Project

Execution and reliability of slip resistant connections for steel structures using CS and SS "SIROCO" (RFSR-CT-2014-00024)

WP 4

Use of alternative surface treatments and
new coating systems in slip resistant connections

Task 4.3

Influence of the application and storage parameter on the slip factor and corrosion protection in case of ethyl-silicate-zinc coatings

Different application and storage parameters in case of ethyl-silicate-zinc coatings,

Deliverable 4.3

Slip factor depending on application on storage parameters

Deliverable 4.4

Corrosion behaviour of ethyl-silicate-zinc (ESI) coatings

Report To:	**European Commission Research Programme of the Research Fund for Coal and Steel Technical Group: TG 8**
Document:	**D 4.3 slip factor depending on application on storage parameters**
Document:	**D 4.4 corrosion behaviour of ethyl-silicate-zinc (ESI) coatings**
Version:	**26.03.2018**

EUROPEAN COMMISSION

Research Program of
The Research Fund for Coal and Steel - Steel RTD

Title of Research Project:	Execution and reliability of slip resistant connections for steel structures using CS and SS (SIROCO)
Executive Committee:	TG 8
Grant Agreement No.:	RFSR-CT-2014-00024
Commencement Date:	July 01, 2014
Completion Date:	June 30, 2017
Work Package No.:	WP4 Use of alternative surface treatments and new coating systems in slip resistant connections Task 4.3 Influence of the application and storage parameter on the slip factor and corrosion protection in case of ethyl-silicate-zinc coatings
Deliverable No. and Title:	D 4.3 - slip factor depending on application on storage parameters D 4.4 - corrosion behaviour of ethyl-silicate-zinc (ESI) coatings
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Abstract

Slip-resistant connections are required, when deformations in bolted connections must be limited to pre-defined values either for serviceability or ultimate limit reasons. Typical applications can be found in bridges, cranes, radio masts and towers of wind turbines, which are loaded by alternate loading and /or fatigue or where functional requirements make slip-resistant connections necessary. Essential characteristics of these connections are firstly, the level of preload in the bolts and secondly, the slip factor which is mainly influenced by the surface coatings. In this investigation ethyl-silicate-zinc ESI is tested due to the use in slip-resistant connections. The conditioning of the samples after application, especially the temperature and relative humidity, has an effect on the slip factor and the corrosion protection. The conditions during storage are a second point. These influences will be investigated with regard to the slip factor and the corrosion protection.

Keywords: ethyl-silicate-zinc ESI, Slip load, Slip factor, Slip-resistant connection, HV bolts, SIROCO-Project

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Abbreviation/ Symbol	Unit	Comment/ Explanation
LVDT	/	Linear Variable Displacement Transducer
ECT	/	Extended Creep Test acc. to EN 1090-2, Annex G.5
$\mu_{start,Fs\text{-}max}$	[-]	slip factor regarding the preload $F_{p,C,start}$ of a bolt at test begin and maximum slip load $F_{Si,max}$
$F_{Si,max}$	[kN]	maximum slip load
$F_{p,C,start}$	[kN]	preload of a bolt at test begin
$\mu_{actual,Fs\text{-}max}$	[-]	slip factor regarding the actual preload $F_{p,C,actual}$ of a bolt during slip of the connection and maximum slip load $F_{Si,max}$

1 Introduction

In practice, the hardening conditions and storage parameters can be very different. The storage stability is the period of time during which the coating material remains ready for use while being stored in a closed original container under standard conditions (specified by the manufacturer).

The conditioning of the samples after application, especially the temperature and relative humidity, and the storage stability has an effect on the slip factor and the corrosion protection. These influences were investigated.

2 Experimental investigations

2.1 Corrosion test

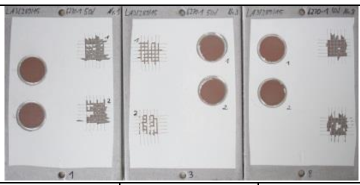
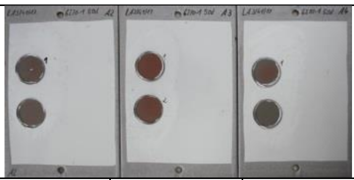
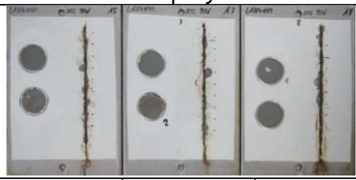
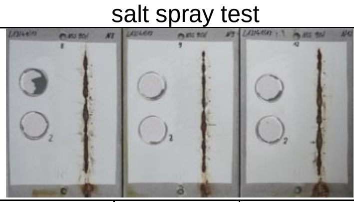
For this, test specimens with a coating material based on ethyl silicate have been prepared (Table 2.1-1 and Table 2.2-1). One part of the test specimens has been conditioned for 7 days (System B, C) and one part of the test specimens has been conditioned for 3 weeks (System A). In order to maintain the hardening conditions constant the test specimens, for this, have been stored in the climate cabinet at 23 °C and 60 % relative humidity. Simultaneously, test specimens coated with ethyl silicate have been prepared. The ethyl silicate had already been stored for 12 month in the Institute for Corrosion Protection (System B). By means of these test specimens the influence of the storage stability was examined by using an expired ESI batch ("old"). Furthermore, coating systems have been prepared on which examinations in regard to corrosion protection were carried out. On the one hand, the detection of weak spots in the coating system is of interest; on the other hand information on barrier effects can be supplied. The duration of stress application was scheduled for 2.160 hours in neutral salt spray in accordance with DIN EN ISO 9227 [1] as well as for 1.200 hours in condensation-water constant climate in accordance with ISO 6270-1 [2].

