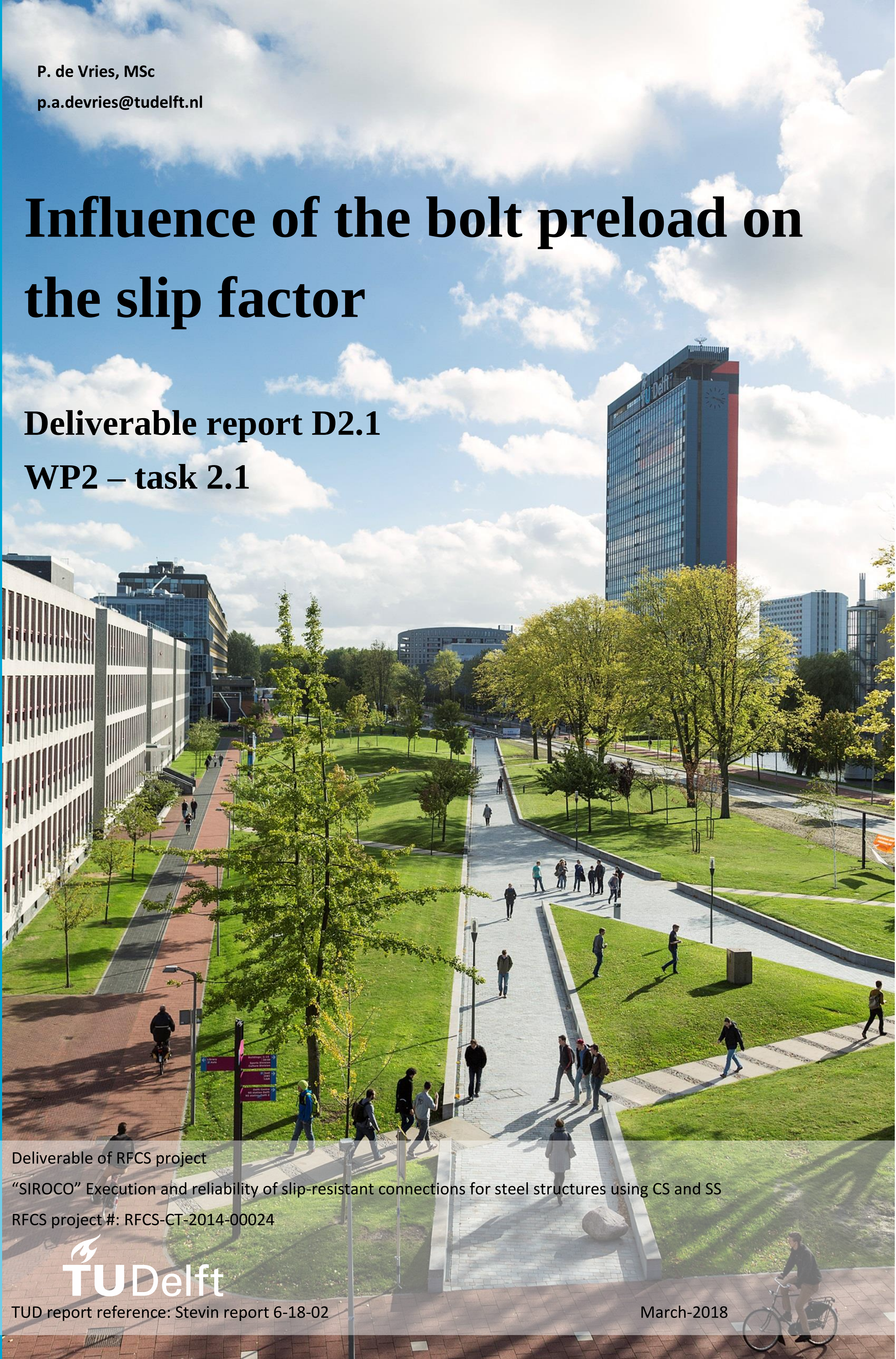

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Influence of the bolt preload on the slip factor

Deliverable report D2.1

WP2 – task 2.1

Deliverable of RFCS project

“SIROCO” Execution and reliability of slip-resistant connections for steel structures using CS and SS

RFCS project #: RFCS-CT-2014-00024

TUD report reference: Stevin report 6-18-02

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Abstract

Objective of the research was to investigate the influence of the bolt type (HR vs HV) and the bolt class (HR8.8 vs HR10.9) on the slip factor of zinc spray metallized and ASI-ZN coated surfaces. In addition to the original test matrix for this task slip factor tests were performed on grit blasted surfaces.

In the context of this task tests were carried out to investigate the potential of the Short term StepWise Loading (SSWL) test procedure. This is an experimental procedure to estimate the load level for extended creep tests that aims to determine the maximum slip factor for creep sensitive coatings. The SSWL tests were merely done in addition to the tests mentioned in the TA for this task.

Table of Contents

1 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	$[\mathrm{L}]$
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	$[\mathrm{F}]$
F_{Sm}	Mean slip load	$[\mathrm{F}]$
t	Time / test duration	$[\mathrm{T}]$

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

2 Introduction

In HSFG connections bolts of class 10.9 but also bolts of class 8.8 can be used. The high preload force in 10.9 bolts potentially leads to more creep of coatings and in more 'flattening' of the plate surfaces compared to the preload in bolts 8.8. This can be of influence on the slip factor. For this reason EN 1090-2 allows slip factors for surfaces and coating systems that were determined by slip factor tests with bolt classes 10.9 to be used to calculate the design slip resistance of connections preloaded with bolt class 8.8. The other way around this is not allowed.

It is unclear if and to what extent slip factors determined by tests with 10.9 bolts change when 8.8 bolts are used. If there is influence of the preload, does this this apply to the short term slip factor only, or also to the sensitivity to creep/long term slip factor? Bolt class 8.8 is available only as HR bolts, where class 10.9 is available both as HV and HR. In the frame of this work package slip factor tests will be carried out on carbon steel plates with 2 different coating systems with variation of the considered bolt types (HR and HV) and classes (8.8 and 10.9). In addition, as reference, a small number of tests on uncoated, grit blasted plates will be tested for both preload levels.

2.1 Research Objectives

If lower preload levels lead to higher slip factors, it could be beneficial to use 8.8 class bolts instead of 10.9 bolts in HSFG connections. After all, when the slip factor for 8.8 bolts is more than 25% higher than for 10.9 bolts, the design slip resistance of a connection made with 8.8 bolts is higher. There is logic in higher slip factors for lower preload, but the magnitude of the influence is unknown. The objective task2.1 is to determine the influence of the preload force on the slip factor of two coating systems . This was done by carrying out a comparative study to the influence of the bolt preload ($F_{p,C,HR8.8}$ = 138 kN vs $F_{p,C,HR10.9}$ = 172 kN) on the slip factor of Zinc spray metallized (ZnSM) and Alkali Silica Zinc coated (ASiZn) surfaces. Both ZnSM and ASiZn series are known to be creep sensitive coatings, therefore to investigate the influence of the preload level extended creep tests are necessary.

It was anticipated that:

- higher bolt preload would have a negative influence on the slip factor
- the influence of the preload level on the short term slip factors would be different than the influence on the long term slip factors
- the influence of the bolt type would be not significant (HR 10.9 vs HV 10.9)

In addition to the original test matrix for this task, slip test were performed on grit blasted, ASiZn and ZnSM surfaces to investigate the influence of the clamp length (48 mm vs 152 mm) on the result of slip factor tests. These test were used

In addition to the original test matrix for this task Short Step Wise Loading (SSWL) tests have been performed on the 4 combinations of preloads and coatings. The SSWL test protocol is developed during the SIROCO project as a means to estimating the maximum load level that can be achieved in extended creep tests. The results of the SSWL test were also evaluated in the context of the research objective of task2.1, to investigate if SSWL testing can be used to estimate the influence of the preload level on the slip factor.

3 Methods and Materials

Experiments on double lap shear connections cf. Annex G of EN 1090-2 have been carried out using M20 bolts. The steel plates used for all experiments in WP2.1 were grade S355J2C+N (originating from the same batch as the plates used for task1.2). 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.

3.1 Material properties

The material properties of the steel plates have been determined and are presented in Table 1.

Table 1 – material properties of the steel plates

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%	-

An overview of the test specimen and surface conditions is presented in Table 4.

A secondary objective of task2.1 was to get data to validate the model that was developed in task1.2 to correct the result of slip factor tests in case larger clamp lengths are used. In task1.2 all slip factor tests were carried out with clamp length 152 mm. In task2.1 all tests are carried out with instrumented bolts with standard (48mm) clamp length. The test results for the grit blasted plates and the ZnSM and ASiZN coated surfaces achieved with 152 and 48 mm could be used for the validation. However, to be able to do this there should be no significant difference between the coatings of the plates used in both tasks.

The Alkali Silicate Zinc coated (ASiZn) and the Zinc sprayed metallized (ZnSM) specimens for task1.2 and task2.1 were produced in 2 batches. The same producers and coating product were used, but still there were some differences between surface roughness and coating thickness between both batches. The differences in the ASiZn coating were negligible, but the layer thickness of the ZnSM specimens of batch 1 was 140 μm, while for batch 2 this was 165 μm. See Table 2 for the specifications of the specimen of batch 2.

To verify that the coating systems of both batches could be considered equivalent the preload losses that were observed in both batches were compared. During the slip factor experiments the preload was continuously registered. The initial preload losses (the losses directly after the required preload level was reached) and the preload losses that were observed during the slip factor experiments were analyzed for all specimens from both batches. For coated surfaces the initial preload losses are mainly caused by the properties of the coating system.

Table 2- Specs test specimens and surface conditions

Series ID	Surface preparation		Clamp length Σt [mm]	Clamp length ratio $\Sigma t/d^{1)}$ [-]	Planned number of tests in task2.1		
	Coating material	coating thickness 2)			Static test	Creep test	Extended creep test
Grit-blasted Sa 2 ½ (R_z: 84 µm) + ASiZn coating							
ASiZn	alkali-zinc silicate	55 µm	48	2.4	8	2	6
Grit-blasted Sa 3 (R_z: 100 µm) + ZnSM coating (R_z: after coating 85 µm)							
ZnSM	Zinc spray metallized	165 µm	48	2.4	8	2	6
Level of preload $F_{p,C}$ = 138/172 kN (M20). │ 1) d = 20 mm │ 2) Nominal dry film thickness (DFT).							

As the preload losses are used to compare results in the current research, the definition of initial preload loss is arbitrary. The loss immediately (in the first few seconds) after the required preload is reached is relatively large. These direct losses are influenced by the tightening of the surrounding bolts and consequently show quite 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 ($FP_{init,30}$) to calculate the loss. The second measurement was taken after 15 minutes ($FP_{init,900}$). The definition of the loss for each bolt is: $loss_{15min} = (FP_{init,30} - FP_{init,900})/FP_{init,30}$. The initial preload losses are reported per connection (average of losses in 2 bolts) of the specimens.

Figure 2 shows the initial losses that were observed in all specimens of task1.2 and task2.1 over the period in which the short term slip factor tests were carried out. The graph confirms the reproducibility of the measurement system over time and illustrates that the coating properties (system and thickness) and the clamping length of the bolts are of major influence on the losses. It can be observed that the ASiZn specimens from batch1 and 2 are equivalent (green data points in boxes marked task1.2 and task2.1 for CL (clamp length) 48mm). The differences in layer thickness of the ZnSM specimens in both batches lead to different initial losses (ZnSM series for 48mm, HV10.9 in both boxes). As in all (both the short term, creep and extended creep tests) specimens of the ZnSM series the bolts were retightened before start of the slip factor test the (small) differences in initial losses were not significant for the preload during the slip factor test. See Figure 1 for an illustration of the preparation of the slip factor tests and the preload losses that are observed.

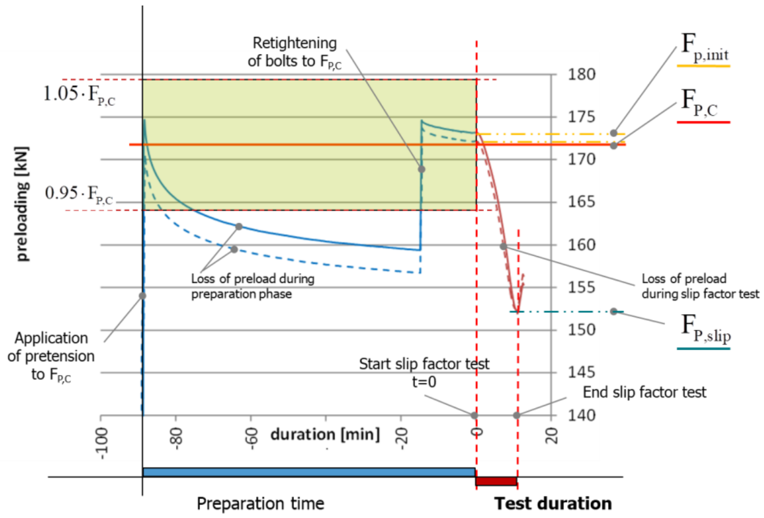


Figure 1- Test protocol: application of preload, preparation time (waiting period >= 30 min), retightening (only when preload drops below 0.95$F_{P,C}$ during waiting period), execution of slip factor test. Preload losses are observed directly after application of preload (bolt settling, creep of coating) and during execution of slip factor test. Preload levels $F_{p,C}$, $F_{p,init}$ and $F_{p,act}$ are respectively the required preload, the preload at the start of the slip factor test and the preload when the slip condition is reached. The named preload levels are used to calculate the different slip factors that are reported on (μ_{nom}, μ_{init} and μ_{act})

During execution of the slip factor tests also losses in preload occur. For coated specimen these losses are mainly caused by the flattening/compacting of the coating that resulst from the mutual displacements of centre and lap plates. The preload loss that occurs during the execution of 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 3 shows the losses that were observed in all specimens of task1.2 and task2.1. It can be observed that the ASiZn specimens from batch1 and 2 are equivalent, so the test results of wp1.2 can be compared to results achieved in task2.1.

Differences in losses are observed between the ZnSM specimens in batch1 and batch2. This means test results can't be compared without taking into consideration the differences in the coatings. For this reason additional tests were carried out on the ZnSM plates that were left over from task1.2 with 48 mm clamp length to investigate the influence of the bolt type (HR vs HV) and to get data to validate the correction model for different clamp lengths (48mm vs 152mm).

Details on surfaces and coatings of batch 1 can be found in the main deliverable report of task1.2. In Figure 28 and Figure 29 the distribution of surface roughness and dry film thickness of the coated specimens of the specimens produced in batch 2 can be found. Table 3 shows how and for what purpose the specimens from both batches were used in task2.1. Table 4 shows the resulting set of slip factor tests that were used to answer the research questions of task2.1.

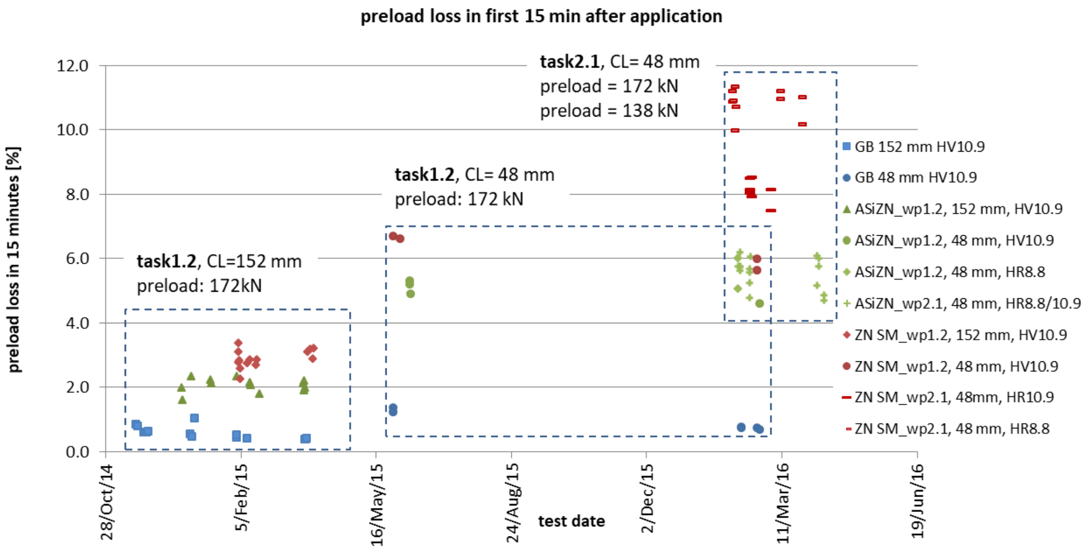


Figure 2 – Initial preload losses, loss of preload 15 minutes after preloading to $F_{P,C}$.

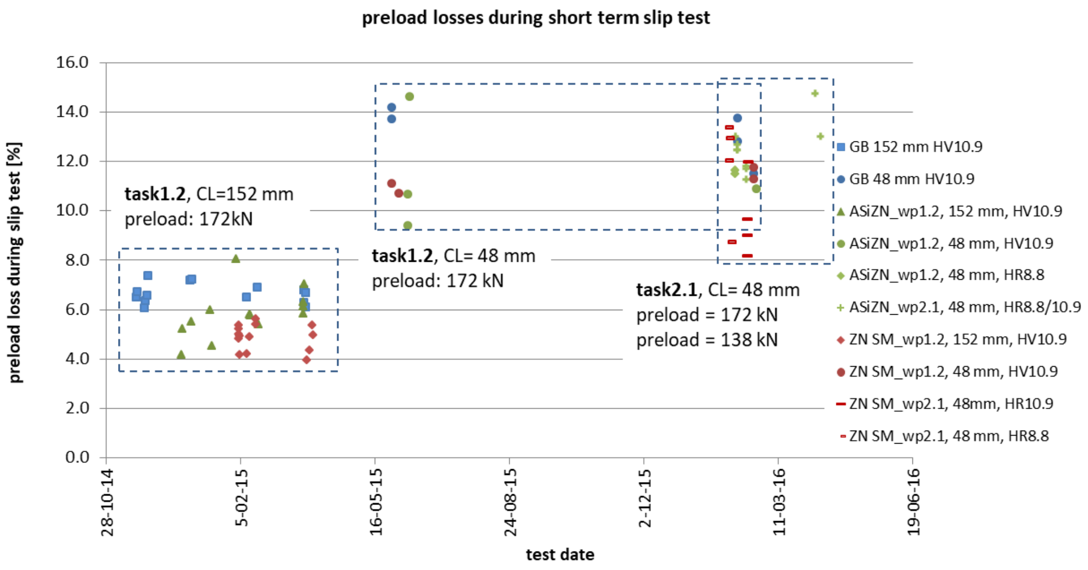


Figure 3 – Preload losses during execution of slip factor test

Table 3 – Specimens used in task 2.1

batch	2		1		
series	AsiZn	ZnSM	Grit Blasted	AsiZn	ZnSM
Surface conditions	Rz = 84 µm DFT[1] = 55 µm Lap plates coated single sided	Rz = 100 µm LT[2] = 165 µm Lap plates have both sides coated	Rz = 80 µm No coating	Rz = 80 µm DFT[1] = 60 µm Lap plates coated single sided	Rz = 104 µm LT [2]= 140 µm Lap plates coated single sided
Used to	Study Influence of preload level HR8.8 – HR10.9		Additional tests to study: Influence of bolt type HR10.9 / HV10.9 Influence of clamp length 152 mm vs 48 mm		
bolts	HR8.8 and HR10.9		HR8.8 and HR10.9		
Σt	48 mm		48 mm		
Tests	4 short term tests 1 creep test 3 ECT tests		HR8.8 1 short term test HV10.9 2 short term tests	HR8.8 2 short term tests HR10.9 1 short term test	HR8.8 2 short term tests HR10.9 2 short term tests 1 ECT test

[1] DFT: dry film thickness; [2]LT: layer thickness

Table 4 – Set of test results used in task2.1

specimen batch	surface treatment / Rz [2]	film thickness (average)	Σt	bolt class	$F_{p,C}$	number of test results (n)
	[µm]	[µm]	[mm]		[kN]	
Grit blasted surfaces (GB)						
wp1.2	Sa [1] 2½ / 80	-	152	HV10.9	172	6
			48	HV10.9	172	4
			48	HR10.9	172	2
			48	HR 8.8	138	4
Alkali-zinc silicate coating (ASiZn)						
wp1.2	Sa 2½ / 80	60	152	HV10.9	172	24
			48	HV10.9	172	4
wp2.1	Sa 2½ / 84	55	48	HR10.9	172	8
			48	HR 8.8	138	8
Zinc spray metalized coating (ZnSM)						
wp1.2	Sa 3 / 104	140	152	HV10.9	172	6
			48	HV10.9	172	4
wp2.1	Sa 3 / 100	165	48	HR10.9	172	8
			48	HR 8.8	138	8

3.2 Short term slip factor tests and Creep Tests

The deliverable report of task 1.2 [11] gives a comprehensive and conscientious description of the preparation and execution of the short-term slip factor tests and creep tests that were performed.

3.3 Extended Creep Tests

The main goal of the research in task2.1 is to compare the long term slip factor for 2 creep sensitive coatings (ZnSM and ASIZn) preloaded with class 8.8 and 10.9 bolts. To make this comparison the maximum load that can be transferred without exceeding the 0.3 mm in 50 years criterion has to be determined. The idea was to find this load by performing extended creep tests on the plates.

An extended creep test is a ‘Proof Loading’ procedure that is used to prove that for a certain load the long term slip is less than or equal to 0.3 mm over a period of 50 years. It is not a test that determines the load that leads to a predefined slip over time. By performing a series of extended creep tests on a surface, one can find an indication of the maximum load that can be transferred, it is however not practically feasible to determine the long term slip factors precisely.

As there was no knowledge of the long term slip factors for the various combinations of coatings and preloads, the procedure that was followed to estimate the slip factors was a ‘trial and error’ approach in which initially 75% $F_{s,m}$ (75% of the average of the short term slip tests) was applied as load in the extended creep tests. Depending on the result of a test, in subsequent tests the load level was reduced or increased to approach the 0.3 mm in 50 years criterion as good as possible, given the number of specimens (and time) that were available for this task.

3.3.1 Bolt sets

The HR bolt sets used in task2.1 were instrumented (and calibrated) by UDE. One set of bolts of HR8.8 and HR10.9 was used to carry out all slip factor tests. The dimensions of the HR bolts that were used for the experiments were slightly different for the class HR8.8 and HR10.9 bolts. The difference concerns the un-threated part of the bolt shank, which was 21 mm for the HR10.9 bolts and 27 mm for the HR8.8 bolts (see Figure 4). The difference in length will have a small effect on the effective stiffness of the bolts and consequently on the preload losses. The influence on the results of the slip factor test will be small and are not taken into consideration in the analysis of the test results. The additional HV10.9 bolt set that was used for some of the reference tests on task1.2 specimens with clamp length 48 mm was produced and calibrated by TUD.

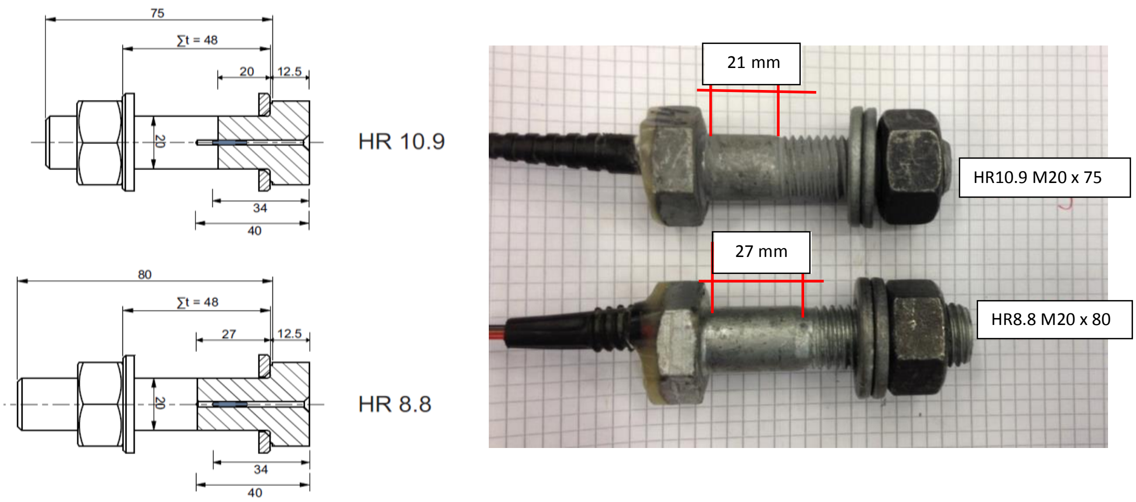
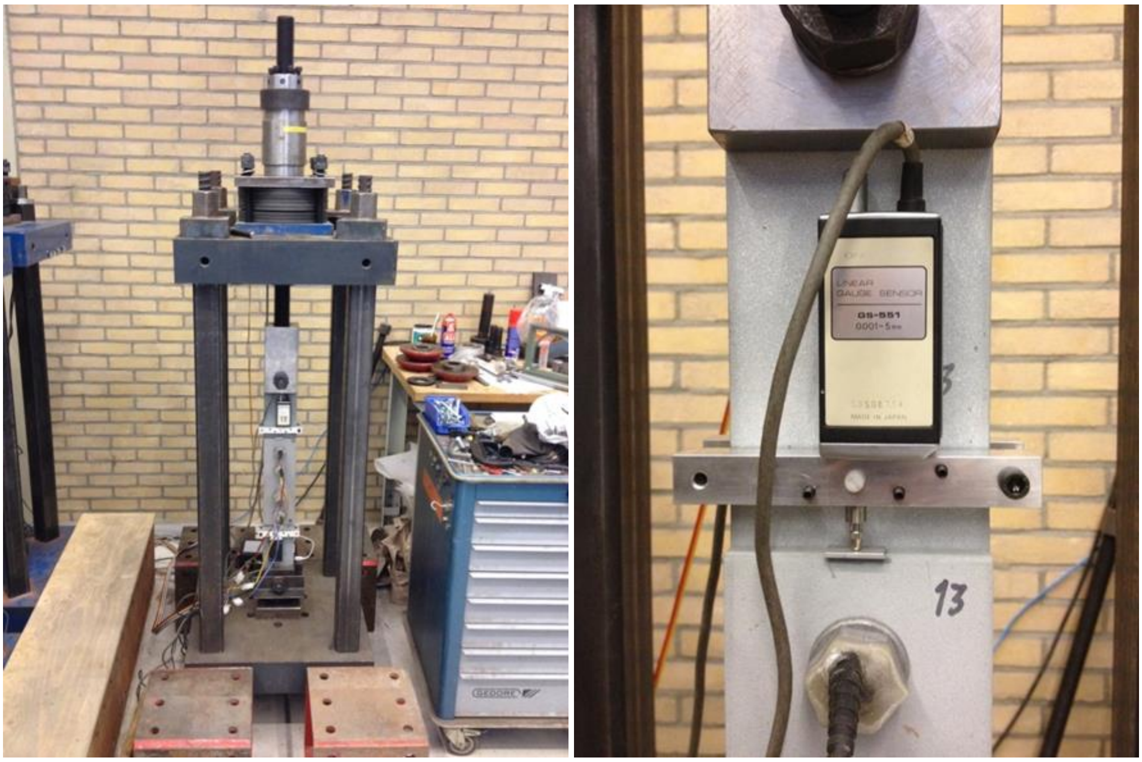


Figure 4 - HR bolt sets used in the slip factor experiments in task 2.1. The drawing indicates the position the stain gauges in the bolt shank. Bolts were instrumented by UDE.

3.3.2 Test rigs used for the extended creep tests

Figure 5 and Figure 6 show (details of) the 4 test rigs that were used by TUD to carry out the extended creep tests. The rigs consist of a stiff steel framework to which the specimen is fixed at the lower end. Load on the specimen is applied by tensioning a M48 threaded rod that is connected to the specimen by a M24 bolt and fork. The tension in the M48 rod is applied by a manually operated hydraulic jack (not on pictures). Load is measured by the load cell the M48 rod passed through. Once the required load level is reached, the force is transferred from the hydraulic jack (Figure 7-c) to a tensioner disc (alternative M48 nut) and the jack is removed from the rig.

The rigs have no active mechanism to continuously control the load level during the test period. The load applied by the hydraulic jack causes an elastic deformation of the specimen and the components of the test rig. This load keeps constant as long as the deformation of the system stays constant. Extended creep tests will typically lead to slip in the connections of the specimen, so during the test a reduction of the elastic deformation and consequently of the load level will occur. To minimise the impact of the slip on the load level, a spring disc package (Figure 6-a) is added as a flexible component (accumulator). The design of the rigs (stiffness of the combination of spring disc package, M48 rod and the specimen itself) ensures a maximum loss of 5% of the initially applied load level for a slip of 0.3 mm in both connections.



a) b)

Figure 5 - a) TUD extended creep test rig. Rig capacity 400 kN.

b) mounting bracket LVDTs. Slip in extended creep tests was measured only at PE position

Adjustment of the load level during the test period is not necessary. The resulting slip factor should be determined based on the load level at the moment the slip test is finished. This will give a conservative value for the slip factor. Load levels that cause more slip than 0.3 mm evidently will cause more loss of load then 5%, but this is in fact irrelevant, as the result of such a test is negative anyhow.

During the project it was decided to add a component to the extended creep test rigs that enabled additional control of the load level. This so called ‘tensioner disc‘ (in fact a homemade super-bolt, see Figure 7) makes it possible to manually adjust the load directly after the hydraulic jack has been removed. The main reason to add the manual post-tensioner was the overshoot in the load level that was needed during the load application with the hydraulic jack to compensate for the loss in the load level caused by the transition from the situation where the load is applied by the jack to the situation in which the M48 nut transfers the load. It appeared to be impossible to transfer the load that was applied with the jack without loss of load. Initial overshoot of the loading applied with the hydraulic jack of >10% was needed to reach the desired load level. As the tests were performed to determine the maximum slip factor this could lead to false (too conservative) conclusions (the higher load could cause a large increase of the slip).

a) b) c)

Figure 6 - a) Spring disc package and load cell (homemade TUD, 450 kN), b) Onno Sokki linear gauge sensor GS-551, c) Specimen load, bolt pretension and slip were measured continuously over test duration.

The overshoot effect was observed in the ECT test rigs of all labs (UDE, FAGP and TUD) that were involved in extended creep testing. All labs changed their setup in the cause of the project and implemented commercial available (UDE and FAGP) or homemade (TUD) tensioner discs to solve this.

An additional benefit of the tensioner disc is the possibility to adjust the load level during the test period. This way the load level can be kept constant within a smaller margin than the original 5%.

For the measurement of the slip 4 Ono Sokki GS-551 linear gauge sensors were used (measurement range 5 mm, accuracy 3 µm, resolution 1 µm). The sensors were fixed to the centre plate of the specimens by a mounting bracket (Figure 5-b)) that is clamped to the centre plates.

Instrumented bolts were used to measure and monitor the preload in the bolts. Identical reference bolts (positioned on the test rig, unloaded) were used to compensate for temperature differences that occurred during the duration of the tests. Specimen load, slip and bolt forces were measured continuously during the duration of the extended creep tests. The data acquisition was done by homemade TUD system (MP3 [10]). This software is capable of data sampling based on both fixed time intervals and instrument output level changes. This way high frequency sampling is available when needed whereas the amount of data stored during the period over which the extended tests run can be kept to a minimum. Typical fixed time intervals that was used during the extended creep tests was 15 minutes. On tripped sampling was set at 1 μm for the LVDT's and 0.1 kN for the external loading and preload level in the bolts.

a) b) c)

Figure 7 - Tensioner discs a) commercial available from Nord-lock b) TUD home made tensioner disc for M48, suited to be used in combination with hydraulic tensioner. c) hydraulic jack was used to apply loading on specimens in extended creep test rig

During extended creep tests only the displacements between the edge of the lap plates and the centre plates (the so called PE position [11] see Figure 5-b) were measured. The elongation of part of the centre plate between the location where the PE sensor is attached and the centre of the bolt group (CBG postion) causes differences between the slip that is measured at CBG and PE position. This difference occurs only during the loading phase of a test. From the moment the load is constant, the increase of the slip measured at CBG and PE positions are equal (provided that there is not creep deformation in the centre plates!).

The critical slip at 50 years is defined as 0.3 mm at CBG position. To be able to use this criterion the results of the short term slip factor tests (that were all carried out with LVDT's on both PE and CBG position) were used to describe the relation between the displacements measured at the PE and CBG position. Using this relation the displacements measured at PE were converted to slip at CBG. Figure 9 shows the graphs of the PE-CBG conversion models that were used for all materials and coating systems that were tested in the SIROCO project. The conversion models were derived by curve fitting the relation between the difference (d) between PE and CBG displacements and the load (F_s) on the specimen during short term slip factor tests, by a second order polynomial ($d = C_1 \cdot F^2 + C_2 \cdot F$). Several short term slip factor tests from each series were used to describe the relation (see Figure 8). The final model used to convert from PE to CBG slip is the average of all individual models. The maximum error by the conversion is less than 0.01 mm.

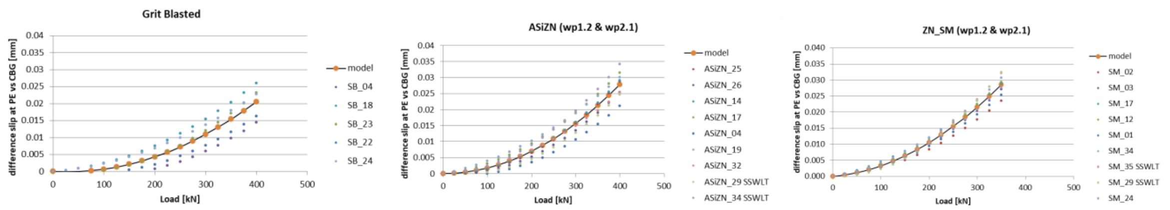
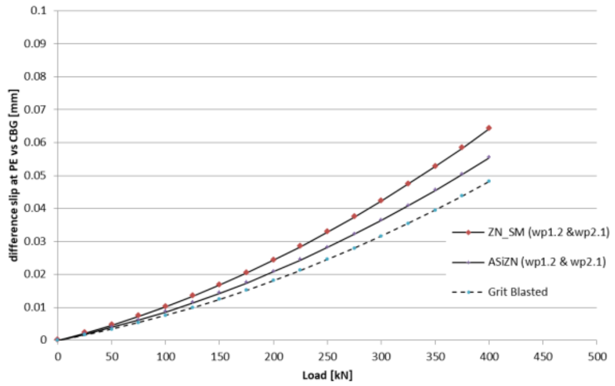


Figure 8 - Difference between displacement (slip) measured at PE and CBG positions during short term slip factor tests



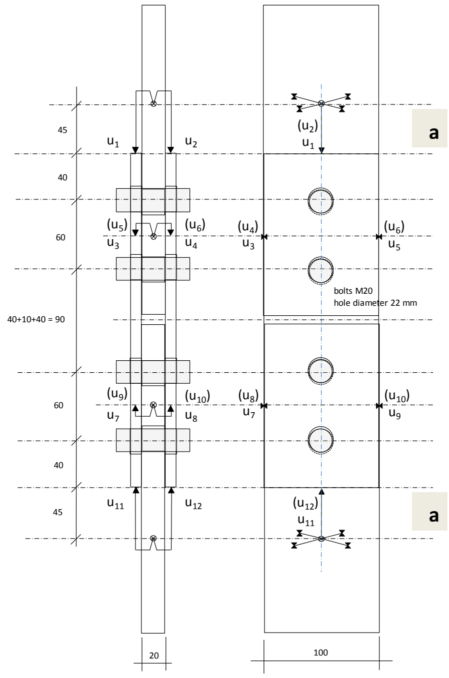


Figure 9 – Final models that were used to convert displacements measured at PE position to the slip at CBG position in extended creep tests. The distance a on which the LVDTs were mounted relative to the edge of the lap plates was 29 mm. The model is valid only for this distance.

3.4 Experiments realized in task2.1

Compared to the TA of the project for each of the ASiZn and ZnSM series extra steel plates were produced for 4 extra specimens. A total of 20 (16+4) 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 general verification reasons. Most of the extra test material was used to answer the research questions of task2.1. Two specimens of both coating systems were used to experiment with the SSWL procedure. See Table 5.

Table 5 – Experiments realized with specimens produced for task2.1

		Number of specimens	
test description		ASiZn	ZnSM
slip factor tests Σt = 48 mm	short term	8	8
	creep test	2	0
	SSWL	2	2
	extended creep test	4	9

additional tests in series			
Σt = 48 mm	short term with cleaned surface	-	1
	relaxation over 24 h	1	-
Total number of TUD test results:		**17**	**20**
specimen to FAGP for ECT testing		1	-
# specimens left		2	0
specimen tested faulty		-	-
total		20	20

4 Results and discussion

The test results (graphs) of all short term slip factor tests and creep tests and special tests are presented in an additional technical report (Stevin report 6-18-02 – Addition A [12]). In this report a short description is given of the type of test that was performed on each individual specimen.

The test results of all extended creep tests (and SSWL tests) can be found in the annexes of this report. All data files are available in raw and processed formats (Excel files).

4.1 Short term Slip factor Tests

In Table 6 the results of the short term (quasi static) slip factor tests are presented, evaluated both by considering the initial preload when the tests started ($\mu_{init,mean}$) and the actual preload at slip ($\mu_{act,mean}$). Figure 10 – Comparison between short term slip factors achieved with HV10.9 and HR10.9 bolts for all series. and Figure 10 present the results graphical. Table 6 also shows the influence of the clamp length of the bolts (152 mm in the task1.2 experiments, 48 mm in all other tests) on the results of a slip factor test.

