h.	
	min	Minimum	555				0.81	0.81	0.86						
	mean	Average F_{Sm} | μ_m	563				0.82	0.82	0.88					Eq. (2), Eq. (4)	
	R	spread	12.2				0.02	0.02	0.03					*R = max – min*	
	s	standard deviation	5.4				0.010	0.008	0.013					Eq. (3), Eq. (5)	
	V	coefficient of variation	**1.0%**				**1.2%**	**1.0%**	**1.5%**					*V = s / mean* ≤ 8%	
	0,9 F_{Sm}		507												
μ_k	Characteristic value slip factor						-	-	-					Eq. (6)	

13 Annex F: Overview results ASiZn series

For all individual short term slip factor results see additional Stevin report:

- **Stevin report 6-18-01 – additon B: Test results ASiZn**

Slip criterion used: slip at CBG: 0.15 mm

- Short term tests
- Creep tests

Clamp length	Speed
[mm]	[mm/s]
152	0.01
152	0.005
48	0.005
152	0.0025
152	0.001

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SIROCO RFSR-CT-2014-00024

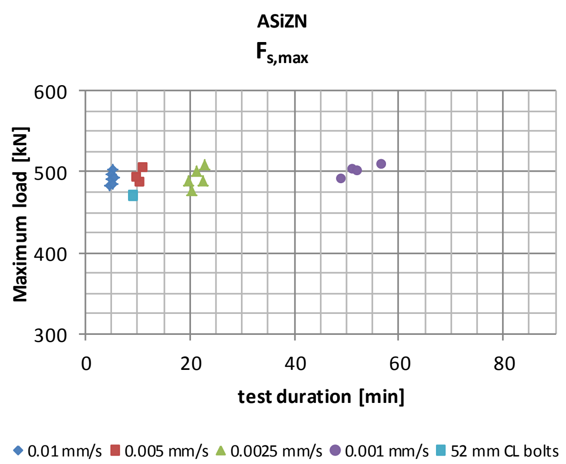
15-02-17

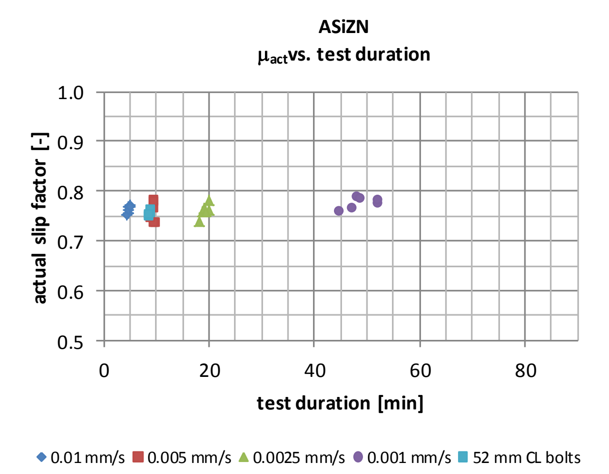
ASiZN

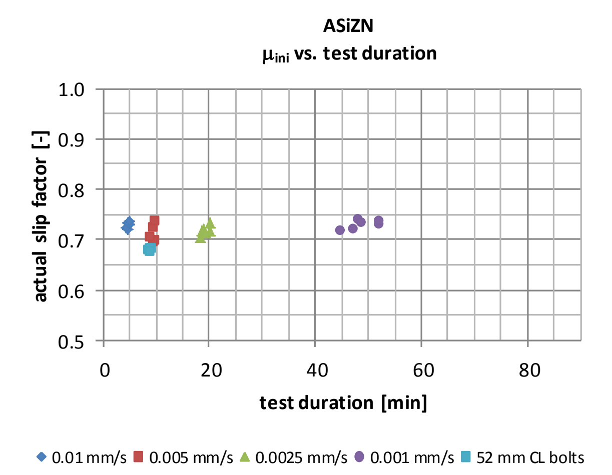
Results overview table

ASiZN

CL	speed	# tests				test results short term tests						test results including creep test				characteristic value acc. to Annex G	
		task 1.2 test matrix		realization		test duration [min]		μ_{act}		μ_{ini}		μ_{act}		μ_{ini}		μ_k	
[mm]	mm/s	short term	creep	short term	creep	mean	COV	mean	COV	mean	COV	mean	COV	mean	COV	actual	Fp,init
152	0.01	8	2	6	2	5	4%	0.76	1%	0.70	1%	0.78	5%	0.72	5%	-	-
152	0.005	8	2	6	2	10	3%	0.76	3%	0.71	2%	0.74	5%	0.69	6%	-	-
48	0.005	-	-	4	2	9	2%	0.75	1%	0.68	0%	0.77	10%	0.68	7%	-	-
152	0.0025	8	2	6	0	19	4%	0.76	2%	0.70	2%	-	-	-	-	-	-
152	0.001	8	2	6	2	49	6%	0.78	1%	0.72	1%	0.77	6%	0.71	6%	-	-

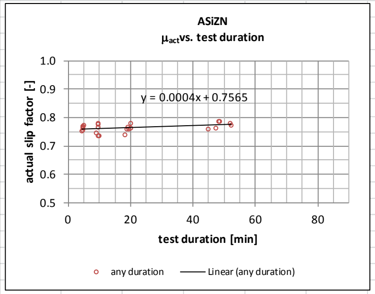






ASiZN			friction coefficient			preload loss$_{test}$						
speed	clamping length	$F_{p,init}$	μ_{act}	μ_{ini}	μ_{nom}	group	outer bolt	inner bolt	sample iD	t_{test}	t_{prep}	loss $_{15\ min}$
[mm/s]	[mm]	[kN]	[-]	[-]	[-]	%	%	%		[min]	[min]	%
0.01	152	169	0.77	0.73	0.72	5%	4%	6%	ASiZN_01	4.8	30	no data
		168	0.76	0.72	0.70	5%	4%	5%		4.6		
		166	0.75	0.72	0.70	4%	4%	5%	ASiZN_02	4.4	968	2.0
		165	0.76	0.73	0.70	4%	4%	4%		4.6		
		162	0.77	0.74	0.70	4%	4%	5%	ASiZN_07	4.9	102	2.1
		162	0.77	0.74	0.69	4%	4%	4%		4.8		
0.005	152	172	0.74	0.70	0.70	5%	5%	5%	ASiZN_03	9.8	16	1.6
		173	0.74	0.69	0.70	6%	5%	6%		9.7		
		169	0.74	0.70	0.69	5%	4%	6%	ASiZN_04	9.0	16	2.3
		169	0.77	0.72	0.71	5%	5%	6%		9.7		
		168	0.78	0.74	0.72	5%	5%	6%	ASiZN_13	9.7	no data	no data
		169	0.78	0.73	0.72	5%	5%	6%		9.7		
0.0025	152	170	0.74	0.70	0.69	5%	4%	5%	ASiZN_05	18	24	no data
		169	0.76	0.72	0.71	5%	4%	7%		19		
		162	0.78	0.73	0.69	6%	6%	6%	ASiZN_06	20	25	2.2
		162	0.76	0.72	0.68	6%	5%	7%		19		
		173	0.76	0.72	0.72	6%	5%	6%	ASiZN_14	20	18	2.1
		173	0.76	0.72	0.72	6%	5%	7%		19		
0.001	152	168	0.77	0.73	0.71	6%	5%	6%	ASiZN_10	52	25	2.1
		168	0.76	0.72	0.70	6%	5%	7%		45		
		168	0.79	0.74	0.72	6%	6%	6%	ASiZN_15	48	19	2.2
		170	0.78	0.73	0.72	7%	6%	8%		49		
		171	0.76	0.72	0.72	6%	5%	7%	ASiZN_17	47	15	no data
		171	0.78	0.73	0.73	6%	5%	6%		52		
	mean	**168**	**0.76**	**0.72**	**0.71**	**5%**	**5%**	**6%**			mean	**2.1**
	stdev	3.45	0.01	0.01	0.01	0.7%	0.7%	0.8%			stdev	0.2
	COV	2%	2%	2%	2%	13%	14%	14%			COV	11%