Table 2.1-1: Coating systems for examinations in regard to corrosion protection

System	Description	Coating structure		Nominal dry film thickness [µm]	Total dry film thickness [µm]
A	ethyl silicate (ESI) new batch	50 µm Interzinc 22 30 µm Intergard 269 80 µm Intergard 345 80 µm Interthane 990	ESI primer EP coupling agent EP intermediate coat PUR top coat	240	247 ± 11
B	ethyl silicate (ESI) stored for 12 month				249 ± 10
C	ethyl silicate (ESI) new batch				241 ± 8

Before the salt spray test an artificial damage is introduced on the test specimens down to the steel substrate in order to evaluate the behaviour of the coating system around the scratch. The scratch ran parallel to one of the longitudinal sides of the test specimen at a distance of 30 mm to the edge of the test specimen. The width of the scratch was 0.5 mm. A scratching tool with a profile based on Clemen was used. Prior to the stress application, parameters for the adhesive strength were determined on the reference test specimens. The pull-off strength and the failure pattern were determined with the sandwich method (ISO 4624 [3]). For the determination of the pull-off strength test cylinders (Ø 20 mm) are adhered to test panels. With the sandwich method two test cylinders each are installed coaxial by means of a centring device. After hardening of the adhesive (cyanoacrylate), using a tensile tester, the pull-off strength information on the failure pattern and, thus, on the weakest part of the coating system is given. Adhesion failure, cohesion failure or mixed failure can occur (see Table 2.1-2).

Table 2.1-2: Results of corrosion protection tests for System A, B and C

	Assessment after 1.200 hours continuous condensation			Assessment after 2.160 hours neutral salt spray test		
System A (ESI new batch)						
Film thickness ISO 2808 [4] [µm]	244 ± 15	248 ± 10	246 ± 18	247 ± 9	245 ± 10	253 ± 7
Visual evaluation	no visual changes			no visual changes		
Pull-off strength [MPa]	11,8	10,7	10,8	18,2	12,2	17,9
Failure pattern	cohesion failure in the 2nd layer			cohesion failure in the 2nd layer		
Corrosion at the scratch [mm]	-			1,9 ± 1,0	1,7 ± 0,4	2,1 ± 0,6
Delamination at the scratch [mm]	-			2,3 ± 0,8	2,2 ± 0,4	2,4 ± 0,6
	Assessment after 1.200 hours continuous condensation			Assessment after 2.160 hours neutral salt spray test		
System B (ESI stored for 12 month)						
Film thickness ISO 2808 [4] [µm]	247 ± 13	247 ± 11	252 ± 8	249 ± 10	252 ± 10	242 ± 12
Visual evaluation	no visual changes			no visual changes		
Pull-off strength [MPa]	6,9	8,5	8,7	9,4	11,1	7,7
Failure pattern	cohesion failure in the 2nd layer			cohesion failure in the 1st and 2nd layer		
Corrosion at the scratch [mm]	-			< 0,5	< 0,5	0,7 ± 0,3
Delamination at the scratch [mm]	-			1,9 ± 0,9	1,9 ± 0,8	1,6 ± 0,8
	Assessment after 1.200 hours continuous condensation			Assessment after 2.160 hours neutral salt spray test		
System C (ESI new batch)						
Film thickness ISO 2808 [4] [µm]	242 ± 8	246 ± 12	247 ± 5	236 ± 5	236 ± 9	240 ± 10
Visual evaluation	no visual changes			no visual changes		
Pull-off strength [MPa]	8,5	9,9	10,8	8,3	10,5	9,6
Failure pattern	cohesion failure in the 1st and 4th layer	cohesion failure in the 4th layer		cohesion failure in the 1st and 4th layer	cohesion failure in the 4th layer	
Corrosion at the scratch [mm]	-			1,4 ± 0,5	1,3 ± 0,5	1,4 ± 0,7
Delamination at the scratch [mm]	-			1,4 ± 0,5	1,3 ± 0,5	1,4 ± 0,7

Regarding their corrosion protection values the systems show no differences with the exception of the failure pattern. The failure pattern is the weakest part of the coating system. System A shows cohesion failures in the 2nd layer, system B shows cohesion failures in the 1st and 2nd layer and system C shows mainly cohesion failures in the 4th layer. A negative influence of storage stability on the corrosion protection values could not be detected.

2.2 Slip factor tests

Slip load tests for three test series were performed to evaluate the coating system ESI for a use in slip-resistant connections, according to the test procedure to determine the slip factor acc. to EN 1090-2, Annex G [5]. Table 2.2-1 summarizes the performed tests. Specimens with ESI system A has been conditioned for 3 week while system B and C has been conditioned for 1 week by using an expired batch for System B.

Table 2.2-1: Test matrix

system	coating	conditioning	batch	∑t clamp length of connection	notation	slip load tests	creep (step) test	ECT[1)]
		[week(s)]		[mm]				
A	ESI	3	new	48 mm	A-ESI-3-n	4	1	1
B	ESI	1	old	48 mm	B-ESI-1-o	4	1	2
C	ESI	1	new	48 mm	C-ESI-1-n	4	1	-

[1)] ECT – Extended Creep Test
Bolting System: Bolt dimensions: HV-M20x75, 10.9, k-class K1, Test specimen acc. EN 1090-2 Annex G "M20"
tightening on defined preload in two steps: 1. step 100 kN 5min setting, 2. step $F_{p,C}$ = 172 kN
test velocities: Slip Load Test: v = 0.004 mm/s, Step Test: v = 1 kN/s, Extended Creep Test: v = 1 kN/s

The tests were performed in the same way as prescribed in Task 1.1 and evaluated with the new criterion of the slip load prescribed in Task 1.3. The test campaign requires as well extended creep tests (ECT) to ensure the slip factor under sustained loads. Therefore the new invented step test (prescribed in Task 1.4) was performed to define a first load level for the ECT. This method is new and developed within this project. It helps to find a load level for an ECT as this is not yet prescribed in the Annex G of EN 1090-2 [8.5-4]. The specimen is shown in Figure 2.2-1.