Table 6 – Results quasi static slip factor tests

specimen batch	surface treatment / Rz [2)]	film thickness (average)	Σt	bolt class	$F_{p,C}$	number of test results (n)	slip factor $\mu_{act,mean}$ [3)]	slip factor $\mu_{init,mean}$ [4)]	ratio $\mu_{init,mean}$ at Σt=152 vs Σt=48 mm	ratio $\mu_{init,mean}$ at $F_{p,C}$=138 vs $F_{p,C}$=172 kN
	[µm]	[µm]	[mm]		[kN]		[-]	[-]	[-]	[-]
Grit blasted surfaces (GB)										
wp1.2	Sa 1) 2½ / 80	-	152	HV10.9	172	6	0,84	0,79	1,14	
			48			4	0,81	0,69		
				HR10.9		2	0,80	0,70		1,05
				HR 8.8	138	4	0,85	0,74		
Alkali-zinc silicate coating (ASiZn)										
wp1.2	Sa 2½ / 80	62	152	HV10.9	172	24	0,76	0,72	1,07	
			48			4	0,76	0,68		
wp2.1	Sa 2½ / 84	55		HR10.9		8	0,78	0,69		1,06
				HR 8.8	138	8	0,84	0,73		
Zinc spray metalized coating (ZnSM)										
wp1.2	Sa 3 / 104	140	152	HV10.9	172	6	0,83	0,79	1,08	
			48			4	0,82	0,73		
wp2.1	Sa 3 / 100	165		HR10.9		8	0,73	0,65		1,21
				HR 8.8	138	8	0,91	0,79		

[1)] Sa: surface preparation grade | [2)] Rz: roughness steel surface | [3)] $\mu_{ini,mean}$: slip factor (mean values) considering the initial preload when the tests started | [4)] $\mu_{act,mean}$: slip factor (mean values) considering the actual preload at slip

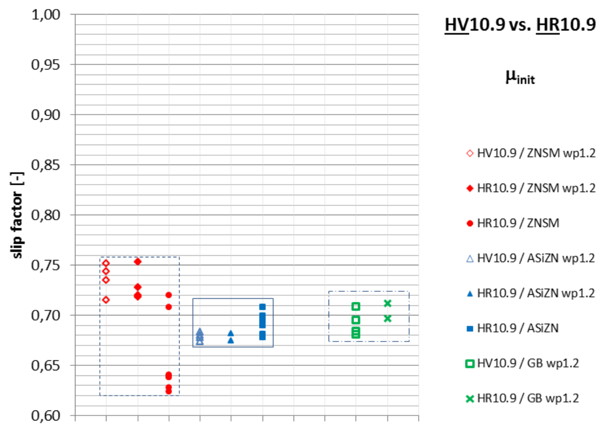


Figure 10 – Comparison between short term slip factors achieved with HV10.9 and HR10.9 bolts for all series.

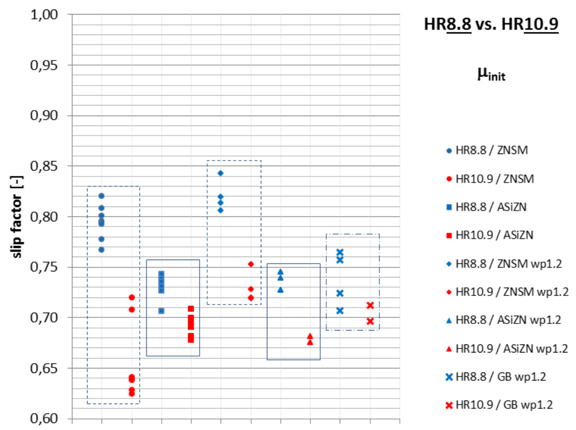


Figure 11– Comparison between short term slip factors achieved with HR8.8 and HR10.9 bolts for all series.

Table 6 and Figure 10 show that no significant differences are observed between the slip factors achieved with bolts HV10.9 and HR10.9 when preloaded to $F_{p,C}$ =172 kN. This is in line with expectations, as the essential differences between the geometry of both bolt types are negligible. The lower values that result of the test with HR10.9 bolts in the ZnSM specimens are the result of the larger layer thickness of the task2.1 batch.

Table 6 and Figure 11 show that the influence of the preload has influence on the results of the quasi static slip factor tests. Higher preload has negative impact on short term slip factors of tested materials. For the ZnSM coating the slip factors achieved with 172kN preload are 15% – 20% lower compared to the slip factors that are found for a preload of 138kN. For the Grit blasted and the ASiZn coated surfaces the difference is smaller: 5% lower.

4.2 Extended Creep Tests

As there was no knowledge of the long term slip factors for the various combinations of coatings and preloads, the procedure that was followed to estimate the slip factors was a 'trial and error' approach in which initially 75% Fs,m (75% of the average of the short term slip tests) was applied as load in the extended creep tests. Depending on the result of a test, in subsequent tests the load level was reduced or increased to approach the 0.3 mm in 50 years criterion as good as possible, given the number of specimens (and time) that were available for this task. In the next paragraphs the results are presented. For each combination of coating and preload 2 result graphs are presented. The top graph shows the load during the extended creep test on a log time scale. In the same graph the loss of preload over time is shown. The lower graph is the actual result of the extended creep test: the progression of the slip on log time scale. An extended creep test in considered 'passed' when the lineair extrapolation of the measured log time-slip relation for a certain load level results in a slip that is maximum 0.3 mm in 50 years.

4.2.1 Zinc Spray Metallized with 8.8 bolts

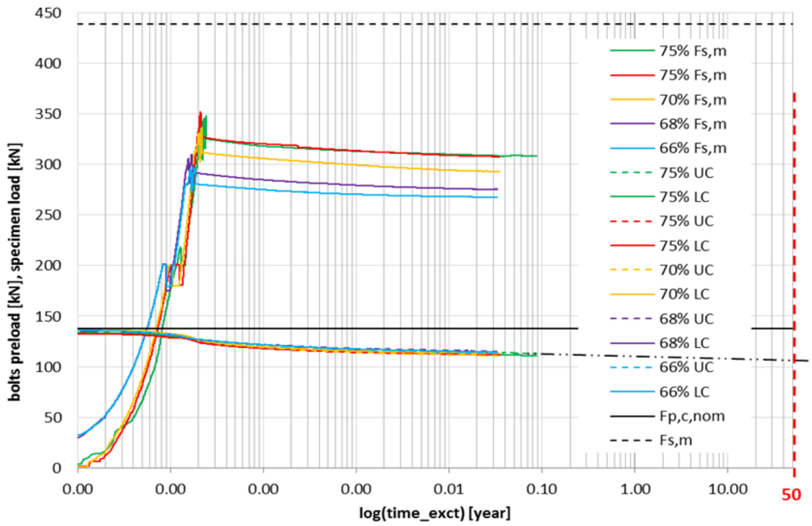


Figure 12 - Load levels and preload (Fp,c,nom=138 kN) during extended creep tests on ZnSM series for HR8.8 bolts.

Explanation legend items: $F_{s,m}$: average slip load short term tests, UC: upper connection, LC: lower connection, $F_{p,c,nom}$: nominal value preload force, xx% $F_{s,m}$: specimen load initially loaded at xx% $F_{s,m}$, yy% UC/LC: (average) bolt preload in upper/lower connection for test at yy% $F_{s,}$

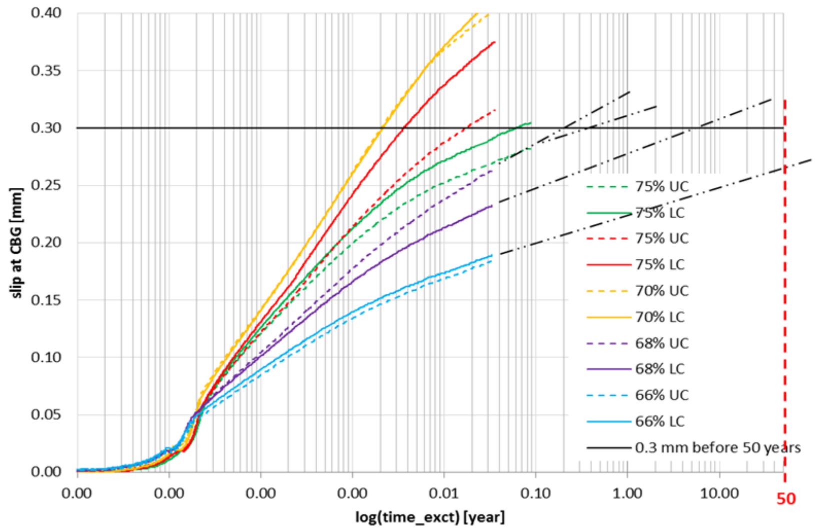


Figure 13 - Results extended creep tests on ZnSM series for HR8.8 bolts

Explanation legend items: UC: upper connection, LC: lower connection, yy% UC/LC: slip at CBG position in upper/lower connection for test at yy% Fs,m

Figure 12 and Figure 13 show the results of the extended creep tests on the ZnSM specimens, preloaded with HR8.8 bolts. In total 5 extended creep tests were carried out for this combination, with initial load levels of 75% (2 tests), 70%, 68% and 66% of $F_{s,m}$ respectively. Figure 12 shows that the load level during the tests gradually decreased over time, but the loss was not more than 5% of the initially applied load

The test with an initial load of 66% of $F_{s,m}$ fulfils the 0.3 mm in 50 years criterion. This test was carried out without the tensioner disc, so there was no way to adjust the load during the test period. The slip in the connections caused the load to drop from 66% to 61% $F_{s,m}$. This value was used to calculate the associated slip factor:

$$\mu_{nom}(ZnSM, HR\,8.8) = \frac{0.61 \cdot F_{s,m}}{4 \cdot F_{p,c,nom}} = \frac{267\ kN}{4 \cdot 138\ kN} = 0.48\ [-]$$

4.2.2 Zinc Spray Metallized with 10.9 bolts

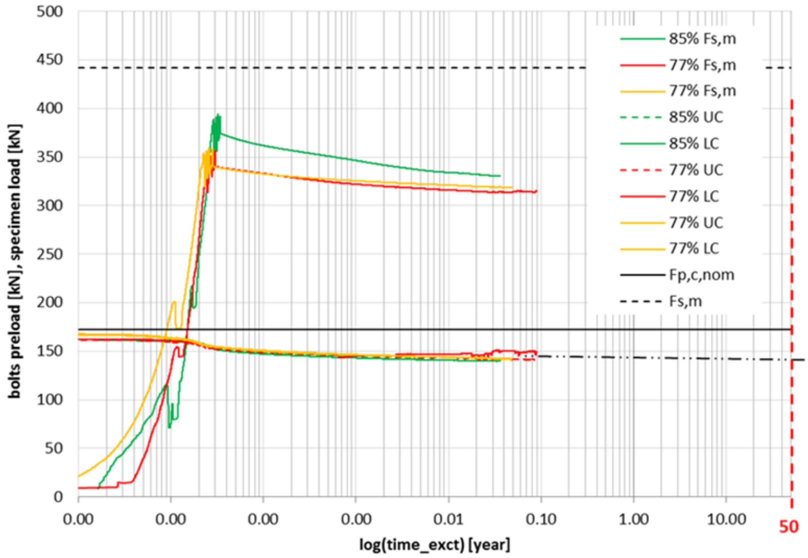


Figure 14 - Load levels and preload ($F_{p,C,nom}$=172 kN) during extended creep tests on ZnSM series for HR10.9 bolts

Explanation legend items: $F_{s,m}$: average slip load short term tests, UC: upper connection, LC: lower connection, $F_{p,c,nom}$: nominal value preload force, xx% $F_{s,m}$: specimen load initially loaded at xx% $F_{s,m}$, yy% UC/LC: (average) bolt preload in upper/lower connection for test at yy% $F_{s,}$

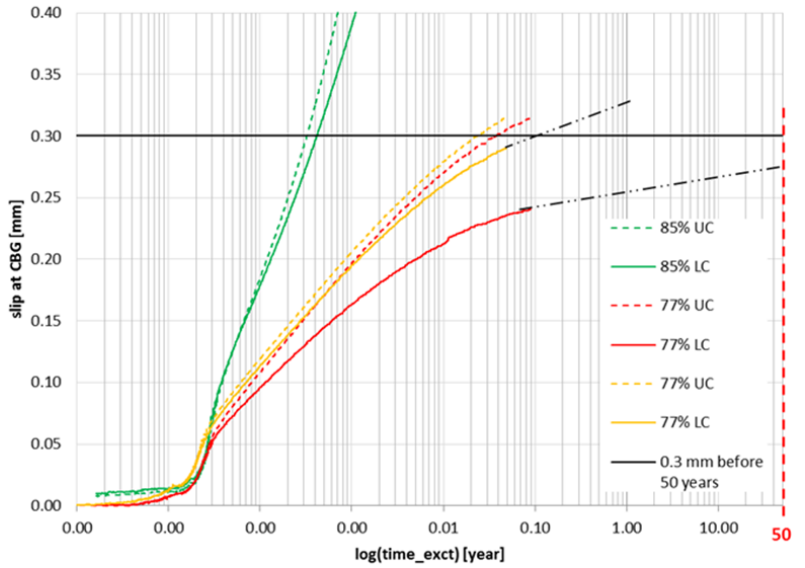


Figure 15 - Results extended creep tests on ZnSM series for HR10.9 bolts

Explanation legend items: UC: upper connection, LC: lower connection, yy% UC/LC: slip at CBG position in upper/lower connection for test at yy% $F_{s,m}$

Figure 14 and Figure 15 show that the test with an initial load of 77% $F_{s,m}$ fulfils the 0.3 mm in 50 years criterion. This test was carried out without the tensioner disc, so there was no way to adjust the load during the test period. The slip in the connections caused the load to drop from 77% to 71% $F_{s,m}$. This value was used to calculate the associated slip factor:

$$\mu_{nom}(ZnSM, HR10.9) = \frac{0.71 \cdot F_{Sm}}{4 \cdot F_{p,c,nom}} = \frac{315\ kN}{4 \cdot 172\ kN} = 0.42\ [-]$$

4.2.3 Alkali Zinc Silicate with 8.8 bolts

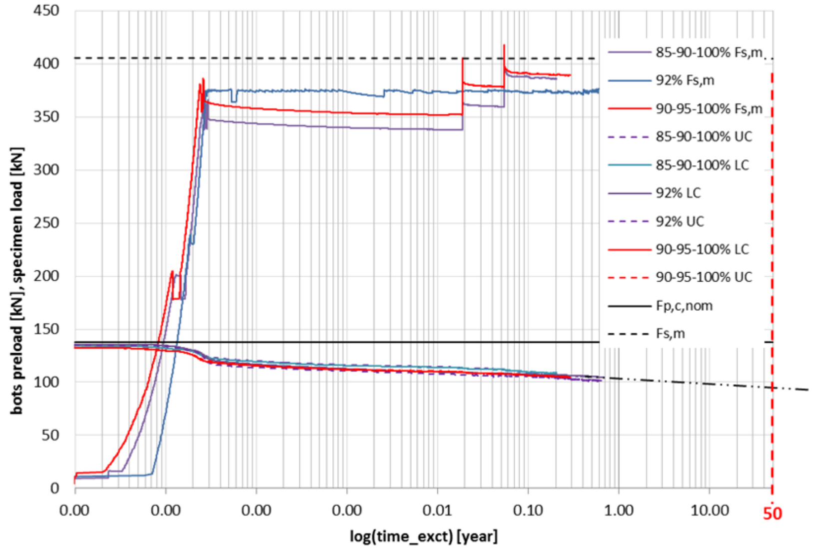


Figure 16 - Load levels and preload ($F_{p,C,nom}$=138 kN) during extended creep tests on ASiZn series for HR8.8 bolts

Explanation legend items: $F_{s,m}$: average slip load short term tests, UC: upper connection, LC: lower connection, $F_{p,c,nom}$: nominal value preload force, xx% $F_{s,m}$: specimen load initially loaded at xx% Fs,m, yy% UC/LC: (average) bolt preload in upper/lower connection for test at yy% $F_{s,m}$

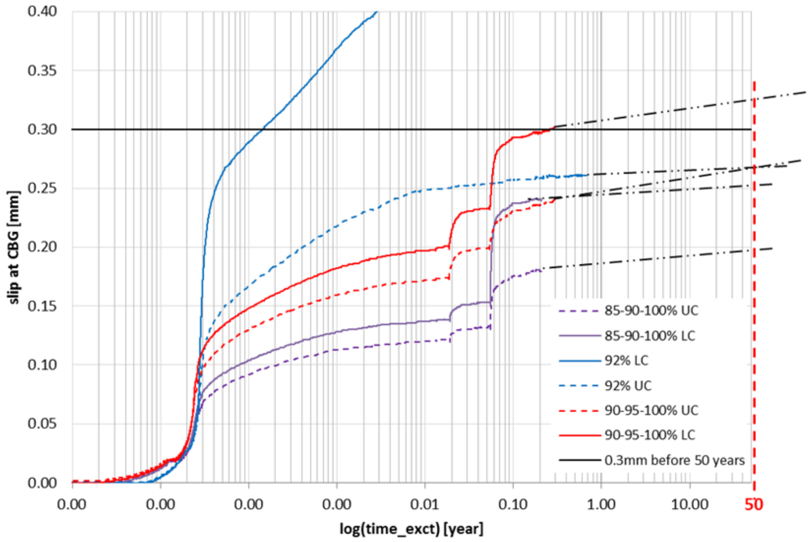


Figure 17 - Results extended creep tests on ASiZn series for HR8.8 bolts

Explanation legend items: UC: upper connection, LC: lower connection, yy% UC/LC: slip at CBG position in upper/lower connection for test at yy% $F_{s,m}$

The test at 92%$F_{s,m}$, was carried out with the tensioner disc, so in this test the load was adjusted during the test period to maintain at the specified level. In this test one of the connections failed, the other passed the test. Figure 16 and Figure 17 show that a conservative conclusion for the maximum load that can be transferred without exceeding the 0.3 mm limit In 50 years is 360 kN (89% of $F_{s,m}$).

$$\mu_{nom}(\text{ASiZn}, \text{HR } 8.8) = \frac{0.89 \cdot F_{Sm}}{4 \cdot F_{p,c,nom}} = \frac{360 \text{ kN}}{4 \cdot 138 \text{ kN}} = 0.65 \text{ [-]}$$

4.2.4 Alkali Zinc Silicate with 10.9 bolts

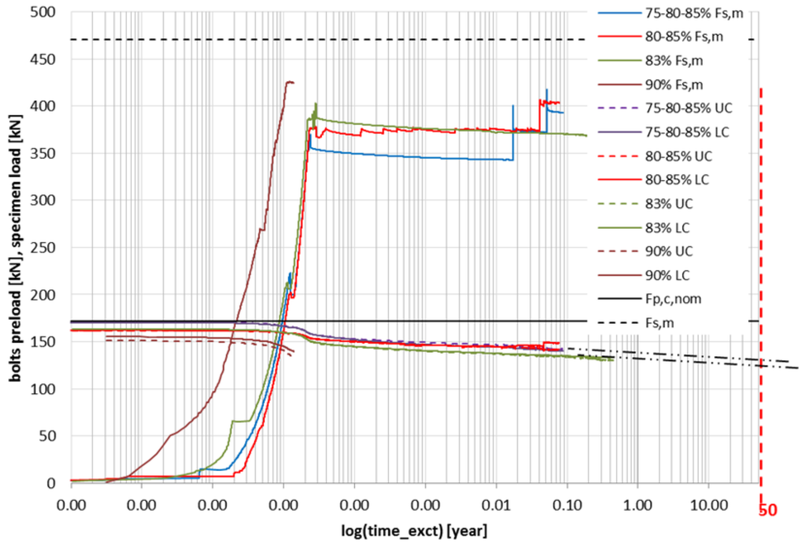


Figure 18 - Load levels and preload ($F_{p,C,nom}$=172 kN) during extended creep tests on ASiZn series for HR10.9 bolts

Explanation legend items: $F_{s,m}$: average slip load short term tests, UC: upper connection, LC: lower connection, $F_{p,c,nom}$: nominal value preload force, xx% $F_{s,m}$: specimen load initially loaded at xx% Fs,m, yy% UC/LC: (average) bolt preload in upper/lower connection for test at yy% $F_{s,m}$.

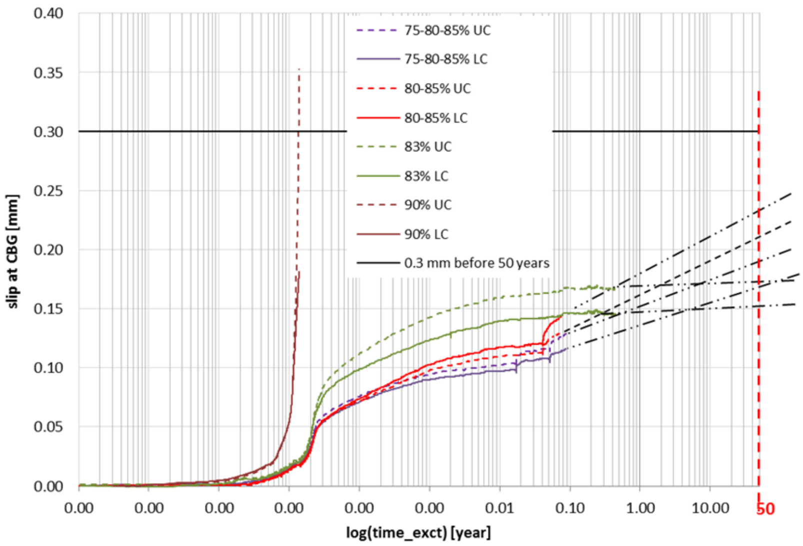


Figure 19 - Results extended creep tests on ASiZn series for HR10.9 bolts

Explanation legend items: UC: upper connection, LC: lower connection, yy% UC/LC: slip at CBG position in upper/lower connection for test at yy% $F_{s,m}$

The test at 80-85%Fs,m, was carried out with the tensioner disc, so in this test the load was adjusted during the test period to maintain at the specified level.

The average load reached in the short term slip tests for the ASiZN-10.9 series was very high: 470 kN (see Table 6.3-2). This meant extended creep tests at TUD could be performed only to approximately 85% of $F_{s,m}$ (test rig capacity 400 kN). Therefore it was decided to perform a test at 90%$F_{s,m}$ (425 kN) at FAGP. For all load levels tested at TUD the ASiZn specimens with the 10.9 bolts were tested on, both connections passed the test. Unfortunately the test at 90% $F_{s,m}$ was not correctly executed (speed of application of load too high), which caused the specimen to fail instantly. Figure 18 and Figure 19 show that based on the test results on the ASiZn-10.9 series we can conclude that the maximum load that can be transferred without exceeding the 0.3 mm limit In 50 years is 405 kN (85% of $F_{s,m}$). This conclusion is conservative.

$$\mu_{nom}(ZnSM, HR10.9) = \frac{0.85 \cdot F_{s,m}}{4 \cdot F_{p,c,nom}} = \frac{405\ kN}{4 \cdot 172\ kN} = 0.59\ [-]$$

Table 7 - Influence of preload on long term slip factor

parameters						load at 0.15 mm slip	slip factors			
specimen batch	surface treatment Rz [μm]	film thickness [μm]	clamp length (CL) [mm]	bolt class	$F_{P,c,nom}$ [kN]	$F_{s,m}$ [kN]	$\mu_{init,mean}$ [-]	$\mu_{nom,exc}$ [-]	ratio slip factors at $F_{P,c,nom}$=138 kN vs $F_{P,c,nom}$=172 kN $\mu_{init,mean}$	$\mu_{nom,exc}$
					Grit blasted (GB)					
wp1.2	80	-	48	HR10.9	172	483	0.70	-	1.05	**-**
				HR 8.8	138	415	0.74	-		
					Alkali-zinc silicate coating (ASiZn)					
wp2.1	85	85	48	HR10.9	172	470	0.69	0.59	1.06	**1.10**
				HR 8.8	138	405	0.73	0.65		
					Zinc spray metalized coating (ZnSM)					
	100	165	48	HR10.9	172	442	0.65	0.42	1.21	**1.14**
				HR 8.8	138	439	0.79	0.48		

The conclusion of the tests in task2.1 is that lower preload has a positive influence on both the short and long term slip factors. The tests confirm that slip factors that result from tests performed with high preload, in engineering practise can be used safely when applied in combination with bolts with lower preload. Slip factors that result from tests with low preload <u>can not</u> be used in combination with bolts with higher preload.

Based on the results of the short term and the extended creep tests no general conclusions can be drawn about the magnitude of the influence of the preload force on the slip factor. This depends on the steel surface and coating properties (surface roughness steel surface, type and thickness of the coating).

The conclusion on the negative impact of the preload on the slip factor raises the question if slip factors determined according to EN1090-2 can be used when the combined method is used for preload application. When in practise the combined method is used to preload bolts high (initial) preloads (up to or above $0.9F_u$) will result. Effectively this means that when the combined method is used 8.8 bolts are preloaded to or above the required preload of 10.9 bolts. As it can not be guaranteed that the high initial preload level will sustain over the lifetime of the structure the slip factors determined with 10.9 bolts should be used to determine the design slip resistance of the connection. Care should be taken to allow lower preload levels during slip factor tests!

If the negative impact of higher preload levels also applies for preloads above 172 kN has not been investigated. It can be questioned if slip factors that were determined for 10.9 bolts can be used to determine the design slip of connections with 10.9 bolts when the combined method is used.

To look into this 4 (2x2) short term slip factor test were carried out on specimens with 10.9 bolts that were preloaded up to $0.9F_u$ (220kN). For this experiment specimens from task4.1 (S355 CS, with Ethyl Silicate Zinc coating, task4.1 series A1 and A2, from both series 2 specimens) were used. The results were compared to results of 'normal' slip tests on same coatings.

In the first experiment (specimens A1-7 and A2-7) the preload of 220 kN was applied. A slip factor test was carried out after 90 minutes, without retightening of the bolts. The slip factor was calculated based on the preload at the start of the test.

In the second experiment (specimens A1-8 and A2-8) also a preload of 220 kN was applied, but this preload was after 30 minutes further reduced to 172 kN. Then a slip factor test was carried out. The slip factor was again calculated based on the preload at the start of the test. This experiment was conducted to simulate the loss of preload from $0.9F_u$ to $0.7F_u$, the minimum required preload for 10.9 bolts.

If the initial high preload would have caused significant additional 'damage' to the coating the slip factors found in these experiments would have been less than the slip factors that were found for the rest of the A1 and A2 series (which were preloaded to precisely 172 kN). This appeared not to be the case. In both experiments slip factors of 0.5 were found, equal to what was found for the standard series. Only short term slip factor tests

Apparently the higher preload that results when the combined method is used to apply the preload in HSFG connections has no negative consequences for the short term slip factor for the coating Ethyl Silicate Zinc coating, it is however unclear if this also applies when extended creep tests are carried on this coating system.

5 Conclusions

In task2.1 a comparative study has been performed to the influence of the bolt preload ($F_{p,C,HR8.8}$ = 138 kN vs $F_{p,C,HR10.9}$ = 172 kN) on the slip factor of Zinc spray metallized (ZnSM) and Alkali Silica Zinc coated (ASiZn) surfaces. From the study it can be concluded that:

1. The type of the bolt (HR / HV) that is used in slip factor tests has no influence on slip factor.
2. Slip factors determined according to EN1090-2 depend on the preload level during the test. On both the short term slip factor and the long term slip factor there is a positive influence of the lower preload of bolt class 8.8 (preloaded to 138kN) compared to 10.9 (preloaded to 172kN). The following influences were found:

   Grit blasted (S355, Rz=80 mm): **+5%**

ASIZN (S355, Rz=85 μm, DFT=85 μm): +6% / **+10%** (short / long)

ZnSM (S355, Rz=100 μm, Ct=165 μm): +21% / **+14%**

- No general conclusions can be drawn on the magnitude of the influence, this is depending on the properties of the coating (system, coating thickness)
- In a limited study no further negative influence on the slip factor was found for preload levels above 172kN

6 Bibliography

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

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

[8] EN 14399-9:2009, High-strength structural bolting assemblies for preloading – Part 9: System HR or HV – Direct tension indicators for bolt and nut assemblies

[9] RCSC - Research Council on Structural Connections: Specification for Structural Joints Using High-Strength Bolts. Chicago, Illinois : s.n., 2009.

[10]Beek, K. van, Schilperoort, F., The MP3 Control and Data Acquisition systems. Delft University of Technology, report 6-18-5, Stevin Laboratory, 2018

[11]Vries, P.A. de, Nijgh, M.P., Influence of the test speed in slip factor tests. Delft University of Technology, report 6-18-01, Stevin Laboratory, 2018

[12]Vries, P.A. de, Test results ASiZn and ZnSM specimens, additional technical report deliverable D2.1 Siroco project, Delft University of Technology, report 6-18-02_A, Stevin Laboratory, 2018

[13]Stranghoner, N., Afzali, N., Vries, P.A. de, Slip factors for typical stainless steel finishes and new types of coatings for stainless steel, UDE: 2018-06, 2018, TUD: Stevin report 6-18-04.

7 Annex A: Development of Short Step Wise Loading (SSWL) Test

7.1 Suggested Testing Procedure

The search for the long term slip factor of new coating systems can be time consuming. Series of extended creep test have to be performed to determine the maximum load level for which the slip after 50 years is still below the threshold value of 0.3 mm. The process described in EN1090-2 Annex G, in which the load is step wise increased until the (on the log timescale linearly) extrapolated slip exceeds the 0.3 mm boundary before t=50 years, typically takes weeks. After this procedure 3 additional extended creep tests on the load level that was found are necessary to prove the slip factor. In these tests the load level is directly brought to the required level and should be kept constant over the entire test period.

The SSWL test protocol is introduced in the project to develop a means to quickly estimate the maximum load level that can be achieved in extended creep tests. The results of the SSWL test were also evaluated in the context of the research objective of task2.1, to investigate if SSWL testing can be used to estimate the influence of the preload level on the slip factor.

In an SSWL test the load on the specimen is kept constant over periods of 1.5 h. The initial loading is set to 60% of $F_{s,m}$ and the load is raised with 5% of $F_{s,m}$ until a slip of 0.3 mm at CBG is reached.

During each load step the development of the slip speed is evaluated. The slip speed appears to be not constant over the 1.5 h periods; it is therefore calculated over 3 intervals of 25 minutes:

- 10 – 35 minutes
- 35 – 60 minutes
- 60 – 85 minutes

The hypothesis is that there is a 'critical SSWL test slip speed', independent of the coating system that can be used to:

1. determine if a coating system is creep sensitive
2. estimate the long duration slip load level for creep sensitive coatings
3. estimate the influence of the preload level on the slip factor

The first part of the hypothesis can be tested by performing SSWL tests on coatings/surfaces that have proven to be not creep sensitive (e.g. grit blasted surface). The SSWL slip speed that is associated with a load level of 90% $F_{s,m}$ for these surfaces can be considered to be the upper boundary for the SSWL slip speed found for a coating that is not sensitive to creep.

The second part of the hypothesis can be tested by combining the results of extended creep tests and the SSWL tests. This way the SSWL slip speed can be determined that is associated with the load level at which the extended creep test still passes. This can be seen as the *critical SSWL slip speed*.

Load levels with lower SSWL slip speed would pass the ECT test, load levels with higher slip speed would not.

The third part of the hypothesis can be tested by combining the results of extended creep tests and the SSWL tests for different preload levels. The ratio of the load at which the critical SSWL slip speed is reached may be suitable as a predictor for the influence of the preload on the long term slip behavior for specific surface preparations/coatings.

The specimens for the SSWL tests were instrumented identical to the short term slip factor tests (slip measurements at both PE and CBG position). The step wise application of the load over time was automated. Load controlled load application was used. The speed to reach the initial load level and to increase the load to the next level varied between 0.65 and 0.75 kN/s (initial load level should be reached in 10 – 15 minutes).

When the load on a specimen is raised to a certain level and then kept constant, the slip still increases when the load is constant. Over the time interval of 1.5 h there is a clear change in the speed (rate) of the slip process (see Figure 20 and Figure 21). The starting point for using the result of step wise loaded slip factor specimen is that the evolution of the slip rate over the 1.5 h intervals can be used to estimate the long term behavior of the coating.

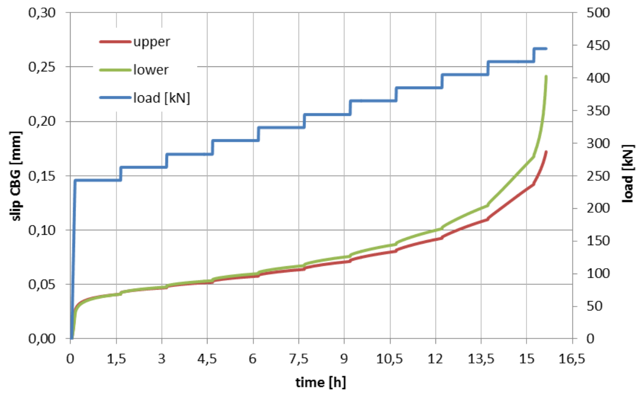


Figure 20 - Evolution of slip at CBG during SSWL test. Load was kept constant over periods of 1.5 h.

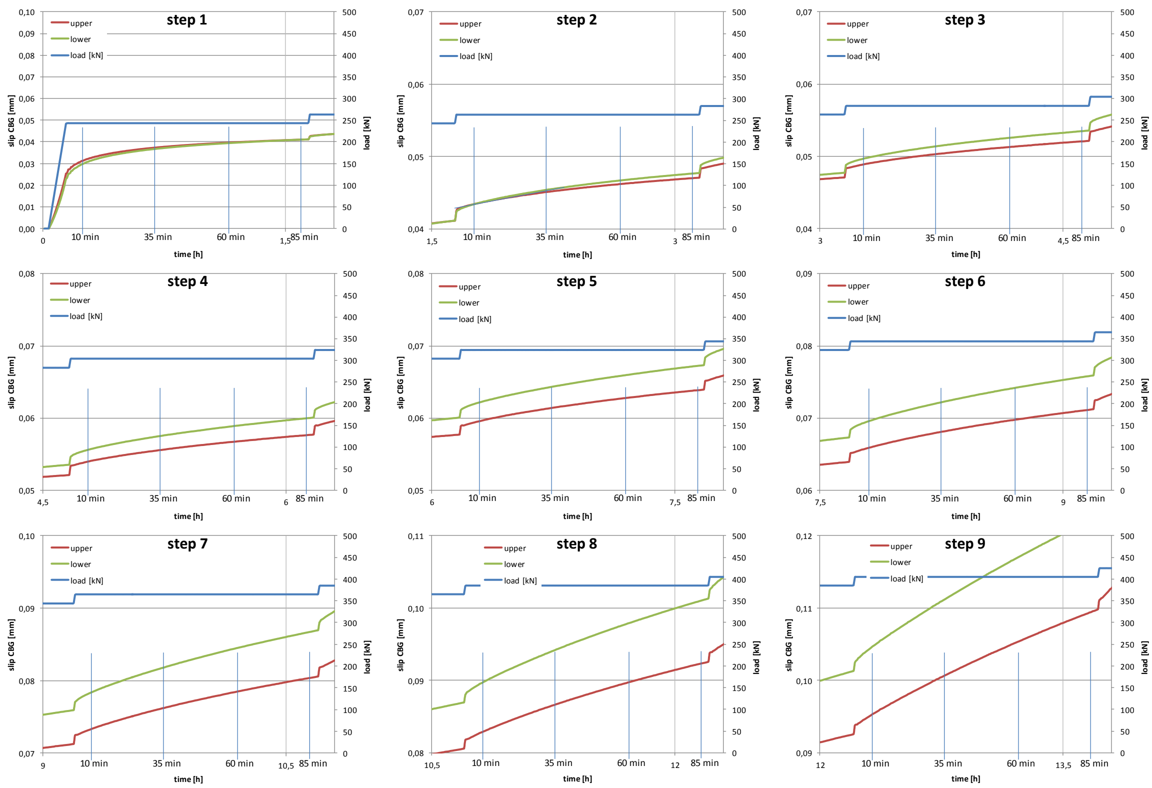


Figure 21 - Evolution of slip at CBG at various load steps during SSWL test. Slip rate for each load step was evaluated for 3 time intervals: 10-35 min, 35-60 min and 60-85 min after reaching the load.

Figure 23 and Figure 24 give an example of the result of a SSWL test and the way it is combined with the results of the extended creep tests to find the critical SSWL slip speed. Figure 23 shows that after the initial load application (0 – 60%$F_{s,m}$) the specimens show high slip speeds. In subsequent loading steps (in which there is a 5%$F_{s,m}$ increase of the load) the slip speed first reduces until a minimum is reached. From a certain load level on, the slip speed increases for increasing load. The critical SSWL slip speed for the series is defined as the slip speed at the load level the extended creep test for the series still (just) passes. Figure 24 shows how the results of SSWL and extended creep tests were combined to find the critical slip speed for the ZnSM-10.9 series.

7.2 SSWL Results

Figure 26 and Figure 27 show all results of the combined SSWL – extended creep test. A lower bound of the critical SSWL slip speed appears to be something like 0.1 μm/min. In terms of maximum allowable slip displacements this comes down to 6 μm over a period of 1 hour. This seems large compared to the 2 μm slip in 3 hours threshold that is used in the standard creep test that is used to determine if a coating is sensitive to creep.

In addition to the 4 tests on the specimens in task2.1 SSWL tests have been carried out on extra specimen that were available in the specimen series of:

- task1.2 (Grit blasted surface, as reference test of typical non creep sensitive, 1 test)
- task 4.1 (CS S355 plates with varying surface roughness, coated with Ethyl Silicate Zinc and Epoxy coatings, 10 tests)
- task6.2/6.3 (Stainless steel plates with varying surface preparation and TSA coating 9 tests).

Apart from executing the SSWL tests there was no time in the project to analyze the obtained data and use them to test the hypotheses stated.

From the results that were achieved with the specimens of task2.1 it has become clear that the 60% of $F_{s,m}$ that was used as initial load level of SSWL tests (which was chosen arbitrary) obviously needs to be adjusted to guarantee a useable SSWL test result. The SSWL test that was carried out on the ZnSM specimen that was preloaded to 138 kN (8.8 bolts) (Figure 26 – a) was useless because the initial load level appeared to be too high! It is essential that the slip rate that results at the end of the second load step is less than 0.1 μm/min.