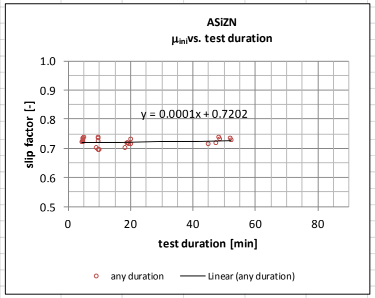
ASiZN			friction coefficient			loss$_{test}$						
speed	clamping length	$F_{p,init}$	μ_{act}	μ_{ini}	μ_{nom}	group	outer bolt	inner bolt	sample iD	t_{test}	t_{prep}	loss $_{15\ min}$
[mm/s]	[mm]	[kN]	[-]	[-]	[-]	%	%	%		[min]	[min]	%
0.005	48	173	0.75	0.68	0.68	9%	8%	11%	ASiZN_19	8.7	1005	5.3
		172	0.76	0.68	0.68	10%	7%	12%		9.1		
		172	0.76	0.68	0.68	11%	9%	12%	ASiZN_20	8.9	90	5.2
		173	0.75	0.67	0.68	10%	8%	12%		8.8		
	mean	**172**	**0.75**	**0.68**	**0.68**	**10%**	**8%**	**12%**			mean	**5.2**
	stdev	0.50	0.01	0.00	0.00	0.01	0.01	0.01			stdev	0.1
	COV	0%	1%	1%	0%	6%	10%	7%			COV	1%



trend line	0.756	0.0004

test duration

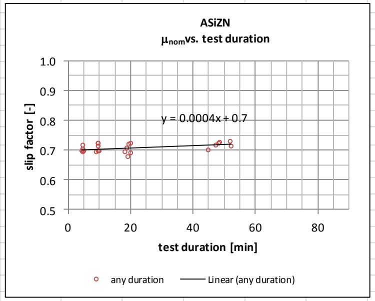
[min]	μ_{act}	diff
5	0.76	**-0.4%**
12.5	**0.76**	-
20	0.76	**0.4%**



trend line	0.72	0.0001

test duration

[min]	μ_{ini}	diff
5	0.72	**-0.1%**
12.5	**0.72**	-
20	0.72	**0.1%**



trend line	0.7	0.0004

test duration

[min]	μ_{nom}	diff
5	0.70	**-0.4%**
12.5	**0.71**	-
20	0.71	**0.4%**

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ASiZN 0.01	CBG	**Test protocol**	15-02-17

basics slip fator experiment

Tested according to	EN 1090-2:2011-10 – Annex G **slip criterion used**: 0.15 mm at Centre Bolt Group
Test date	
test performed by	P.A. de Vries, F. Schilperoord
Steel	S355JR +N (hot rolled)
Coating	**ASiZN coating 60 micron (measured mean DCT)**
Coating composition	?
Surface treatment	Grit Blasted Rz = 80 micron
Maximum coating thickness	?
Curing procedure	?
Duration of curing	?
Time between application coating and testing	?
Specimen	Standard test piece M20 (EN 1090-2, drawing Annex G.1 b)
Bolt class, bolt type	10.9 (EN 14399-4 – HV – M20 x 180 – 10.9/10 – tZn)
Nominal Preload level	172 kN = $F_{p,C}$
Measuring of the preload level	Load cells, continuously measured, bolt length Σt = 152 mm
load head speed	0,010 mm/sec

	specimen mark	plate ID's	**slip** (average at CBG) u_i [mm]	**Slip load** F_{Si} [kN]	**Pre loading at start test (initial pre load)** outer Bolt $F_{bi,o,ini}$ [kN]	average mean $F_{bi,ini}$ [kN]	inner Bolt $F_{bi,i,ini}$ [kN]	**slip factor** based on initial preload $\mu_{i,ini}$ [–]	based on nominal preload $F_{p,C}$ [kN] 172 $\mu_i = \mu_{i,nom}$ [–]	based on preload at reaching slip criterion $\mu_{i,act}$ [–]	**Preload at reaching slip criterion** outer bolt $F_{bi,o,act}$ [kN]	average mean $F_{bi,act}$ [kN]	inner bolt $F_{bi,i,act}$ [kN]	**test duration** t [min]	**comment** Equations from EN 1090-2 annex G	**test date** start test
Static load	ASiZN_01	0	0.150	492	170	169	168	0.73	0.72	0.77	162	160	158	4.8	0.00	22-12-14 12:21
		0	0.150	484	168	168	168	0.72	0.70	0.76	161	160	159	4.6	0.00	
	ASiZN_02	0	0.150	480	167	166	165	0.72	0.70	0.75	161	159	158	4.4	0.00	23-12-14 9:21
		0	0.150	483	165	165	165	0.73	0.70	0.76	159	158	157	4.6	0.00	
	ASiZN_07	0	0.150	479	162	162	163	0.74	0.70	0.77	156	155	154	4.9	0.00	14-01-15 13:04
		0	0.150	477	163	162	161	0.74	0.69	0.77	157	156	154	4.8	0.00	
	Statistics (3 specimen, 6 test results)	n=6	number of tests													
		max	Maximum	492				0.74	0.72	0.77				4.9		
		min	Minimum	477				0.72	0.69	0.75				4.4		
		mean	Average F_{Sm} | μ_m	**483**				**0.73**	**0.70**	**0.76**				**4.7**	Eq. (2), Eq. (4)	
		R	spread	15.2				0.02	0.02	0.02				0.4	*R = max – min*	
		s	standard deviation	5.4				0.007	0.008	0.007				0.2	Eq. (3), Eq. (5)	
		V	coefficient of variation	1.1%				0.9%	1.1%	1.0%				4%	*V = s / mean*	
	creep test	**0,9 F_{Sm}**		434										slip [μm]	Load level creep test [kN]	
	ASiZN_16	0	0.150	538	168	169	169	0.80	0.78	0.85	159	158	157	27.3	**380**	23-03-15 16:36
		0	0.150	539	171	172	173	0.78	0.78	0.84	163	161	159	24.8	NOT passed	
	Statistics (4 specimen, 8 test results)	n=8	number of tests											**result**		
		max	Maximum	539				0.80	0.78	0.85				failed	Δ slip < 2 μm in 3 h.	
		min	Minimum	477				0.72	0.69	0.75						
		mean	Average F_{Sm} | μ_m	497				0.75	0.72	0.78					Eq. (2), Eq. (4)	
		R	spread	61.6				0.08	0.09	0.10					*R = max – min*	
		s	standard deviation	26.1				0.029	0.038	0.038					Eq. (3), Eq. (5)	
		V	coefficient of variation	**5.3%**				**3.9%**	**5.3%**	**4.9%**					*V = s / mean* ≤ 8%	
		0,9 F_{Sm}		447												
	μ_k	Characteristic value slip factor						-	-	-					Eq. (6)	

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ASiZI	0.005	CBG

Test protocol

15-02-17

basics slip fator experiment		
	Tested according to	EN 1090-2:2011-10 – Annex G **slip criterion used**: 0.15 mm at Centre Bolt Group
	Test date	
	test performed by	P.A. de Vries, F. Schilperoord
	Steel	S355JR +N (hot rolled)
	Coating	**ASiZN coating 60 micron (measured mean DCT)**
	Coating composition	?
	Surface treatment	Grit Blasted Rz = 80 micron
	Maximum coating thickness	?
	Curing procedure	?
	Duration of curing	?
	Time between application coating and testing	?
	Specimen	Standard test piece M20 (EN 1090-2, drawing Annex G.1 b)
	Bolt class, bolt type	10.9 (EN 14399-4 – HV – M20 x 180 – 10.9/10 – tZn)
	Nominal Preload level	172 kN = $F_{p,C}$
	Measuring of the preload level	Load cells, continuously measured, bolt length Σt = 152 mm
	load head speed	0,005 mm/sec

	specimen mark	plate ID's	slip (average at CBG) u_i [mm]	Slip load F_{Si} [kN]	Pre loading at start test (initial pre load): outer Bolt $F_{bi,o,ini}$ [kN]	average mean $F_{bi,ini}$ [kN]	inner Bolt $F_{bi,i,ini}$ [kN]	slip factor: based on initial preload $\mu_{i,ini}$ [–]	based on nominal preload $F_{p,C}$ [kN] 172 $\mu_i = \mu_{i,nom}$ [–]	based on preload at reaching slip criterion $\mu_{i,act}$ [–]	Preload at reaching slip criterion: outer bolt $F_{bi,o,act}$ [kN]	average mean $F_{bi,act}$ [kN]	inner bolt $F_{bi,i,act}$ [kN]	test duration t [min]	comment Equations from EN 1090-2 annex G	test date start test
Static load	ASiZN_03	0	0.150	480	171	172	173	0.70	0.70	0.74	163	163	164	9.8	0.00	23-12-14 16:24
		0	0.150	480	172	173	173	0.69	0.70	0.74	164	163	162	9.7	0.00	
	ASiZN_04	0	0.150	476	170	169	168	0.70	0.69	0.74	163	160	157	9.0	0.00	30-12-14 13:23
		0	0.150	491	170	169	168	0.72	0.71	0.77	162	160	158	9.7	0.00	
	ASiZN_13	0	0.150	496	168	168	168	0.74	0.72	0.78	160	159	158	9.7	0.00	23-03-15 10:44
		0	0.150	496	169	169	169	0.73	0.72	0.78	161	160	159	9.7	0.00	
	Statistics (3 specimen, 6 test results)	n=6	number of tests													
		max	Maximum	496				0.74	0.72	0.78				9.8		
		min	Minimum	476				0.69	0.69	0.74				9.0		
		mean	Average F_{Sm} | μ_m	**487**				**0.72**	**0.71**	**0.76**				**9.6**	Eq. (2), Eq. (4)	
		R	spread	20.0				0.04	0.03	0.05				0.8	*R = max – min*	
		s	standard deviation	8.9				0.019	0.013	0.020				0.3	Eq. (3), Eq. (5)	
		V	coefficient of variation	1.8%				2.7%	1.8%	2.7%				3%	*V = s / mean*	
	creep test	0,9 F_{Sm}		438										slip [μm]	Load level creep test [kN]	
	ASiZN_09	0	0.150	432	167	167	166	0.65	0.63	0.69	158	157	156	40.5	**430**	11-02-15 17:19
		0	0.150	432	169	167	166	0.64	0.63	0.68	162	159	156	52.2	NOT passed	
	Statistics (4 specimen, 8 test results)	n=8	number of tests											**result**		
		max	Maximum	496				0.74	0.72	0.78				failed	Δ slip < 2 μm in 3 h.	
		min	Minimum	432				0.64	0.63	0.68						
		mean	Average F_{Sm} | μ_m	473				0.70	0.69	0.74					Eq. (2), Eq. (4)	
		R	spread	64.7				0.09	0.09	0.10					*R = max – min*	
		s	standard deviation	26.5				0.036	0.039	0.038					Eq. (3), Eq. (5)	
		V	coefficient of variation	**5.6%**				**5.1%**	**5.6%**	**5.2%**					*V = s / mean* ≤ 8%	
		0,9 F_{Sm}		426												
	μ_k	Characteristic value slip factor						-	-	-					Eq. (6)	