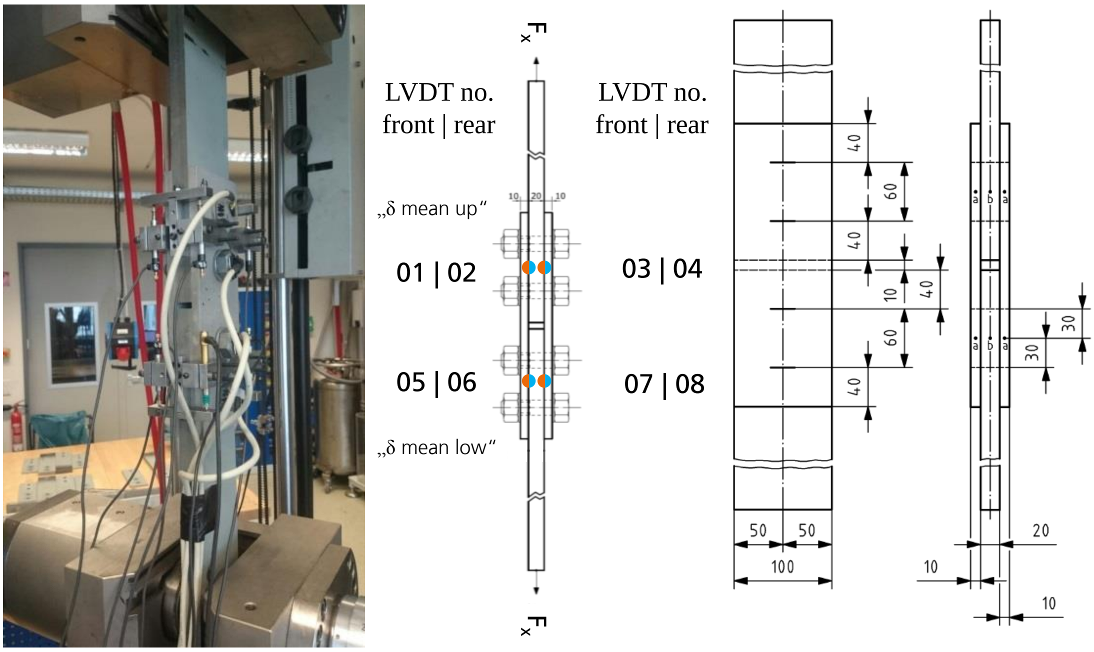


Figure 2.2-1: M20-test specimen according to Annex G of EN 1090-2 [8.5-4] and LVDT position

For measuring the displacement four LVDTs were mounted in the upper and lower part of the connection (see Figure 2.2-1). The evaluation of the slip load F_{Si} is based on these displacement measurements while taking four values to the mean value. The mean value of the displacement measurements of the upper connection is based on LVDT No. 01, 02, 03 and 04. The mean value of the displacement measurements of the lower connection is based on LVDT No. 05, 06, 07 and 08. The slip load-displacement curves for the test series A-ESI-3-n are shown in Figure 2.2-2.

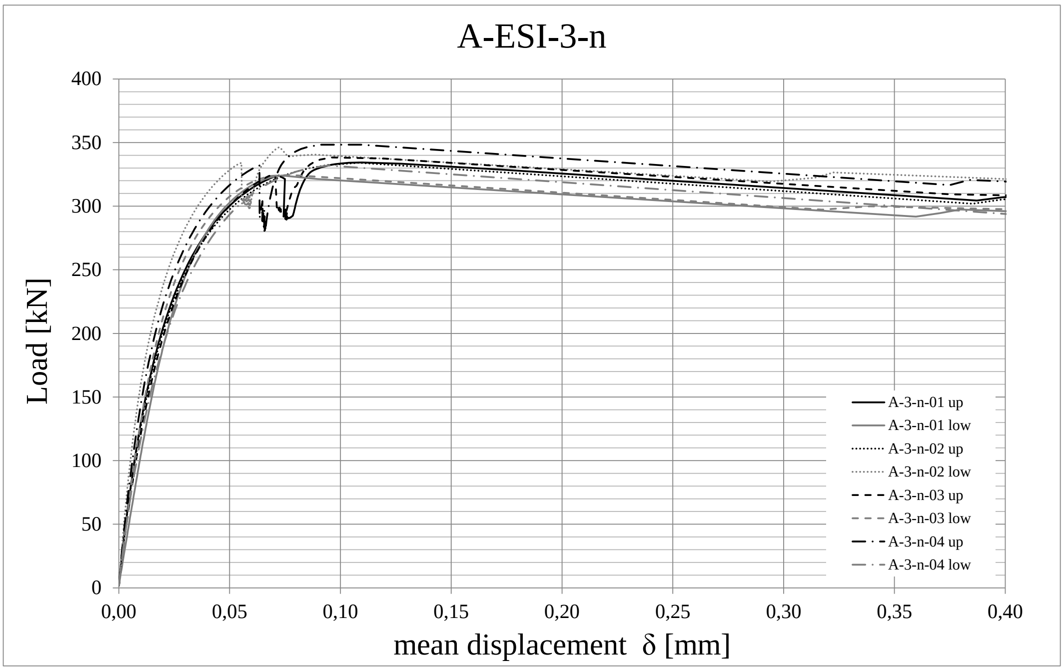


Figure 2.2-2: Slip load-displacement curves of test series A-ESI-3-n

The evaluation of the slip load tests is given in Table 2.2-2.

Table 2.2-2: Results on slip load test of test series A-ESI-3-n

specimen	part	$F_{p,C,start\_01}$	$F_{p,C,start\_02}$	$F_{p,C,slip01}$	$F_{p,C,slip02}$	$F_{Si,max}$	$\mu_{start,Fs-max}$	$\mu_{actual,Fs-max}$
		[kN]	[kN]	[kN]	[kN]	[kN]	[-]	[-]
A-3-n-01	up	160.4	161,2	151.9	145.5	334.4	0.52	0.56
	low	164.5	159.0	147.3	151.9	324.1	0.50	0.54
A-3-n-02	up	161.4	160.7	147.9	142.5	334.3	0.52	0.58
	low	161.6	160.2	143.5	134.4	346.4	0.54	0.62
A-3-n-03	up	163.7	162.6	156.7	150.4	338.7	0.52	0.55
	low	158.1	163.5	136.6	147.0	324.8	0.51	0.57
A-3-n-04	up	163.5	161.2	152.7	147.3	348.9	0.54	0.58
	low	159.5	163.0	138.7	145.9	332.2	0.51	0.58
	x	161.6	161.4	146.9	145.6	335.5	0.52	0.57
	Vx	1.37%	0.95%	4.75%	3.70%	2.68%	2.55%	4.31%

The mean slip factor $\mu_{start,Fs-max}$ results from the preload at the beginning of test as prescribed in EN 1090-2, Annex G and the slip load $F_{Si,max}$ is $\mu_{start,Fs-max}$ = 0.52. The faying surfaces of the specimens before and after testing is shown in Figure 2.2-3.