It’s clear that further research is needed to proof the value of SSWL tests to estimate critical load levels for long term loadings and/or use SSWL tests to determine if coatings are sensitive to creep (alternative for current creep test) or to estimate the influence of the preload on the long term slip behavior. A standardized method that increases the efficiency of the method to determine the long term slip factors would be highly appreciated in practice!

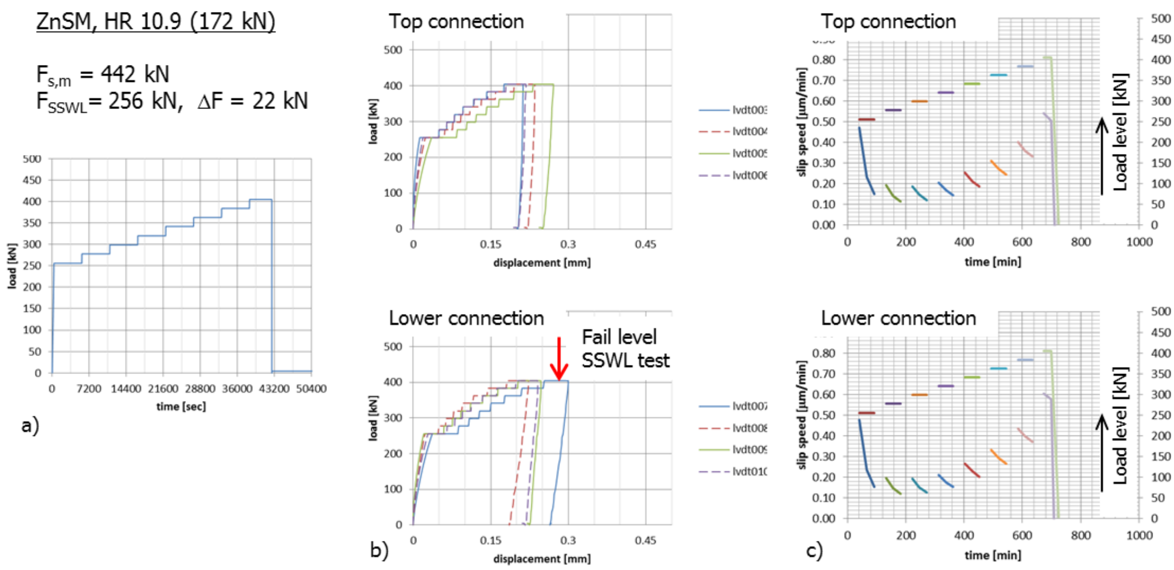


Figure 22 - SSWL test a) load vs time; initial load level (256 kN) load level is increased in steps of 5% and kept constant over 1.h intervals b) slip at CBG vs load level for both connections c) slip rate vs time per load level

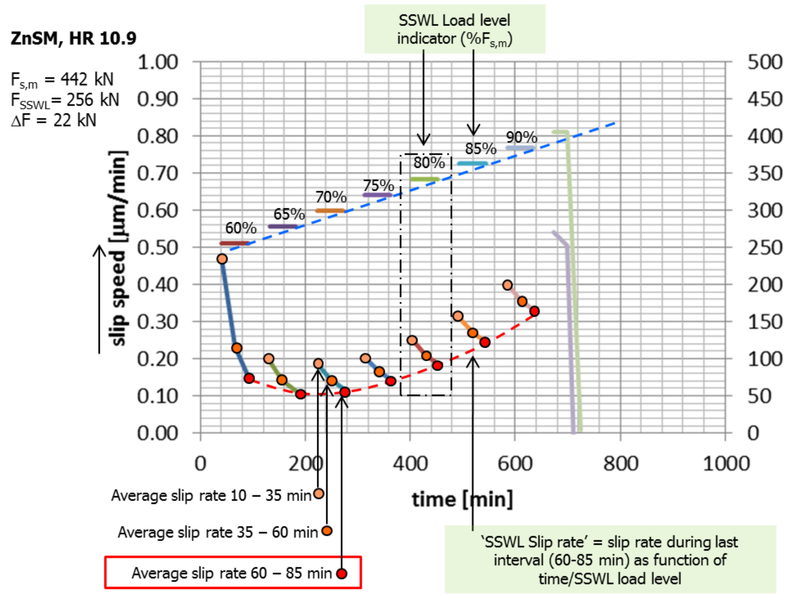


Figure 23 - Result of SSWL test. Slip speed for different load levels. Dotted red line indicates that SSWL slip rate (slip speed) increases with increasing loading.

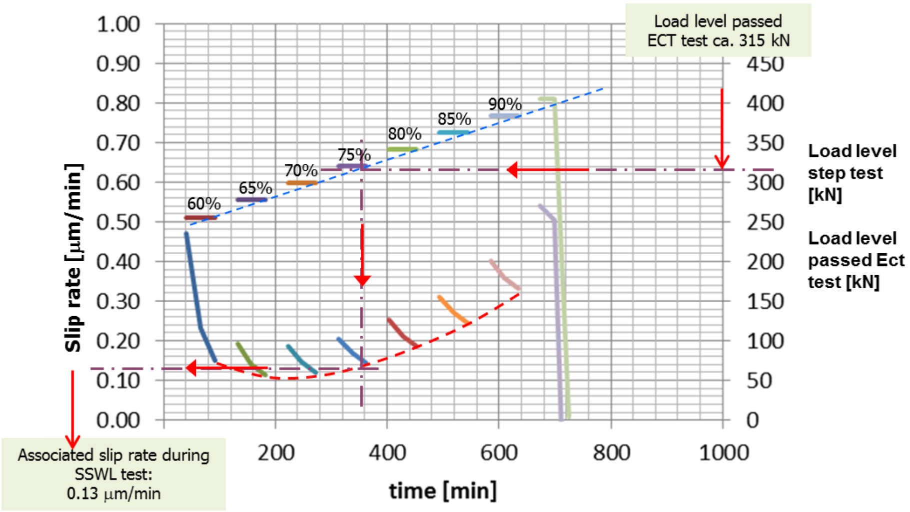


Figure 24 - Result of SSWL and extended creep test are used to determine the SSWL slip rate at the load level for which the extended creep test just passed.

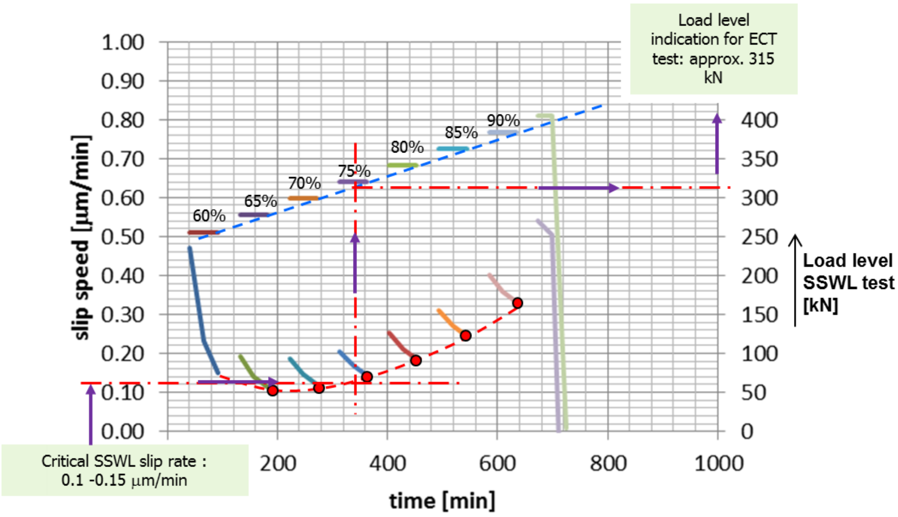


Figure 25 - Illustration of intended use of SSWL test result for new coatings: the (generic) critical SSWL slip rate (0.1 – 0.15 µm/min) is used to get an indication of the maximum load level that will pass (slip <0.3 mm over 50 years) during extended creep tests on the coating. SSWL testing is not a replacement for Extended creep tests!

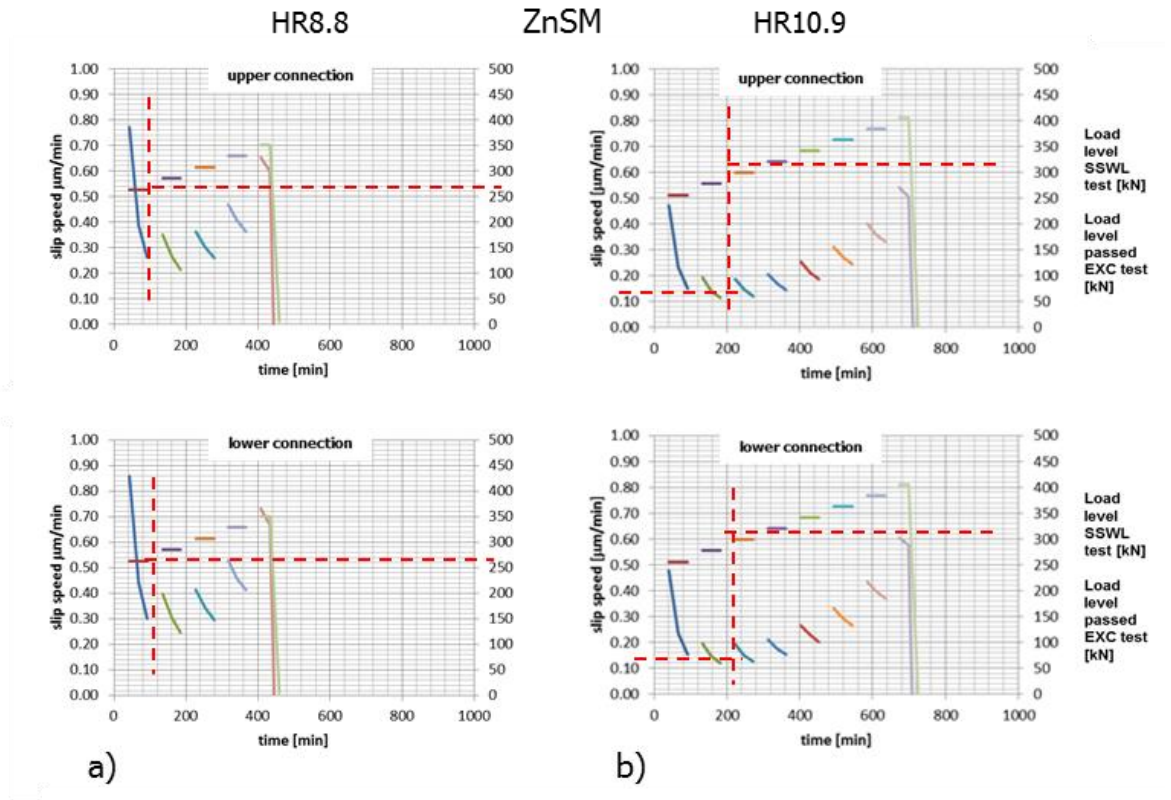


Figure 26 - Results of the SSWL experiments on ZnSM specimens. The results of the ZnSM-8.8 test (a) are not usable for analysis because the initial load level and the load increase steps were too high.
Critical SSWL slip rate for the ZnSM coating is 0.1 – 0.15 µm/min.

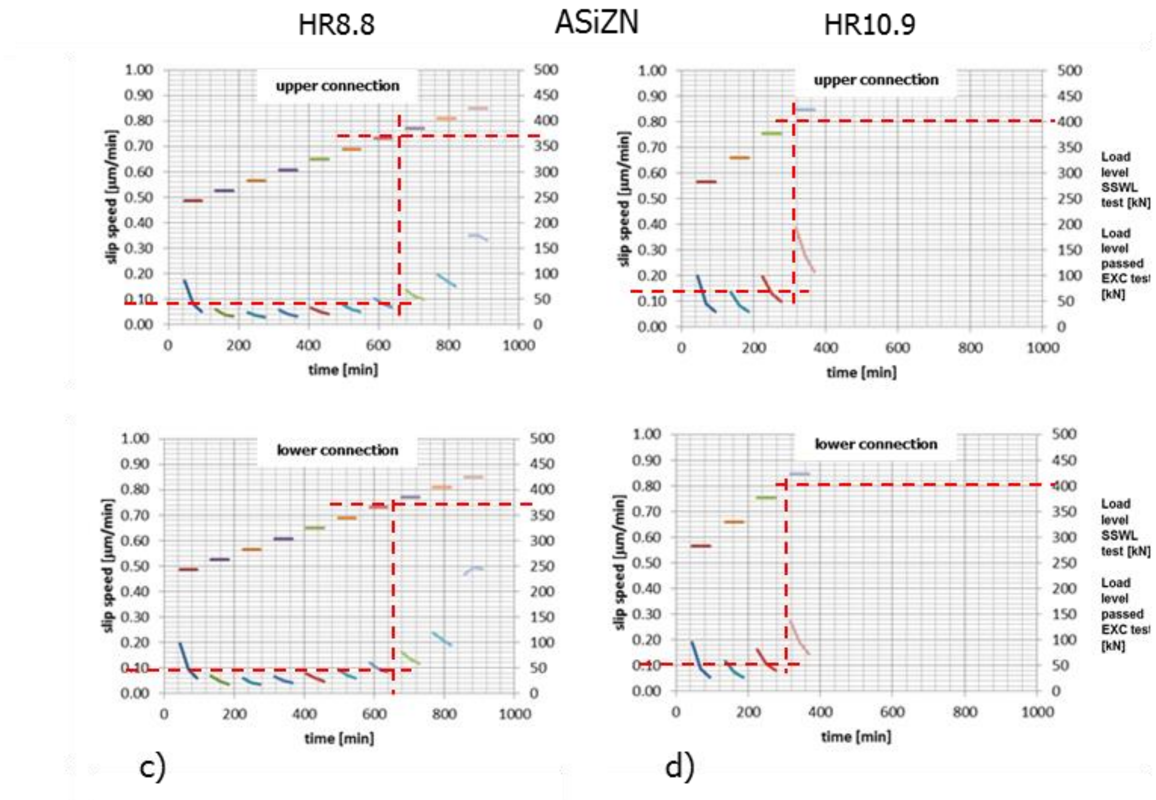


Figure 27 - Results of SSWL experiments on ASiZn specimens coating. c): preloaded to 136 kN, d) preloaded to 172 kN
Critical SSWL slip rate for the ASiZn coating is approximately 0.1 µm/min.

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8 Annex B - result overview short term slip factor tests

8.1 HR bolts preloaded at $F_{p,C,10.9}$ (172kN) vs $F_{p,C,8.8}$ (138kN)

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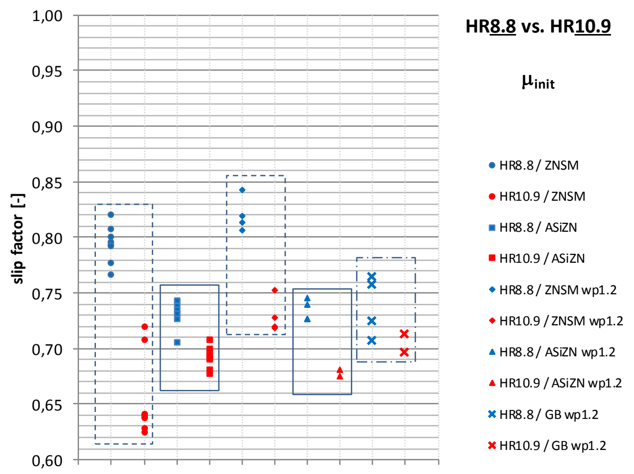
15-3-2018

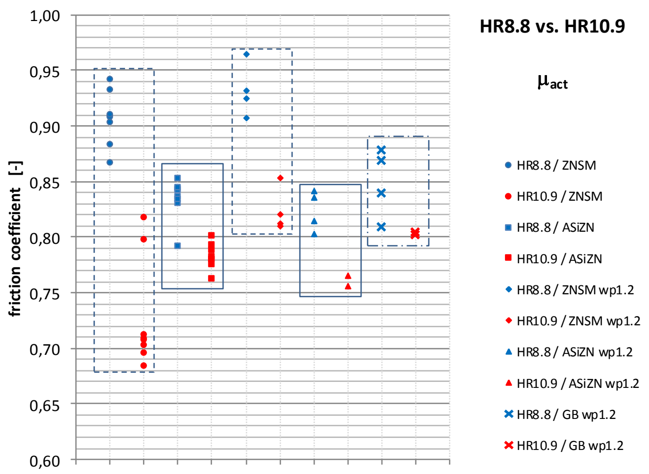
0	

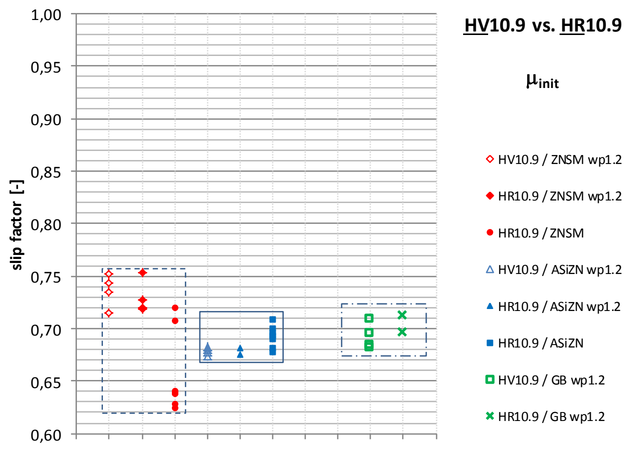
Results overview table WP2.1

HR bolts bolts preloaded at $F_{p,c,10.9}$ (172 kN) vs $F_{p,c,8.8}$ (138 kN)

		# tests				test results short term tests						test results including creep test				characteristic value acc. to Annex G	
coating	HR	task 2.1 test matrix		realization		test duration [min]		μ_{act}		μ_{ini}		μ_{act}		μ_{ini}		μ_k	
		short term	creep	short term	SSWLT	mean	COV	mean	COV	mean	COV	mean	COV	mean	COV	actual	Fp,init
ASiZN	8,8	8	2	8	1	13	6%	0,84	2%	0,73	2%	0,82	3%	0,72	4%	-	-
ASiZN	10,9	8	2	8	1	11	13%	0,78	1%	0,68	1%	0,77	4%	0,67	4%	-	-
ZNSM	8,8	8	2	8	1	15	12%	0,91	3%	0,79	3%	-	-	-	-	-	-
ZNSM	10,9	8	2	8	1	11	8%	0,73	7%	0,64	6%	-	-	-	-	-	-







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ASIZN	HR8.8	CBG

Test protocol

15-3-2018

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	08-02-2016 - 09-02-2016
	test performed by	F. Schilperoord
	Steel	S355
	Coating	Alkali Silicon Zinc
	Coating composition	-
	Surface treatment	Sa 2½, Rz = 84 micron (average)
	Maximum coating thickness	centre plates: 57 micron, lap plates: 53 micron (average values)
	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	8.8 (EN 14399-4 – HR – M20 x 70 – 8.8/8 – tZn)
	Nominal Preload level	138 kN = $F_{p,C}$
	Measuring of the preload level	Instrumented bolts, continuously measured, clamping length St = 48 mm
	load head speed	0,003 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] 138 $\mu_i = \mu_{i,nom}$ [–]	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_25	0	0,150	409	136	138	139	0,74	0,74	0,85	121	120	118	13,9	0,00	08-02-16 14:03
		0	0,150	405	137	136	136	0,74	0,73	0,84	122	120	118	13,6	0,00	
	ASiZN_26	0	0,150	408	141	141	140	0,73	0,74	0,83	125	123	120	12,5	0,00	09-02-16 10:30
		0	0,150	410	141	140	139	0,73	0,74	0,84	125	123	121	12,4	0,00	
	ASiZN_27	0	0,150	409	139	139	138	0,74	0,74	0,84	124	121	118	12,9	0,00	09-02-16 12:04
		0	0,150	407	140	138	137	0,74	0,74	0,85	124	120	117	12,8	0,00	
	ASiZN_28	0	0,147	403	138	138	138	0,73	0,73	0,83	123	121	118	13,7	0,00	09-02-16 14:05
		0	0,150	391	139	139	138	0,71	0,71	0,79	127	123	120	11,6	0,00	
	Statistics (4 specimen, 8 test results)	n=8	number of tests													
		max	Maximum	410				0,74	0,74	0,85				13,9		
		min	Minimum	391	SSWL test	dF (5%)		0,71	0,71	0,79				11,6		
		mean	Average F_{Sm} | μ_m	**405**	**243**	**20**		**0,73**	**0,73**	**0,84**				**12,9**	Eq. (2), Eq. (4)	
		R	spread	18,8				0,04	0,03	0,06				2,3	*R = max – min*	
		s	standard deviation	6,1				0,012	0,011	0,018				0,8	Eq. (3), Eq. (5)	
		V	coefficient of variation	1,5%				1,6%	1,5%	2,2%				6%	*V = s / mean*	
	creep test	**0,9 F_{Sm}**		**365**										slip [μm]	Load level creep test [kN]	
	ASiZN_41 S(	0	0,150	365	136	137	137	0,67	0,66	0,78	118	117	115	62,3	**365**	07-04-16 15:05
		0	0,150	365	137	137	137	0,67	0,66	0,78	119	117	116	61,5	NOT passed	
	Statistics (5 specimen, 10 test results)	n=10	number of tests											**result**		
		max	Maximum	410				0,74	0,74	0,85				failed	Δ slip < 2 μm in 3 h.	
		min	Minimum	365				0,67	0,66	0,78						
		mean	Average F_{Sm} | μ_m	410				0,72	0,72	0,82					Eq. (2), Eq. (4)	
		R	spread	45,1				0,08	0,08	0,08					*R = max – min*	
		s	standard deviation	17,9				0,029	0,032	0,028					Eq. (3), Eq. (5)	
		V	coefficient of variation	**4,5%**				**4,1%**	**4,5%**	**3,4%**					*V = s / mean* ≤ 8%	
	μ_k	Characteristic value slip factor						-	-	-					Eq. (6)	

8.3 Annex D - results ASiZn – HR10.9

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ASIZN | HR10.9 | CBG **Test protocol** 15-3-2018

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	F. Schilperoord
Steel	S355
Coating	Alkali Silicon Zinc
Coating composition	-
Surface treatment	Sa 2½, Rz = 84 micron (average)
Maximum coating thickness	centre plates: 57 micron, lap plates: 53 micron (average values)
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 – HR – M20 x 70 – 10.9/10 – tZn) chek length
Nominal Preload level	172 kN = $F_{p,C}$
Measuring of the preload level	Instrumented bolts, continuously measured, clamping length Σt = 48 mm
load head speed	0,004 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_30	0	0,150	469	170	169	169	0,69	0,68	0,78	154	150	147	9,5	0,00	15-02-16 15:30
	0	0,150	470	170	169	169	0,69	0,68	0,78	153	150	147	9,6	0,00	
ASiZN_31	0	0,150	471	169	168	168	0,70	0,68	0,79	152	148	144	11,2	0,00	16-02-16 9:50
	0	0,150	470	168	169	170	0,70	0,68	0,79	151	149	147	11,0	0,00	
ASiZN_32	0	0,150	481	170	170	170	0,71	0,70	0,80	154	150	146	13,6	0,00	16-02-16 11:09
	0	0,150	472	171	171	171	0,69	0,69	0,78	155	151	148	10,8	0,00	
ASiZN_33	0	0,150	462	170	170	171	0,68	0,67	0,76	154	151	148	10,6	0,00	16-02-16 12:37
	0	0,150	467	171	171	172	0,68	0,68	0,78	153	151	148	13,1	0,00	
Statistics (4 specimen, 8 test results)	n=8	number of tests													
	max	Maximum	481				0,71	0,70	0,80				13,6		
	min	Minimum	462	SSWL test	dF (10%)		0,68	0,67	0,76				9,5		
	mean	Average F_{Sm} | μ_m	**470**	**282**	**47,03**		**0,69**	**0,68**	**0,78**				**11,2**	Eq. (2), Eq. (4)	
	R	spread	18,6				0,03	0,03	0,04				4,1	*R = max – min*	
	s	standard deviation	5,3				0,010	0,008	0,012				1,5	Eq. (3), Eq. (5)	
	V	coefficient of variation	1,1%				1,4%	1,1%	1,5%				13%	*V = s / mean*	
creep test	0,9 F_{Sm}		423										slip [μm]	Load level creep test [kN]	
ASiZN_42 SCT	0	0,150	423	171	171	171	0,62	0,61	0,71	152	148	145	62,7	423	11-04-16 16:26
	0	0,150	423	171	171	171	0,62	0,61	0,72	149	146	143	58,5	NOT passed	
Statistics (5 specimen, 10 test results)	n=10	number of tests											result		
	max	Maximum	481				0,71	0,70	0,80				failed	Δ slip < 2 μm in 3 h.	
	min	Minimum	423				0,62	0,61	0,71						
	mean	Average F_{Sm} | μ_m	481				0,68	0,67	0,77					Eq. (2), Eq. (4)	
	R	spread	57,8				0,09	0,08	0,09					*R = max – min*	
	s	standard deviation	20,5				0,032	0,030	0,029					Eq. (3), Eq. (5)	
	V	coefficient of variation	**4,4%**				**4,7%**	**4,4%**	**3,8%**					*V = s / mean* ≤ 8%	
μ_k	Characteristic value slip factor						-	-	-					Eq. (6)	

8.4 Annex E - results ZnSM – HR8.8

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ZNSM | HR8.8 | CBG

Test protocol

15-3-2018

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	26-01-2016 - 02-02-2016
	test performed by	F. Schilperoord
	Steel	S355
	Coating	Zinc spray metallized
	Coating composition	-
	Surface treatment	Sa 2½, Rz = 100 micron
	Maximum coating thickness	centre plates 164 micron, lap plates 159 micron (average)
	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	8.8 (EN 14399-4 – HR – M20 x 70 – 8.8/8 – tZn)
	Nominal Preload level	138 kN = $F_{p,C}$
	Measuring of the preload level	Instrumented bolts, continuously measured, clamping length St = 48 mm
	load head speed	0,003 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] 138	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	SM_23	0	0,150	431	136	136	135	0,80	0,78	0,91	121	118	116	13,6	0,00	26-01-16 15:42
		0	0,150	432	136	136	136	0,79	0,78	0,91	122	119	116	13,7	0,00	
	SM_25	0	0,150	426	137	137	137	0,78	0,77	0,88	122	121	119	13,7	0,00	01-02-16 14:07
		0	0,133	427	139	139	139	0,77	0,77	0,87	125	123	120	13,9	0,00	
	SM_26	0	0,150	447	140	138	137	0,81	0,81	0,93	123	120	116	14,5	0,00	01-02-16 15:55
		0	0,150	450	140	141	142	0,80	0,82	0,90	125	125	124	18,8	0,00	
	SM_27	0	0,150	455	139	139	139	0,82	0,82	0,94	123	121	119	14,6	0,00	02-02-16 9:38
		0	0,150	441	140	139	138	0,79	0,80	0,91	124	121	119	13,3	0,00	
	Statistics (4 specimen, 8 test results)	n=8	number of tests													
		max	Maximum	455				0,82	0,82	0,94				18,8		
		min	Minimum	426	SSWL test	dF (5%)		0,77	0,77	0,87				13,3		
		mean	Average F_{Sm} | μ_m	**439**	**263**	**22**		**0,79**	**0,79**	**0,91**				**14,5**	Eq. (2), Eq. (4)	
		R	spread	29,1				0,05	0,05	0,07				5,5	*R = max – min*	
		s	standard deviation	11,2				0,017	0,020	0,024				1,8	Eq. (3), Eq. (5)	
		V	coefficient of variation	2,6%				2,1%	2,6%	2,6%				12%	*V = s / mean*	
	creep test	0,9 F_{Sm}		395										slip [μm]	Load level creep test [kN]	
	Statistics (4 specimen, 8 test results)	n=8	number of tests											result		
		max	Maximum	-				-	-	-				failed	Δ slip < 2 μm in 3 h.	
		min	Minimum	-				-	-	-						
		mean	Average F_{Sm} | μ_m	-				-	-	-					Eq. (2), Eq. (4)	
		R	spread	-				-	-	-					*R = max – min*	
		s	standard deviation	-				-	-	-					Eq. (3), Eq. (5)	
		V	coefficient of variation	**-**				**-**	**-**	**-**					*V = s / mean* ≤ 8%	
	μ_k	Characteristic value slip factor						-	-	-					Eq. (6)	

8.5 Annex F - results ZnSM – HR10.9

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ZnSM | HR10.9 | CBG

Test protocol

15-3-2018

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	F. Schilperoord
Steel	S355
Coating	Zinc spray metallized
Coating composition	-
Surface treatment	Sa 2½, Rz = 100 micron
Maximum coating thickness	centre plates 164 micron, lap plates 159 micron (average)
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 – HR – M20 x 70 – 10.9/10 – tZn)
Nominal Preload level	172 kN = Fp,C
Measuring of the preload level	Instrumented bolts, continuously measured, clamping length St = 48 mm
load head speed	0,004 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_32	0	0,138	433	170	169	168	0,64	0,63	0,71	157	153	149	10,7	0,00	17-02-16 9:42
	0	0,150	432	169	169	169	0,64	0,63	0,71	155	152	149	10,5	0,00	
SM_33	0	0,150	419	167	167	166	0,63	0,61	0,68	156	153	150	10,2	0,00	17-02-16 12:21
	0	0,150	417	168	167	167	0,62	0,61	0,70	156	150	143	10,4	0,00	
SM_34	0	0,150	430	168	168	168	0,64	0,62	0,70	154	153	152	10,9	0,00	17-02-16 14:04
	0	0,150	430	169	169	169	0,64	0,63	0,71	154	152	150	10,4	0,00	
SM_36	0	0,150	490	170	170	171	0,72	0,71	0,82	152	150	148	12,7	extremely high slip load ?	18-02-16 13:09
	0	0,150	482	170	170	170	0,71	0,70	0,80	154	151	148	12,0	extremely high slip load ?	
Statistics (4 specimen, 8 test results)	n=8	number of tests													
	max	Maximum	490				0,72	0,71	0,82				12,7		
	min	Minimum	417	SSWL test	dF (5%)		0,62	0,61	0,68				10,2		
	mean	Average F_{Sm} | μ_m	**442**	**265**	**22,1**		**0,65**	**0,64**	**0,73**				**11,0**	Eq. (2), Eq. (4)	
	R	spread	72,5				0,10	0,11	0,13				2,5	*R = max – min*	
	s	standard deviation	27,9				0,037	0,041	0,050				0,9	Eq. (3), Eq. (5)	
	V	coefficient of variation	6,3%				5,7%	6,3%	6,9%				8%	*V = s / mean*	
creep test	**0,9 F_{Sm}**		**398**										slip [μm]	Load level creep test [kN]	
Statistics (4 specimen, 8 test results)	n=8	number of tests											**result**		
	max	Maximum	-				-	-	-				failed	Δ slip < 2 μm in 3 h.	
	min	Minimum	-				-	-	-						
	mean	Average F_{Sm} | μ_m	-				-	-	-					Eq. (2), Eq. (4)	
	R	spread	-				-	-	-					*R = max – min*	
	s	standard deviation	-				-	-	-					Eq. (3), Eq. (5)	
	V	coefficient of variation	-				-	-	-					*V = s / mean* ≤ 8%	
μ_k	Characteristic value slip factor						-	-	-					Eq. (6)	

9 Annex G – reference tests on WP1.2 specimens + additional tests on WP2.1 – HR8.8

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	HR8.8	CBG	Test protocol	15-3-2018

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	F. Schilperoord
	Steel	
	Coating	**WP1.2 plates for reference + 1 experiment on WP2.1 plates to test if coating of both sides of the lap plates has influence one the test**
	Coating composition	
	Surface treatment	
	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	HR8.8
	Nominal Preload level	138 kN
	Measuring of the preload level	Instrumented bolts, continuously measured, clamping length St = 48 mm
	load head speed	0,005 mm/sec

	specimen		**slip**	**Slip load**	**Pre loading**			**slip factor**			**Preload**			**test duration**	**comment**	**test date**
	mark	plate ID's	**(average at CBG)**		**at start test (initial pre load)**			based on initial preload	based on nominal preload	based on preload at reaching slip criterion	**at reaching slip criterion**				Equations from EN 1090-2 annex G	
					outer Bolt	average	inner Bolt		$F_{p,C}$ [kN] 138		outer bolt	average	inner bolt			start test
			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		
			[mm]	[kN]	[kN]	[kN]	[kN]	[–]	[–]	[–]	[kN]	[kN]	[kN]	[min]		
Static load	**SM_22**	0	0,150	456	140	140	140	0,81	0,83	0,92	126	123	120	15,1	wp1.2 ZN_SM plates	26-01-16 11:27
		0	0,150	460	140	140	141	0,82	0,83	0,93	125	123	122	15,3	wp1.2 ZN_SM plates	
	SM_24	0	0,150	466	139	138	137	0,84	0,84	0,96	124	121	117	20,7	wp1.2 ZN_SM plates	01-02-16 10:56
		0	0,150	449	139	139	140	0,81	0,81	0,91	126	124	122	13,7	wp1.2 ZN_SM plates	
	ASiZN_23	0	0,150	403	136	136	136	0,74	0,73	0,84	122	121	119	14,0	wp1.2 ASiZn plates	08-02-16 9:36
		0	0,150	397	137	137	136	0,73	0,72	0,81	124	122	120	12,4	wp1.2 ASiZn plates	
	ASiZN_24	0	0,150	408	137	137	136	0,75	0,74	0,84	123	121	119	12,5	wp1.2 ASiZn plates	08-02-16 11:02
		0	0,150	403	139	139	138	0,73	0,73	0,80	128	126	123	11,8	wp1.2 ASiZn plates	
	SB_22	0	0,128	412	142	142	143	0,72	0,75	0,84	124	123	121	13,8	wp1.2 Grit blasted plates	10-02-16 14:10
		0	0,150	406	144	144	143	0,71	0,74	0,81	128	126	123	12,9	wp1.2 Grit blasted plates	
	SB_23	0	0,150	418	138	138	139	0,76	0,76	0,87	122	120	119	12,6	wp1.2 Grit blasted plates	10-02-16 15:39
		0	0,150	424	138	139	139	0,76	0,77	0,88	124	121	118	12,6	wp1.2 Grit blasted plates	
	SM_28	0	0,125	395	137	137	136	0,72	0,72	0,79	127	125	123	12,2	**wp2.1 ZN_SM plates, on**	03-02-16 12:17
		0	0,150	408	136	138	139	0,74	0,74	0,84	124	122	121	25,8	**wp2.1 ZN_SM plates, on**	

SM_28 coating removed from one side of the lap plates

10 Annex H – Reference tests on WP1.2 plates – HR10.9

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HR10.8	CBG	Test protocol	15-3-2018

basics slip fator experiment

Tested according to	EN 1090-2:2011-10 – Annex G **slip criterion used**: 0.15 mm at Centre Bolt Group / SSWL protol
Test date	
test performed by	F. Schilperoord
Steel	
Coating	**WP1.2 plates for reference + SSWL reference test on grit blasted plates**
Coating composition	
Surface treatment	
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	0,004 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_38	0	0,150	488	169	170	170	0,72	0,71	0,81	153	151	148	12,6	wp1.2 ZN_SM plates	22-02-16 10:07
	0	0,150	500	173	172	170	0,73	0,73	0,82	156	152	148	13,6	wp1.2 ZN_SM plates	
SM_39	0	0,150	513	169	170	171	0,75	0,75	0,85	152	150	149	13,6	wp1.2 ZN_SM plates	22-02-16 12:20
	0	0,150	494	171	172	172	0,72	0,72	0,81	155	152	149	11,9	wp1.2 ZN_SM plates	
ASiZN_36	0	0,150	468	172	172	171	0,68	0,68	0,76	156	153	150	11,9	wp1.2 ASiZn plates	24-02-16 12:03
	0	0,150	464	172	172	171	0,68	0,67	0,76	158	153	149	11,0	wp1.2 ASiZn plates	
SB_24	0	0,150	487	171	171	171	0,71	0,71	0,80	154	151	149	16,8	0,00	22-02-16 13:56
	0	0,150	480	171	172	174	0,70	0,70	0,80	152	150	148	11,2	0,00	

Slip load	SSWL test	dF (5%)	
483	**290**	**24,2**	setting used for SSWL test GB, 10.9

short stepwise loading test

	t0 [min]	t1 [min]	slip load steps	60%	65%	70%	75%	80%	85%	90%	95%	100%	105%	x Fs,m [kN]	date
	interval			**290**	**314**	**338**	**363**	**386**	**410**	**434**	**458**	**482**	**506**		
				slip speed											
SB_26 SSW	10	35	upper connection	0,008	0,008	0,008	0,012	0,011	0,010	0,011	0,016	0,020	0,030	[μm/min]	21-06-16 12:12
	35	60		0,002	0,002	0,003	0,004	0,004	0,003	0,004	0,004	0,007	0,009	[μm/min]	
	60	85		0,002	0,002	0,001	0,003	0,003	0,002	0,002	0,001	0,005	0,004	[μm/min]	
			lower connection	0,006	0,007	0,007	0,011	0,009	0,009	0,010	0,013	0,015	0,022	[μm/min]	
				0,002	0,003	0,002	0,004	0,004	0,003	0,003	0,003	0,004	0,005	[μm/min]	
				0,001	0,001	0,002	0,003	0,002	0,002	0,001	0,001	0,003	0,003	[μm/min]	