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ASiZN	0.005	CBG	**Test protocol**	15-02-17

basics slip fator experiment		
	Tested according to	EN 1090-2:2011-10 – Annex G **slip criterion used**: 0.15 mm at Centre Bolt Group
	Test date	
	test performed by	P.A. de Vries
	Steel	S355JR +N (hot rolled)
	Coating	**ASiZN coating 60 micron (measured mean DCT)**
	Coating composition	?
	Surface treatment	Grit Blasted Rz = 80 micron
	Maximum coating thickness	?
	Curing procedure	?
	Duration of curing	?
	Time between application coating and testing	?
	Specimen	Standard test piece M20 (EN 1090-2, drawing Annex G.1 b)
	Bolt class, bolt type	10.9 (EN 14399-4 – HV – M20 x 80 – 10.9/10 – tZn)
	Nominal Preload level	172 kN = $F_{p,C}$
	Measuring of the preload level	Instrumented bolts, continuously measured, clamping length St = 48 mm
	load head speed	0,005 mm/sec

	specimen mark	plate ID's	slip (average at CBG) u_l [mm]	Slip load F_{Sl} [kN]	Pre loading at start test (initial pre load): outer Bolt $F_{bl,o,ini}$ [kN]	average: mean $F_{bl,ini}$ [kN]	inner Bolt $F_{bl,i,ini}$ [kN]	slip factor: based on initial preload $\mu_{i,ini}$ [-]	based on nominal preload $F_{p,C}$ [kN] 172 $\mu_i = \mu_{i,nom}$ [-]	based on preload at reaching slip criterion $\mu_{i,act}$ [-]	Preload at reaching slip criterion: outer bolt $F_{bl,o,act}$ [kN]	average: mean $F_{bl,act}$ [kN]	inner bolt $F_{bl,i,act}$ [kN]	test duration t [min]	comment: Equations from EN 1090-2 annex G	test date: start test
Static load	ASiZN_19	0	0.150	468	174	173	171	0.68	0.68	0.75	160	156	153	8.7	0.00	10-06-15 8:38
		0	0.138	470	174	172	170	0.68	0.68	0.76	162	155	149	9.1	0.00	
	ASiZN_20	0	0.150	468	173	172	171	0.68	0.68	0.76	157	154	150	8.9	0.00	10-06-15 11:29
		0	0.150	467	175	173	171	0.67	0.68	0.75	160	155	150	8.8	0.00	
	Statistics (2 specimen, 4 test results)	n=4	number of tests													
		max	Maximum	470				0.68	0.68	0.76				9.1		
		min	Minimum	467				0.67	0.68	0.75				8.7		
		mean	Average F_{Sm} | μ_m	468				0.68	0.68	0.75				8.9	Eq. (2), Eq. (4)	
		R	spread	3.4				0.01	0.00	0.01				0.4	*R = max – min*	
		s	standard deviation	1.4				0.004	0.002	0.005				0.2	Eq. (3), Eq. (5)	
		V	coefficient of variation	0.3%				0.6%	0.3%	0.7%				2%	*V = s / mean*	
	creep test	0,9 F_{Sm}		421										slip [mm]	Load level creep test [kN]	
	ASiZN_21	0	0.140	532	170	171	171	0.78	0.77	0.91	148	146	144	40.7	421	11-06-15 15:19
		0	0.150	421	174	174	173	0.61	0.61	0.69	157	153	149	55.2	NOT passed	
	Statistics (3 specimen, 6 test results)	n=6	number of tests											result		
		max	Maximum	532				0.78	0.77	0.91				failed	D slip < 2 mm in 3 h.	
		min	Minimum	421				0.61	0.61	0.69						
		mean	Average F_{Sm} | μ_m	471				0.68	0.68	0.77					Eq. (2), Eq. (4)	
		R	spread	110.5				0.17	0.16	0.22					*R = max – min*	
		s	standard deviation	35.2				0.055	0.051	0.074					Eq. (3), Eq. (5)	
		V	coefficient of variation	7.5%				8.0%	7.5%	9.6%					*V = s / mean* ≤ 8%	
		0,9 F_{Sm}		424												
	μ_k	Characteristic value slip factor						-	-	-					Eq. (6)	

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ASiZN 0.0025 CBG

Test protocol

15-02-17

basics slip fator experiment

Tested according to	EN 1090-2:2011-10 – Annex G **slip criterion used**: 0.15 mm at Centre Bolt Group
Test date	
test performed by	P.A. de Vries, F. Schilperoord
Steel	S355JR +N (hot rolled)
Coating	**ASiZN coating 60 micron (measured mean DCT)**
Coating composition	?
Surface treatment	Grit Blasted Rz = 80 micron
Maximum coating thickness	?
Curing procedure	?
Duration of curing	?
Time between application coating and testing	?
Specimen	Standard test piece M20 (EN 1090-2, drawing Annex G.1 b)
Bolt class, bolt type	10.9 (EN 14399-4 – HV – M20 x 180 – 10.9/10 – tZn)
Nominal Preload level	172 kN = $F_{p,C}$
Measuring of the preload level	Load cells, continuously measured, bolt length Σt = 152 mm
load head speed	0,0025 mm/sec

Static load

specimen mark	plate ID's	slip (average at CBG) u_i [mm]	Slip load F_{Si} [kN]	Pre loading at start test (initial pre load): outer Bolt $F_{bi,o,ini}$ [kN]	average mean $F_{bi,ini}$ [kN]	inner Bolt $F_{bi,i,ini}$ [kN]	slip factor based on initial preload $\mu_{i,ini}$ [–]	based on nominal preload $F_{p,C}$ [kN] 172 $\mu_i = \mu_{i,nom}$ [–]	based on preload at reaching slip criterion $\mu_{i,act}$ [–]	Preload at reaching slip criterion: outer bolt $F_{bi,o,act}$ [kN]	average mean $F_{bi,act}$ [kN]	inner bolt $F_{bi,i,act}$ [kN]	test duration t [min]	comment Equations from EN 1090-2 annex G	test date start test
ASiZN_05	0	0.150	478	169	170	170	0.70	0.69	0.74	162	162	161	18.3	0.00	13-01-15 10:47
	0	0.150	486	168	169	170	0.72	0.71	0.76	161	160	159	18.8	0.00	
ASiZN_06	0	0.150	476	160	162	164	0.73	0.69	0.78	151	152	154	20.1	0.00	13-01-15 13:13
	0	0.150	467	163	162	161	0.72	0.68	0.76	156	153	150	19.1	0.00	
ASiZN_14	0	0.150	497	174	173	172	0.72	0.72	0.76	165	163	162	20.1	0.00	23-03-15 11:58
	0	0.150	495	175	173	171	0.72	0.72	0.76	166	163	160	19.3	0.00	
Statistics (3 specimen, 6 test results)	n=6	number of tests													
	max	Maximum	497				0.73	0.72	0.78				20.1		
	min	Minimum	467				0.70	0.68	0.74				18.3		
	mean	Average F_{Sm} | μ_m	**483**				**0.72**	**0.70**	**0.76**				**19.3**	Eq. (2), Eq. (4)	
	R	spread	30.2				0.03	0.04	0.04				1.8	*R = max – min*	
	s	standard deviation	11.8				0.010	0.017	0.013				0.7	Eq. (3), Eq. (5)	
	V	coefficient of variation	2.4%				1.4%	2.4%	1.7%				4%	*V = s / mean*	
creep test	**0,9 F_{Sm}**		**435**										slip [μm]	Load level creep test [kN]	
Statistics (3 specimen, 6 test results)	n=6	number of tests											**result**		
	max	Maximum	497				0.73	0.72	0.78				failed	Δ slip < 2 μm in 3 h.	
	min	Minimum	467				0.70	0.68	0.74						
	mean	Average F_{Sm} | μ_m	483				0.72	0.70	0.76					Eq. (2), Eq. (4)	
	R	spread	30.2				0.03	0.04	0.04					*R = max – min*	
	s	standard deviation	11.8				0.010	0.017	0.013					Eq. (3), Eq. (5)	
	V	coefficient of variation	**2.4%**				**1.4%**	**2.4%**	**1.7%**					*V = s / mean* ≤ 8%	
	0,9 F_{Sm}		435												
μ_k	Characteristic value slip factor						-	-	-					Eq. (6)	