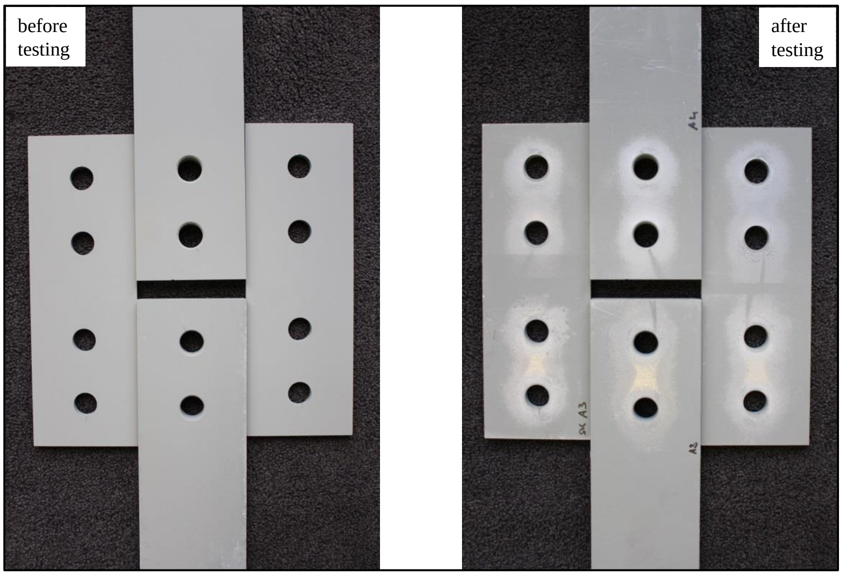


Figure 2.2-3: Faying surfaces of specimen with the coating system A-ESI-3-n

Around the holes the pressure contact areas which results from the preload of the bolts and which are responsible for the transmission of the acting shear load by friction are visible.

The ongoing procedure is the (creep) step test. The load-time-displacement behaviour is shown in Figure 2.2-4 for the step test A-ESI-3-n.

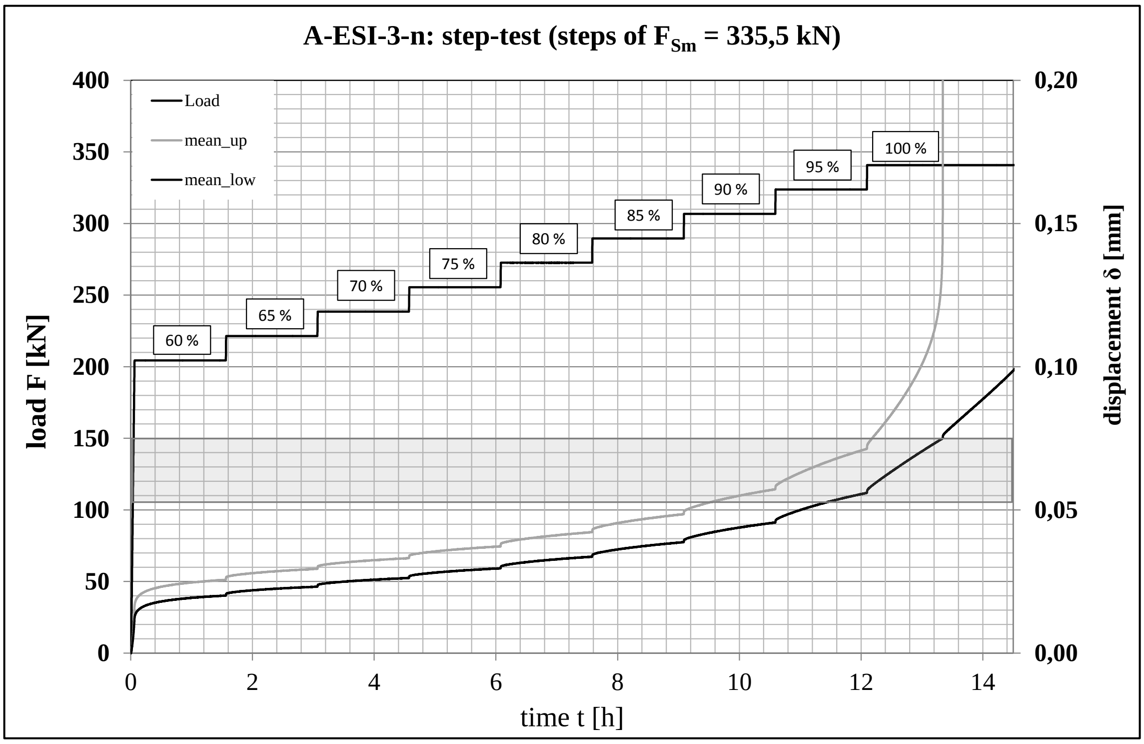


Figure 2.2-4: Load-time-displacement curve of the step test of specimen with A-ESI-3-n

The load-time-displacement behaviour shows an increase of the displacement (right ordinate) while incrementally increasing the test load in steps of 5 % of F_{Sm} from Table 2.2-2 (left ordinate). The whole procedure is explained in Task 1.4 more detailed. The highlighted grey area shows the displacement area in which the slip load tests (curves displayed in Figure 2.2-2) failed. Choosing the load level below the “failure area” for an extended creep test (ECT), the test will pass the requirements of EN 1090-2, Annex G.5. During the load level of 90 % F_{Sm} the displacement measurements will reach the highlighted grey area. This indicates the failure of the step test and for an extended creep a load level below this 90 % shall be chosen. In this case the load level of 80 % · F_{Sm} = 80 % · 335.5 kN. During the evaluation process a number mixed up that was corrected after testing. That means the chosen load for the ECT shown in Figure 2.2-5 corresponds to 81.3 % of F_{Sm}.