11 Annex I - coating thickness WP2.1 plates

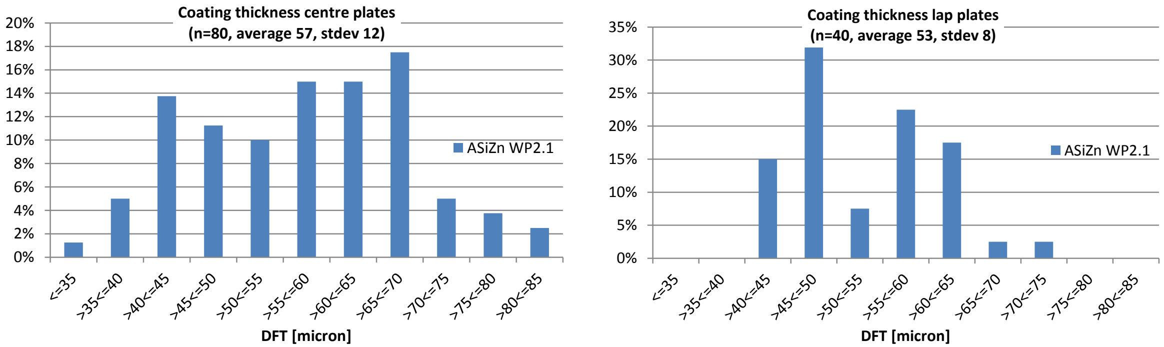


Figure 28 - Dry film thickness ASiZn plates

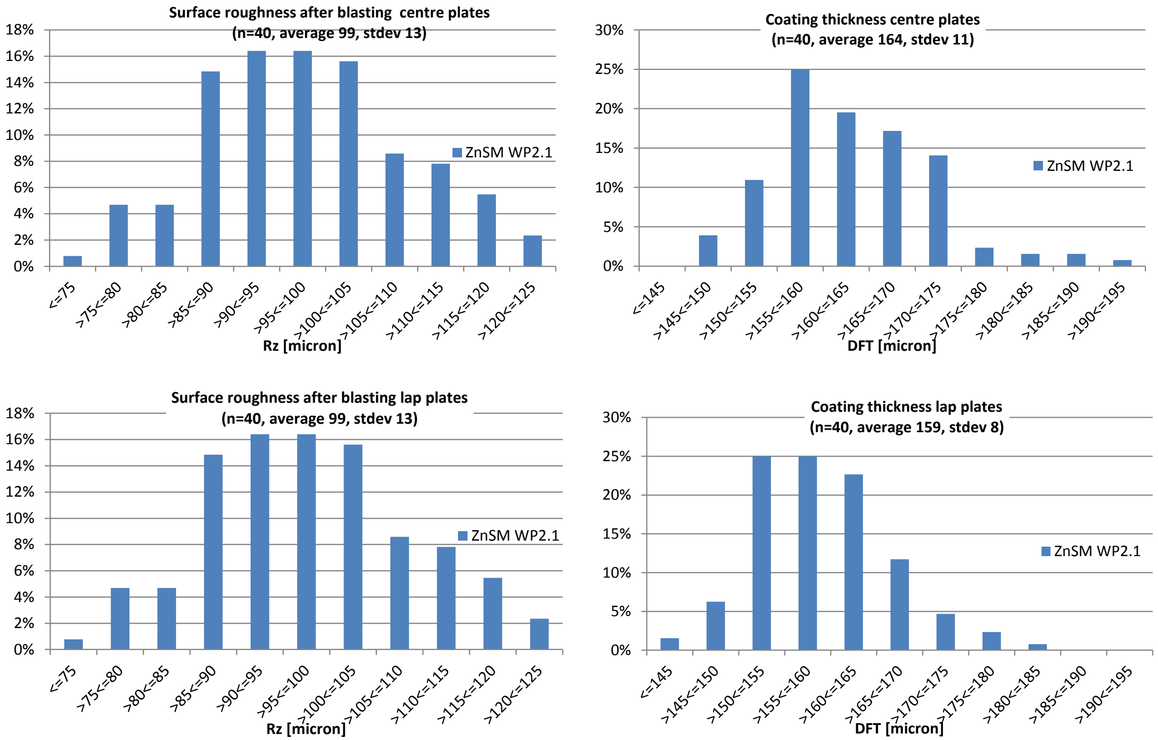


Figure 29 – Left: Surface roughness, Right: Layer thickness ZnSM plates

12 Annex J: Overview table results extended creep tests

series	coating	bolts		short term tests				Extended creep tests										
		type	Σt [mm]	spec ID	$F_{slip,i}$ [kN]	$F_{s,m}$ [kN]	COV [-]	spec ID	$F_{p,nom}$ [kN]	$F_{v,ect,init}$ / $F_{v,ect,final}$ [kN]	$F_{v,ect,init}$ / $F_{s,m}$ [%]	start date / end date	test duration [days]	$F_{v,slip,min}$ [kN]	$F_{v,slip,max}$ [kN]	slip CBG end test [mm]	slip CBG at 50 year < 0.3 mm	$\mu_{ect,nom}$ [-]
wp2.1	ASiZN	HR 8.8	48	ASiZN_25	409	405	1,5%	ASiZN_37	137	344	**85%**	6-apr-16	322	382	<405	0,18	pass	0,70
					405					382	**94%**	22-feb-17				0,24	pass	
				ASiZN_26	408			ASiZN_38	137	365	**90%**	6-apr-16	322	387	<405	0,24	pass	0,71
					410					387	**95%**	22-feb-17				0,30	pass	
				ASiZN_27	409			ASiZn_43	**177**	385	**95%**	20-jun-16	247	367	<385	0,15	pass	0,52
					407					367	**91%**	22-feb-17				0,17	pass	
				ASiZN_28	403			ASiZn_44	137	375	**92%**	21-jun-16	246	375	375	0,26	pass	-
					391					375	**92%**	22-feb-17				0,47	fail	
		HR 10.9	48	ASiZN_30	469	470	1,1%	ASiZN_39	172	353	**75%**	7-apr-16	74	389	<405	0,12	pass	0,57
					470					389	**83%**	20-jun-16				0,13	pass	
				ASiZN_31	471			ASiZN_40	172	376	**80%**	11-apr-16	70	404	<405	0,14	pass	0,59
					470					404	**86%**	20-jun-16				0,15	pass	
				ASiZN_32	481			ASiZn_45	172	425	**90%**	FAGP	0	425	425	>0.3	fail	-
					472					425	**90%**	FAGP				>0.3	fail	
				ASiZN_33	462													
					467													
	ZnSM	HR 8.8	48	SM_23	431	439	2,6%	SM_31	137	329	**75%**	4-feb-16	32	308	< 329	0,28	pass	-
					432					308	70%	7-mrt-16				0,30	fail	
				SM_25	426			SM_42	137	329	**75%**	8-mrt-16	15	308	< 329	>0.3	fail	-
					427					308	70%	23-mrt-16				>0.35	fail	
				SM_26	447			SM_43	137	313	**71%**	8-mrt-16	15	293	<313	>0.35	fail	-
					450					293	67%	23-mrt-16				>0.35	fail	
				SM_27	455			SM_44	137	295	**67%**	24-mrt-16	12	276	<295	0,23	pass ?	-
					441					276	63%	5-apr-16				0,26	fail	
								SM_45	137	280	**64%**	24-mrt-16	12	268	<280	0,19	pass	0,49
										268	61%	5-apr-16				0,19	pass	
								SM_46	137	325	**74%**	24-mrt-16	12	301	<325	0,27	fail	-
										301	69%	5-apr-16				0,30	fail	
		HR 10.9	48	SM_32	433	442	6,3%	SM_37	172	376	**85%**	18-feb-16	14	331	<< 376	0,65	fail	-
					432					331	75%	3-mrt-16				0,80	fail	
				SM_33	419			SM_40	172	340	**77%**	3-mrt-16	33	315	<340	0,24	pass ?	-
					417					315	71%	5-apr-16				0,31	fail	
				SM_34	430			SM_41	172	340	**77%**	3-mrt-16	20	319	< 340	0,29	fail	-
					430					319	72%	23-mrt-16				0,31	fail	
				SM_36	490			x	x	307	**70%**							-
					482					285	65%							
wp1.2	ZnSM	HV 10.9	48	load stepwise increased				SM_19	172	325, 358		9-jul-15	207	320	< 349	0,17	pass	0,47
										320, 349		1-feb-16				0,22	pass	
			152	load stepwise increased				SM_20	172	327, 323		9-jul-15	207	323	< 351	0,20	pass	0,47
										361, 351		1-feb-16				0,20	pass	
		HR 10.9	48					x	x									-
								SM_48	172									-
		HR 8.8						SM_30	137	329		4-feb-16	32	314	< 329	0,21	pass	0,57
										314		7-mrt-16				0,27	pass	

13 Annex K - Test results extended creep tests on ASiZn specimens

Average bolt preload Average preload vs time on linear scale during first hours. Preparation phase, average initial preload losses, effect of retightening, effect of application external load preload.	**Average bolt preload** Average preload vs time on log scale over full test period. Preparation phase, average initial preload losses, effect of retightening, effect of application external load preload.	**Individual bolt preload** Preload per bolt vs time on linear scale during first hours. Preparation phase, average initial preload losses, effect of retightening, effect of application external load preload.
External load Application of initial external load vs. time on linear scale. Magnitude of initial external load Indication of speed of load application (in 10 – 15 min)	**External load** External load vs. time on log scale over full test period. Overshoot in / loss of external load Increase of external load during test period	
Slip measurement at PE position Slip at PE vs time on linear scale during first hours Slip at PE during application of external load. Average slip per connection	**Slip measurement at PE position** Slip at PE vs. time on log scale over full test period.	**Slip measurement at PE position** Slip at PE vs time on linear scale during first hours Slip at PE during application of external load. Slip per LVDT
Effective slip at CBG Calculated slip at CBG position vs time on linear scale during first hours. Model used to convert from PE to CBG. Graph shifted in time. t=0 : start of application of external load	**Effective slip at CBG** Calculated slip at CBG position vs time on log scale over full test period. **This graph is used for the evaluation of the extended creep test.** **The dotted lines connect the last slip measurement and 0.3 mm at 50 years. The tangent of the dotted lines determine if the load level is accepted.**	

13.1 ASIZN_37 – 8.8

test piece	XCT_ASiZN_37

start date	6-04-16 11:15	
last record da	22-02-17 12:00	
test running for		
	322.0	days

bolts	HR8.8	
clamping L	52	mm
Fp.c	138	kN

load level based on		
SSWLT	ASiZN_29	
Fxtc (L0)	344	kN

static tests	creep test	SSWL test
ASiZN_25		
ASiZN_26		
ASiZN_27		
ASiZN_28		
CBG-PE	E	A
correction app	210000	2000
	29	L
0.044	mm	
orrection mode	C1	C2
ZN (wp1.2 & wp	1.735E-07	9.374E-08

start time loading
133 min
start time EXCT
149 min

loading	[kN]	applied on	days
L0	344	6-apr-16	6.9
L1	363	13-apr-16	13.1
L2	397	26-apr-16	301.9

Fp,c

1	138
3.00E+07	138

Fxtc	L0	L1	L2
1	344	363	397
3.00E+07	344	363	397

start loading

132.9531136	0
132.9531136	350

start EXCT

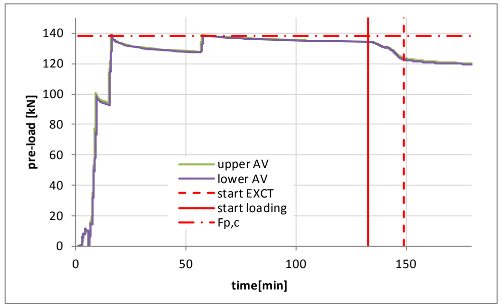
148.9951803	0	16	0
148.9951803	350	16	350

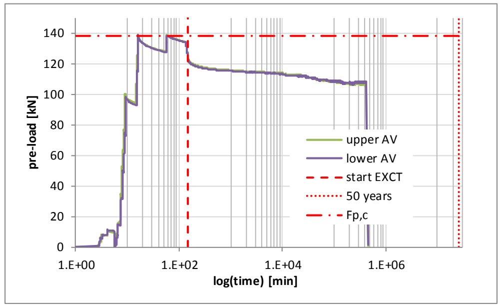
50 years

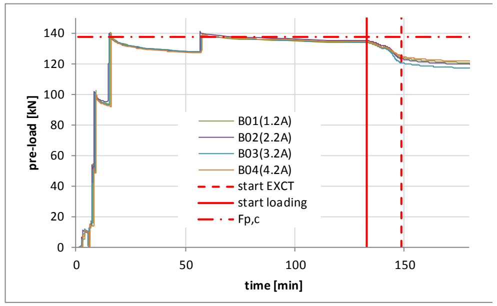
26280000	0
26280000	350

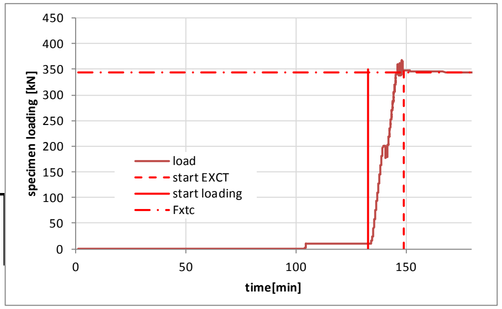
xtrpl 50y

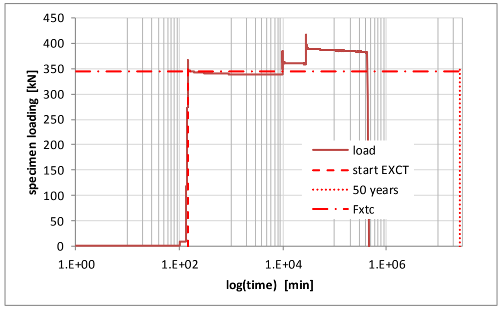
463652	3.63295E-05
26280000	0.3
463652	3.63295E-05
26280000	0.3

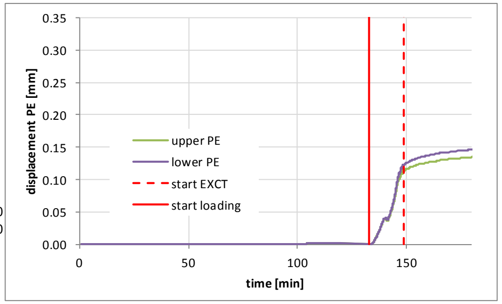


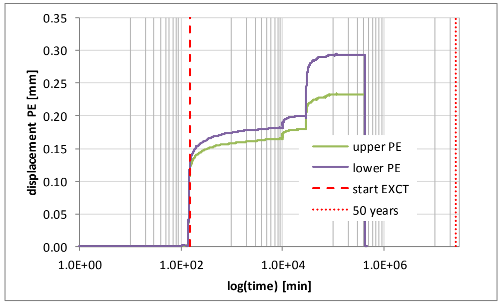


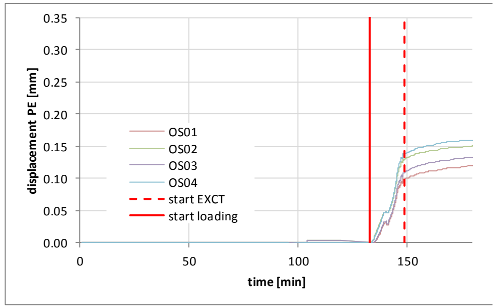


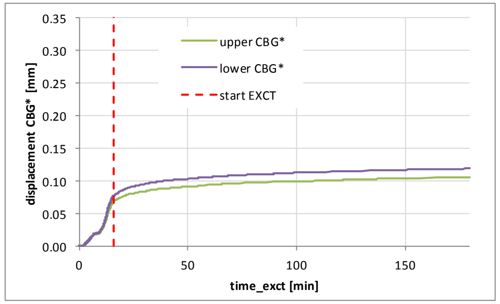


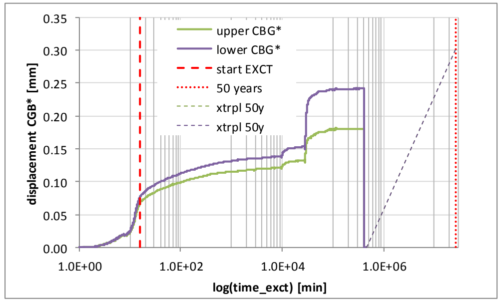






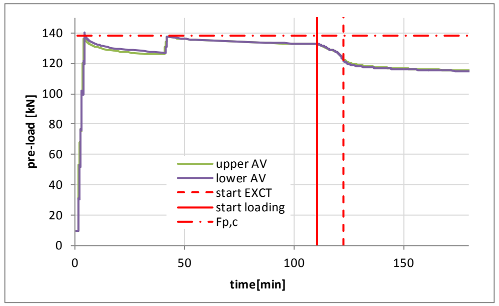


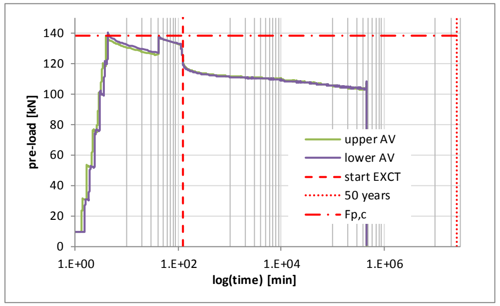


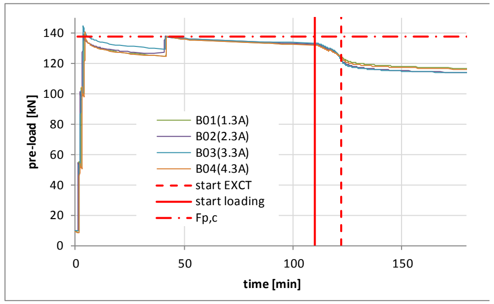


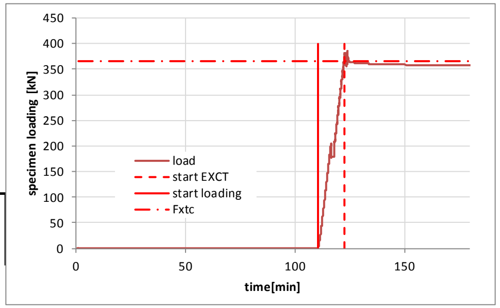
13.2 ASIZN_38 – 8.8

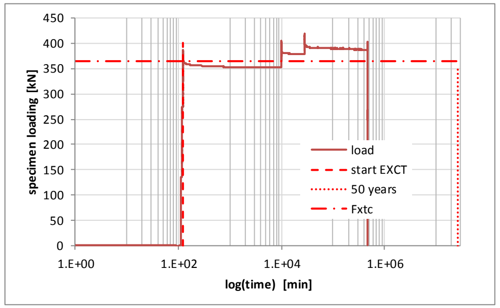
test piece	XCT_ASiZN_38			
start date	6-04-16 13:09			
last record da	22-02-17 9:15			
test running for				
	321.8	days		
bolts	HR8.8			
clamping L	52	mm		
$F_{p,c}$	138	kN		
load level based on				
SSWLT	ASiZN_29			
F_{xtc}	365	kN		
static tests	creep test	SSWL test		
ASiZN_25				
ASiZN_26				
ASiZN_27				
ASiZN_28				
CBG-PE	E	A		
correction app	210000	2000		
	29	L		
0.048	mm			
orrection mode	C1	C2		
ASiZN (wp1.2	1.735E-07	9.374E-08		
start time loading				
110	min			
start time EXCT				
122	min			
loading	[kN]	applied on	days	
L0	365	6-04-16 15:15	6.9	
L1	385	13-04-16 12:01	13.0	
L2	398	26-04-16 12:20	301.9	
$F_{p,c}$				
1	138			
3.00E+07	138			
F_{xtc}	L0	L1	L2	
1	365	385	398	
3.00E+07	365	385	398	
start loading				
110.3121065	0			
110.3121065	400			
start EXCT				
122.3900335	0	12	0	
122.3900335	400	12	400	
50 years				
26280000	0			
26280000	350			
xtrpl 50y				
463395	0.217467189			
26280000	0.3			
463395	0.278467189			
26280000	0.3			

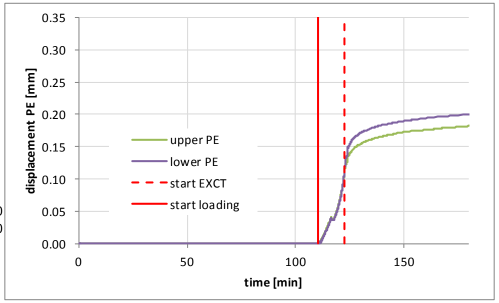


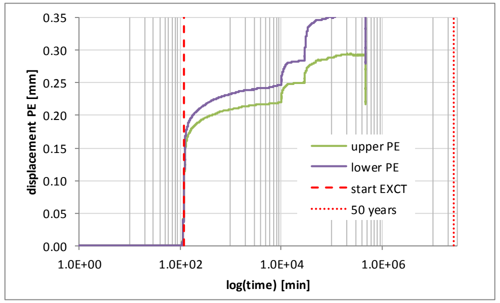


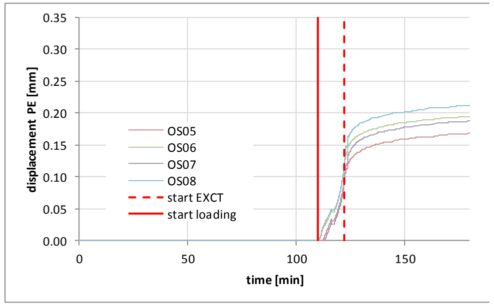


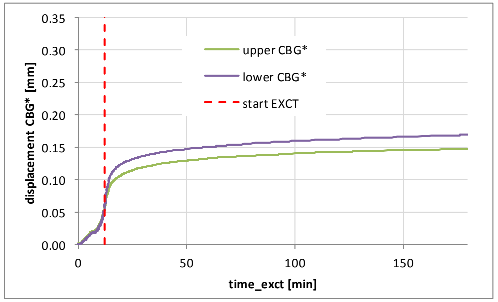


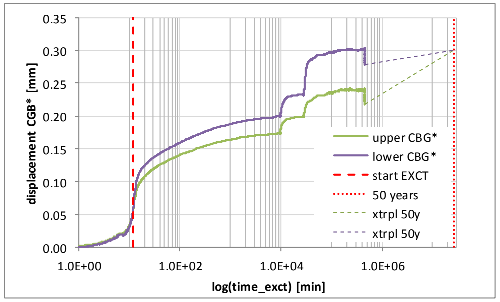








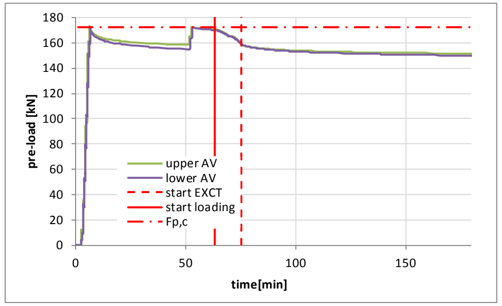


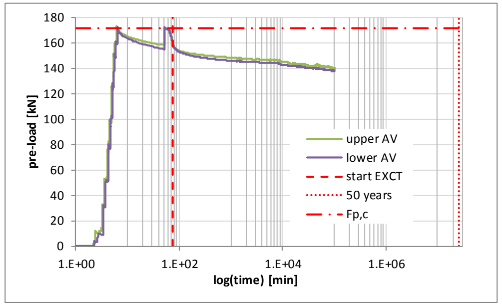


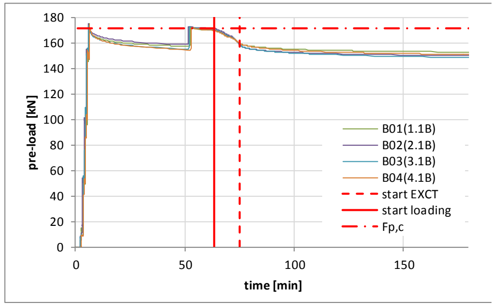
13.3 ASIZN_39 – 10.9

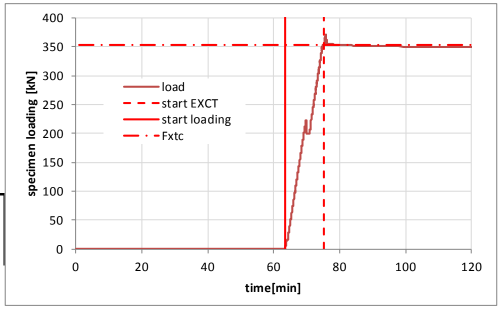
test piece	XCT_ASiZN_39		
start date	7-04-16 9:07		
last record da	17-06-16 9:15		
test running for			
	71.0	days	
bolts	HR10.9		
clamping L	52	mm	
$F_{p,c}$	172	kN	
load level based on			
SSWLT	ASIZN_34		
F_{xtc}	**353**	kN	
static tests	creep test	SSWL test	
ASiZN_30			
ASiZN_31			
ASiZN_32			
ASiZN_33			
CBG-PE	E	A	
correction app	210000	2000	
	29	L	
0.046	mm		
orrection mode	C1	C2	
ZN (wp1.2 & wp	1.735E-07	9.374E-08	
start time loading			
63	min		
start time EXCT			
75	min		
loading	[kN]	applied on	days
L0	353	07-apr-16	6.2
L1	380	13-apr-16	12.8
L2	400	26-04-16 11:56	51.9

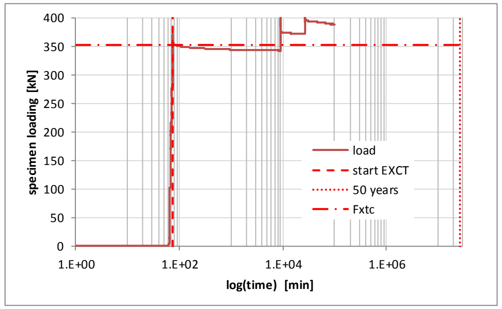
$F_{p,c}$			
1	172		
3.00E+07	172		
F_{xtc}			
1	353		
3.00E+07	353		
start loading			
63.3846095	0		
63.3846095	400		
start EXCT			
75.34438413	0	12	0
75.34438413	400	12	400
50 years			
26280000	0		
26280000	400		
xtrpl 50y			
102184	0.13543782		
26280000	0.3		
102184	0.12343782		
26280000	0.3		

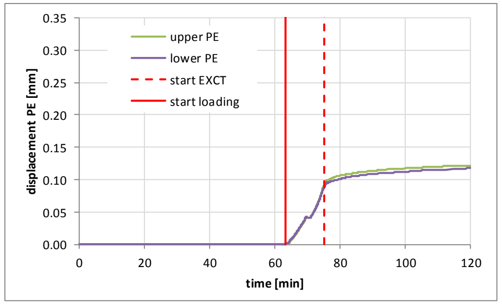


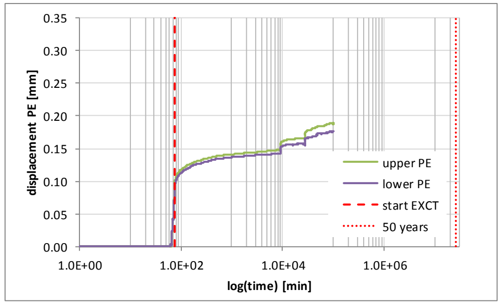


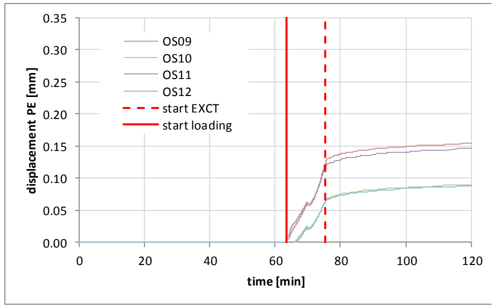


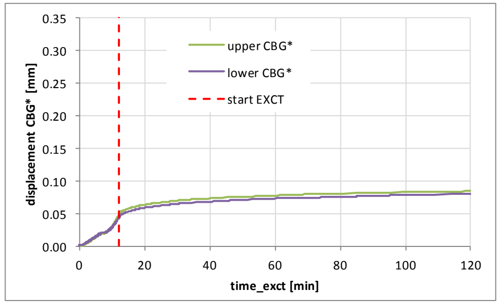


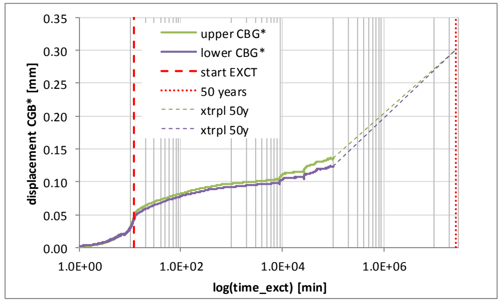












13.4 ASIZN_40 – 10.9

test piece	XCT_ASiZN_40	
start date	11-04-16 8:00	
last record da	17-06-16 9:15	
test running for		
	67.1	days
bolts	HR10.9	
clamping L	52	mm
$F_{p,c}$	172	kN
load level based on		
SSWLT	ASIZN_34	
F_{xtc}	376	kN

static tests	creep test	SSWL test
ASiZN_30		
ASiZN_31		
ASiZN_32		
ASiZN_33		
CBG-PE	E	A
correction app	210000	2000
	29	L
0.051	mm	
orrection mode	C1	C2
ASiZN (wp1.2	1.735E-07	9.374E-08

start time loading
116 min
start time EXCT
128 min

loading	[kN]	applied on	days
L0	376	11-apr-16	15.1
L1	405	26-apr-16	51.8
L2	0		42538.4

$F_{p,c}$

1	172
3.00E+07	172

F_{xtc}

1	376
3.00E+07	376

start loading

115.8817284	0
115.8817284	400

start EXCT

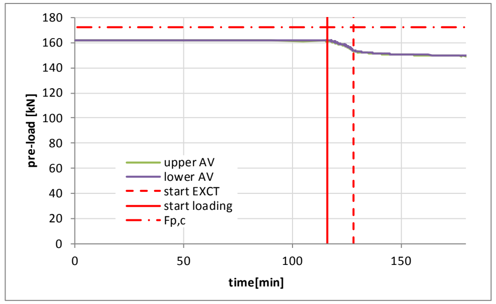
128.1330076	0	12	0
128.1330076	400	12	400

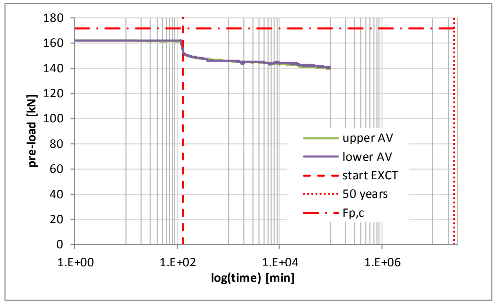
50 years

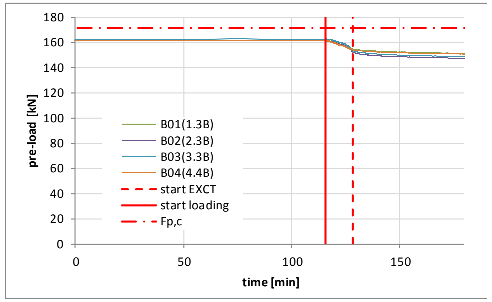
26280000	0
26280000	400

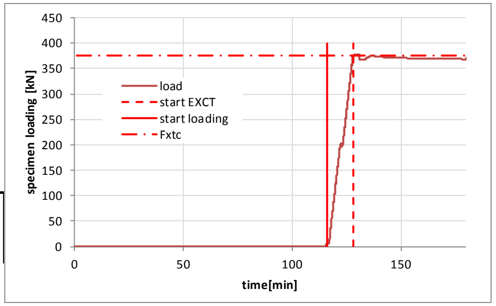
xtrpl 50y

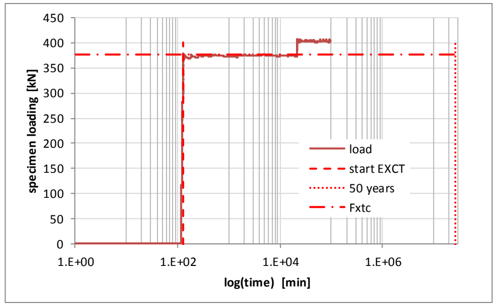
96424	0.138904283
26280000	0.3
96424	0.155904283
26280000	0.3

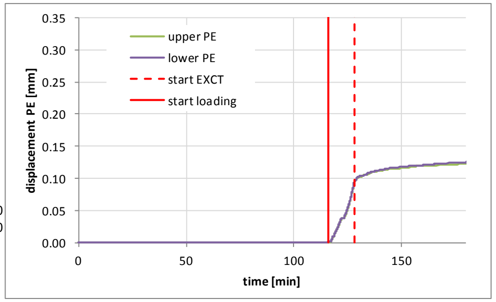


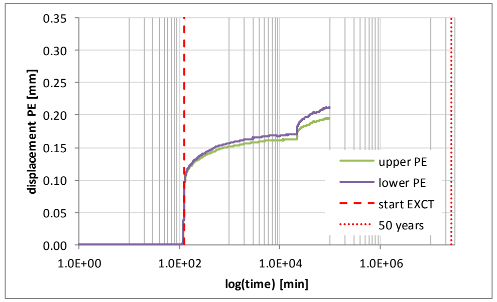


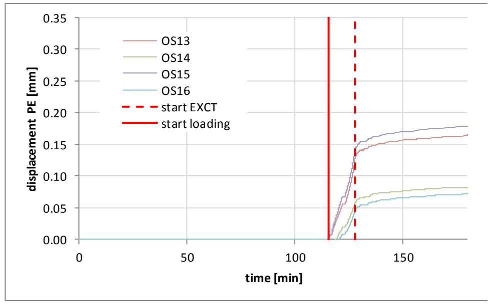


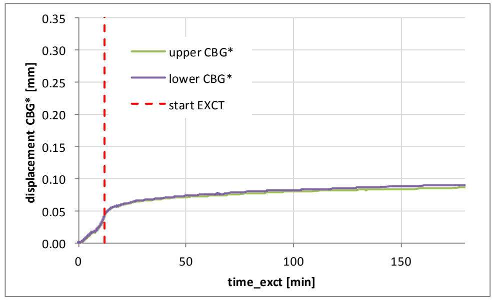


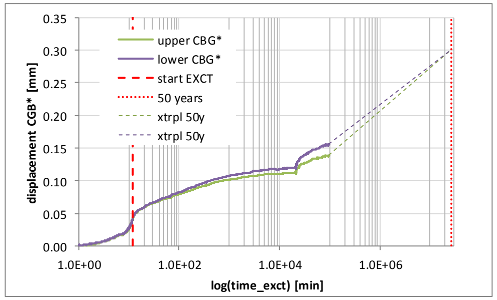












13.5 ASIZN_43 – 8.8

test piece	XCT_ASiZN_44	

start date	21-06-16 8:51	
last record da	22-02-17 10:29	
test running for		
	246.1	days

bolts	HR10.9 (used as if HR 8.8)	
clamping L	48	mm
Fp.c	138	kN

load level based on		
Fxtc	**375**	kN

static tests	creep test	SSWL test

CBG-PE	E	A
correction app	210000	2000
	29	L
0.050	mm	
orrection mode	C1	C2
ASiZN (wp1.2	1.735E-07	9.374E-08

start time loading
65 min
start time EXCT
80 min

loading	[kN]	applied on	days
L0	375	21-jun-16	246.0
L1	0		
L2	0		

Fp.c

1	138
3.00E+07	138

Fxtc

1	375
3.00E+07	375

start loading

65.00099198	0
65.00099198	400

start EXCT

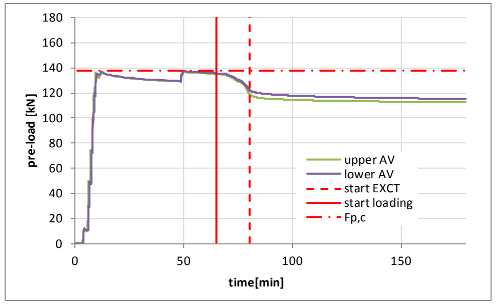
80.17853978	0	15	0
80.17853978	400	15	400

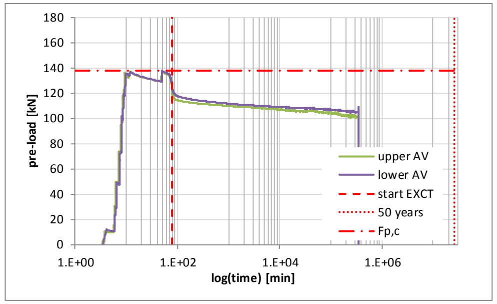
50 years

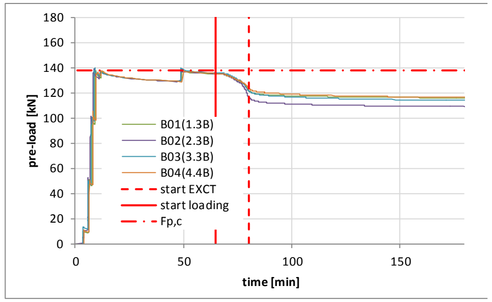
26280000	0
26280000	400

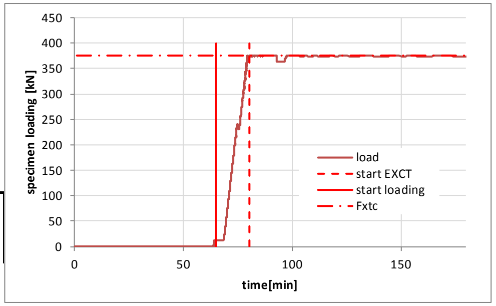
xtrpl 50y

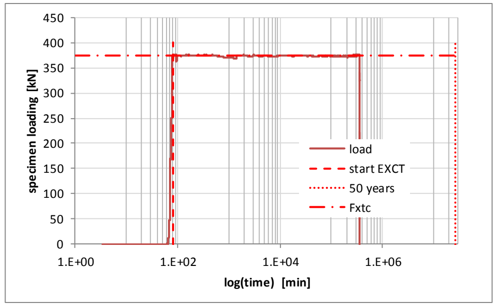
354333	0.082541299
26280000	0.3
354333	4.12988E-05
26280000	0.3