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ASiZN 0.001	CBG

Test protocol

15-02-17

basics slip fator experiment		
	Tested according to	EN 1090-2:2011-10 – Annex G **slip criterion used**: 0.15 mm at Centre Bolt Group
	Test date	
	test performed by	P.A. de Vries, F. Schilperoord
	Steel	S355JR +N (hot rolled)
	Coating	**ASiZN coating 60 micron (measured mean DCT)**
	Coating composition	?
	Surface treatment	Grit Blasted Rz = 80 micron
	Maximum coating thickness	?
	Curing procedure	?
	Duration of curing	?
	Time between application coating and testing	?
	Specimen	Standard test piece M20 (EN 1090-2, drawing Annex G.1 b)
	Bolt class, bolt type	10.9 (EN 14399-4 – HV – M20 x 180 – 10.9/10 – tZn)
	Nominal Preload level	172 kN = $F_{p,C}$
	Measuring of the preload level	Load cells, continuously measured, bolt length Σt = 152 mm
	load head speed	0,001 mm/sec

	specimen mark	plate ID's	slip (average at CBG) u_i [mm]	Slip load F_{Si} [kN]	Pre loading at start test (initial pre load): outer Bolt $F_{bi,o,ini}$ [kN]	average mean $F_{bi,ini}$ [kN]	inner Bolt $F_{bi,i,ini}$ [kN]	slip factor: based on initial preload $\mu_{i,ini}$ [–]	based on nominal preload $F_{p,C}$ [kN] 172; $\mu_i = \mu_{i,nom}$ [–]	based on preload at reaching slip criterion $\mu_{i,act}$ [–]	Preload at reaching slip criterion: outer bolt $F_{bi,o,act}$ [kN]	average mean $F_{bi,act}$ [kN]	inner bolt $F_{bi,i,act}$ [kN]	test duration t [min]	comment Equations from EN 1090-2 annex G	test date start test
Static load	ASiZN_10	0	0.150	491	169	168	168	0.73	0.71	0.77	160	159	158	52.2	0.00	12-02-15 13:49
		0	0.150	481	169	168	167	0.72	0.70	0.76	161	158	156	44.9	0.00	
	ASiZN_15	0	0.150	498	168	168	169	0.74	0.72	0.79	158	158	159	48.3	0.00	23-03-15 13:41
		0	0.150	499	171	170	170	0.73	0.72	0.78	161	159	157	48.7	0.00	
	ASiZN_17	0	0.150	492	170	171	172	0.72	0.72	0.76	161	161	161	47.2	0.00	24-03-15 10:02
		0	0.119	502	171	171	171	0.73	0.73	0.78	161	161	160	52.0	0.00	
	Statistics (3 specimen, 6 test results)	n=6	number of tests													
		max	Maximum	502				0.74	0.73	0.79				52.2		
		min	Minimum	481				0.72	0.70	0.76				44.9		
		mean	Average F_{Sm} | μ_m	**494**				**0.73**	**0.72**	**0.78**				**48.9**	Eq. (2), Eq. (4)	
		R	spread	20.5				0.02	0.03	0.03				7.3	*R = max – min*	
		s	standard deviation	7.4				0.009	0.011	0.011				2.8	Eq. (3), Eq. (5)	
		V	coefficient of variation	1.5%				1.2%	1.5%	1.4%				6%	*V = s / mean*	
	creep test	**0,9 F_{Sm}**		**444**										slip [μm]	Load level creep test [kN]	
	ASiZN_11	0	0.150	425	167	167	167	0.64	0.62	0.67	158	158	157	53.5	**425**	18-02-15 16:25
		0	0.132	516	168	168	168	0.77	0.75	0.83	156	155	154	33.5	NOT passed	
	Statistics (4 specimen, 8 test results)	n=8	number of tests											**result**		
		max	Maximum	516				0.77	0.75	0.83				failed	Δ slip < 2 μm in 3 h.	
		min	Minimum	425				0.64	0.62	0.67						
		mean	Average F_{Sm} | μ_m	488				0.72	0.71	0.77					Eq. (2), Eq. (4)	
		R	spread	91.2				0.13	0.13	0.16					*R = max – min*	
		s	standard deviation	27.4				0.038	0.040	0.045					Eq. (3), Eq. (5)	
		V	coefficient of variation	**5.6%**				**5.3%**	**5.6%**	**5.8%**					*V = s / mean* ≤ 8%	
		0,9 F_{Sm}		439												
	μ_k	Characteristic value slip factor						-	-	-					Eq. (6)	

14 Annex G: Overview results ZnSM series

For all individual short term slip factor results see additional Stevin report:

- **Stevin report 6-18-01 – additon C: Test results ZnSM**

Slip criterion used: slip at CBG: 0.15 mm

- Short term tests
- Creep tests

Clamp length	Speed
[mm]	[mm/s]
152	0.01
152	0.005
48	0.005
152	0.0025
152	0.001
152	0.0005

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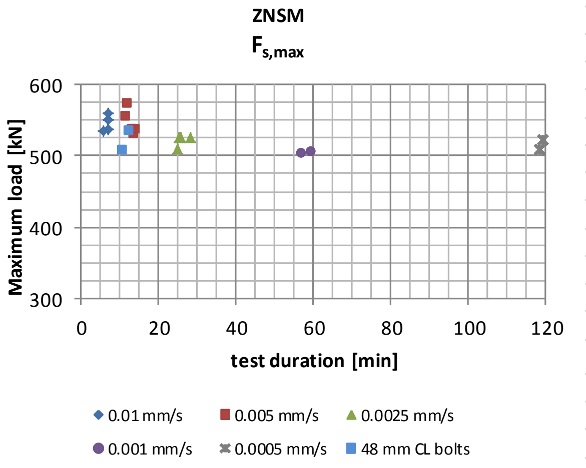
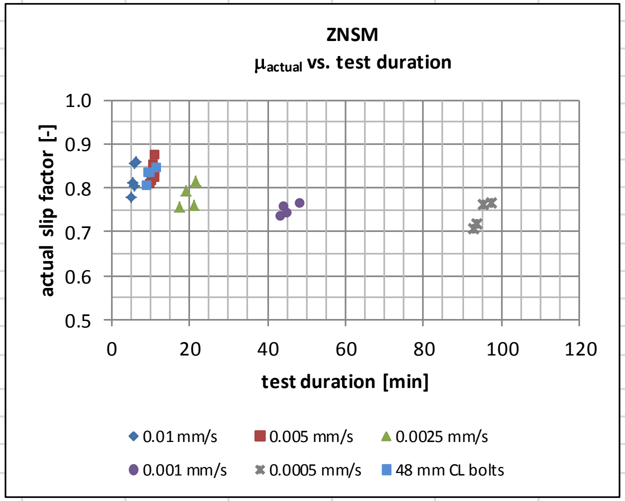
15-02-17

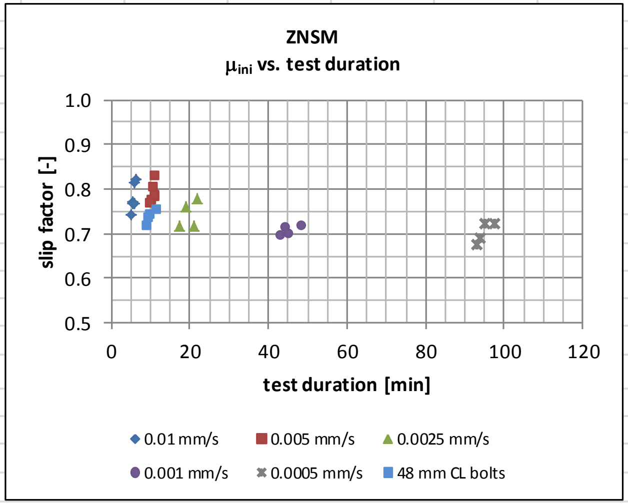
ZNSM — Results overview table

ZNSM

speed		# tests				test results short term tests						test results including creep test				characteristic value acc. to Annex G	
	CL	task 1.2 test matrix		realization		test duration [min]		μ_{act}		μ_{ini}		μ_{act}		μ_{ini}		μ_k	
mm/s	[mm]	short term	creep	short term	creep	mean	COV	mean	COV	mean	COV	mean	COV	mean	COV	actual	Fp,init
0.01	152	8	2	6	2	6	7%	0.82	4%	0.76	2%	0.77	13%	0.71	13%	-	-
0.005	152	8	2	6	2	11	5%	0.83	3%	0.76	3%	0.79	10%	0.72	9%	-	-
0.005	48	-	-	4	0	10	10%	0.83	2%	0.74	4%	-	-	-	-	-	-
0.0025	152	8	2	4	0	20	10%	0.78	4%	0.72	3%	-	-	-	-	-	-
0.001	152	8	2	4	0	45	5%	0.75	2%	0.69	2%	-	-	-	-	-	-
0.0005	152	0	0	4	2	95	2%	0.74	4%	0.69	1%	0.68	14%	0.63	15%	-	-