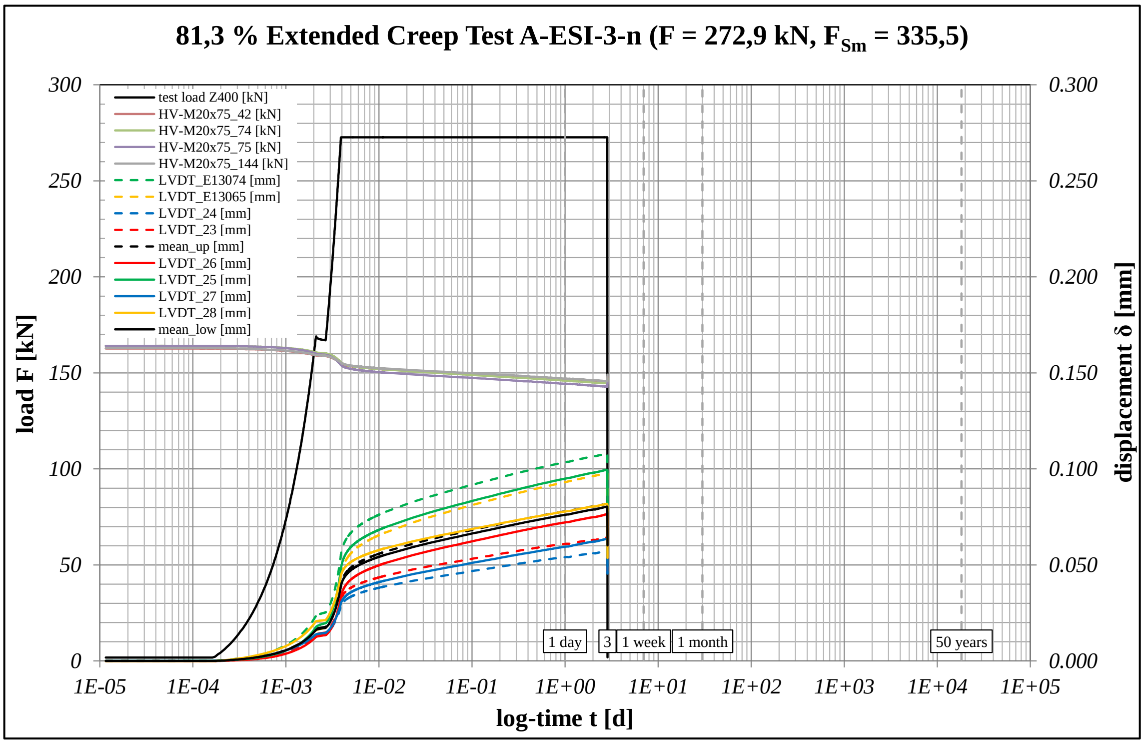


Figure 2.2-5: Extended creep test (ECT) with 81.3 % load of F_{Sm} for the specimen A-ESI-3-n

The result of the ECT (Figure 2.2-5) shows that the presented slip factor in Table 2.2-2 $\mu_{start,Fs\text{-}max}$ = 0.52 has to be reduced by the factor 0.81. The remaining slip factor for this coating system A-ESI-n is 0.81 · 0.52 = 0.42.

The Figure 2.2-6 shows the slip load-displacement curves of the test series B-ESI-1-o and C-ESI-1-n.