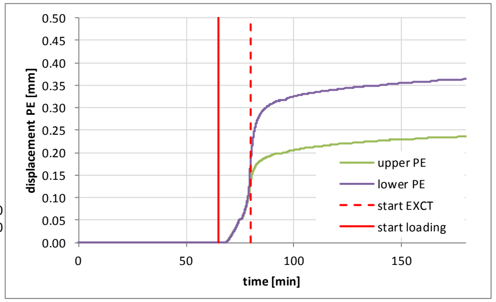


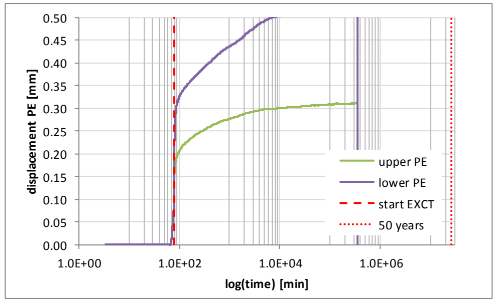


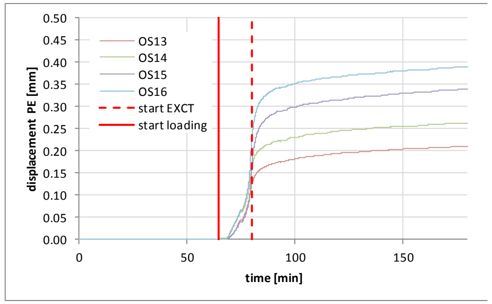


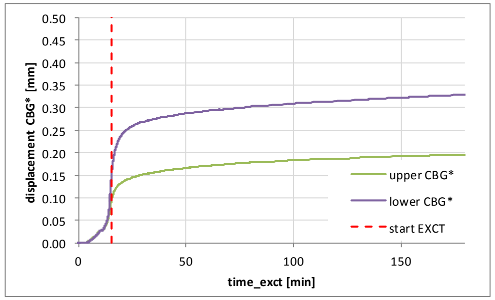


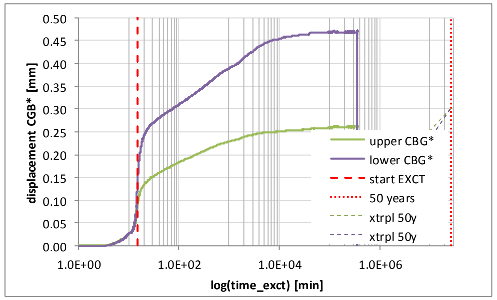








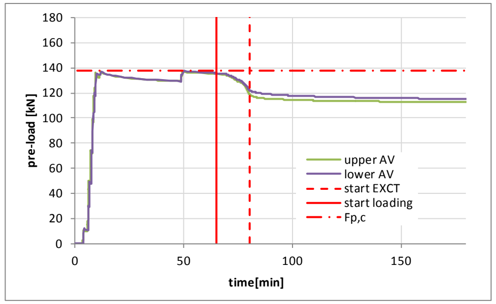


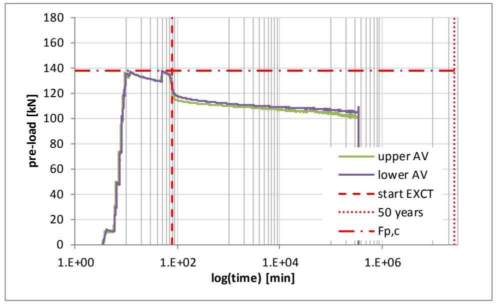


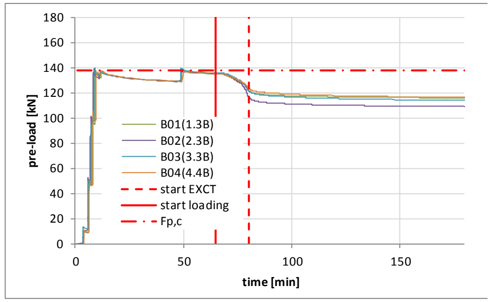
13.6 ASIZN_44 – 8.8

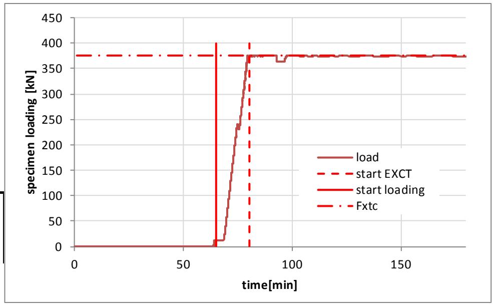
test piece	XCT_ASiZN_44		
start date	21-06-16 8:51		
last record da	22-02-17 10:29		
test running for			
	246.1	days	
bolts	HR10.9 (used as if HR 8.8)		
clamping L	48	mm	
Fp,c	138	kN	
load level based on			
Fxtc	**375**	kN	
static tests	creep test	SSWL test	
CBG-PE	E	A	
correction app	210000	2000	
	29	L	
0.050	mm		
orrection mode	C1	C2	
ASiZN (wp1.2	1.735E-07	9.374E-08	
start time loading			
65	min		
start time EXCT			
80	min		
loading	[kN]	applied on	days
L0	375	21-jun-16	246.0
L1	0		
L2	0		

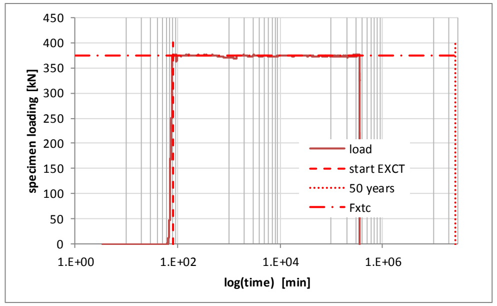
Fp,c			
1	138		
3.00E+07	138		
Fxtc			
1	375		
3.00E+07	375		
start loading			
65.00099198	0		
65.00099198	400		
start EXCT			
80.17853978	0	15	0
80.17853978	400	15	400
50 years			
26280000	0		
26280000	400		
xtrpl 50y			
354333	0.082541299		
26280000	0.3		
354333	4.12988E-05		
26280000	0.3		

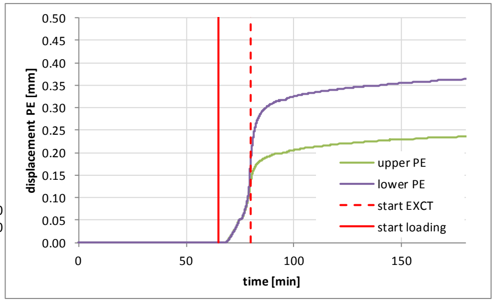


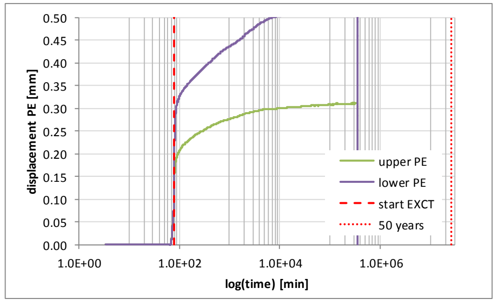


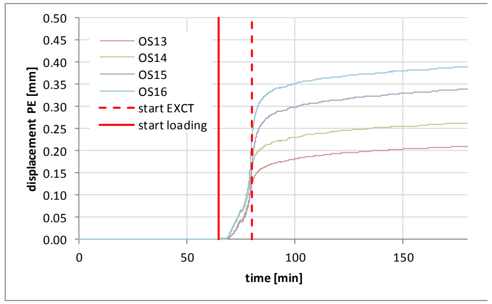


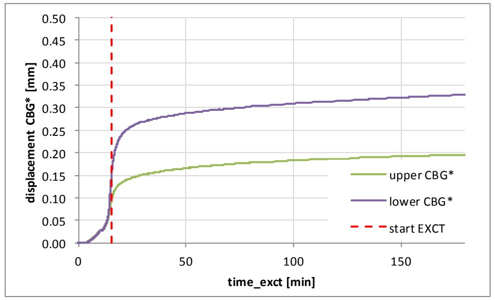


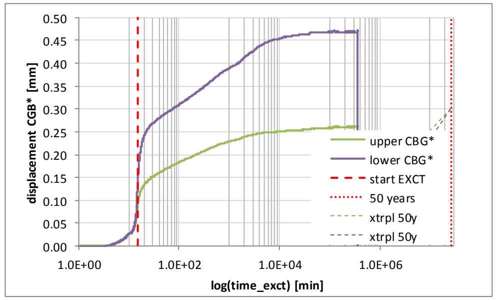












13.7 ASIZN_all - Bolt class 10.9

series ASiZN, HR10.9	1.00E-08	0.3	1.00E-08	172	1.00E-08	470
	50	0.3	50	172	5.00E+01	470

$F_{P,c}$	172 kN	nominal preload level
$F_{s,m}$	470 kN	average short term tests
$F_{fail,SSWLT}$	447 kN	load level before failure SSWL test

75-80-85% — ASiZn_39

Fs,m: 75-80-85% Fs,m
UC: 75-80-85% UC
LC: 75-80-85% LC

FP,c	171	kN	upper					
FP,c	170	kN	lower					long term
	initially			finally	initiallly	finally		slip factor
loading	[kN]	applied on	days	[kN]				μ_{nom}
L0	**353**	7-apr-16	6	**343**	75%	73%		0.50
L1	**380**	13-apr-16	13	**372**	81%	79%		0.54
L2	**400**	26-apr-16	52	**393**	85%	84%		0.57
last record		17-jun-16						

80-85% — ASiZn_40

Fs,m: 80-85% Fs,m
UC: 80-85% UC
LC: 80-85% LC

FP,c	161	kN	upper				
FP,c	162	kN	lower				long term
	initially			finally	initiallly	finally	slip factor
loading	[kN]	applied on	days	[kN]			μ_{nom}
L0	**376**	11-04-16	15	**376**	80%	80%	0.55
L1	**405**	26-04-16	52	**405**	86%	86%	0.59
last record		17-jun-16					

82% — ASiZn_43

HR8.8 bolts loaded to 177 kN
no retightening

Fs,m: 82% Fs,m
UC: 82% UC
LC: 82% LC

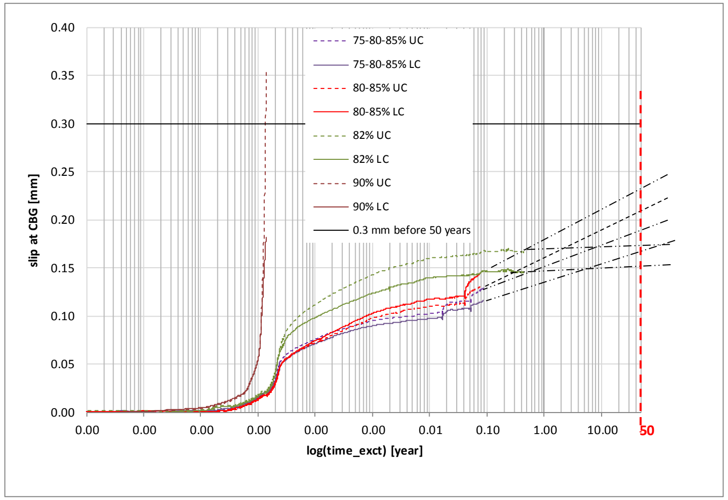
FP,c	163	kN	upper				
FP,c	164	kN	lower				long term
	initially			finally	initiallly	finally	slip factor
loading	[kN]	applied on	days	[kN]			μ_{nom}
L0	**385**	20-06-16	247	**367**	82%	78%	0.53
last record		22-feb-17					

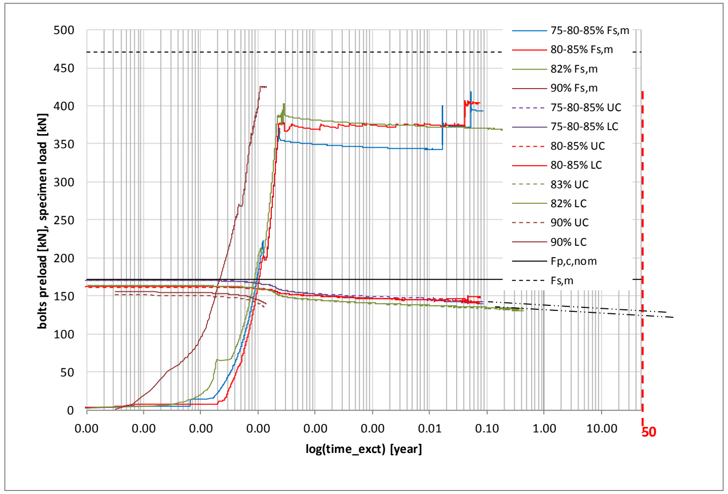
90% — ASiZn_45 test performed at FAGP

Fs,m: 90% Fs,m
UC: 90% UC
LC: 90% LC

FP,c	150	kN	upper				
FP,c	155	kN	lower				long term
	initially			finally	initiallly	finally	slip factor
loading	[kN]	applied on	days	[kN]			μ_{nom}
L0	**425**		0		90%		

immediate failing
low preload (no retightening applied)
extremely high loading speed (2x higher!)





13.8 ASIZN_all - Bolt class 8.8

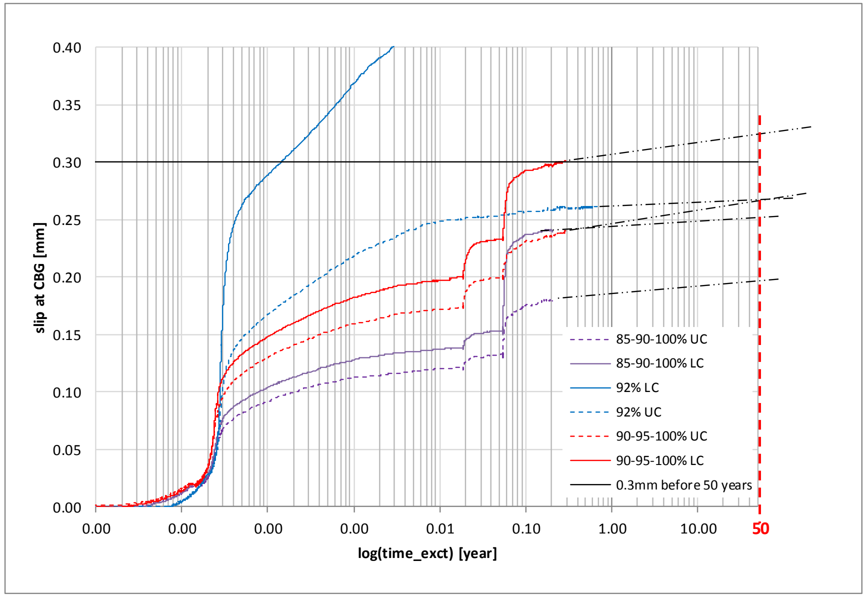
series ASiZN, HR8.8				1.00E-08	0.3	1.00E-06	138	1.00E-06	405
				50	0.3	50	138	50	405

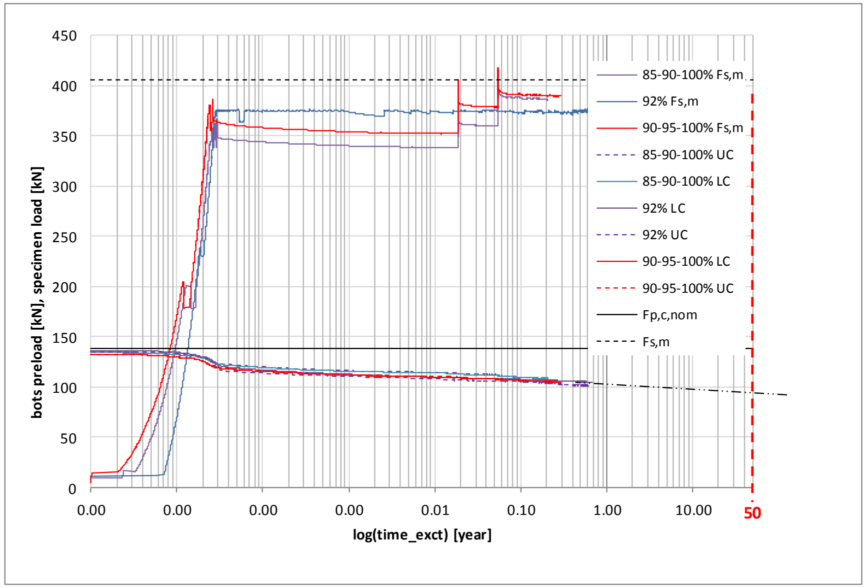
$F_{P,c}$	138	kN	nominal preload level
$F_{s,m}$	405	kN	average short term tests
$F_{fail,SSWLT}$	405	kN	load level before failure SSWL test

85-90-100%				Fs,m	85-90-100% Fs,m		
ASiZn_37				UC	85-90-100% UC		
				LC	85-90-100% LC		
FP,c	134	kN	upper				
FP,c	134	kN	lower				long term
	initially			finally	initiallly	finally	slip factor
loading	[kN]	applied on	days	[kN]			μ_{nom}
L0	**344**	6-apr-16	7	**338**	85%	83%	0.61
L1	**363**	13-apr-16	13	**360**	90%	89%	0.65
L2	**397**	26-apr-16	302	**391**	98%	96%	0.71
last record		22-feb-17					

90-95-100%				Fs,m	90-95-100% Fs,m		
ASiZn_38				UC	90-95-100% UC		
				LC	90-95-100% LC		
FP,c	132	kN	upper				
FP,c	133	kN	lower				long term
	initially			finally	initiallly	finally	slip factor
loading	[kN]	applied on	days	[kN]			μ_{init}
L0	**365**	6-apr-16	7	**352**	90%	87%	0.64
L1	**385**	13-apr-16	13	**378**	95%	93%	0.68
L2	**398**	26-apr-16	302	**392**	98%	97%	0.71
last record		22-feb-17					

92%				Fs,m	92% Fs,m		
ASiZn_44				UC	92% UC		
				LC	92% LC		
FP,c	132	kN	upper				
FP,c	133	kN	lower				long term
	initially			finally	initiallly	finally	slip factor
loading	[kN]	applied on	days	[kN]			μ_{init}
L0	**375**	21-jun-16	246	**375**	92%	92%	0.68
L1							
L2							
last record		22-feb-17					





14 Annex L - Test results extended creep tests on ZnSM specimens

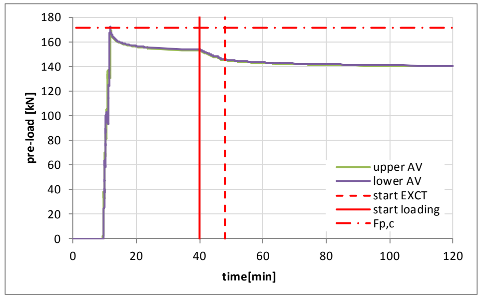
Average bolt preload Average preload vs time on linear scale during first hours. Preparation phase, average initial preload losses, effect of retightening, effect of application external load preload.	**Average bolt preload** Average preload vs time on log scale over full test period. Preparation phase, average initial preload losses, effect of retightening, effect of application external load preload.	**Individual bolt preload** Preload per bolt vs time on linear scale during first hours. Preparation phase, average initial preload losses, effect of retightening, effect of application external load preload.
External load Application of initial external load vs. time on linear scale. Magnitude of initial external load Indication of speed of load application (in 10 – 15 min)	**External load** External load vs. time on log scale over full test period. Overshoot in / loss of external load Increase of external load during test period	
Slip measurement at PE position Slip at PE vs time on linear scale during first hours Slip at PE during application of external load. Average slip per connection	**Slip measurement at PE position** Slip at PE vs. time on log scale over full test period.	**Slip measurement at PE position** Slip at PE vs time on linear scale during first hours Slip at PE during application of external load. Slip per LVDT
Effective slip at CBG Calculated slip at CBG position vs time on linear scale during first hours. Model used to convert from PE to CBG. Graph shifted in time. t=0 : start of application of external load	**Effective slip at CBG** Calculated slip at CBG position vs time on log scale over full test period. **This graph is used for the evaluation of the extended creep test.** **The dotted lines connect the last slip measurement and 0.3 mm at 50 years. The tangent of the dotted lines determine if the load level is accepted.**	

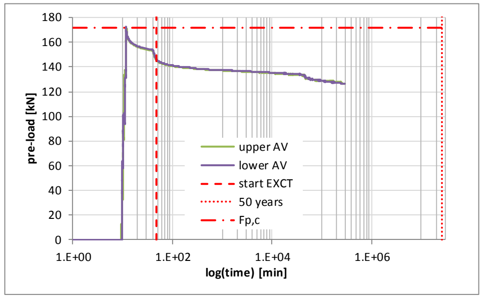
14.1 ZnSM_19 – 10.9

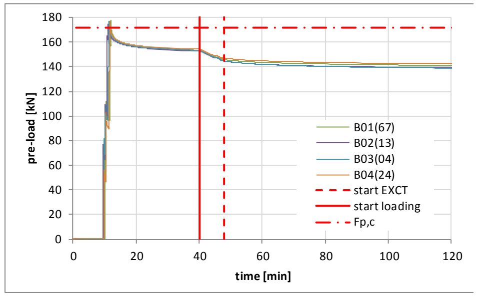
test piece	XCT_SM_19	
start date	9-07-15 11:04	
last record date	1-02-16 11:17	
test running for		
	206.0	days
bolts	HV10.9	
clamping L	52	mm
$F_{p,c}$	172	kN
load level based on		
SSWLT	no sswlt available	
F_{xtc}	380	kN
static tests	slip PE-CBG at F_{xct}	
	0.050	
CBG-PE	E	A
correction applie	210000	2000
	29	L
0.059	mm	
correction model	C1	C2
SM (wp1.2 &wp:	1.945E-07	1.356E-05
start time loading		
40	min	
start time EXCT		
48	min	

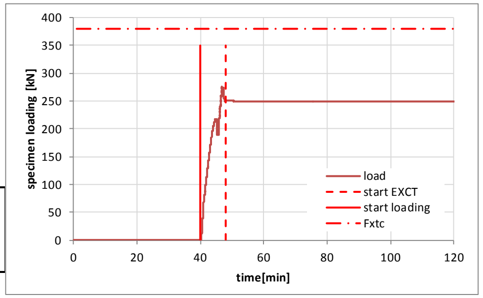
loading	[kN]	applied on	days
L0	275	9-07-15 11:51	32.1
L1	336	10-08-15 14:47	10.0
L2	351	20-08-15 15:18	125.1
L3	380	23-12-15 16:53	39.8

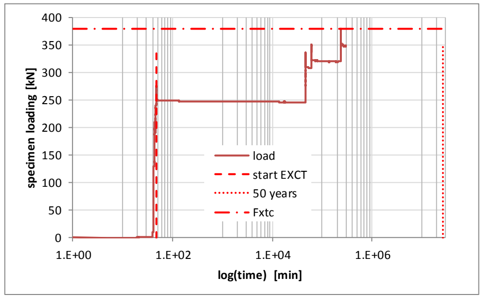
$F_{p,c}$			
1	172		
3.00E+07	172		
F_{xtc}			
1	380		
3.00E+07	380		
start loading			
40	0		
40	350		
start EXCT			
48	0	8	0
48	350	8	350
50 years			
26280000	0		
26280000	350		
xtrpl 50y			
296663	0.219574614		
26280000	0.3		
296663	0.172074614		
26280000	0.3		

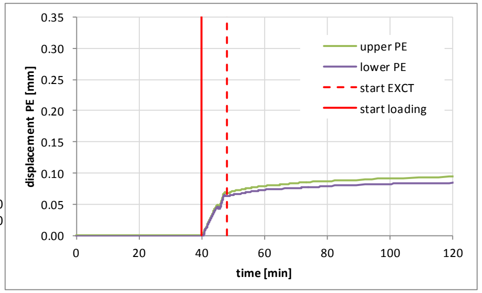


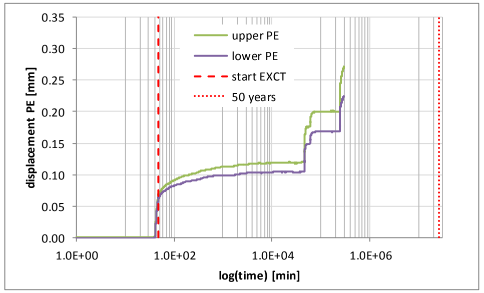


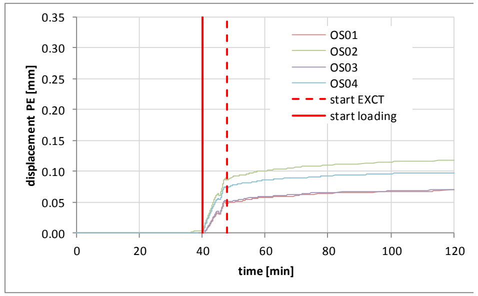


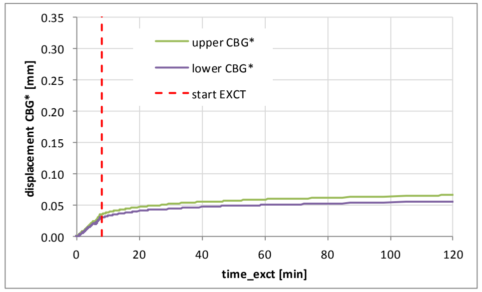


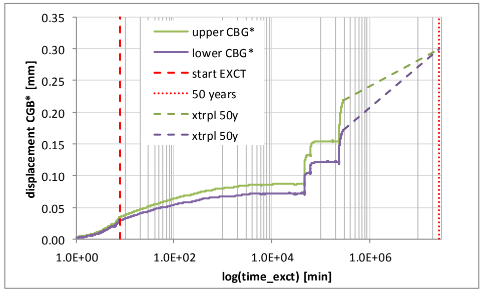












14.2 ZnSM_20 – 10.9

test piece	XCT_SM_20

start date	9-jul-15	
last record da	1-feb-16	
test running for		
	207	days

bolts	HV10.9	
clamping L	152	mm
Fp,c	172	kN

load level based on		
SSWLT	no sswlt available	
Fxtc	350	kN

static tests		

CBG-PE	E	A
correction app	210000	2000
	29	L
0.053	mm	
orrection mode	C1	C2
SM (wp1.2 &wp	1.945E-07	1.356E-05

start time loading

58	min

start time EXCT

64	min

loading	[kN]	applied on	days
L0	275	9-jul-15	32
L1	336	10-aug-15	10
L2	352	20-aug-15	125
L3	379	23-dec-15	40

Fp,c

1	172
3.00E+07	172

Fxtc

1	350
3.00E+07	350

start loading

58	0
58	350

start EXCT

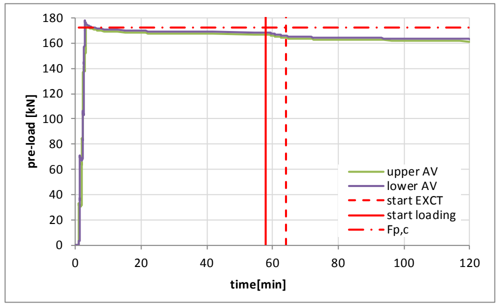
64	0	6	0
64	350	6	350

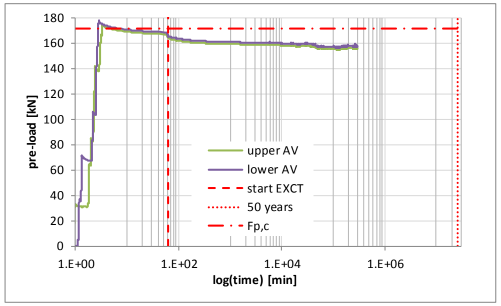
50 years

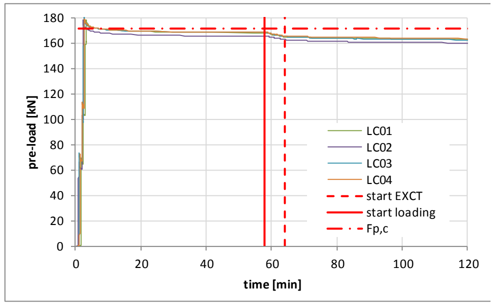
26280000	0
26280000	350

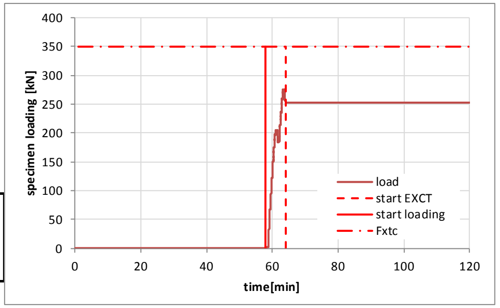
xtrpl 50y

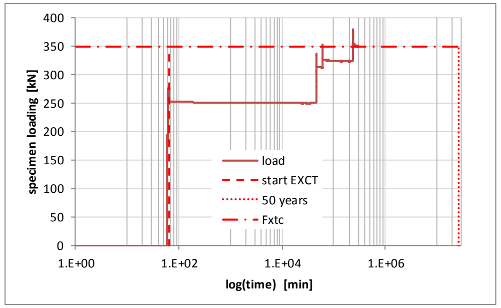
297819	0.19562683
26280000	0.3
297819	0.2019315
26280000	0.3

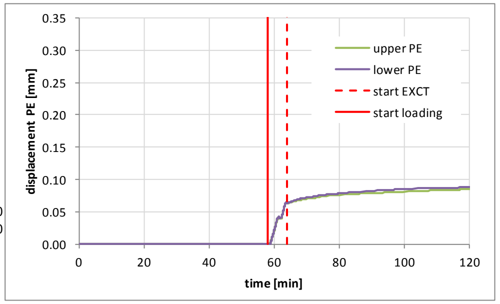


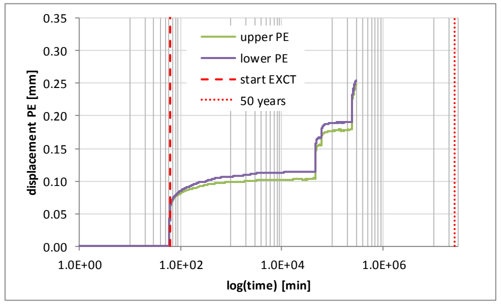


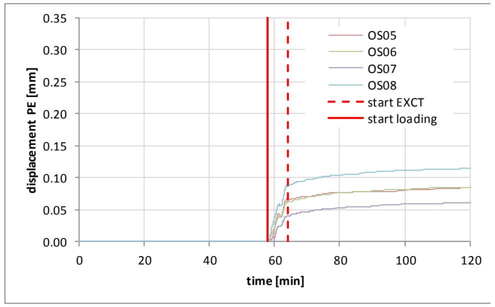


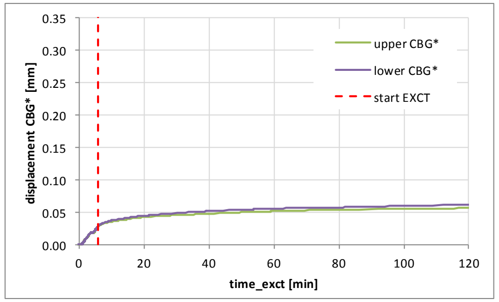


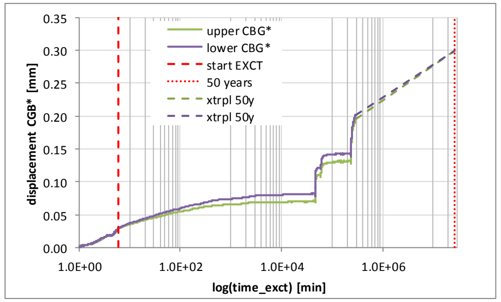












14.3 ZnSM_30 – 8.8

test piece	XCT_SM_30	
start date	4-02-16 11:05	
last record date	7-03-16 15:14	
test running for		
	32.2	days
bolts	HR8.8	
clamping L	52	mm
$F_{p,c}$	138	kN
load level based on		
SSWLT	ZN_SM_29	
F_{xtc}	329	kN
static tests	creep test	SSWL test
ZN_SM_23	Siroco_160203_SM_29 SSWLT	
ZN_SM_25		
ZN_SM_26		
ZN_SM_27		
CBG-PE	E	A
correction applie	210000	2000
	29	L
0.048	mm	
correction model	C1	C2
SM (wp1.2 &wp2	1.945E-07	1.356E-05
start time loading		
88	min	
start time EXCT		
104	min	

$F_{p,c}$

1	138		
3.00E+07	138		

F_{xtc}

1	329		
3.00E+07	329		

start loading

88	0		
88	350		

start EXCT

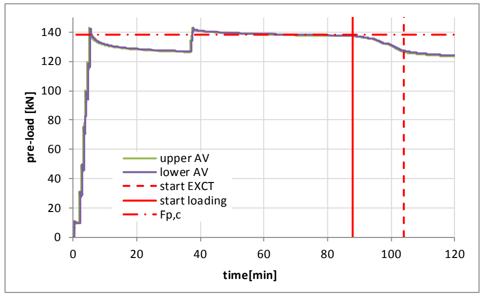
104	0	16	0
104	350	16	350

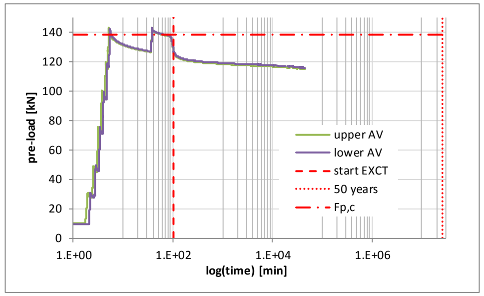
50 years

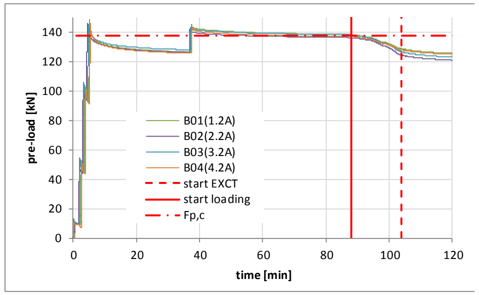
26280000	0		
26280000	350		

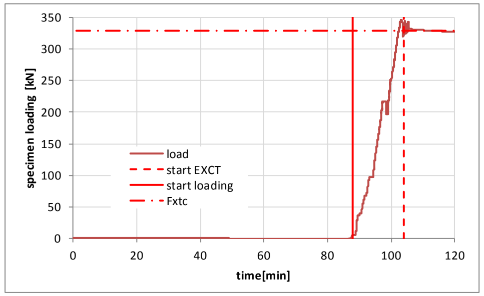
xtrpl 50y

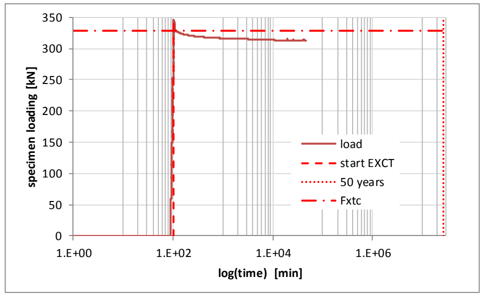
46138	0.266981048
26280000	0.3
46138	0.211481048
26280000	0.3

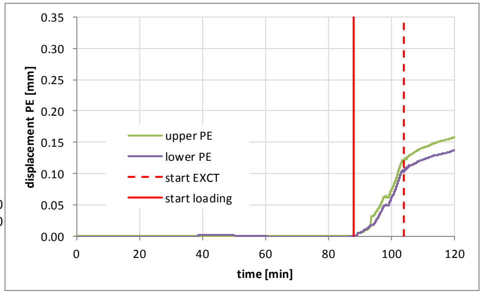


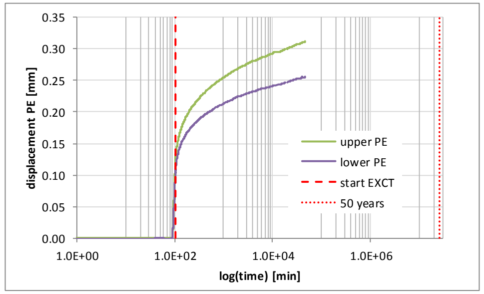


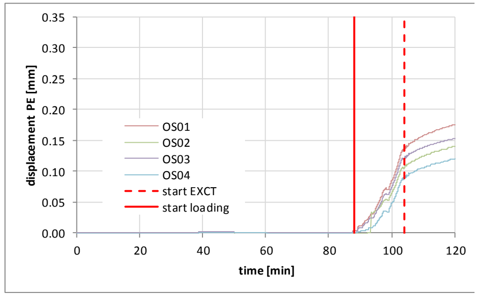


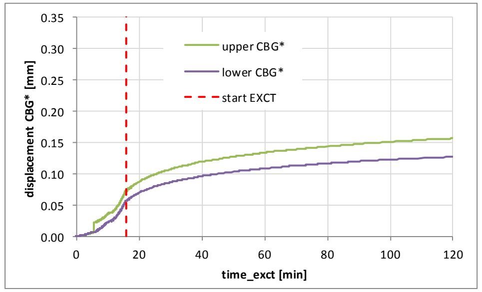


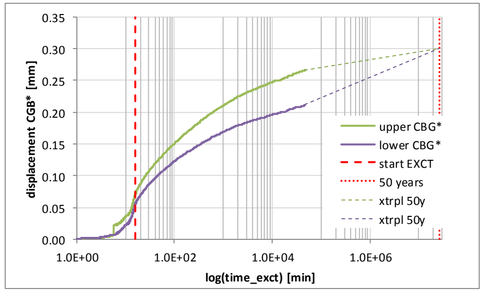












14.4 ZnSM_31 – 8.8

test piece	XCT_SM_31	
start date	4-02-16 13:32	
last record da	7-03-16 15:14 finished	
test running for		
	32.1	days
bolts	HR8.8	
clamping L	52	mm
$F_{p,c}$	138	kN
load level based on		
SSWLT	ZN_SM_29	
F_{xtc}	329	kN
static tests	creep test	SSWL test
ZM_SM_23		
ZM_SM_25		
ZM_SM_26		
ZM_SM_27		
CBG-PE	E	A
correction app	210000	2000
	29	L
0.048	mm	
orrection mode	C1	C2
SM (wp1.2 &w	1.945E-07	1.356E-05
start time loading		
86	min	
start time EXCT		
99	min	