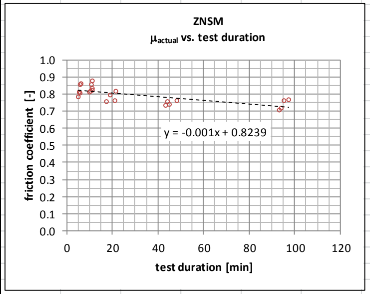






ZNSM			friction coefficient			$loss_{test}$						
speed	clamping length	$F_{p,init}$	μ_{act}	μ_{ini}	μ_{nom}	group	outer bolt	inner bolt	sample iD	t_{test}	t_{prep}	loss $_{15\ min}$
[mm/s]	[mm]	[kN]	[-]	[-]	[-]	%	%	%		[min]	[min]	%
0.01	152	164	0.86	0.81	0.77	5%	4%	5%	SM_03	6.0	no data	no data
		164	0.86	0.82	0.78	5%	5%	5%		6.2		
		166	0.81	0.77	0.74	5%	5%	5%	SM_04	5.4	20	2.8
		166	0.81	0.77	0.74	6%	5%	6%		5.5		
		174	0.81	0.77	0.78	5%	4%	5%	SM_12	5.7	no data	no data
		175	0.78	0.74	0.76	5%	4%	6%		5.0		
0.005	152	163	0.81	0.77	0.73	5%	4%	5%	SM_01	10	21	3.4
		165	0.82	0.78	0.75	5%	5%	5%		11		
		165	0.81	0.77	0.73	5%	5%	5%	SM_02	10	17	3.1
		165	0.83	0.78	0.75	6%	5%	6%		11		
		166	0.87	0.83	0.80	5%	5%	5%	SM_07	11	19	2.8
		166	0.85	0.80	0.78	6%	5%	7%		11		
0.0025	152	165	0.79	0.76	0.73	4%	4%	4%	SM_05	19	1195	2.2
		166	0.82	0.78	0.75	5%	4%	5%		22		
		167	0.76	0.72	0.70	5%	5%	5%	SM_06	18	27	2.6
		168	0.76	0.72	0.70	6%	5%	7%		21		
0.001	152	167	0.73	0.70	0.68	5%	5%	6%	SM_10	43	27	2.7
		167	0.76	0.71	0.69	5%	5%	6%		44		
		167	0.74	0.70	0.68	6%	5%	6%	SM_11	45	16	2.8
		167	0.76	0.72	0.70	6%	6%	7%		48		
0.0005	152	165	0.76	0.72	0.69	5%	5%	6%	SM_13	95	88	2.9
		166	0.76	0.72	0.70	6%	5%	6%		98		
		171	0.72	0.69	0.68	4%	4%	5%	SM_14	94	1338	3.2
		173	0.71	0.67	0.68	5%	4%	5%		93		
	mean	**167**	**0.80**	**0.76**	**0.74**	**5%**	**5%**	**6%**			mean	**2.8**
	stdev	3.1	0.04	0.04	0.04	0.01	0.01	0.01			stdev	0.3
	COV	2%	5%	5%	5%	10%	11%	13%			COV	12%

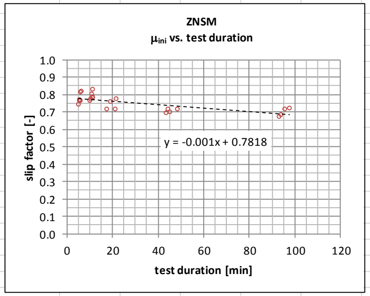
ZNSM			friction coefficient			$loss_{test}$						
speed	clamping length	$F_{p,init}$	μ_{act}	μ_{ini}	μ_{nom}	group	outer bolt	inner bolt	sample iD	t_{test}	t_{prep}	loss $_{15\ min}$
[mm/s]	[mm]	[kN]	[-]	[-]	[-]	%	%	%		[min]	[min]	%
0.005	48	171	0.80	0.72	0.71	11%	9%	13%	SM_17	9.3	51	6.7
		171	0.83	0.73	0.73	12%	11%	12%		9.6		
		175	0.83	0.74	0.75	11%	9%	12%	SM_18	10.2	6951	6.6
		176	0.84	0.75	0.77	11%	8%	13%		11.5		
	mean	**173**	**0.83**	**0.74**	**0.74**	**11%**	**9%**	**13%**			mean	**6.7**
	stdev	2.8	0.02	0.02	0.03	0.00	0.01	0.00			stdev	0.1
	COV	2%	2%	2%	4%	4%	12%	4%			COV	1%



trend line	0.824	-0.001

test duration

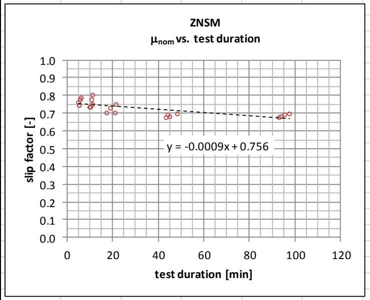
[min]	μ_{act}	diff
5	0.82	**0.9%**
12.5	**0.81**	-
20	0.80	**-0.9%**



trend line	0.782	-0.001

test duration

[min]	μ_{ini}	diff
5	0.78	**1.0%**
12.5	**0.77**	-
20	0.76	**-1.0%**



trend line	0.756	-0.0009

test duration

[min]	μ_{nom}	diff
5	0.75	**0.9%**
12.5	**0.74**	-
20	0.74	**-0.9%**

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ZNSM	0.01	CBG

Test protocol

15-02-17

basics slip fator experiment		
	Tested according to	EN 1090-2:2011-10 – Annex G **slip criterion used**: 0.15 mm at Centre Bolt Group
	Test date	
	test performed by	P.A. de Vries, F. Schilperoord
	Steel	S355JR +N (hot rolled)
	Coating	**Zinc sprayed metallized, thickness 140 micron (mean of measured DCT of all plates)**
	Coating composition	?
	Surface treatment	Grit Blasted Rz = 104 micron (mean of measured value of all plates)
	Maximum coating thickness	?
	Curing procedure	?
	Duration of curing	?
	Time between application coating and testing	?
	Specimen	Standard test piece M20 (EN 1090-2, drawing Annex G.1 b)
	Bolt class, bolt type	10.9 (EN 14399-4 – HV – M20 x 180 – 10.9/10 – tZn)
	Nominal Preload level	172 kN = $F_{p,C}$
	Measuring of the preload level	Load cells, continuously measured, bolt length Σt = 152 mm
	load head speed	0,010 mm/sec

	specimen mark	plate ID's	slip (average at CBG) u_i [mm]	Slip load F_{Si} [kN]	Pre loading at start test (initial pre load): outer Bolt $F_{bi,o,ini}$ [kN]	average mean $F_{bi,ini}$ [kN]	inner Bolt $F_{bi,i,ini}$ [kN]	slip factor: based on initial preload $\mu_{i,ini}$ [–]	based on nominal preload $F_{p,C}$ [kN] 172 $\mu_i = \mu_{i,nom}$ [–]	based on preload at reaching slip criterion $\mu_{i,act}$ [–]	Preload at reaching slip criterion: outer bolt $F_{bi,o,act}$ [kN]	average mean $F_{bi,act}$ [kN]	inner bolt $F_{bi,i,act}$ [kN]	test duration t [min]	comment Equations from EN 1090-2 annex G	test date start test
Static load	SM_03	0	0.150	533	163	164	164	0.81	0.77	0.86	156	156	155	6.0	0.00	03-02-15 13:37
		0	0.150	539	165	164	164	0.82	0.78	0.86	158	157	156	6.2	0.00	
	SM_04	0	0.150	511	165	166	167	0.77	0.74	0.81	158	158	158	5.4	0.00	03-02-15 14:47
		0	0.150	510	167	166	166	0.77	0.74	0.81	159	157	155	5.5	0.00	
	SM_12	0	0.150	535	174	174	174	0.77	0.78	0.81	166	166	166	5.7	0.00	26-03-15 13:41
		0	0.150	522	175	175	176	0.74	0.76	0.78	169	167	166	5.0	0.00	
	Statistics (3 specimen, 6 test results)	n=6	number of tests													
		max	Maximum	539				0.82	0.78	0.86				6.2		
		min	Minimum	510				0.74	0.74	0.78				5.0		
		mean	Average F_{Sm} | μ_m	**525**				**0.78**	**0.76**	**0.82**				**5.6**	Eq. (2), Eq. (4)	
		R	spread	29.1				0.08	0.04	0.08				1.1	*R = max – min*	
		s	standard deviation	12.6				0.030	0.018	0.031				0.4	Eq. (3), Eq. (5)	
		V	coefficient of variation	2.4%				3.8%	2.4%	3.8%				7%	*V = s / mean*	
	creep test	**0,9 F_{Sm}**		**473**										slip [μm]	Load level creep test [kN]	
	Statistics (3 specimen, 6 test results)	n=6	number of tests											**result**		
		max	Maximum	539				0.82	0.78	0.86				failed	Δ slip < 2 μm in 3 h.	
		min	Minimum	510				0.74	0.74	0.78						
		mean	Average F_{Sm} | μ_m	525				0.78	0.76	0.82					Eq. (2), Eq. (4)	
		R	spread	29.1				0.08	0.04	0.08					*R = max – min*	
		s	standard deviation	12.6				0.030	0.018	0.031					Eq. (3), Eq. (5)	
		V	coefficient of variation	**2.4%**				**3.8%**	**2.4%**	**3.8%**					*V = s / mean* ≤ 8%	
		0,9 F_{Sm}		473												
	μ_k	Characteristic value slip factor						-	-	-					Eq. (6)	

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ZNSM	0.005	CBG

Test protocol

15-02-17

basics slip fator experiment

Tested according to	EN 1090-2:2011-10 – Annex G **slip criterion used**: 0.15 mm at Centre Bolt Group
Test date	
test performed by	P.A. de Vries, F. Schilperoord
Steel	S355JR +N (hot rolled)
Coating	**Zinc sprayed metallized, thickness 140 micron (mean of measured DCT of all plates)**
Coating composition	?
Surface treatment	Grit Blasted Rz = 104 micron (mean of measured value of all plates)
Maximum coating thickness	?
Curing procedure	?
Duration of curing	?
Time between application coating and testing	?
Specimen	Standard test piece M20 (EN 1090-2, drawing Annex G.1 b)
Bolt class, bolt type	10.9 (EN 14399-4 – HV – M20 x 180 – 10.9/10 – tZn)
Nominal Preload level	172 kN = $F_{p,C}$
Measuring of the preload level	Load cells, continuously measured, bolt length Σt = 152 mm
load head speed	0,005 mm/sec