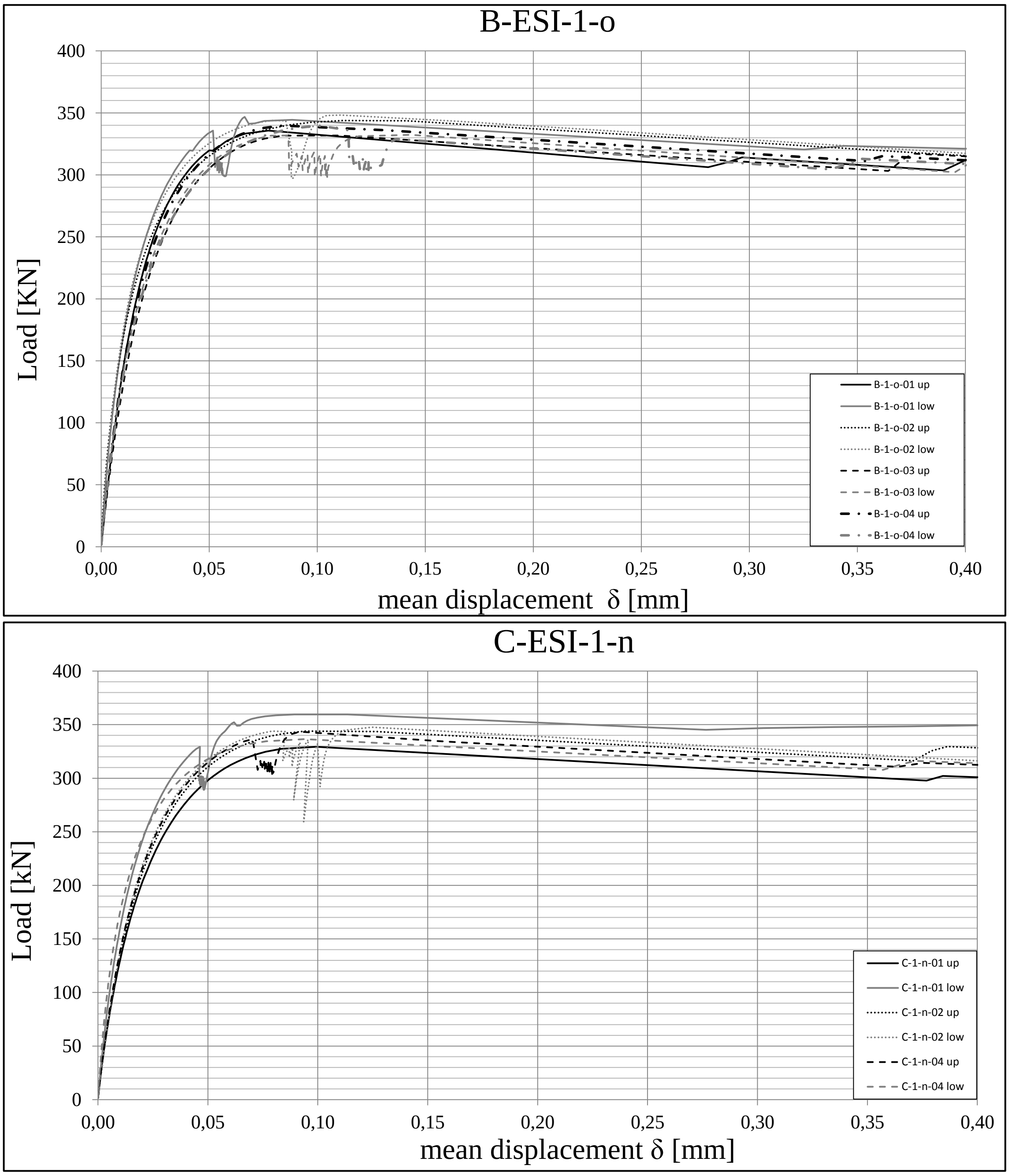


Figure 2.2-6: Slip load-displacement curves of the test series B-ESI-1-o and C-ESI-1-n

Both diagram of Figure 2.2-6 show the same slip load-displacement behaviour as A-ESI-3-n curves. That indicates a similar performance of the coating systems in slip-resistant connections. The evaluation of the test data is summarized in Table 2.2-3.

Table 2.2-3: Results of slip load test of test series B-ESI-1-o and C-ESI-1-n

specimen	part	$F_{p,C,start\_01}$ [kN]	$F_{p,C,start\_02}$ [kN]	$F_{p,C,slip\_01}$ [kN]	$F_{p,C,slip\_02}$ [kN]	$F_{Si,max}$ [kN]	$\mu_{start,Fs\text{-}max}$ [-]	$\mu_{actual,Fs\text{-}max}$ [-]
B-1-o-01	up	161.9	160.1	147.8	144.9	335.9	0.52	0.57
	low	163.1	169.8	147.5	158.8	346.8	0.52	0.57
B-1-o-02	up	160.7	161.2	147.8	142.1	344.2	0.53	0.59
	low	165.5	162.0	145.2	147.8	348.4	0.53	0.59
B-1-o-03	up	162.1	160.9	150.6	145.8	332.5	0.51	0.56
	low	164.4	162.3	145.7	150.2	332.6	0.51	0.56
B-1-o-04	up	163.0	168.1	148.1	151.9	340.0	0.51	0.57
	low	166.7	164.1	148.9	147.1	329.0	0.50	0.56
	x	163.4	163.6	147.7	148.6	338.7	0.52	0.57
	V_x	1.22%	2.18%	1.14%	3.45%	2.14%	2.34%	2.59%
C-1-n-01	up	163.0	163.0	151.4	149.2	329.3	0.51	0.55
	low	164.7	167.3	146.3	142.2	359.9	0.54	0.62
C-1-n-02	up	162.7	162.2	147.7	144.1	344.7	0.53	0.59
	low	162.5	164.6	144.9	152.3	347.7	0.53	0.58
C-1-n-03	up	161.0	160.9	147.6	144.1	335.4	0.52	0.57
	low	161.6	159.8	138.4	142.5	328.4	0.51	0.58
C-1-n-04	up	162.4	163.0	150.6	147.9	343.9	0.53	0.58
	low	162.8	161.8	149.5	152.3	336.6	0.52	0.56
	x	162.6	162.8	147.0	146.8	340.7	0.52	0.58
	Vx	0.68%	1.43%	2.81%	2.85%	3.07%	2.29%	3.94%

As a result all three tested ESI coating systems have the same slip factor out of the slip factor tests. For the series B-ESI-1-o curves of the step test is shown in Figure 2.2-7.

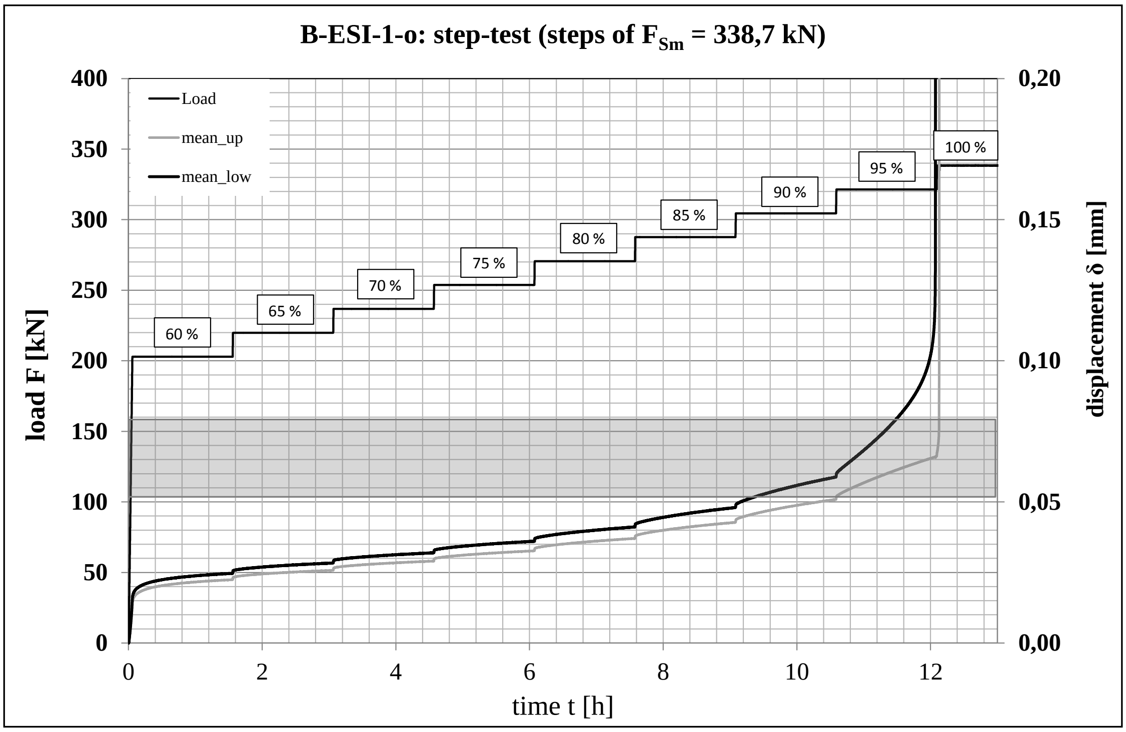


Figure 2.2-7: Load-time-displacement curve of the step test of specimen with B-ESI-1-o