$F_{p,c}$

1	138		
3.00E+07	138		

F_{xtc}

1	329		
3.00E+07	329		

start loading

86	0		
86	350		

start EXCT

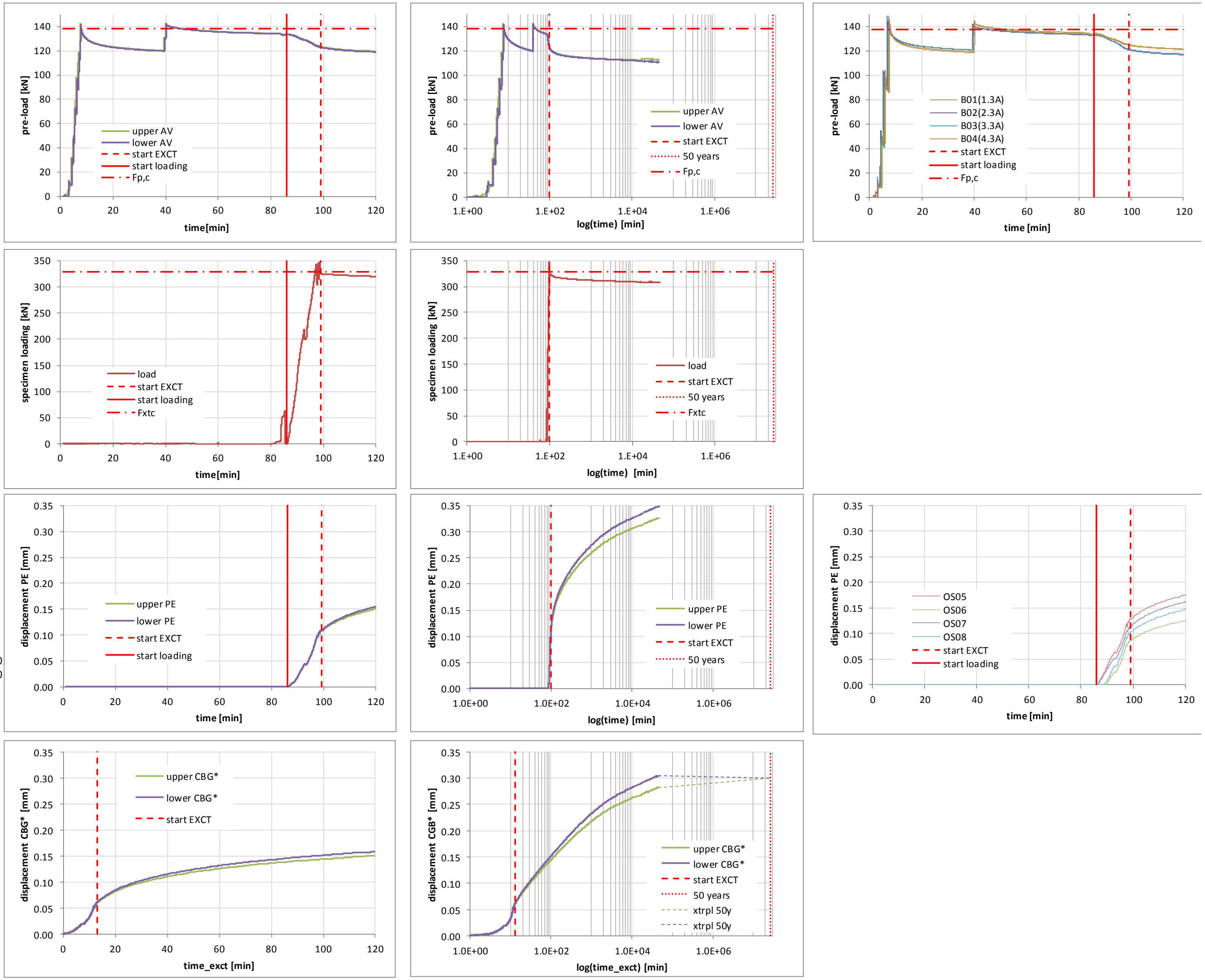
99.13272045	0	13	0
99.13272045	350	13	350

50 years

26280000	0		
26280000	350		

xtrpl 50y

46062	0.282032673
26280000	0.3
46062	0.304532673
26280000	0.3



14.5 ZnSM_37 – 10.9

test piece	XCT_SM_37	

start date	18-02-16 9:42	
last record da	3-03-16 14:45 finished	
test running for		
	14.2	days

bolts	HR10.9	
clamping L	52	mm
$F_{p,c}$	172	kN

load level based on		
SSWLT	ZN_SM_29	
F_{xtc}	376	kN

static tests	creep test	
ZM_SM_32		
ZM_SM_33		
ZM_SM_34		
ZM_SM_36		
CBG-PE	E	A
correction app	210000	2000
	29	L
0.059	mm	
orrection mode	C1	C2
SM (wp1.2 &wj	1.945E-07	1.356E-05

start time loading

108	min

start time EXCT

126	min

$F_{p,c}$

1	172
3.00E+07	172

F_{xtc}

1	376
3.00E+07	376

start loading

108	0
108	400

start EXCT

126	0	18	0
126	400	18	400

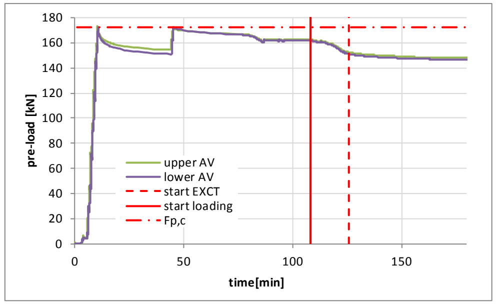
50 years

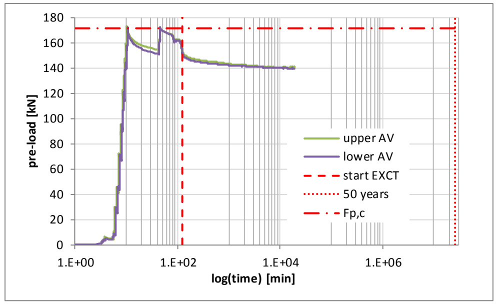
26280000	0
26280000	400

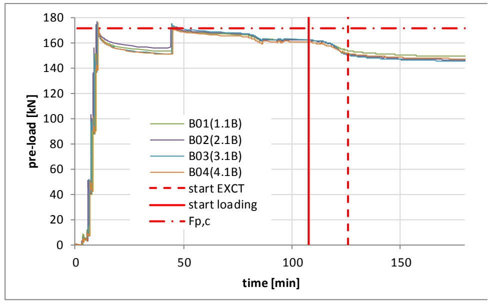
xtrpl 50y

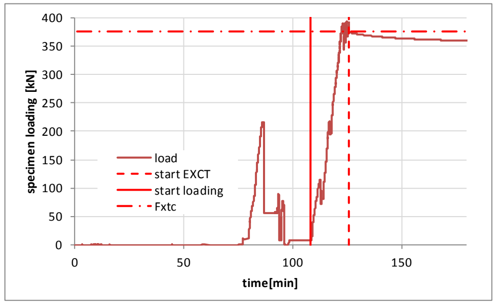
18959	0.80188781
26280000	0.3

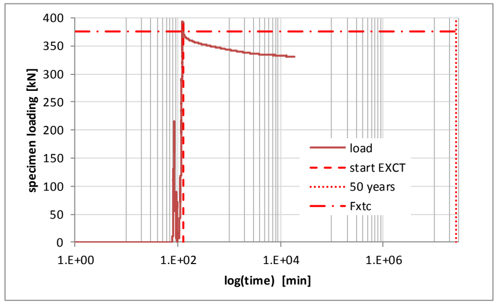
18959	0.64988781
26280000	0.3

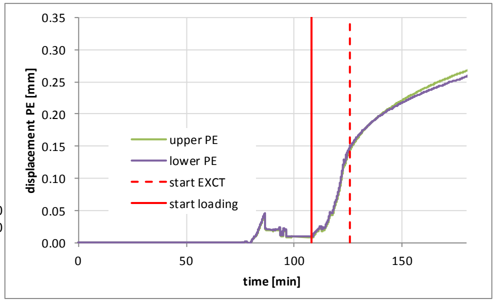


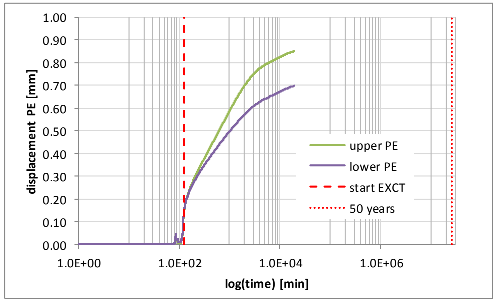


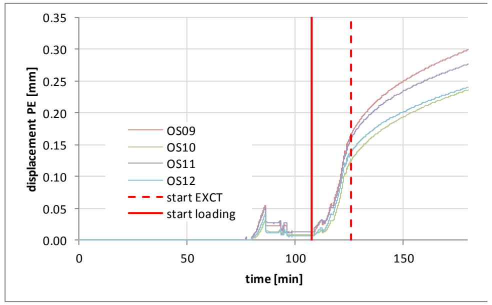


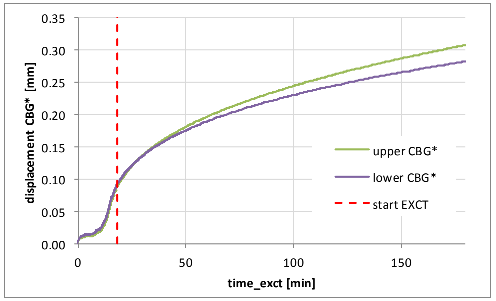


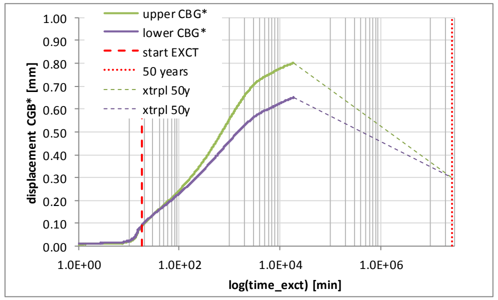












14.6 ZnSM_40 – 10.9

test piece	XCT_SM_40	

start date	2-03-16 15:37	
last record da	5-04-16 15:15	
test running for		
	34.0	days

bolts	HR10.9	
clamping L	52	mm
$F_{p,c}$	172	kN

load level based on		
SSWLT	ZN_SM_35	
F_{xtc}	340	kN

static tests	creep test	
ZM_SM_32		
ZM_SM_33		
ZM_SM_34		
ZM_SM_36		
CBG-PE	E	A
correction app	210000	2000
	29	L
0.051	mm	
orrection mode	C1	C2
SM (wp1.2 &wp	1.945E-07	1.356E-05
start time loading		
1296	min	
start time EXCT		
1311	min	

$F_{p,c}$

1	172
3.00E+07	172

F_{xtc}

1	340
3.00E+07	340

start loading

1295.680825	0
1295.680825	400

start EXCT

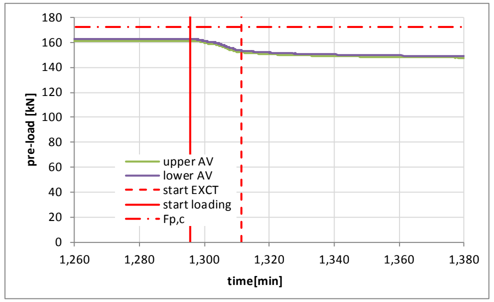
1311.457225	0	16	0
1311.457225	400	16	400

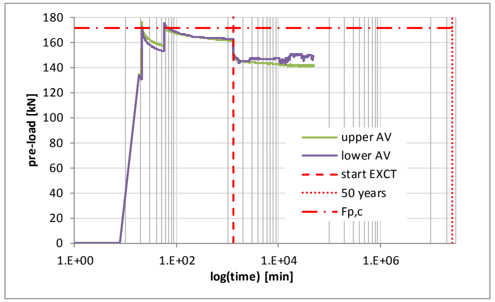
50 years

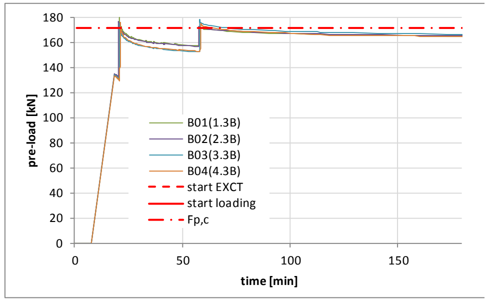
26280000	0
26280000	400

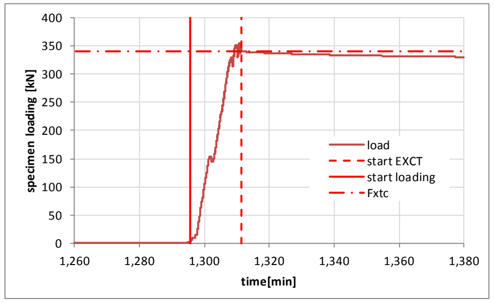
xtrpl 50y

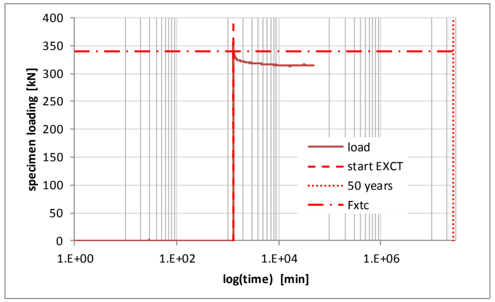
47432	0.3151772
26280000	0.3
47432	0.2406772
26280000	0.3

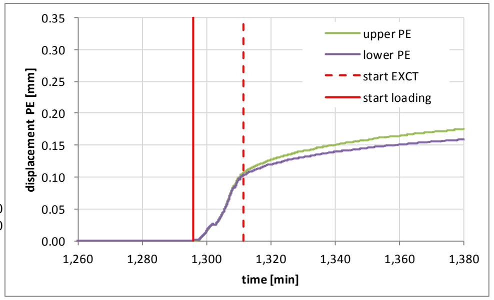


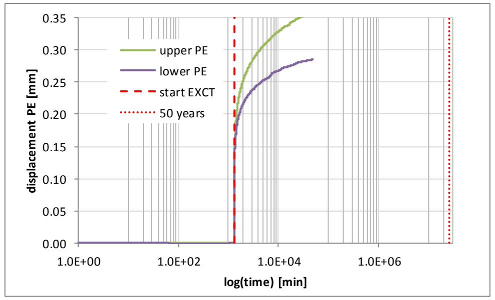


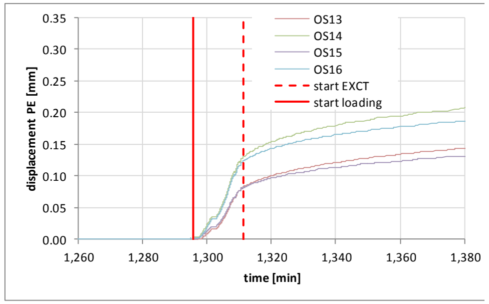


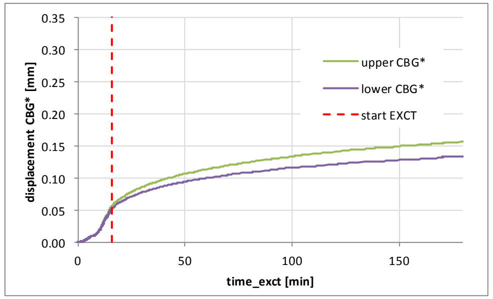


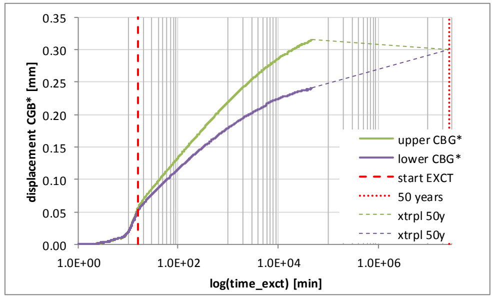












14.7 ZnSM_41 – 10.9

test piece	XCT_SM_41	

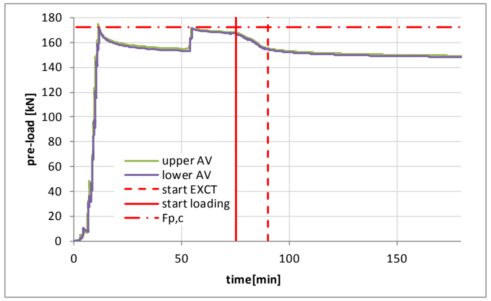
start date	3-03-16 14:54	
last record da	21-03-16 10:30	
test running for		
	17.8	days

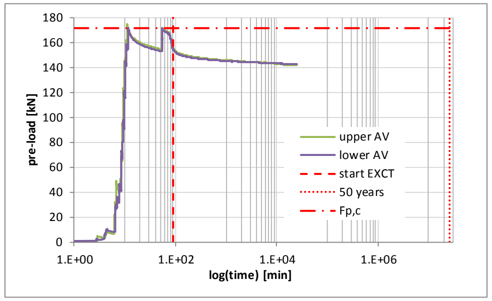
bolts	HR10.9	
clamping L	52	mm
$F_{p,c}$	172	kN

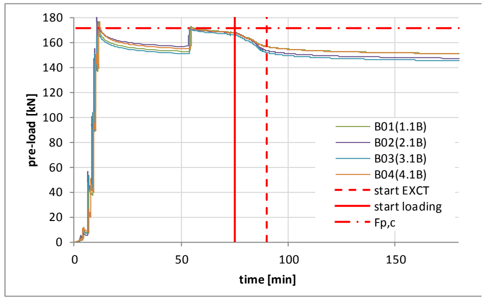
load level based on		
SSWLT	ZN_SM_35	
F_{xtc}	**340**	kN

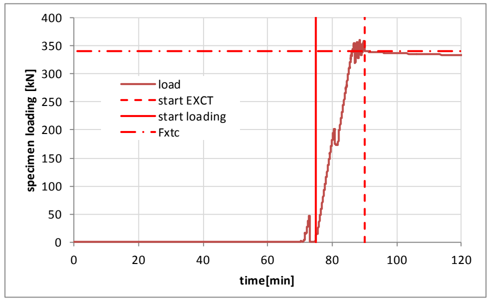
static tests	creep test	SSWL test
ZM_SM_32		
ZM_SM_33		
ZM_SM_34		
ZM_SM_36		
CBG-PE	E	A
correction app	210000	2000
	29	L
0.051	mm	
orrection mode	C1	C2
SM (wp1.2 &w	1.945E-07	1.356E-05

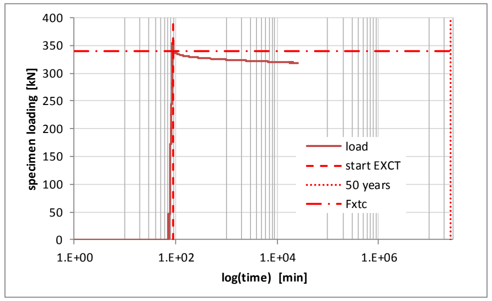
start time loading	
75	min
start time EXCT	
90	min





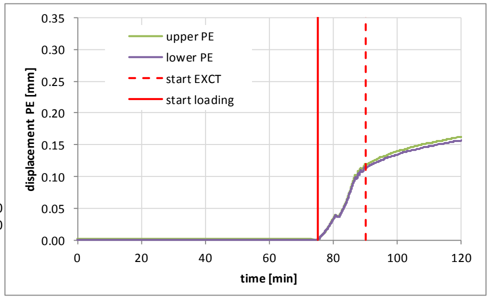


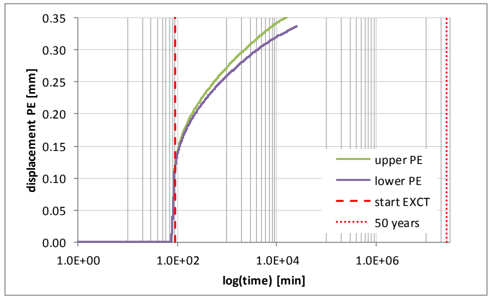


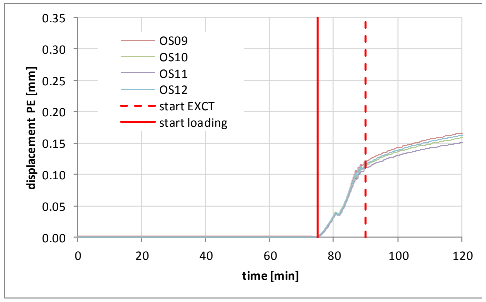


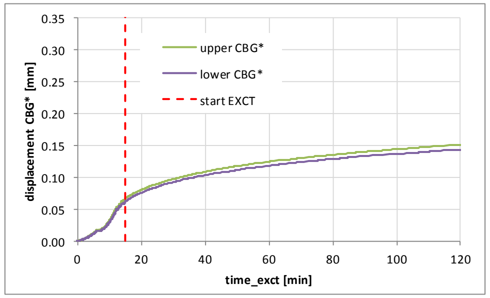
$F_{p,c}$			
1	172		
3.00E+07	172		
F_{xtc}			
1	340		
3.00E+07	340		
start loading			
75.03332275	0		
75.03332275	400		
start EXCT			
90.01435518	0	15	0
90.01435518	400	15	400
50 years			
26280000	0		
26280000	400		

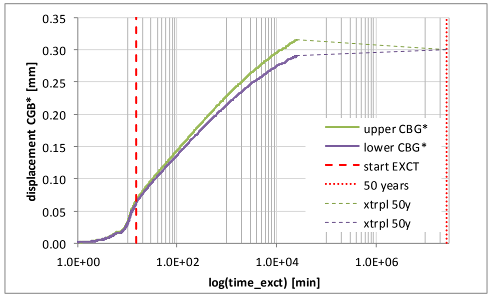
xtrpl 50y	
25580	0.315422441
26280000	0.3
25580	0.290422441
26280000	0.3











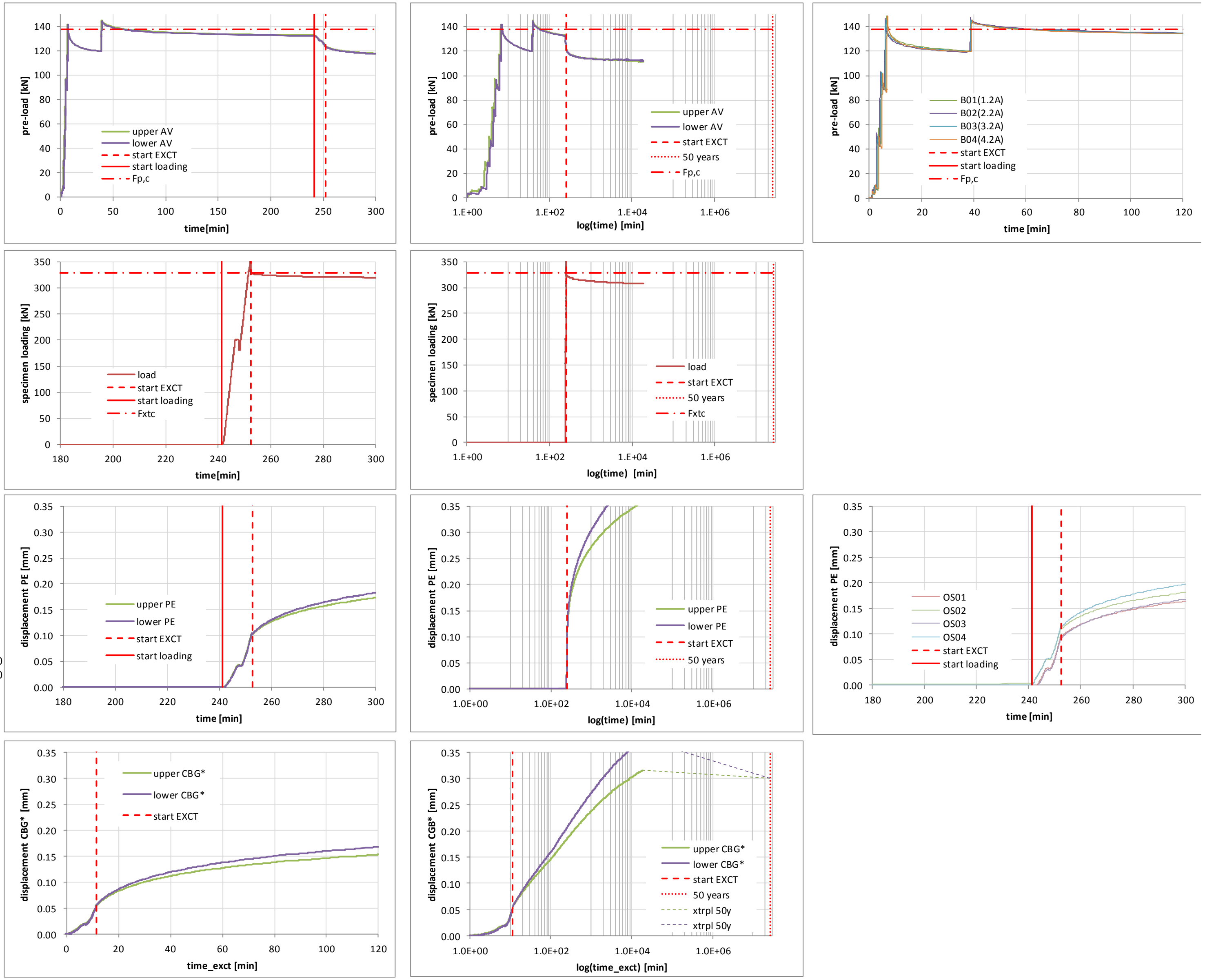
14.8 ZnSM_42 – 8.8

test piece	XCT_SM_42	
start date	8-03-16 9:22	
last record da	21-03-16 10:30	
test running for		
	13.0	days
bolts	HR8.8	
clamping L	52	mm
$F_{p,c}$	138	kN
load level based on		
SSWLT	ZN_SM_29	
F_{xtc}	329	kN

static tests	slip PE-CBG at F_{xct}	
ZM_SM_23	0.052	0.050
ZM_SM_25	0.057	0.064
ZM_SM_26	0.063	0.056
ZM_SM_27	0.060	0.053
CBG-PE	E	A
correction app	210000	2000
	29	L
0.048	mm	
orrection mode	C1	C2
SM (wp1.2 &w	1.945E-07	1.356E-05

start time loading
241 min
start time EXCT
253 min

$F_{p,c}$			
1	138		
3.00E+07	138		
F_{xtc}			
1	329		
3.00E+07	329		
start loading			
241.1999896	0		
241.1999896	350		
start EXCT			
252.5517282	0	11	0
252.5517282	350	11	350
50 years			
26280000	0		
26280000	350		
xtrpl 50y			
18546	0.315149173		
26280000	0.3		
18546	0.374649173		
26280000	0.3		

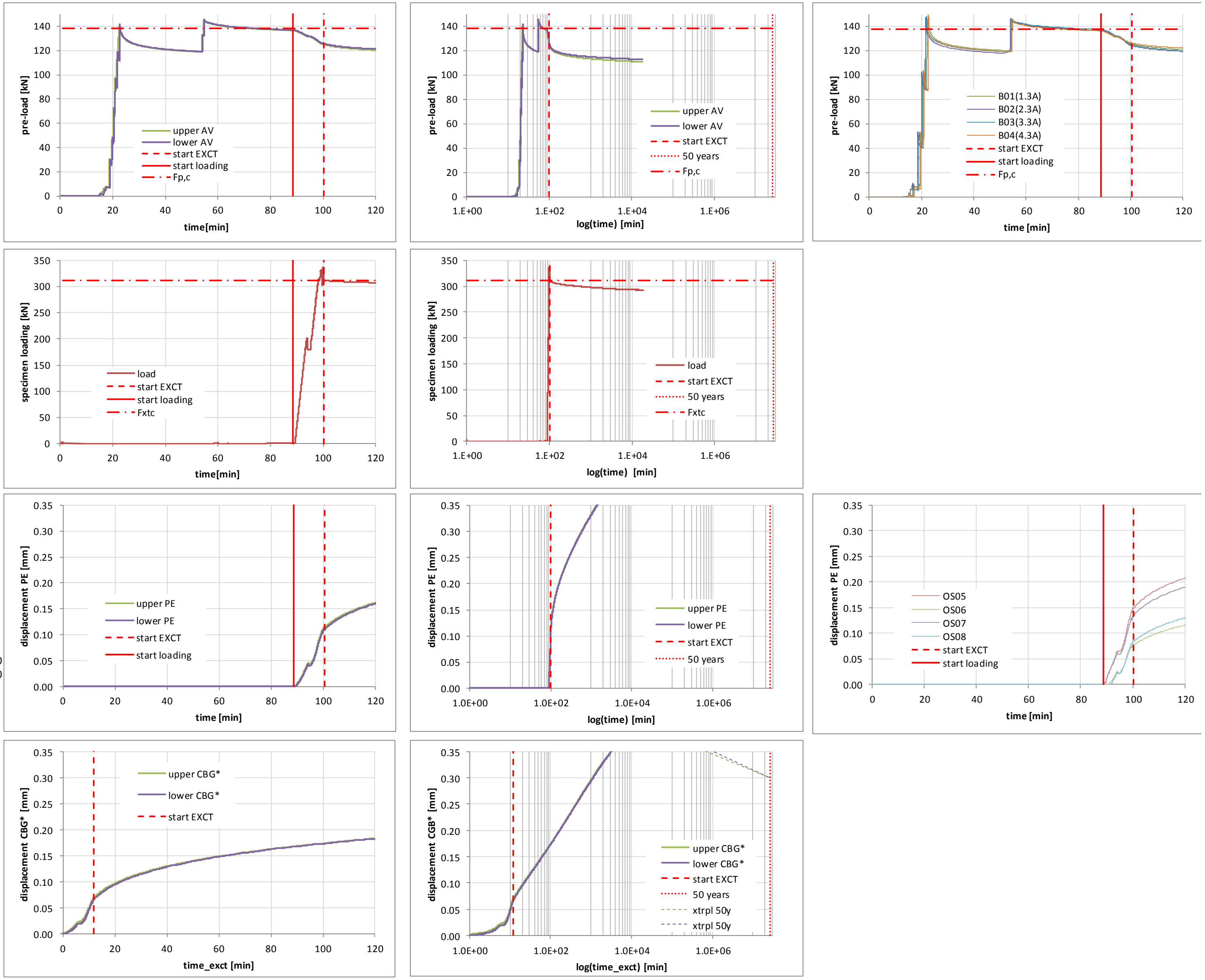


14.9 ZnSM_43 – 8.8

test piece	XCT_SM_43	
start date	8-03-16 13:49	
last record da	21-03-16 10:30	
test running for		
	12.9	days
bolts	HR8.8	
clamping L	52	mm
$F_{p,c}$	138	kN
load level based on		
SSWLT	ZN_SM_29	
F_{xtc}	312	kN

static tests	creep tets	SSWL test
ZM_SM_23		
ZM_SM_25		
ZM_SM_26		
ZM_SM_27		
CBG-PE	E	A
correction app	210000	2000
	29	L
0.045	mm	
orrection mode	C1	C2
SM (wp1.2 &wp	1.945E-07	1.356E-05
start time loading		
89	min	
start time EXCT		
100	min	

$F_{p,c}$			
1	138		
3.00E+07	138		
F_{xtc}			
1	312		
3.00E+07	312		
start loading			
88.65765655	0		
88.65765655	350		
start EXCT			
100.4025744	0	12	0
100.4025744	350	12	350
50 years			
26280000	0		
26280000	350		
xtrpl 50y			
18432	0.401632241		
26280000	0.3		
18432	0.413632241		
26280000	0.3		



14.10 ZnSM_44 – 8.8

test piece	XCT_SM_44

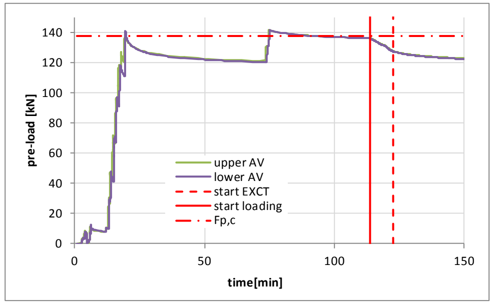
start date	24-03-16 9:03	
last record da	5-04-16 15:15	
test running for		
	12.3	days

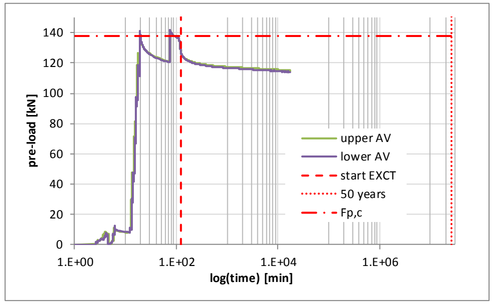
bolts	HR8.8	
clamping L	52	mm
$F_{p,c}$	138	kN

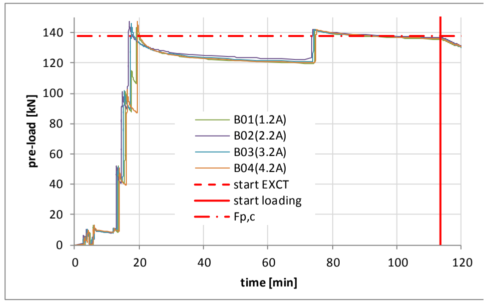
load level based on		
SSWLT	ZN_SM_29	
F_{xtc}	290	kN

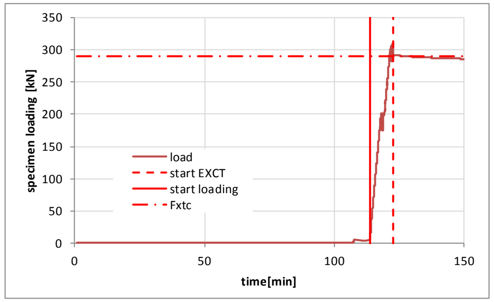
static tests	slip PE-CBG at F_{xct}	
ZM_SM_23		
ZM_SM_25		
ZM_SM_26		
ZM_SM_27		
CBG-PE	E	A
correction app	210000	2000
	29	L
0.040	mm	
orrection mode	C1	C2
SM (wp1.2 &w	1.945E-07	1.356E-05
start time loading		
114	min	
start time EXCT		
123	min	

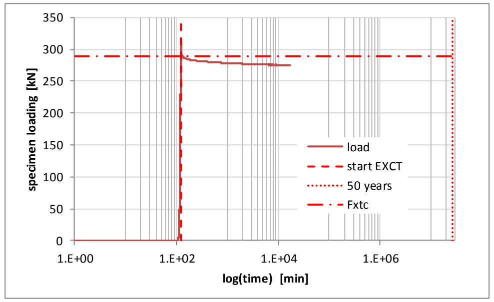
$F_{p,c}$			
1	138		
3.00E+07	138		
F_{xtc}			
1	290		
3.00E+07	290		
start loading			
113.6572431	0		
113.6572431	350		
start EXCT			
122.739412	0	9	0
122.739412	350	9	350
50 years			
26280000	0		
26280000	350		
xtrpl 50y			
17352	0.263460006		
26280000	0.3		
17352	0.232460006		
26280000	0.3		

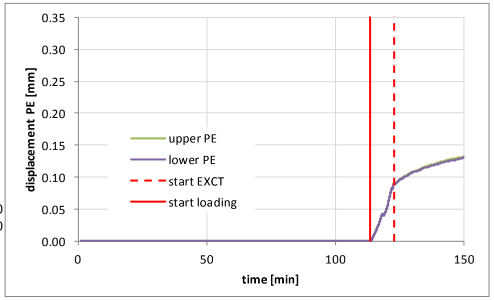


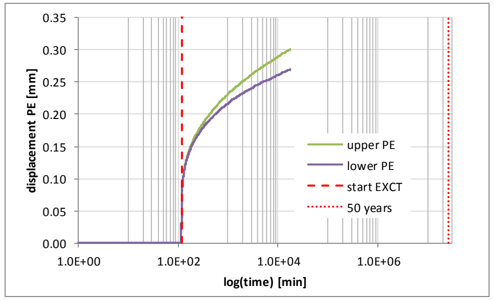


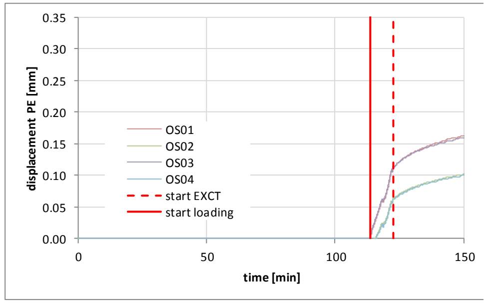


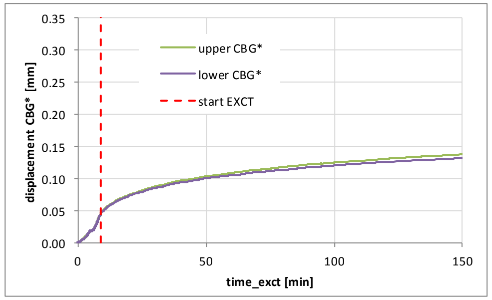


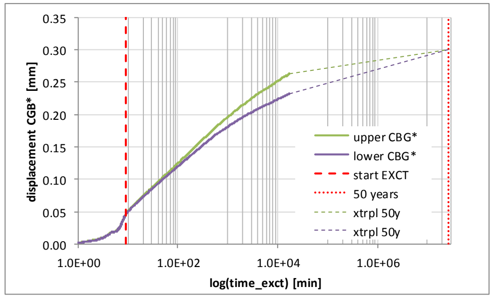












14.11 ZnSM_45 – 8.8

test piece	XCT_SM_45	

start date	24-03-16 11:22	
last record da	5-04-16 15:15	
test running for		
	12.2	days

bolts	HR8.8	
clamping L	52	mm
$F_{p,c}$	138	kN

load level based on		
SSWLT	ZN_SM_29	
F_{xtc}	280	kN

static tests	creep test	SSWL test
ZM_SM_23		
ZM_SM_25		
ZM_SM_26		
ZM_SM_27		
CBG-PE	E	A
correction app	210000	2000
	29	L
0.038	mm	
orrection mode	C1	C2
SM (wp1.2 &w	1.945E-07	1.356E-05

start time loading
78 min
start time EXCT
88 min

$F_{p,c}$

1	138		
3.00E+07	138		

F_{xtc}

1	280		
3.00E+07	280		

start loading

77.67212505	0		
77.67212505	350		

start EXCT

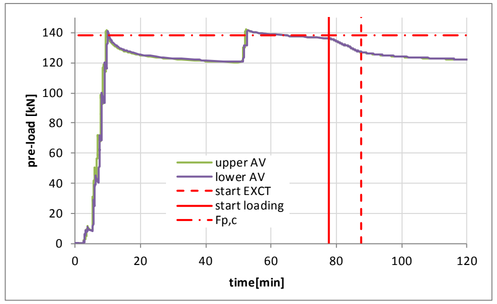
87.65898028	0	10	0
87.65898028	350	10	350