Static load

specimen mark	plate ID's	slip (average at CBG) u_i [mm]	Slip load F_{Si} [kN]	Pre loading at start test (initial pre load): outer Bolt $F_{bi,o,ini}$ [kN]	average mean $F_{bi,ini}$ [kN]	inner Bolt $F_{bi,i,ini}$ [kN]	slip factor based on initial preload $\mu_{i,ini}$ [–]	based on nominal preload $F_{p,C}$ [kN] 172 $\mu_i = \mu_{i,nom}$ [–]	based on preload at reaching slip criterion $\mu_{i,act}$ [–]	Preload at reaching slip criterion: outer bolt $F_{bi,o,act}$ [kN]	average mean $F_{bi,act}$ [kN]	inner bolt $F_{bi,i,act}$ [kN]	test duration t [min]	comment Equations from EN 1090-2 annex G	test date start test
SM_01	0	0.150	505	163	163	163	0.77	0.73	0.81	155	155	155	10.5	0.00	03-02-15 9:51
	0	0.150	515	165	165	165	0.78	0.75	0.82	157	157	156	11.2	0.00	
SM_02	0	0.150	504	164	165	165	0.77	0.73	0.81	156	156	156	10.0	0.00	03-02-15 11:27
	0	0.150	517	166	165	163	0.78	0.75	0.83	157	155	153	11.3	0.00	
SM_07	0	0.150	550	166	166	166	0.83	0.80	0.87	157	157	157	11.3	load controlled 0.8 kN/s	04-02-15 15:13
	0	0.150	534	166	166	166	0.80	0.78	0.85	158	156	155	10.8	0.00	
Statistics (3 specimen, 6 test results)	n=6	number of tests													
	max	Maximum	550				0.83	0.80	0.87				11.3		
	min	Minimum	504				0.77	0.73	0.81				10.0		
	mean	Average F_{Sm} | μ_m	**521**				**0.79**	**0.76**	**0.83**				**10.9**	Eq. (2), Eq. (4)	
	R	spread	45.6				0.06	0.07	0.07				1.3	*R = max – min*	
	s	standard deviation	17.9				0.023	0.026	0.026				0.5	Eq. (3), Eq. (5)	
	V	coefficient of variation	3.4%				2.9%	3.4%	3.1%				5%	*V = s / mean*	
creep test	0,9 F_{Sm}		**469**										slip [μm]	Load level creep test [kN]	
SM_09	0	0.150	427	165	165	165	0.65	0.62	0.68	158	157	157	278.6	**425**	11-02-15 10:21
	0	0.150	427	165	165	165	0.65	0.62	0.68	159	158	157	527.6	NOT passed	
Statistics (4 specimen, 8 test results)	n=8	number of tests											**result**		
	max	Maximum	550				0.83	0.80	0.87				failed	Δ slip < 2 μm in 3 h.	
	min	Minimum	427				0.65	0.62	0.68						
	mean	Average F_{Sm} | μ_m	497				0.75	0.72	0.79					Eq. (2), Eq. (4)	
	R	spread	123.0				0.18	0.18	0.20					*R = max – min*	
	s	standard deviation	46.0				0.069	0.067	0.076					Eq. (3), Eq. (5)	
	V	coefficient of variation	**9.2%**				**9.2%**	**9.2%**	**9.5%**					*V = s / mean* ≤ 8%	
	0,9 F_{Sm}		448												
μ_k	Characteristic value slip factor						-	-	-					Eq. (6)	

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SIROCO RFSR-CT-2014-00024

ZNSM 0.005 CBG | # Test protocol | 15-02-17

basics slip fator experiment		
	Tested according to	EN 1090-2:2011-10 – Annex G **slip criterion used**: 0.15 mm at Centre Bolt Group
	Test date	
	test performed by	P.A. de Vries
	Steel	S355JR +N (hot rolled)
	Coating	**Zinc sprayed metallized, thickness 140 micron (mean of measured DCT of all plates)**
	Coating composition	?
	Surface treatment	Grit Blasted Rz = 104 micron (mean of measured value of all plates)
	Maximum coating thickness	?
	Curing procedure	?
	Duration of curing	?
	Time between application coating and testing	?
	Specimen	Standard test piece M20 (EN 1090-2, drawing Annex G.1 b)
	Bolt class, bolt type	10.9 (EN 14399-4 – HV – M20 x 180 – 10.9/10 – tZn)
	Nominal Preload level	172 kN = $F_{p,C}$
	Measuring of the preload level	Instrumented bolts, continuously measured, clamping length St = 48 mm
	load head speed	0,005 mm/sec

	specimen mark	plate ID's	**slip (average at CBG)** u_i [mm]	**Slip load** F_{Si} [kN]	**Pre loading at start test (initial pre load)** outer Bolt $F_{bi,o,ini}$ [kN]	average mean $F_{bi,ini}$ [kN]	inner Bolt $F_{bi,i,ini}$ [kN]	**slip factor** based on initial preload $\mu_{i,ini}$ [–]	based on nominal preload $F_{p,C}$ [kN] 172 $\mu_i = \mu_{i,nom}$ [–]	based on preload at reaching slip criterion $\mu_{i,act}$ [–]	**Preload at reaching slip criterion** outer bolt $F_{bi,o,act}$ [kN]	average mean $F_{bi,act}$ [kN]	inner bolt $F_{bi,i,act}$ [kN]	**test duration** t [min]	**comment** Equations from EN 1090-2 annex G	**test date** start test
Static load	**SM_17**	0	0.150	489	169	171	173	0.72	0.71	0.80	154	152	150	9.3	0.00	29-05-15 11:56
		0	0.150	502	171	171	170	0.73	0.73	0.83	152	151	149	9.6	0.00	
	SM_18	0	0.150	519	173	175	176	0.74	0.75	0.83	157	156	154	10.2	0.00	03-06-15 13:54
		0	0.150	531	175	176	178	0.75	0.77	0.84	161	157	154	11.5	0.00	
	Statistics (2 specimen, 4 test results)	n=4	number of tests													
		max	Maximum	531				0.75	0.77	0.84				11.5		
		min	Minimum	489				0.72	0.71	0.80				9.3		
		mean	Average F_{Sm} | μ_m	**510**				**0.74**	**0.74**	**0.83**				**10.1**	Eq. (2), Eq. (4)	
		R	spread	41.5				0.04	0.06	0.04				2.2	*R = max – min*	
		s	standard deviation	18.4				0.016	0.027	0.017				1.0	Eq. (3), Eq. (5)	
		V	coefficient of variation	3.6%				2.1%	3.6%	2.0%				10%	*V = s / mean*	
	creep test	**0,9 F_{Sm}**		**459**										slip [μm]	Load level creep test [kN]	
	Statistics (2 specimen, 4 test results)	n=4	number of tests											**result**		
		max	Maximum	531				0.75	0.77	0.84				failed	Δ slip < 2 μm in 3 h.	
		min	Minimum	489				0.72	0.71	0.80						
		mean	Average F_{Sm} | μ_m	510				0.74	0.74	0.83					Eq. (2), Eq. (4)	
		R	spread	41.5				0.04	0.06	0.04					*R = max – min*	
		s	standard deviation	18.4				0.016	0.027	0.017					Eq. (3), Eq. (5)	
		V	coefficient of variation	**3.6%**				**2.1%**	**3.6%**	**2.0%**					*V = s / mean* ≤ 8%	
		0,9 F_{Sm}		459												
	μ_k	Characteristic value slip factor						-	-	-					Eq. (6)	

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ZNSM 0.0025 CBG

Test protocol

15-02-17

basics slip fator experiment		
	Tested according to	EN 1090-2:2011-10 – Annex G **slip criterion used**: 0.15 mm at Centre Bolt Group
	Test date	
	test performed by	P.A. de Vries, F. Schilperoord
	Steel	S355JR +N (hot rolled)
	Coating	**Zinc sprayed metallized, thickness 140 micron (mean of measured DCT of all plates)**
	Coating composition	?
	Surface treatment	Grit Blasted Rz = 104 micron (mean of measured value of all plates)
	Maximum coating thickness	?
	Curing procedure	?
	Duration of curing	?
	Time between application coating and testing	?
	Specimen	Standard test piece M20 (EN 1090-2, drawing Annex G.1 b)
	Bolt class, bolt type	10.9 (EN 14399-4 – HV – M20 x 180 – 10.9/10 – tZn)
	Nominal Preload level	172 kN = $F_{p,C}$
	Measuring of the preload level	Load cells, continuously measured, bolt length Σt = 152 mm
	load head speed	0,0025 mm/sec