The grey failure area is taken from the slip load tests. If testing the specimen in an ECT with a load level below/near this area the "limit load" to pass the test can be found. In this case 80 % of F_{Sm} seems most reasonable. Figure 2.2-8 shows the load-log time-displacement curves.

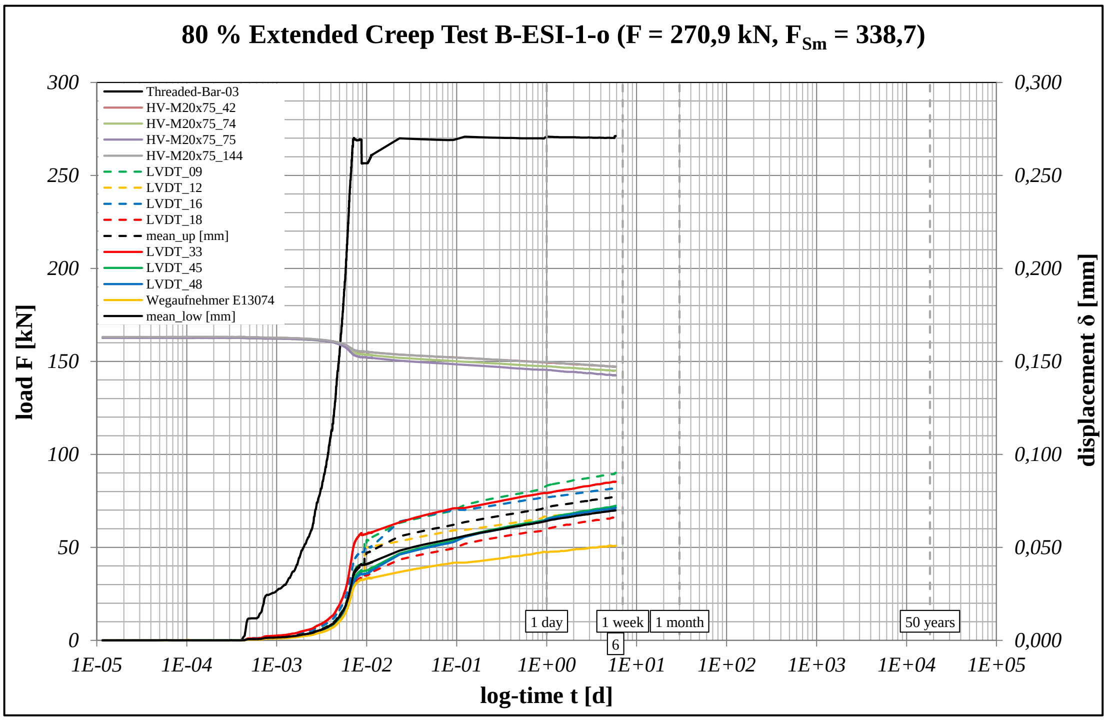


Figure 2.2-8: Load-log-time-displacement of the extended creep test (ECT) with 80 % load of F_{Sm} for specimen B-ESI-1-o

The failure criterion acc. to EN 1090-2, Annex G.5 is given with a displacement of 0.3 mm within 50 years or the life time of the structure. It shall be shown that the measured displacements in Figure 2.2-8 will not exceed the 0.3 mm criterion (right ordinate) within 50 years. To proof this results there have been performed a second ECT with 85 % of F_{Sm}. The load-log-time-displacement curve is shown in Figure 2.2-9.