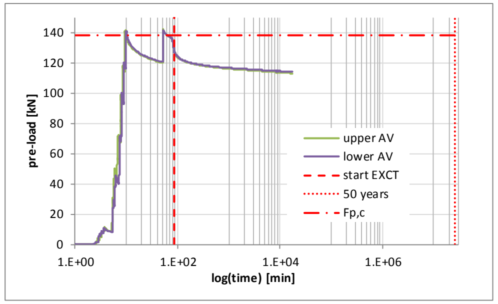
50 years

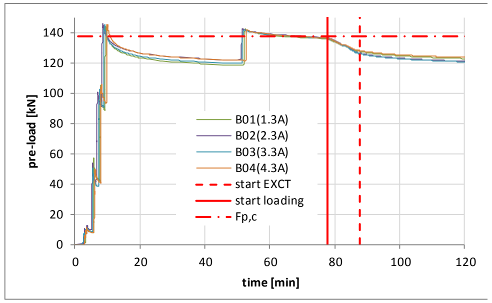
26280000	0
26280000	350

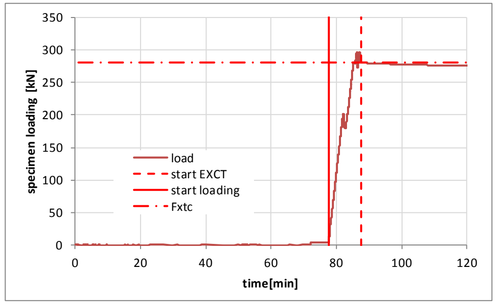
xtrpl 50y

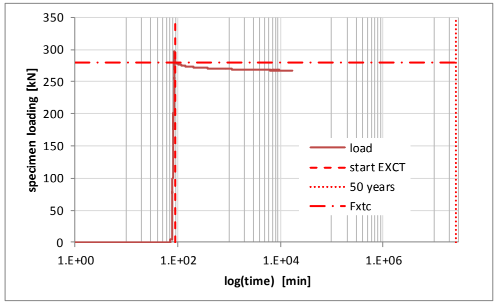
17251	0.184912564
26280000	0.3
17251	0.189412564
26280000	0.3

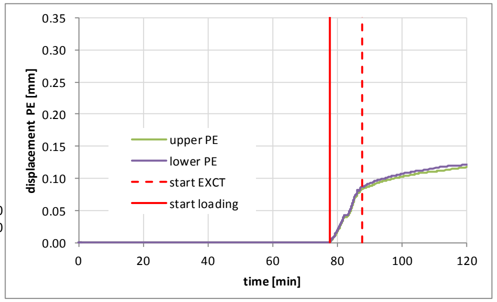


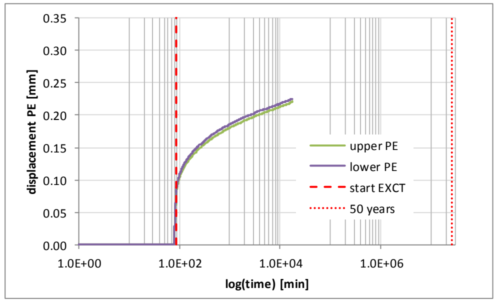


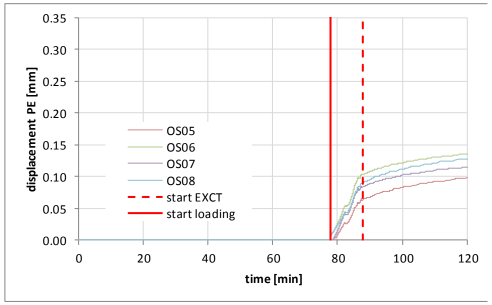


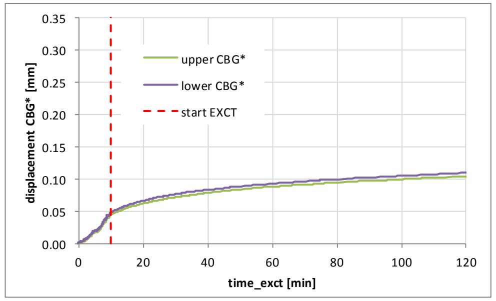


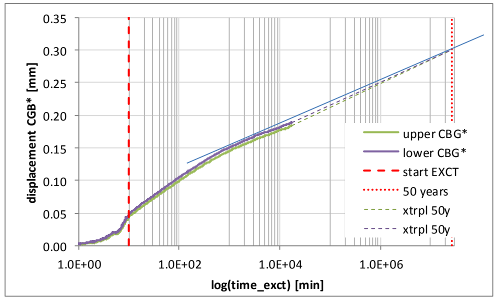












14.12 ZnSM_46 – 8.8

test piece	XCT_SM_46	

start date	24-03-16 13:12	
last record da	5-04-16 15:15	
test running for		
	12.1	days

bolts	HR10.9	
clamping L	52	mm
$F_{p,c}$	138	kN

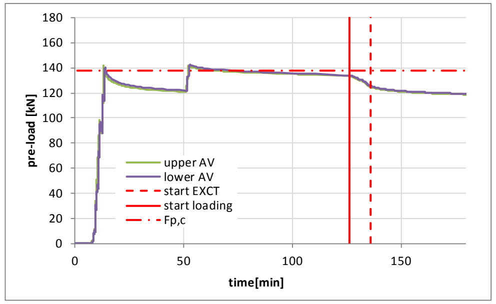
load level based on		
SSWLT	ZN_SM_35	
F_{xtc}	**325**	kN

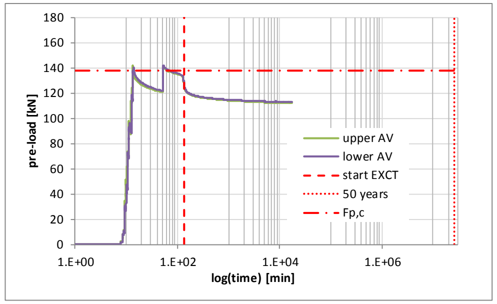
static tests	creep test	SSWL test
ZM_SM_23		
ZM_SM_25		
ZM_SM_26		
ZM_SM_27		
CBG-PE	E	A
correction app	210000	2000
	29	L
0.047	mm	
orrection mode	C1	C2
SM (wp1.2 &wp	1.945E-07	1.356E-05

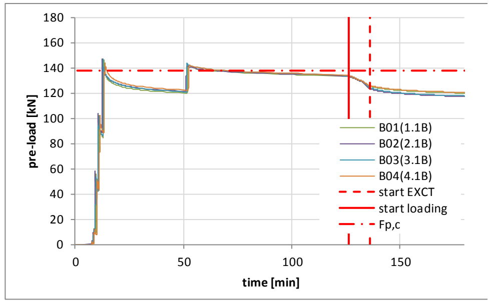
start time loading	
126	min
start time EXCT	
136	min

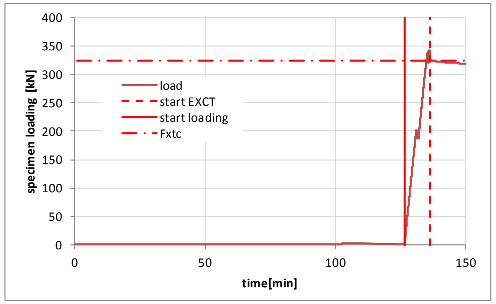
$F_{p,c}$			
1	138		
3.00E+07	138		
F_{xtc}			
1	325		
3.00E+07	325		
start loading			
126.4358872	0		
126.4358872	400		
start EXCT			
136.1242282	0	10	0
136.1242282	400	10	400
50 years			
26280000	0		
26280000	400		

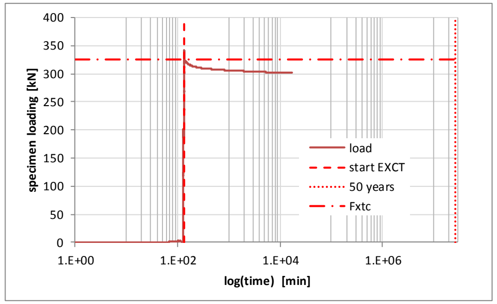
xtrpl 50y	
17101	0.297902169
26280000	0.3
17101	0.270902169
26280000	0.3

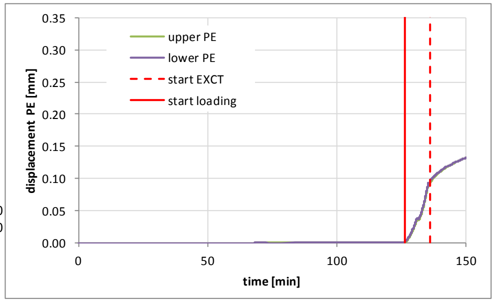


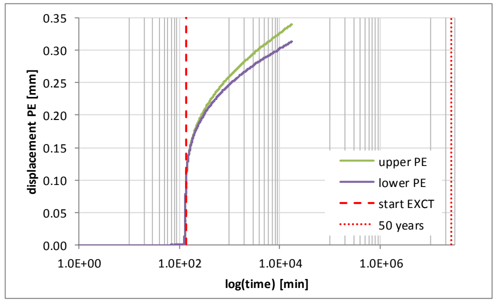


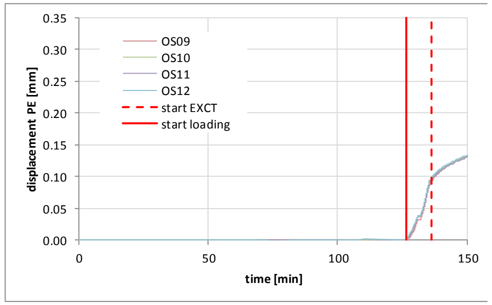


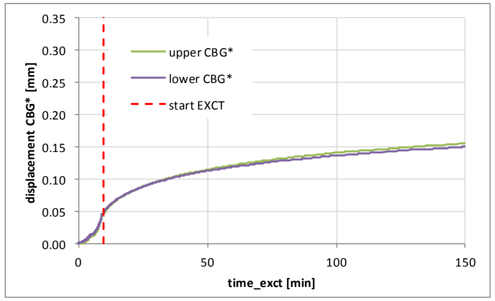


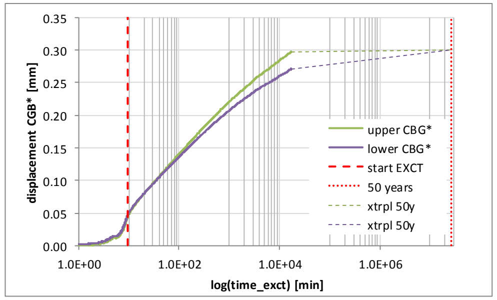








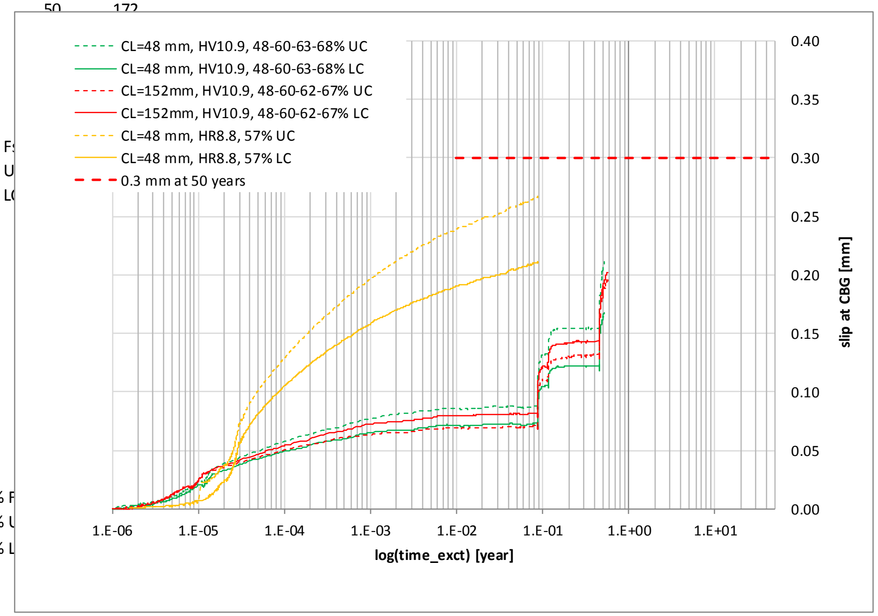




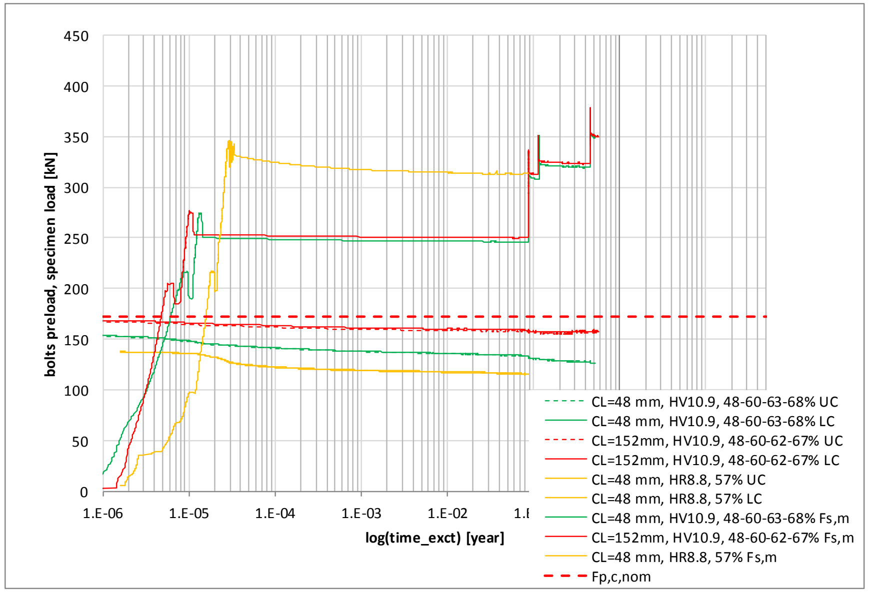
14.13 ZnSM_all - Bolt class 10.9 – WP1.2 batch

ZnSM, HR10.9			1.00E-02	0.3	1.00E-06	172
			50	0.3	50	172
$F_{P,c}$	172	kN	nominal preload level HV10.9			
$F_{s,m}$	442	kN	average short term tests			
$F_{fail,SSWLT}$	383	kN	load level before failure SSWL test			

CL=48 mm, HV10.9, 48-60-63-68%				Fs,m	CL=48 mm, HV10.9, 48-60-63-68% F			
ZnSm_19, HV10.9, 48 mm CL				UC	CL=48 mm, HV10.9, 48-60-63-68% U			
	510			LC	CL=48 mm, HV10.9, 48-60-63-68% L			
FP,c	153	kN	upper					
FP,c	154	kN	lower				long term	
	initially			finally	initiallly	finally	slip factor	
loading	[kN]	[kN]					μ_{nom}	
L0	275	246	48%	349	54%	68%	0.51	
L1	336	308	60%				0.51	
L2	351	320	63%					
L3	380	349	68%					



CL=152mm, HV10.9, 48-60-62-67%				Fs,m	CL=152mm, HV10.9, 48-60-62-67% F		
ZnSm_20, HV10.9, 152 mm CL				UC	CL=152mm, HV10.9, 48-60-62-67% U		
$F_{s,m}$	521	kN		LC	CL=152mm, HV10.9, 48-60-62-67% L		
FP,c	167	kN	upper				
FP,c	169	kN	lower				long term
	initially	finally				finally	slip factor
loading	[kN]	[kN]					μ_{nom}
L0	275	250	48%	351		67%	0.51
L1	336	312	60%				0.51
L2	352	323	62%				
L3	379	351	67%				



CL=48 mm, HR8.8, 57%				Fs,m	CL=48 mm, HR8.8, 57% Fs,m		
ZnSm_30, HR8.8, 48 mm CL				UC	CL=48 mm, HR8.8, 57% UC		
Fs,m	550.8 kN			LC	CL=48 mm, HR8.8, 57% LC		
FP,c	137	kN	upper				
FP,c	138	kN	lower				long term
	initially			finally	initiallly	finally	slip factor
loading	[kN]	applied on	days	[kN]			μ_{nom}
L0	329	3-mrt-16	17.8	313	60%	57%	0.57
							0.57
last record		21-mrt-16					

14.14 ZnSM_all - Bolt class 10.9 – WP2.1 batch

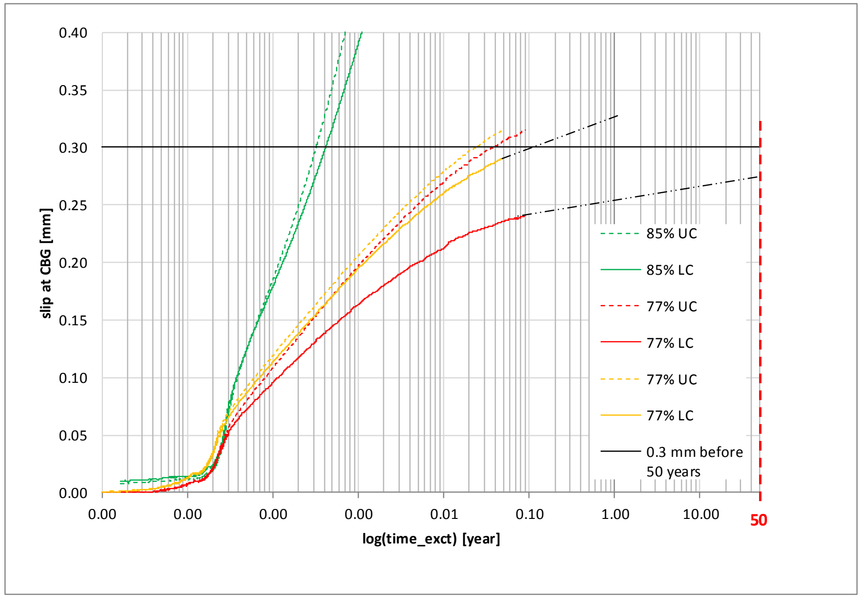
ZnSM, HR10.9		1.00E-07	0.3	1.00E-06	172	1.00E-06	442
		50	0.3	50	172	50	442

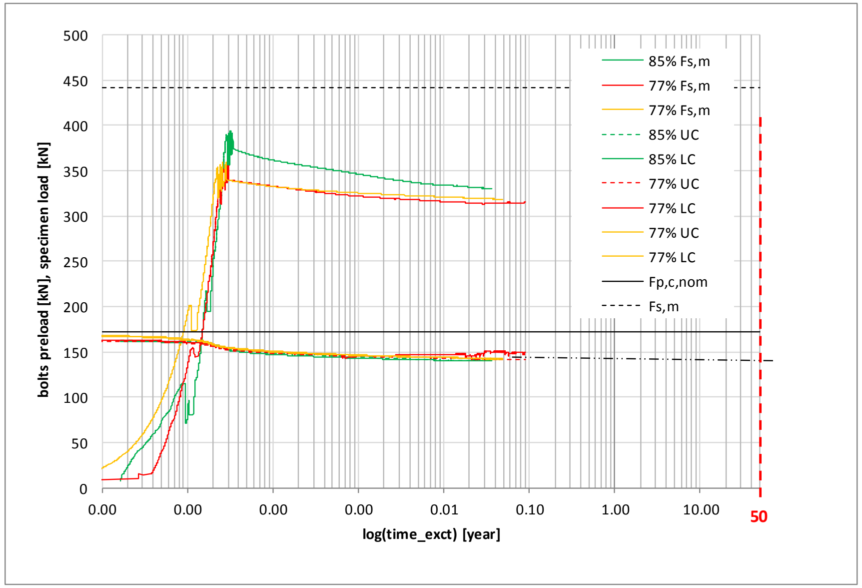
$F_{P,c}$	172	kN	nominal preload level
$F_{s,m}$	442	kN	average short term tests
$F_{fail,SSWLT}$	383	kN	load level before failure SSWL test

85%				Fs,m	85% Fs,m		
ZnSm_37				UC	85% UC		
				LC	85% LC		
FP,c	162	kN	upper				
FP,c	162	kN	lower				long term
	initially			finally	initiallly	finally	slip factor
loading	[kN]	applied on	days	[kN]			μ_{nom}
L0	376	18-feb-16	14.2	331	85%	75%	0.48
							0.48
last record		3-mrt-16					

77%				Fs,m	77% Fs,m		
ZnSm_40				UC	77% UC		
				LC	77% LC		
FP,c	161	kN	upper				
FP,c	163	kN	lower				long term
	initially			finally	initiallly	finally	slip factor
loading	[kN]	applied on	days	[kN]			μ_{nom}
L0	340	2-mrt-16	34.0	315	77%	71%	0.46
							0.46
last record		5-apr-16					

77%				Fs,m	77% Fs,m		
ZnSm_41				UC	77% UC		
				LC	77% LC		
FP,c	168	kN	upper				
FP,c	167	kN	lower				long term
	initially			finally	initiallly	finally	slip factor
loading	[kN]	applied on	days	[kN]			μ_{nom}
L0	340	3-mrt-16	17.8	318	77%	72%	0.46
							0.46
last record		21-mrt-16					





14.15 ZnSM_all - Bolt class 8.8 – WP2.1 batch

ZnSm, HR8.8

1.00E-07	0.3	1.00E-06	138	1.00E-06	439
50	0.3	50	138	50	439

$F_{P,c}$	138	kN	nominal preload level
$F_{s,m}$	439	kN	average short term tests
$F_{fail,SSWLT}$	329	kN	load level before failure SSWL test

75% **ZnSm_31** — Fs,m: 75% Fs,m; UC: 75% UC; LC: 75% LC

FP,c 134 kN upper
FP,c 134 kN lower

loading	initially [kN]	applied on	days	finally [kN]	initiallly	finally	long term slip factor μ_{nom}
L0	329	4-feb-16	32.1	308	75%	70%	0.56

last record 7-mrt-16

75% **ZnSm_42** — Fs,m: 75% Fs,m; UC: 75% UC; LC: 75% LC

FP,c 133 kN upper
FP,c 132 kN lower

loading	initially [kN]	applied on	days	finally [kN]	initiallly	finally	long term slip factor μ_{init}
L0	329	8-mrt-16	13.0	308	75%	70%	0.56

last record 21-mrt-16

70% **ZnSm_43** — Fs,m: 70% Fs,m; UC: 70% UC; LC: 70% LC

FP,c 137 kN upper
FP,c 137 kN lower

loading	initially [kN]	applied on	days	finally [kN]	initiallly	finally	long term slip factor μ_{init}
L0	312	8-mrt-16	12.9	293	71%	67%	0.53

last record 21-mrt-16

68% **ZnSm_44** — Fs,m: 68% Fs,m; UC: 68% UC; LC: 68% LC

FP,c 136 kN upper
FP,c 136 kN lower

loading	initially [kN]	applied on	days	finally [kN]	initiallly	finally	long term slip factor μ_{init}
L0	290	24-mrt-16	12.2	275	66%	63%	0.50
							0.50

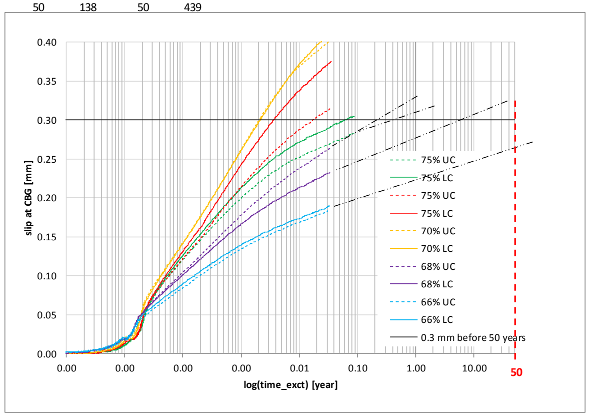
last record 5-apr-16

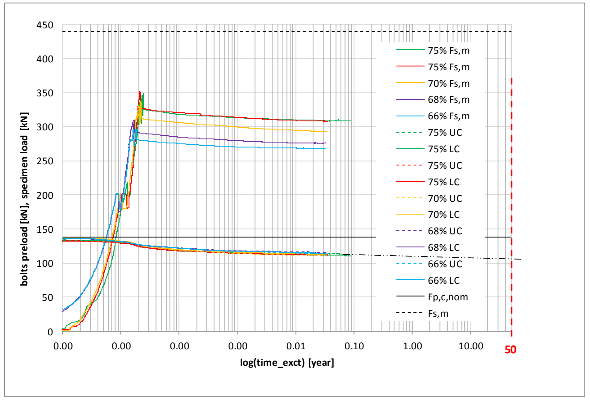
66% ZnSm_45 — Fs,m: 66% Fs,m; UC: 66% UC; LC: 66% LC

FP,c 136 kN upper
FP,c 136 kN lower

loading	initially [kN]	applied on	days	finally [kN]	initiallly	finally	long term slip factor μ_{init}
L0	280	8-mrt-16	13.0	267	64%	61%	0.48
							0.48

last record 21-mrt-16

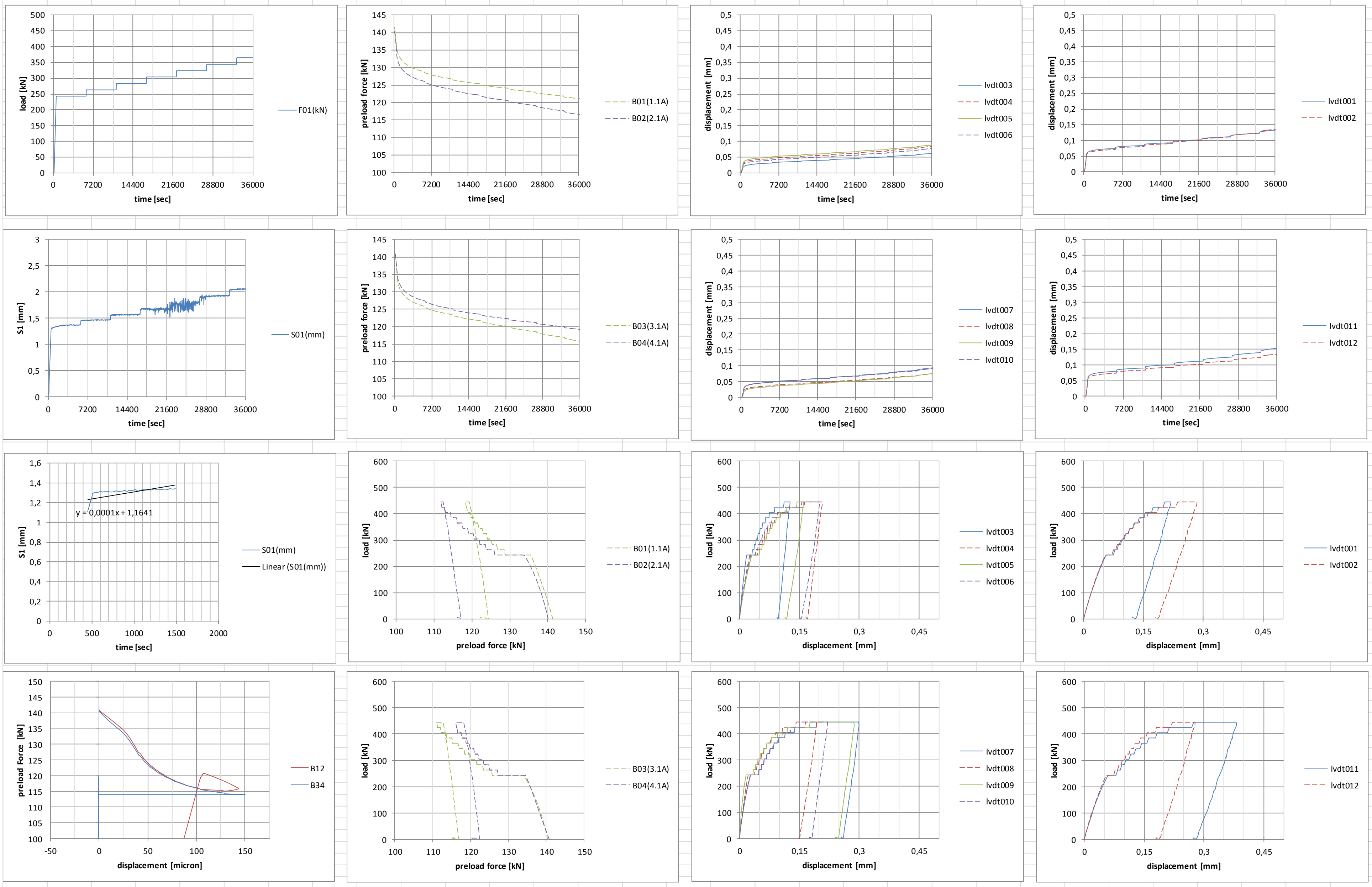


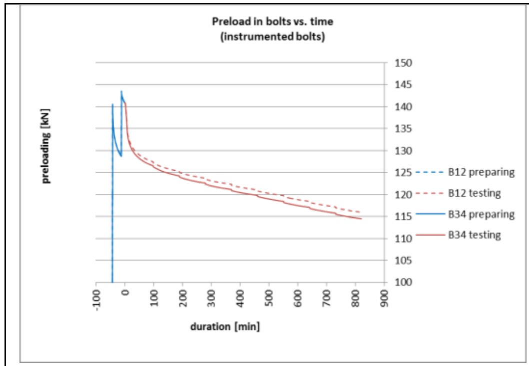


15 Annex K - Test results SSWL test ASiZn and ZnSM

bolts				short term tests				SSWL test			
series	coating	type	Σt	spec ID	$F_{slip,i}$	$F_{s,m}$	COV	spec ID	F_{init}	ΔF	$F_{fail,sswl}$
			[mm]		[kN]	[kN]	[-]		[kN]	[kN]	[kN]
wp2.1	ASiZN	HR 8.8	48	ASiZN_25	409	405	1,5%	ASiZN_29	243	20	446
					405						
				ASiZN_26	408						
					410						
				ASiZN_27	409						
					407						
				ASiZN_28	403						
					391						
		HR 10.9	48	ASiZN_30	469	470	1,1%	ASiZN_34	282	47	470
					470						
				ASiZN_31	471						
					470						
				ASiZN_32	481						
					472						
				ASiZN_33	462						
					467						
	ZN_SM	HR 8.8	48	SM_23	431	439	2,6%	SM_29	263	22	351
					432						
				SM_25	426						
					427						
				SM_26	447						
					450						
				SM_27	455						
					441						
		HR 10.9	48	SM_32	433	442	6,3%	SM_35	265	22	405
					432						
				SM_33	419						
					417						
				SM_34	430						
					430						
				SM_36	490						
					482						

15.1 ASiZN_29 - 138 kN





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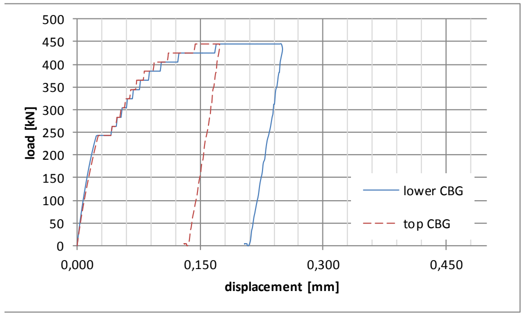
ASIZN | HR8.8

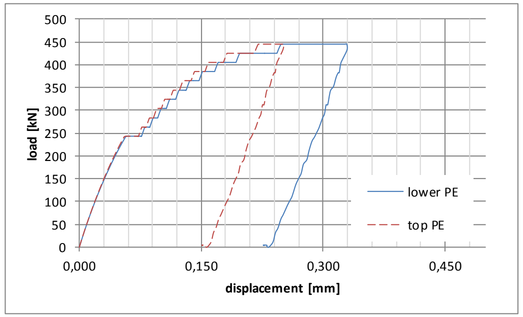
SSWL protocol

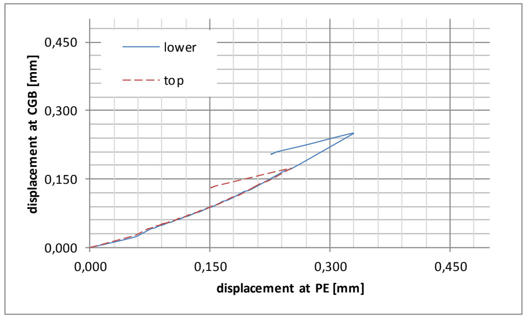
15-3-2018

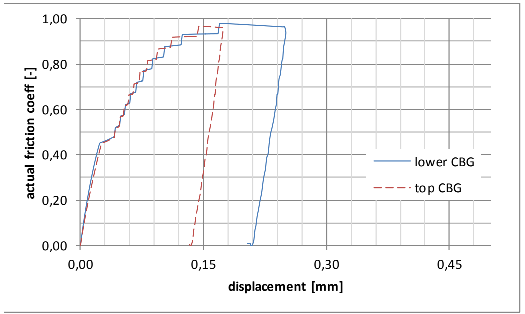
basics slip fator experiment		
	Tested according to	Short stepwise loading protocol
	Test date	08-02-2016 - 09-02-2016
	test performed by	F. Schilperoord
	Steel	S355
	Coating	Alkali Silicon Zinc
	Coating composition	-
	Surface treatment	Sa 2½, Rz = 84 micron (average)
	Maximum coating thickness	centre plates: 57 micron, lap plates: 53 micron (average values)
	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	8.8 (EN 14399-4 – HR – M20 x 70 – 8.8/8 – tZn)
	Nominal Preload level	138 kN = $F_{p,C}$
	Measuring of the preload level	Instrumented bolts, continuously measured, clamping length St = 48 mm
	loading speed during SSWL test	0,003 mm/sec

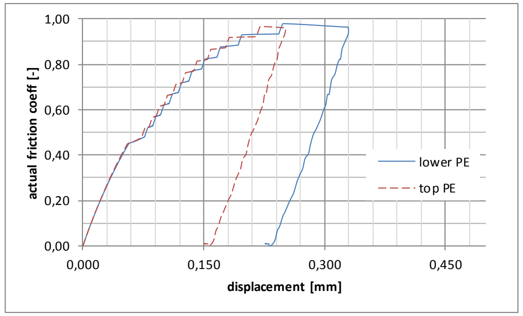
short stepwise loading test	t0 [min]	t1 [min]	slip load steps	60% 243	65% 263	70% 283	75% 304	80% 324	85% 344	90% 365	95% 385	100% 405	105% 425	x Fs,m [kN]	date
	interval		0	slip speed											
ASiZN_29 S	10	35	upper connection	0,172	0,058	0,048	0,056	0,065	0,078	0,102	0,135	0,195	0,350	[mm/min]	09-02-16 15:56
	35	60		0,079	0,039	0,036	0,041	0,049	0,061	0,082	0,112	0,171	0,349	[mm/min]	
	60	85		0,051	0,031	0,029	0,034	0,041	0,050	0,070	0,098	0,152	0,332	[mm/min]	
			lower connection	0,196	0,068	0,059	0,067	0,077	0,092	0,121	0,161	0,238	0,469	[mm/min]	
				0,092	0,047	0,042	0,049	0,058	0,072	0,097	0,135	0,212	0,494	[mm/min]	
				0,059	0,036	0,035	0,040	0,049	0,060	0,082	0,117	0,191	0,488	[mm/min]	