	specimen mark	plate ID's	slip (average at CBG) u_i [mm]	Slip load F_{Si} [kN]	Pre loading at start test (initial pre load): outer Bolt $F_{bi,o,ini}$ [kN]	average mean $F_{bi,ini}$ [kN]	inner Bolt $F_{bi,i,ini}$ [kN]	slip factor: based on initial preload $\mu_{i,ini}$ [–]	based on nominal preload $F_{p,C}$ [kN] 172 $\mu_i = \mu_{i,nom}$ [–]	based on preload at reaching slip criterion $\mu_{i,act}$ [–]	Preload at reaching slip criterion: outer bolt $F_{bi,o,act}$ [kN]	average mean $F_{bi,act}$ [kN]	inner bolt $F_{bi,i,act}$ [kN]	test duration t [min]	comment Equations from EN 1090-2 annex G	test date start test
Static load	SM_05	0	0.150	502	165	165	165	0.76	0.73	0.79	159	158	158	19.1	0.00	04-02-15 11:31
		0	0.150	516	165	166	167	0.78	0.75	0.82	158	158	158	21.7	0.00	
	SM_06	0	0.150	481	168	167	167	0.72	0.70	0.76	160	159	159	17.5	0.00	04-02-15 13:14
		0	0.150	481	168	168	167	0.72	0.70	0.76	159	158	156	21.2	0.00	
	Statistics (2 specimen, 4 test results)	n=4	number of tests													
		max	Maximum	516				0.78	0.75	0.82				21.7		
		min	Minimum	481				0.72	0.70	0.76				17.5		
		mean	Average $F_{Sm} \mid \mu_m$	**495**				**0.74**	**0.72**	**0.78**				**19.9**	Eq. (2), Eq. (4)	
		R	spread	34.8				0.06	0.05	0.06				4.2	*R = max – min*	
		s	standard deviation	17.1				0.031	0.025	0.028				1.9	Eq. (3), Eq. (5)	
		V	coefficient of variation	3.5%				4.1%	3.5%	3.6%				10%	*V = s / mean*	
	creep test	**0,9 F_{Sm}**		**445**										slip [μm]	Load level creep test [kN]	
	Statistics (2 specimen, 4 test results)	n=4	number of tests											**result**		
		max	Maximum	516				0.78	0.75	0.82				failed	Δ slip < 2 μm in 3 h.	
		min	Minimum	481				0.72	0.70	0.76						
		mean	Average $F_{Sm} \mid \mu_m$	495				0.74	0.72	0.78					Eq. (2), Eq. (4)	
		R	spread	34.8				0.06	0.05	0.06					*R = max – min*	
		s	standard deviation	17.1				0.031	0.025	0.028					Eq. (3), Eq. (5)	
		V	coefficient of variation	**3.5%**				**4.1%**	**3.5%**	**3.6%**					*V = s / mean* ≤ 8%	
		0,9 F_{Sm}		445												
	μ_k	Characteristic value slip factor						-	-	-					Eq. (6)	

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ZNSM	0.001	CBG

Test protocol

15-02-17

basics slip fator experiment		
	Tested according to	EN 1090-2:2011-10 – Annex G **slip criterion used**: 0.15 mm at Centre Bolt Group
	Test date	
	test performed by	P.A. de Vries, F. Schilperoord
	Steel	S355JR +N (hot rolled)
	Coating	**Zinc sprayed metallized, thickness 140 micron (mean of measured DCT of all plates)**
	Coating composition	?
	Surface treatment	Grit Blasted Rz = 104 micron (mean of measured value of all plates)
	Maximum coating thickness	?
	Curing procedure	?
	Duration of curing	?
	Time between application coating and testing	?
	Specimen	Standard test piece M20 (EN 1090-2, drawing Annex G.1 b)
	Bolt class, bolt type	10.9 (EN 14399-4 – HV – M20 x 180 – 10.9/10 – tZn)
	Nominal Preload level	172 kN = $F_{p,C}$
	Measuring of the preload level	Load cells, continuously measured, bolt length Σt = 152 mm
	load head speed	0,001 mm/sec

	specimen mark	plate ID's	slip (average at CBG) u_i [mm]	Slip load F_{Si} [kN]	Pre loading at start test (initial pre load): outer Bolt $F_{bi,o,ini}$ [kN]	average mean $F_{bi,ini}$ [kN]	inner Bolt $F_{bi,i,ini}$ [kN]	slip factor: based on initial preload $\mu_{i,ini}$ [–]	based on nominal preload $F_{p,C}$ [kN] 172 $\mu_i = \mu_{i,nom}$ [–]	based on preload at reaching slip criterion $\mu_{i,act}$ [–]	Preload at reaching slip criterion: outer bolt $F_{bi,o,act}$ [kN]	average mean $F_{bi,act}$ [kN]	inner bolt $F_{bi,i,act}$ [kN]	test duration t [min]	comment Equations from EN 1090-2 annex G	test date start test
Static load	**SM_10**	0	0.150	464	167	167	167	0.70	0.68	0.73	158	158	158	43.3	0.00	16-02-15 10:22
		0	0.150	477	167	167	166	0.71	0.69	0.76	159	158	157	44.3	0.00	
	SM_11	0	0.150	467	166	167	168	0.70	0.68	0.74	157	157	158	45.2	0.00	16-02-15 15:12
		0	0.150	479	168	167	167	0.72	0.70	0.76	158	157	155	48.4	0.00	
	Statistics (2 specimen, 4 test results)	n=4	number of tests													
		max	Maximum	479				0.72	0.70	0.76				48.4		
		min	Minimum	464				0.70	0.68	0.73				43.3		
		mean	Average F_{Sm} | μ_m	**472**				**0.71**	**0.69**	**0.75**				**45.3**	Eq. (2), Eq. (4)	
		R	spread	14.5				0.02	0.02	0.03				5.1	*R = max – min*	
		s	standard deviation	7.1				0.010	0.010	0.013				2.2	Eq. (3), Eq. (5)	
		V	coefficient of variation	1.5%				1.5%	1.5%	1.7%				5%	*V = s / mean*	
	creep test	**0,9 F_{Sm}**		**425**										slip [μm]	Load level creep test [kN]	
	Statistics (2 specimen, 4 test results)	n=4	number of tests											**result**		
		max	Maximum	479				0.72	0.70	0.76				failed	Δ slip < 2 μm in 3 h.	
		min	Minimum	464				0.70	0.68	0.73						
		mean	Average F_{Sm} | μ_m	472				0.71	0.69	0.75					Eq. (2), Eq. (4)	
		R	spread	14.5				0.02	0.02	0.03					*R = max – min*	
		s	standard deviation	7.1				0.010	0.010	0.013					Eq. (3), Eq. (5)	
		V	coefficient of variation	**1.5%**				**1.5%**	**1.5%**	**1.7%**					*V = s / mean* ≤ 8%	
		0,9 F_{Sm}		425												
	μ_k	Characteristic value slip factor						-	-	-					Eq. (6)	

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ZNSM	0.0010	CBG

Test protocol

15-02-17

basics slip fator experiment

Tested according to	EN 1090-2:2011-10 – Annex G **slip criterion used**: 0.15 mm at Centre Bolt Group
Test date	
test performed by	P.A. de Vries, F. Schilperoord
Steel	S355JR +N (hot rolled)
Coating	**Zinc sprayed metallized, thickness 140 micron (mean of measured DCT of all plates)**
Coating composition	?
Surface treatment	Grit Blasted Rz = 104 micron (mean of measured value of all plates)
Maximum coating thickness	?
Curing procedure	?
Duration of curing	?
Time between application coating and testing	?
Specimen	Standard test piece M20 (EN 1090-2, drawing Annex G.1 b)
Bolt class, bolt type	10.9 (EN 14399-4 – HV – M20 x 180 – 10.9/10 – tZn)
Nominal Preload level	172 kN = $F_{p,C}$
Measuring of the preload level	Load cells, continuously measured, bolt length Σt = 152 mm
load head speed	0,0005 mm/sec

Static load

specimen mark	plate ID's	slip (average at CBG) u_i [mm]	Slip load F_{Si} [kN]	Pre loading at start test (initial pre load): outer Bolt $F_{bi,o,ini}$ [kN]	average mean $F_{bi,ini}$ [kN]	inner Bolt $F_{bi,i,ini}$ [kN]	slip factor: based on initial preload $\mu_{i,ini}$ [–]	based on nominal preload $F_{p,C}$ [kN] 172 $\mu_i = \mu_{i,nom}$ [–]	based on preload at reaching slip criterion $\mu_{i,act}$ [–]	Preload at reaching slip criterion: outer bolt $F_{bi,o,act}$ [kN]	average mean $F_{bi,act}$ [kN]	inner bolt $F_{bi,i,act}$ [kN]	test duration t [min]	comment Equations from EN 1090-2 annex G	test date start test
SM_13	0	0.150	475	164	165	166	0.72	0.69	0.76	156	156	157	95.4	0.00	30-03-15 13:21
	0	0.150	479	166	166	166	0.72	0.70	0.76	158	157	156	97.6	0.00	
SM_14	0	0.150	470	171	171	171	0.69	0.68	0.72	164	164	163	94.0	0.00	28-03-15 16:24
	0	0.150	465	171	173	175	0.67	0.68	0.71	164	165	165	93.2	0.00	
Statistics (2 specimen, 4 test results)	n=4	number of tests													
	max	Maximum	479				0.72	0.70	0.76				97.6		
	min	Minimum	465				0.67	0.68	0.71				93.2		
	mean	Average F_{Sm} | μ_m	**472**				**0.70**	**0.69**	**0.74**				**95.0**	Eq. (2), Eq. (4)	
	R	spread	13.4				0.05	0.02	0.06				4.3	*R = max – min*	
	s	standard deviation	5.9				0.024	0.009	0.029				1.9	Eq. (3), Eq. (5)	
	V	coefficient of variation	1.2%				3.4%	1.2%	4.0%				2%	*V = s / mean*	
creep test	**0,9 F_{Sm}**		425										slip [μm]	Load level creep test [kN]	
Statistics (2 specimen, 4 test results)	n=4	number of tests											**result**		
	max	Maximum	479				0.72	0.70	0.76				failed	Δ slip < 2 μm in 3 h.	
	min	Minimum	465				0.67	0.68	0.71						
	mean	Average F_{Sm} | μ_m	472				0.70	0.69	0.74					Eq. (2), Eq. (4)	
	R	spread	13.4				0.05	0.02	0.06					*R = max – min*	
	s	standard deviation	5.9				0.024	0.009	0.029					Eq. (3), Eq. (5)	
	V	coefficient of variation	**1.2%**				**3.4%**	**1.2%**	**4.0%**					*V = s / mean* ≤ 8%	
	0,9 F_{Sm}		425												
μ_k	Characteristic value slip factor						-	-	-					Eq. (6)	