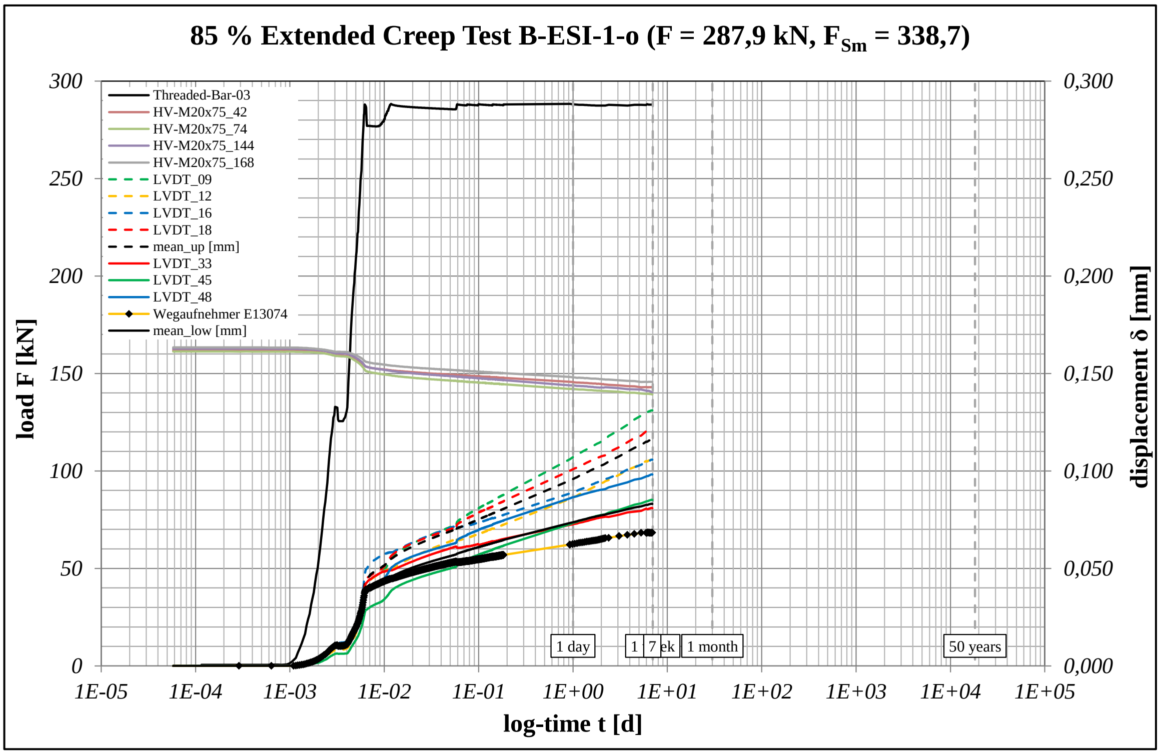


Figure 2.2-9: Load-log time-displacement of the extended creep test (ECT) with 85 % load of F_{Sm} for specimen B-ESI-1-o

The 85 % ECT in Figure 2.2-9 has to be evaluated as “not passed” because of the increasing displacements (dashed lines) of the upper part of the connection. This part of the connection will exceed the 0.3 mm criterion with the 50 years. A comparison of the three coating systems of their load-displacement is shown in Figure 2.2-10.

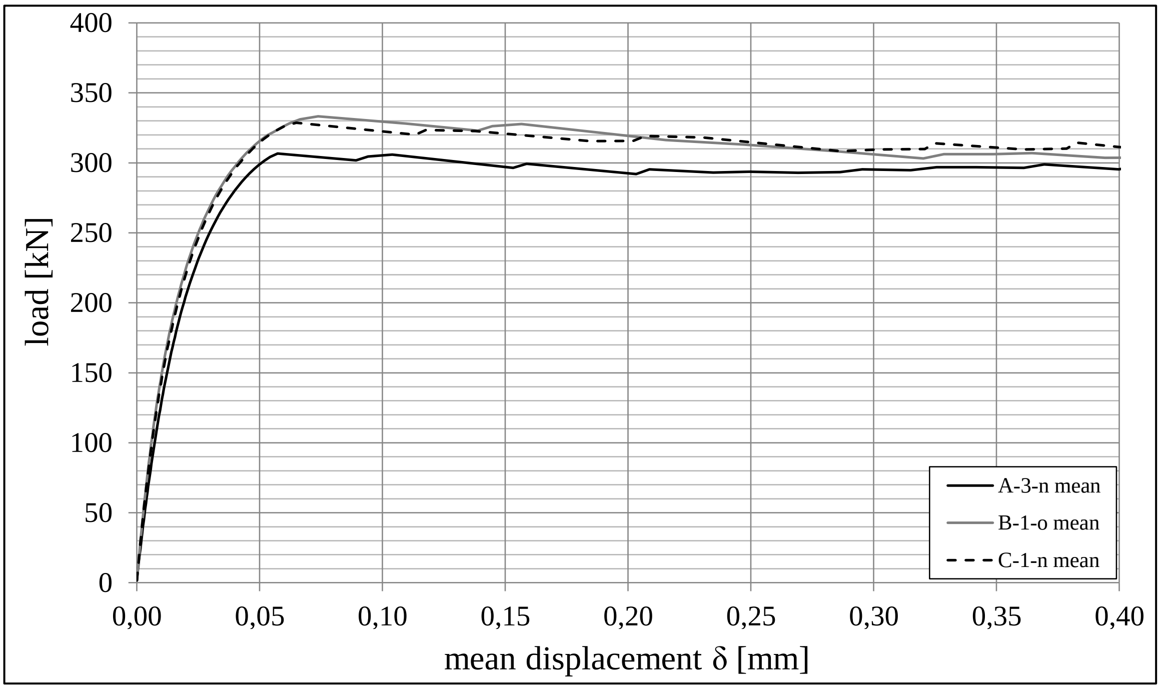


Figure 2.2-10: Comparison of the slip load- mean displacement curves of the three test series A-ESI-3-n, B-ESI-1-o and C-ESI-1-n

The three coating systems behave in a similar way during the slip load tests plotted in the slip load- mean displacement diagram of Figure 2.2-10. The failure of the slip-resistant connections occurs at a displacement between δ = 0.06 mm…0.07 mm.

3 Conclusion

In this investigation (Task 4.3 of SIROCO Project) ethyl-silicate-zinc ESI is tested due to the use in slip-resistant connections. The conditioning of the samples after application, especially the temperature and relative humidity, may have an effect on the slip factor and the corrosion protection. The conditions during storage are as well part of investigation. These influences were investigated with regard to the slip factor and the corrosion protection.

Regarding their corrosion protection values the systems show no differences with the exception of the failure pattern. The failure pattern is the weakest part of the coating system. System A shows cohesion failures in the 2nd layer, system B shows cohesion failure in the 1st and 2nd layer and system C shows mainly cohesion failures in the 4th layer. An negative influence of storage stability on the corrosion protection values could not be detected.

A final conclusion is that there is no influence on the slip factor due to the different conditioning times and storage times. The final slip factor for series A and B was evaluated from the results of the extended creep tests with μ = 0.42. The loads for those tests were determined by the new invented step test.

List of References

[1] DIN EN ISO 9227:2017-07, *Corrosion tests in artificial atmospheres - Salt spray tests (ISO 9227:2017); German version EN ISO 9227:2017.*

[2] ISO 6270-1:2017-11, *Paints and varnishes - Determination of resistance to humidity - Part 1: Condensation (single-sided exposure).*

[3] DIN EN ISO 4624:2016-08, *Paints and varnishes - Pull-off test for adhesion (ISO 4624:2016); German version EN ISO 4624:2016.*

[4] ISO 2808:2007-05, *Paints and varnishes - Determination of film thickness (ISO 2808:2007); German version EN ISO 2808:2007.*

[5] DIN EN 1090-2:2011-10, *Execution of steel structures and aluminium structures - Part 2: Technical requirements for steel structures; German version EN 1090-2:2008+A1:2011.*