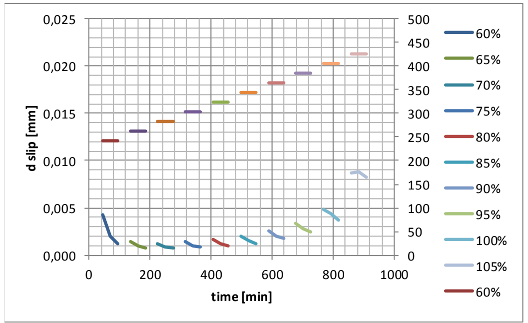

load [kN]
displacement [mm]
lower CBG
top CBG

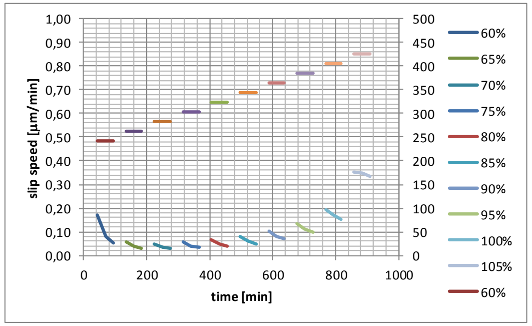

load [kN]
displacement [mm]
lower PE
top PE

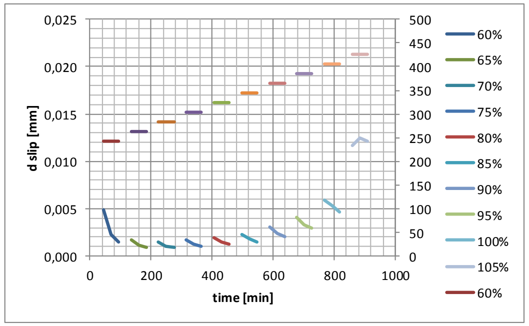

displacement at CGB [mm]
displacement at PE [mm]
lower
top

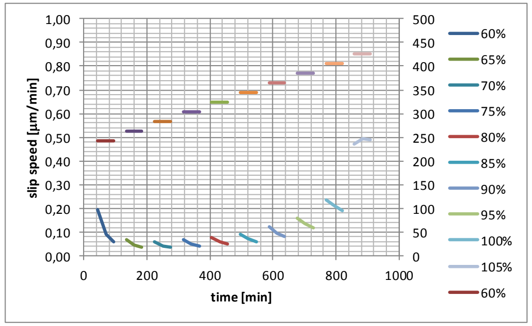

actual friction coeff [-]
displacement [mm]
lower CBG
top CBG


actual friction coeff [-]
displacement [mm]
lower PE
top PE

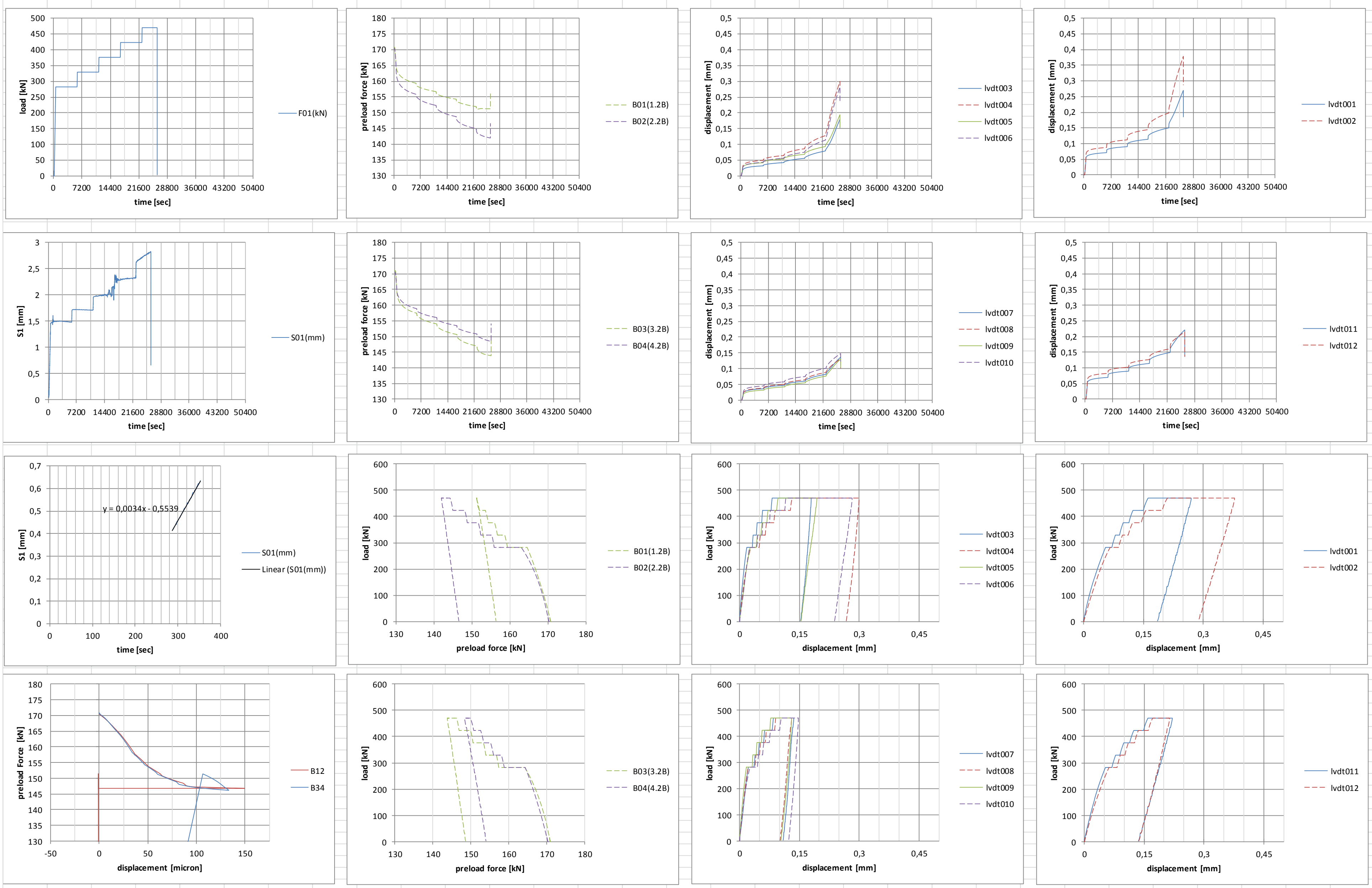

d slip [mm]
time [min]
60%
65%
70%
75%
80%
85%
90%
95%
100%
105%
60%

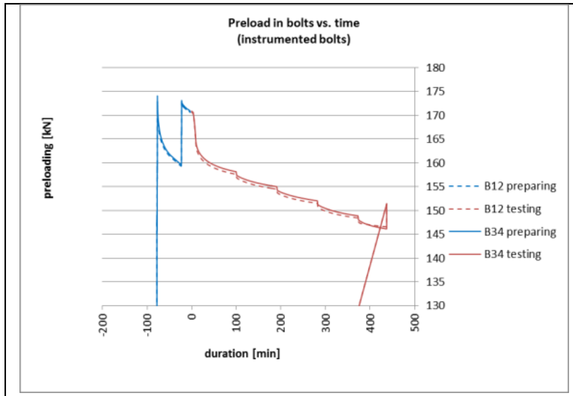

slip speed [µm/min]
time [min]
60%
65%
70%
75%
80%
85%
90%
95%
100%
105%
60%


d slip [mm]
time [min]
60%
65%
70%
75%
80%
85%
90%
95%
100%
105%
60%


slip speed [µm/min]
time [min]
60%
65%
70%
75%
80%
85%
90%
95%
100%
105%
60%

15.2 ASiZn_34 – 172 kN





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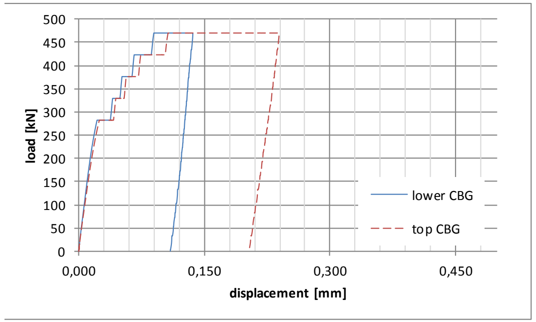
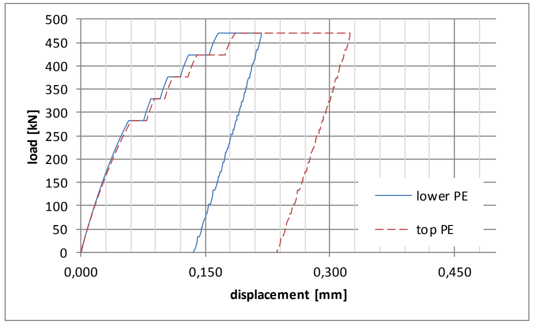
ASIZN HR10.9 — SSWL protocol

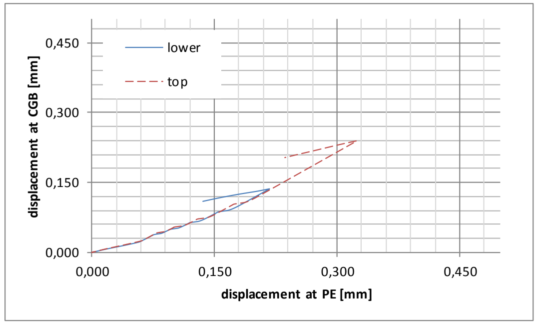
15-3-2018

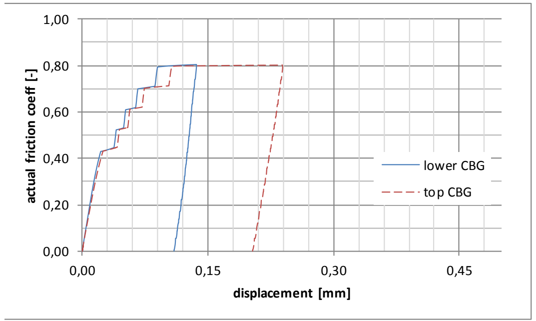
basics slip fator experiment		
	Tested according to	Short stepwise loading protocol
	Test date	08-02-2016 - 09-02-2016
	test performed by	F. Schilperoord
	Steel	S355
	Coating	Alkali Silicon Zinc
	Coating composition	-
	Surface treatment	Sa 2½, Rz = 84 micron (average)
	Maximum coating thickness	centre plates: 57 micron, lap plates: 53 micron (average values)
	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	8.8 (EN 14399-4 – HR – M20 x 70 – 8.8/8 – tZn)
	Nominal Preload level	138 kN = $F_{p,C}$
	Measuring of the preload level	Instrumented bolts, continuously measured, clamping length St = 48 mm
	loading speed during SSWL test	

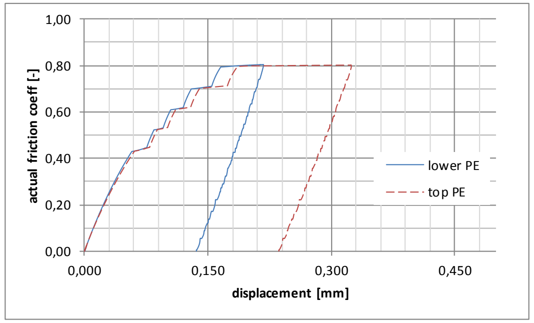
short stepwise loading test	t0 [min]	t1 [min]	slip load steps	60% 282	65% 0	70% 329	75% 0	80% 376	85% 0	90% 423	95% 0	100% 470	105% 0	x Fs,m [kN]	date
	interval		0	slip speed											
ASiZN_34 SSW	10	35	upper connection	0,199		0,134		0,197		0,387		2,233		[mm/min]	16-02-16 15:58
	35	60		0,091		0,084		0,130		0,278		2,051		[mm/min]	
	60	85		0,059		0,061		0,097		0,215		-9,448		[mm/min]	
			lower connection	0,190		0,116		0,161		0,270		0,760		[mm/min]	
				0,087		0,074		0,106		0,188		0,639		[mm/min]	
				0,055		0,053		0,079		0,145		-7,932		[mm/min]	

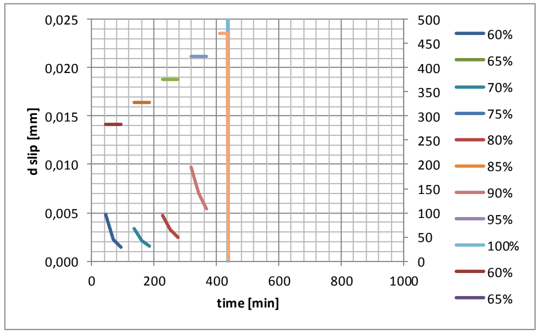

load [kN]
displacement [mm]
lower CBG
top CBG

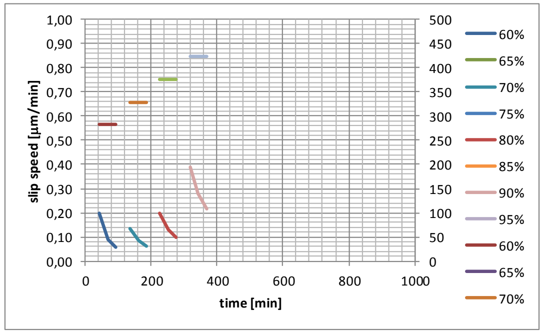

load [kN]
displacement [mm]
lower PE
top PE

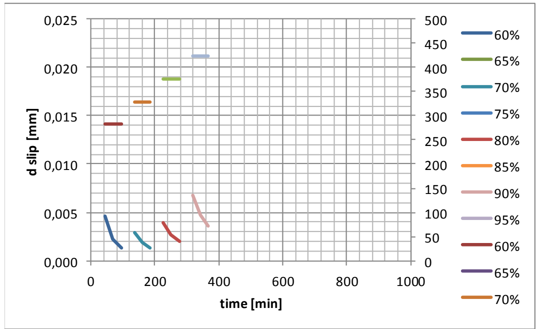

displacement at CGB [mm]
displacement at PE [mm]
lower
top

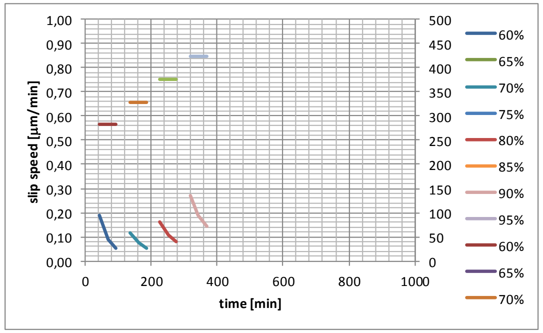

actual friction coeff [-]
displacement [mm]
lower CBG
top CBG


actual friction coeff [-]
displacement [mm]
lower PE
top PE

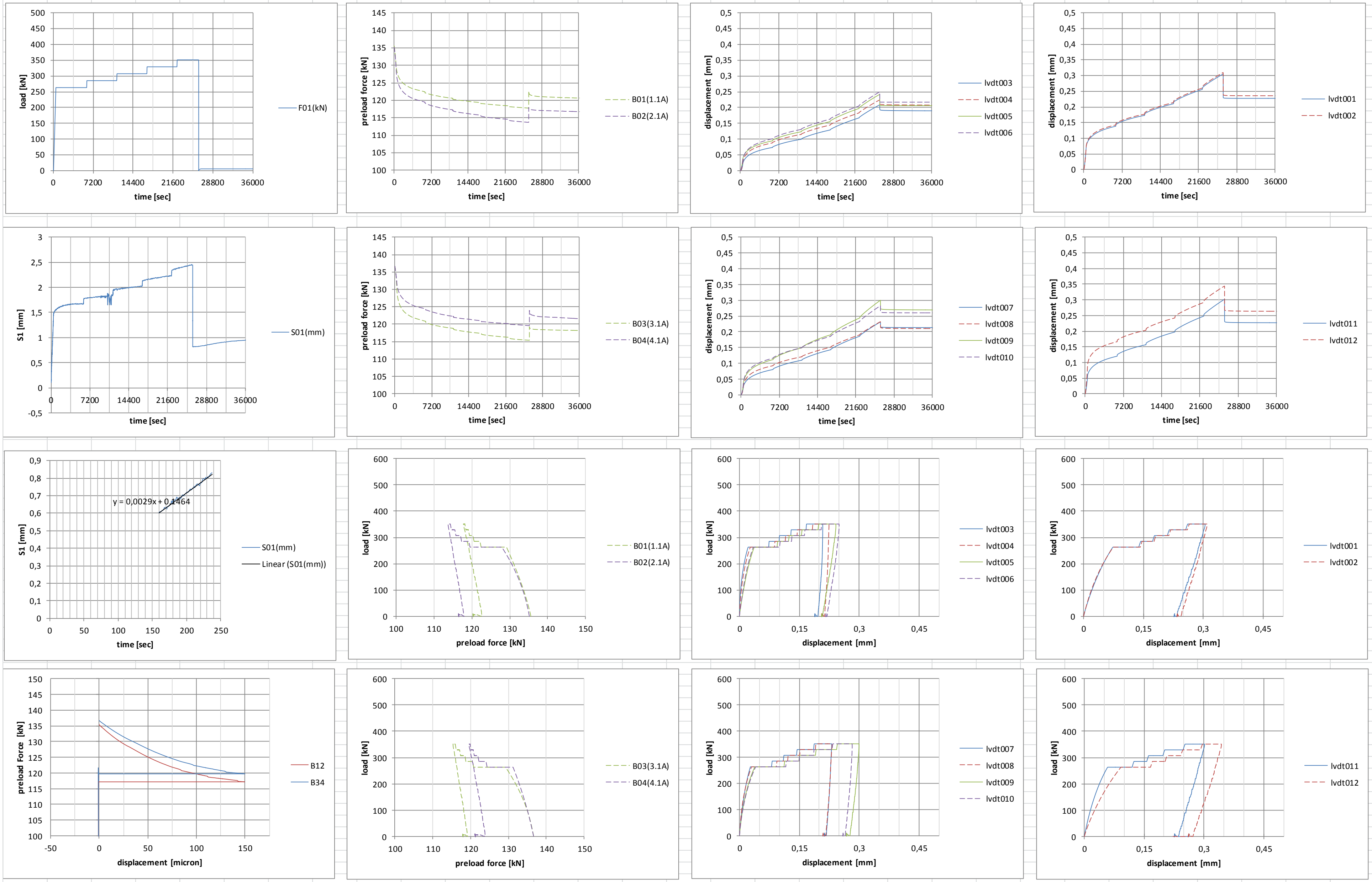

d slip [mm]
time [min]
60%
65%
70%
75%
80%
85%
90%
95%
100%
60%
65%

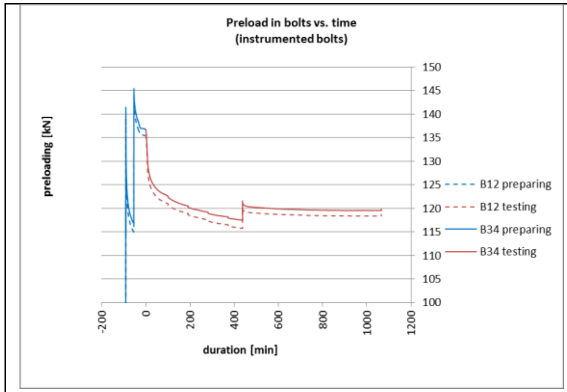

slip speed [µm/min]
time [min]
60%
65%
70%
75%
80%
85%
90%
95%
60%
65%
70%


d slip [mm]
time [min]
60%
65%
70%
75%
80%
85%
90%
95%
60%
65%
70%


slip speed [µm/min]
time [min]
60%
65%
70%
75%
80%
85%
90%
95%
60%
65%
70%

15.3 SM_29 – 138 kN





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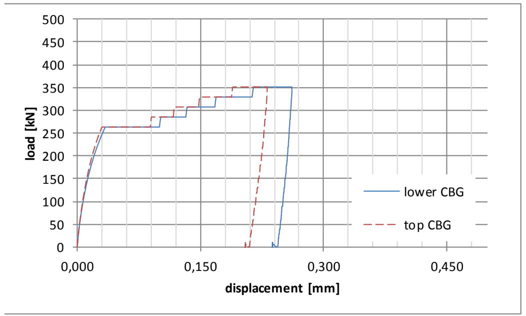
ZNSM | **HR8.8**

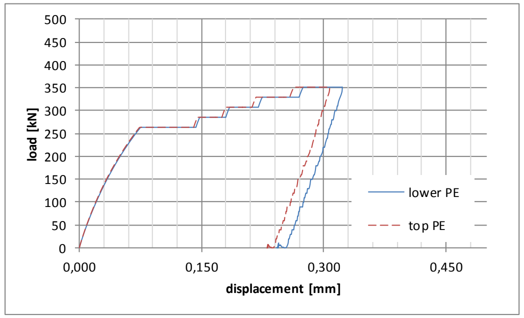
SSWL protocol

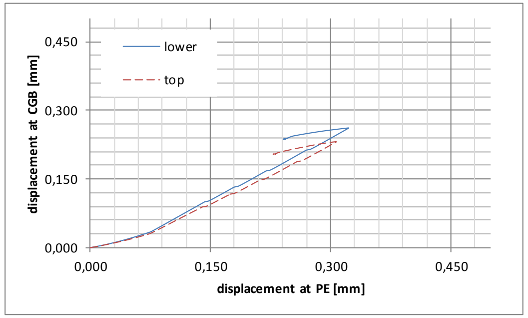
15-3-2018

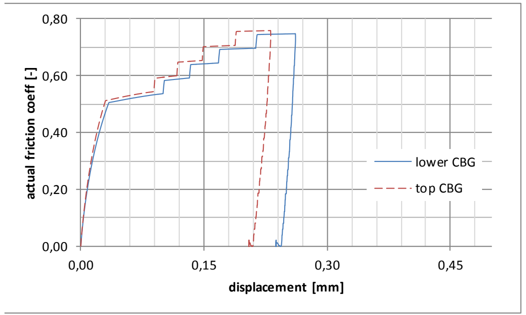
basics slip fator experiment		
	Tested according to	Short stepwise loading protocol
	Test date	08-02-2016 - 09-02-2016
	test performed by	F. Schilperoord
	Steel	S355
	Coating	Zinc spray metallized
	Coating composition	-
	Surface treatment	Sa 2½, Rz = 100 micron
	Maximum coating thickness	centre plates 164 micron, lap plates 159 micron (average)
	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	8.8 (EN 14399-4 – HR – M20 x 70 – 8.8/8 – tZn)
	Nominal Preload level	138 kN = Fp,C
	Measuring of the preload level	Instrumented bolts, continuously measured, clamping length St = 48 mm
	loading speed during SSWL test	

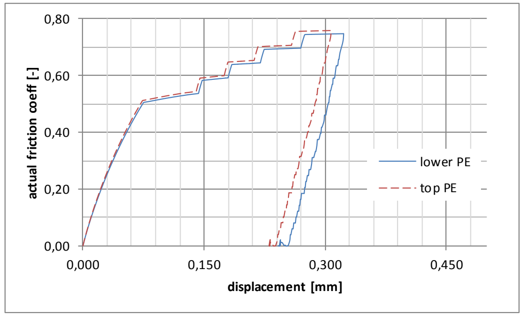
short stepwise loading test	t0 [min]	t1 [min]	slip load steps	60%	65%	70%	75%	80%	85%	90%	95%	100%	105%	x Fs,m [kN]	date
				263	**285**	**307**	**329**	**351**	**0**	**0**	**0**	**0**	**0**		
	interval		0	slip speed											
SM_29 SSW	10	35	upper connection	0,771	0,350	0,362	0,469	0,654						[mm/min]	03-02-16 15:18
	35	60		0,387	0,264	0,300	0,406	0,598						[mm/min]	
	60	85		0,263	0,213	0,258	0,363	-0,923						[mm/min]	
			lower connection	0,859	0,399	0,413	0,529	0,730						[mm/min]	
				0,441	0,303	0,344	0,460	0,669						[mm/min]	
				0,301	0,247	0,295	0,413	-0,791						[mm/min]	

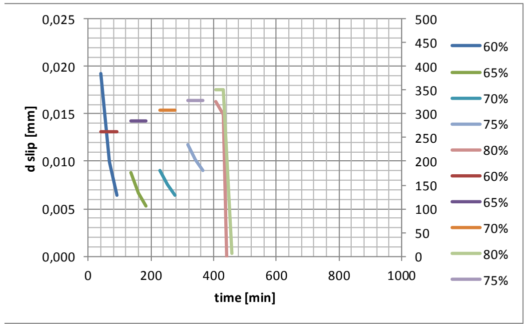

load [kN]
0
50
100
150
200
250
300
350
400
450
500
0,000
0,150
0,300
0,450
displacement [mm]
lower CBG
top CBG

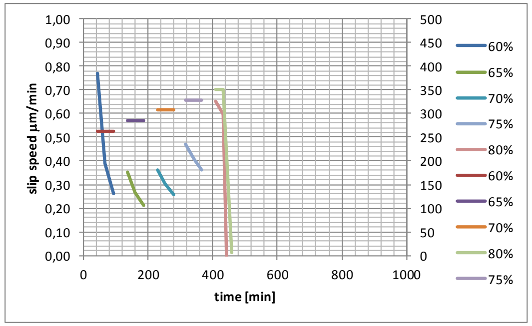

load [kN]
0
50
100
150
200
250
300
350
400
450
500
0,000
0,150
0,300
0,450
displacement [mm]
lower PE
top PE

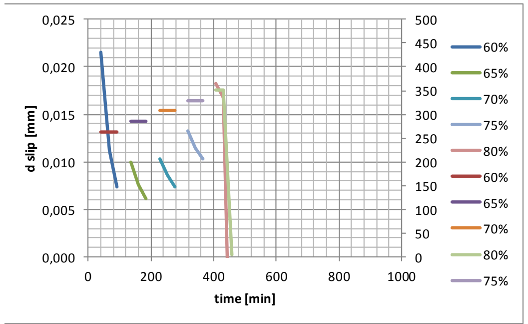

displacement at CGB [mm]
0,000
0,150
0,300
0,450
0,000
0,150
0,300
0,450
displacement at PE [mm]
lower
top

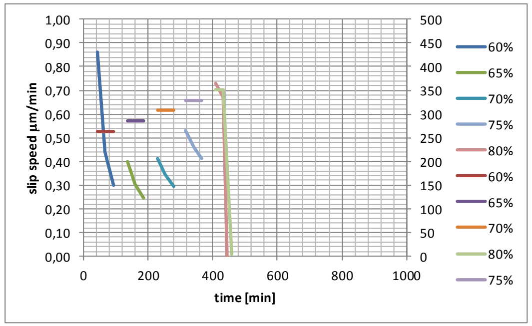

actual friction coeff [-]
0,00
0,20
0,40
0,60
0,80
0,00
0,15
0,30
0,45
displacement [mm]
lower CBG
top CBG


actual friction coeff [-]
0,00
0,20
0,40
0,60
0,80
0,000
0,150
0,300
0,450
displacement [mm]
lower PE
top PE

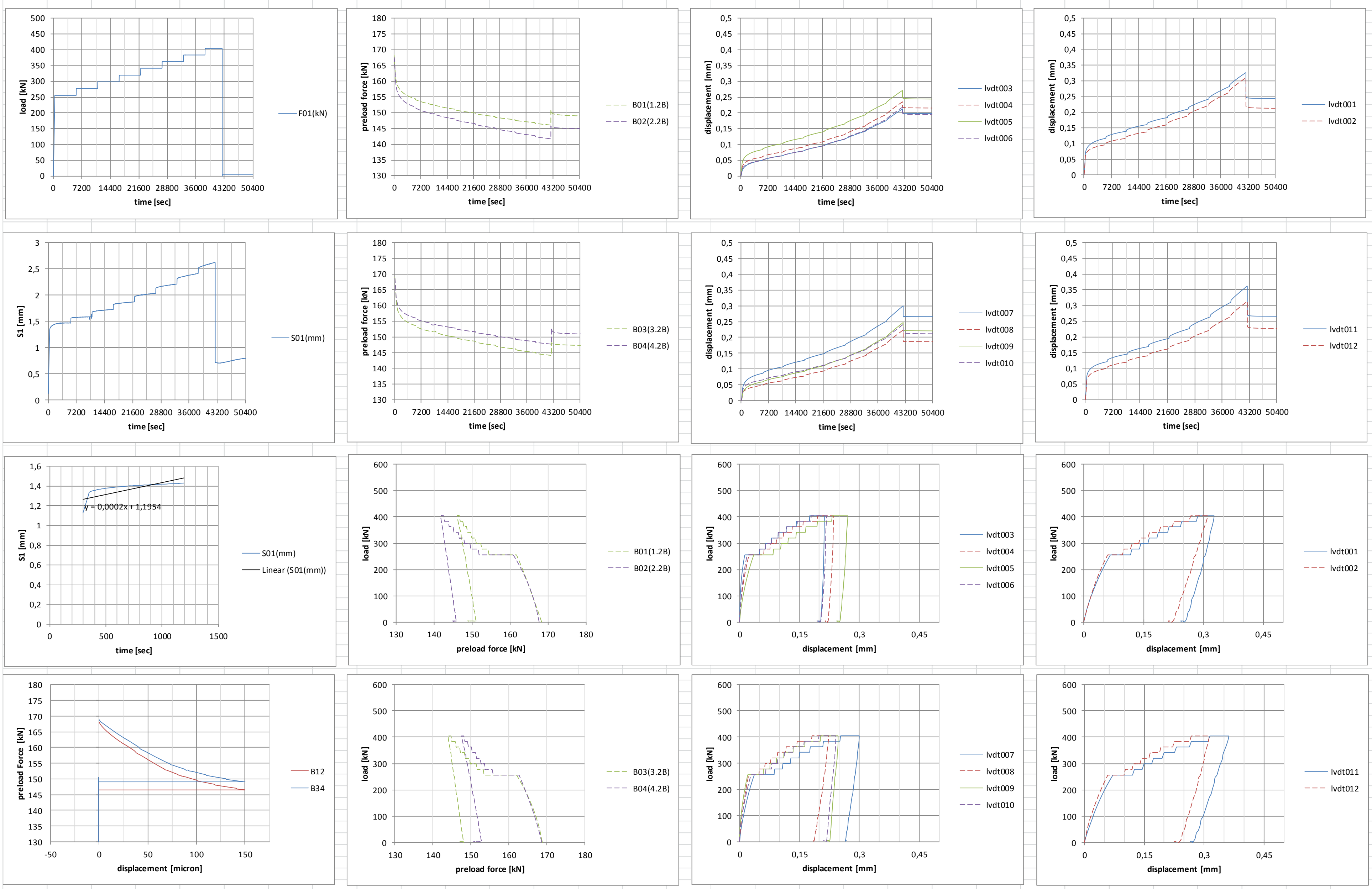

d slip [mm]
0,000
0,005
0,010
0,015
0,020
0,025
0
50
100
150
200
250
300
350
400
450
500
0
200
400
600
800
1000
time [min]
60%
65%
70%
75%
80%
60%
65%
70%
80%
75%

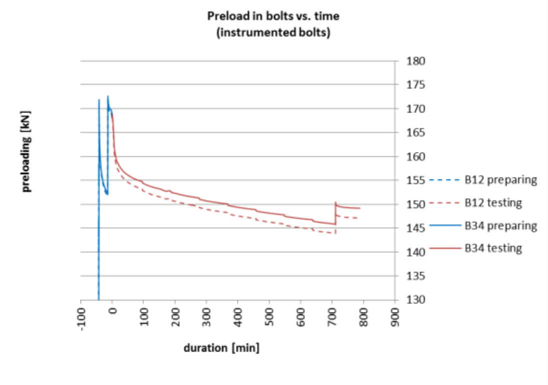

slip speed µm/min
0,00
0,10
0,20
0,30
0,40
0,50
0,60
0,70
0,80
0,90
1,00
0
50
100
150
200
250
300
350
400
450
500
0
200
400
600
800
1000
time [min]
60%
65%
70%
75%
80%
60%
65%
70%
80%
75%


d slip [mm]
0,000
0,005
0,010
0,015
0,020
0,025
0
50
100
150
200
250
300
350
400
450
500
0
200
400
600
800
1000
time [min]
60%
65%
70%
75%
80%
60%
65%
70%
80%
75%


slip speed µm/min
0,00
0,10
0,20
0,30
0,40
0,50
0,60
0,70
0,80
0,90
1,00
0
50
100
150
200
250
300
350
400
450
500
0
200
400
600
800
1000
time [min]
60%
65%
70%
75%
80%
60%
65%
70%
80%
75%

15.4 SM_35 – 172 kN





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ZnSM	HR10.9

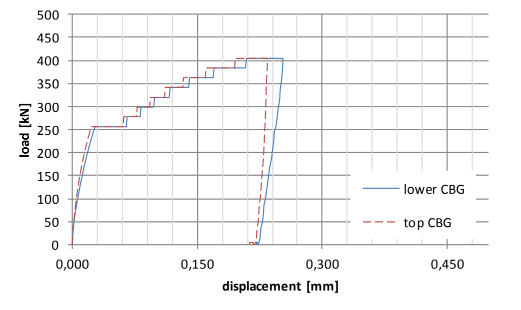
SSWL protocol

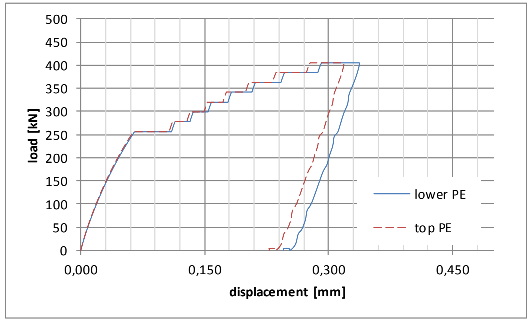
15-3-2018

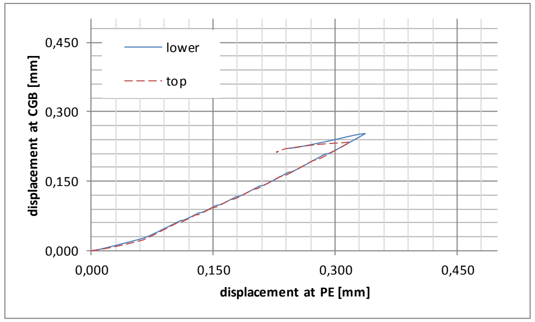
basics slip fator experiment		
	Tested according to	Short stepwise loading protocol
	Test date	08-02-2016 - 09-02-2016
	test performed by	F. Schilperoord
	Steel	S355
	Coating	Zinc spray metallized
	Coating composition	-
	Surface treatment	Sa 2½, Rz = 100 micron
	Maximum coating thickness	centre plates 164 micron, lap plates 159 micron (average)
	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 – HR – M20 x 70 – 10.9/10 – tZn)
	Nominal Preload level	172 kN = Fp,C
	Measuring of the preload level	Instrumented bolts, continuously measured, clamping length St = 48 mm
	loading speed during SSWL test	

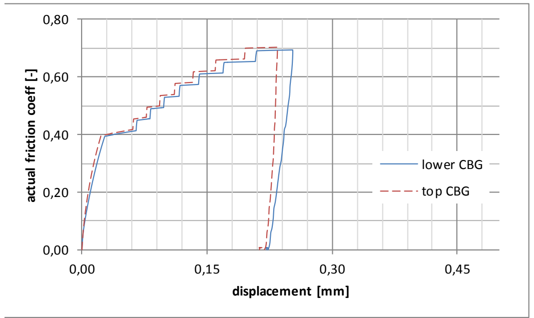
short stepwise loading test	t0 [min]	t1 [min]	slip load steps	60%	65%	70%	75%	80%	85%	90%	95%	100%	105%	x Fs,m [kN]	date
				256	**278**	**299**	**320**	**342**	**363**	**384**	**405**	**0**	**0**		0
	interval		0	slip speed											
SM_35 SSW	10	35	upper connection	0,470	0,194	0,186	0,206	0,254	0,312	0,400	0,542			[mm/min]	17-02-16 16:43
	35	60		0,231	0,141	0,146	0,167	0,212	0,271	0,360	0,505			[mm/min]	
	60	85		0,151	0,112	0,121	0,144	0,186	0,243	0,332	-0,585			[mm/min]	
			lower connection	0,475	0,197	0,192	0,212	0,266	0,332	0,435	0,604			[mm/min]	
				0,235	0,147	0,150	0,176	0,227	0,294	0,399	0,575			[mm/min]	
				0,154	0,119	0,126	0,152	0,200	0,266	0,371	-0,990			[mm/min]	

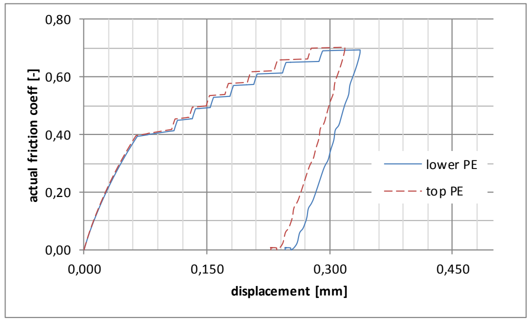
error in initial load level (should have been 265 kN); typing error operator

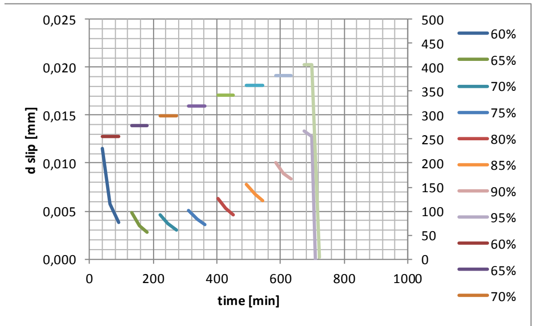

load [kN]
displacement [mm]
lower CBG
top CBG

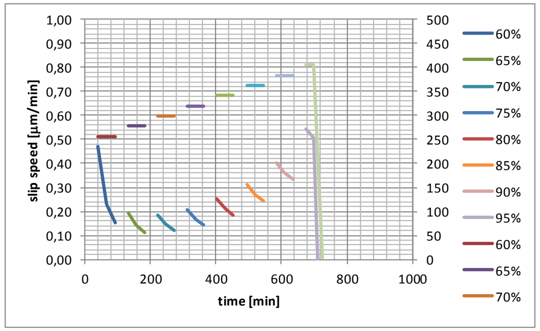

load [kN]
displacement [mm]
lower PE
top PE

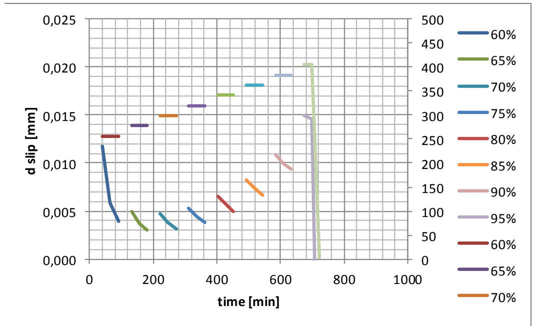

displacement at CGB [mm]
displacement at PE [mm]
lower
top

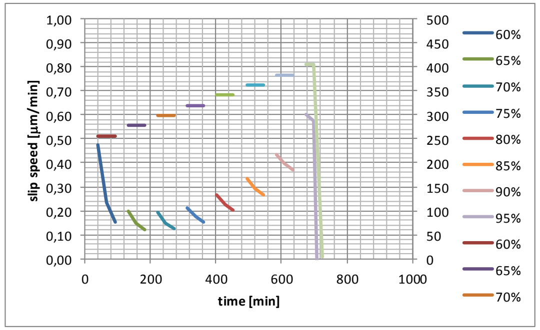

actual friction coeff [-]
displacement [mm]
lower CBG
top CBG


actual friction coeff [-]
displacement [mm]
lower PE
top PE


d slip [mm]
time [min]
60%
65%
70%
75%
80%
85%
90%
95%
60%
65%
70%


slip speed [µm/min]
time [min]
60%
65%
70%
75%
80%
85%
90%
95%
60%
65%
70%


d slip [mm]
time [min]
60%
65%
70%
75%
80%
85%
90%
95%
60%
65%
70%


slip speed [µm/min]
time [min]
60%
65%
70%
75%
80%
85%
90%
95%
60%
65%
70%