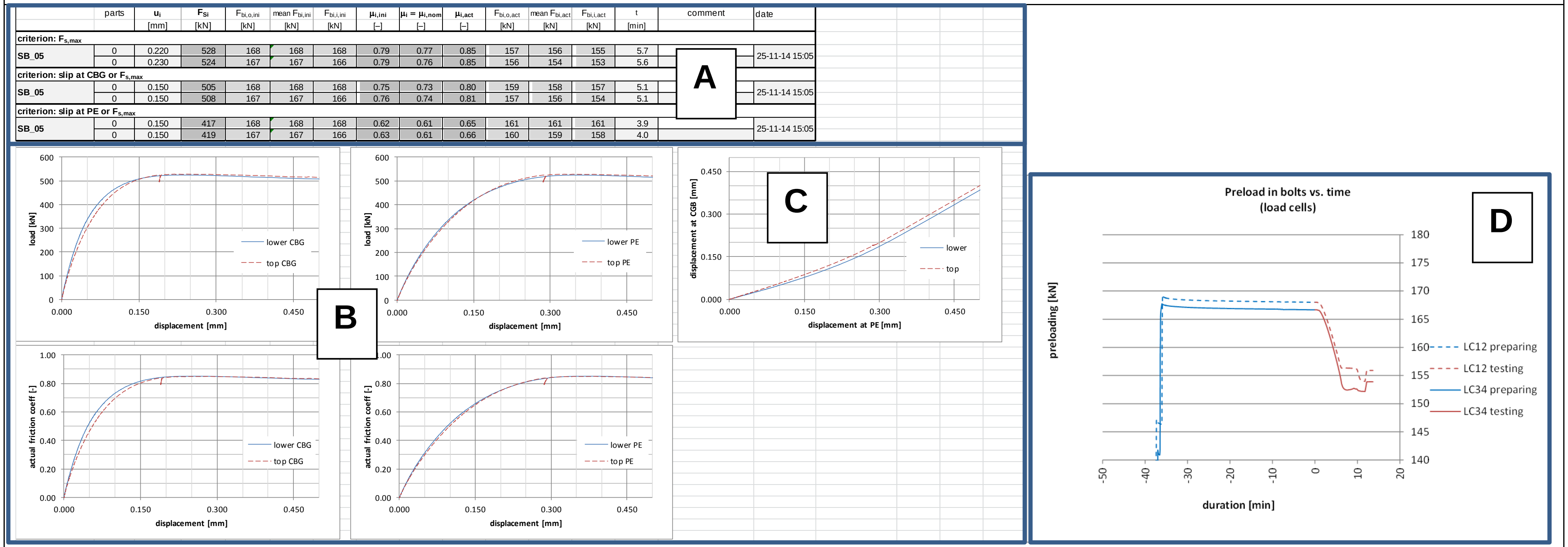
15 Annex H: Example of presentation individual test results Additional Stevin Reports

For all individual short term slip factor results see additional Stevin reports

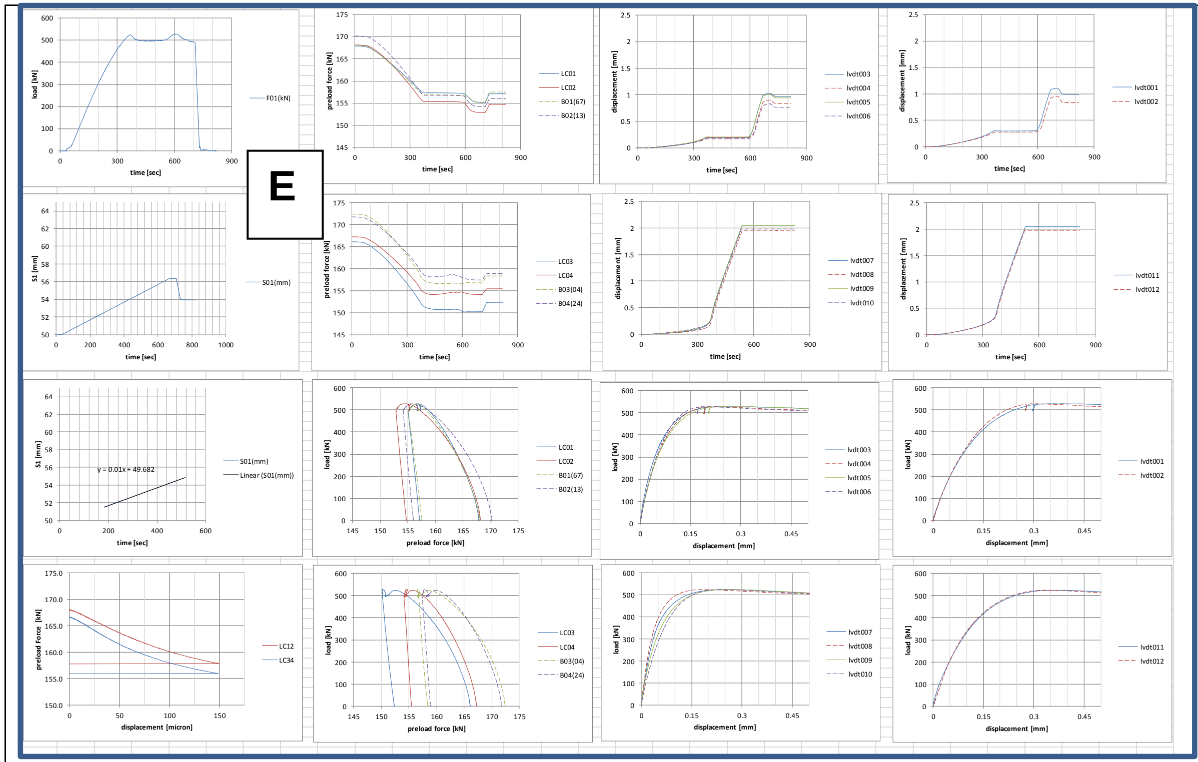
- Stevin report 6-18-01 – additon A: Test results Grit Blasted
- Stevin report 6-18-01 – additon B: Test results ASiZn
- Stevin report 6-18-01 – additon C: Test results ZnSM

In these reports the results of each short term slip factor test are presented as follows:

A. Table: results of evaluation of test result for different criteria (Fmax, 0,15 mm slipat CBG, 0,15 mm slip at PE)
B. Graphs of processed slip measurements at CBG and PE positions
C. Graph of relation between slip at CBG and PE position
D. Graph of preload in time directly after preloading and during slip test
E. Raw data op the experiment



	parts	u_i	F_{Si}	$F_{bi,o,ini}$	mean $F_{bi,ini}$	$F_{bi,i,ini}$	$\mu_{i,ini}$	$\mu_i = \mu_{i,nom}$	$\mu_{i,act}$	$F_{bi,o,act}$	mean $F_{bi,act}$	$F_{bi,i,act}$	t	comment	date
		[mm]	[kN]	[kN]	[kN]	[kN]	[–]	[–]	[–]	[kN]	[kN]	[kN]	[min]		
criterion: $F_{s,max}$															
SB_05	0	0.220	528	168	168	168	0.79	0.77	0.85	157	156	155	5.7		25-11-14 15:05
	0	0.230	524	167	167	166	0.79	0.76	0.85	156	154	153	5.6		
criterion: slip at CBG or $F_{s,max}$															
SB_05	0	0.150	505	168	168	168	0.75	0.73	0.80	159	158	157	5.1		25-11-14 15:05
	0	0.150	508	167	167	166	0.76	0.74	0.81	157	156	154	5.1		
criterion: slip at PE or $F_{s,max}$															
SB_05	0	0.150	417	168	168	168	0.62	0.61	0.65	161	161	161	3.9		25-11-14 15:05
	0	0.150	419	167	167	166	0.63	0.61	0.66	160	159	158	4.0		



The raw data slip test data is presented in the 4x4 graph matrix, with the following lay-out

External load as a function of time	Bolt preload as a function of time for top and bottom connection	Slip at CBG (Centre Bolt Group) as a function of time for top connection	Slip at PE (Plate Edge) as a function of time for top connection
Actuator position as a function of time	Bolt preload as a function of time for bottom connection	Slip at CBG (Centre Bolt Group) as a function of time for bottom connection	Slip at PE (Plate Edge) as a function of time for bottom connection
Actuator position as a function of time including trendline to determine slope	External load vs. bolt preload for top connection	External load vs. slip at CBG (Centre Bolt Group) for top connection	External load vs. slip at PE (Plate Edge) for top connection
Bolt preload as a function of slip at CBG (Centre Bolt Group)	External load vs. bolt preload for bottom connection	External load vs. slip at CBG (Centre Bolt Group) for top connection	External load vs. slip at PE (Plate Edge) for bottom connection

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