INSTITUTE FOR
Metal and Lightweight Structures
Prof. Dr.-Ing. habil. Natalie Stranghöner
Universitätsstr. 15 | D-45141 Essen | Fon: +49 (0)201 183-2757 | Fax: +49 (0)201 183-2710
E-Mail: iml@uni-due.de | www.uni-due.de/iml

UNIVERSITÄT DUISBURG ESSEN
Open-Minded

Faculty of Civil Engineering and Geosciences, Department of
Steel and Composite Structures
Prof. Dr. Milan Veljkovic
Stevinweg 1 | 2628CN Delft, Netherlands | Phone: +31 (0)152784034
E-Mail: P.A.devries@tudelft.nl | www.tudelft.nl/citg

TU Delft
Delft University of Technology

Slip factors for typical stainless steel surface finishes and new types of coatings for stainless steel

Deliverable report D6.2

WP 6 – Task 6.2 and Task 6.3

Prof. Dr.-Ing. habil. Natalie Stranghöner
natalie.stranghoener@uni-due.de

Nariman Afzali M.Sc.
nariman.afzali@uni-due.de

Peter de Vries M.Sc.
p.a.devries@tudelft.nl

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

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1 Scope of investigation

The use of stainless steel components can lead to a significant reduction of maintenance costs compared to a structure executed in carbon steel. Because of its high material strength, ductility and corrosion resistance stainless steels are becoming more and more popular as a construction material in both building and civil engineering structures. Consequently, slip-resistant bolted connections made of stainless steel are becoming more important. Slip-resistant bolted connections are used in joints where slip is not acceptable (because they are subject to reversal of shear load or any other reason) or in joints that are subject to cyclic shear load (to improve the fatigue class of the connecting plates). Existing design codes/standards do not specify slip factors for surface treatments of stainless steel grades, the minimum values of slip factors for common surface treatments/coatings that are specified in EN 1090-2 are exclusively valid for carbon steels. One of the reasons for this is that stainless steel alloys are thought to suffer more than carbon steels from time dependent behaviour (creep and relaxation) at room temperature. This could lead to higher preload losses and consequently to lower slip factors than used for carbon steels with comparable surface treatment. However, no evidence of this can be found in literature. Creep and relaxation are stress dependant phenomena and the stresses in the components of preloaded bolted connections are locally highly non-uniform. Therefore, slip factors of different stainless steel grades have to be determined by experiments to investigate the effects of time dependant material behaviour. In this investigation, the results of slip factor tests on four stainless steel grades are presented and the influence of surface treatments and the preload level on the slip factor of stainless steel slip-resistant connections is discussed.

2 State of the art

2.1 General

The slip resistance of bolted slip-resistant connections is mainly determined by two factors: the condition of the faying surfaces and the preload level of the bolts. EN 1090-2 [1] defines slip factors only for slip-resistant connections made of carbon steel. Slip-resistant connections made of stainless steel are not standardized. This means that an individual qualification is required to apply stainless steel slip-resistant connections, which clearly hinders the expansion of the use of stainless steel in civil engineering and building constructions. In the frame of the European research project “Execution and reliability of slip-resistant connections for steel structures using CS and SS” (SIROCO), funded by the Research Fund for Coal and Steel (RFCS) of the European Community (RFSR-CT-2014-00024), a comprehensive first investigation has been conducted to define design parameters and slip factors for preloaded joints made of stainless steel that are subjected to shear loading.

The behaviour of preloaded bolted assemblies made of stainless steel components is thought to be influenced by creep and relaxation more than carbon steels in that way that preload losses resulting from the time-dependant behaviour would have a negative influence on the long term slip resistance and would consequently lead to reduced slip factors in comparison to those used for slip-resistant connections made of carbon steel.

3 Experimental investigations

3.1 Pre-study

Additional slip factor tests as originally planned according to the Technical Annex were carried out for two different purposes. First purpose was to establish the requirements for the test specimens and the most appropriate grades of stainless steel to test. The second purpose was to the effectivity of the surface treatment methods on the slip factors / friction coefficients of stainless steel plates. Tests were carried out on the stainless steel plates that were used in an earlier phase of the project to preliminary study the slip behaviour of stainless steel with 'as rolled' surface treatment (so called 1D surfaces).

3.1.1 Establish the requirements for slip factor test

Two series of slip factor tests according to Annex G of EN 1090-2 were conducted to determine the slip coefficient of austenitic (1.4307) and duplex (1.4462 for 16 mm plates and 1.4401 for 8 mm plates) specimens. The test specimens consist of two inner plates (16 mm thickness) and two cover plates (8 mm thickness). Eight displacement transducers were used (as shown in Figure 1) to measure the relative displacement between an inner plate and a cover plate point, positions a and b as illustrated in Figure 1.

For each test specimen four HV bolts M16, class 10.9 were applied. All bolts were instrumented with a strain gauge embedded in a 2 mm hole along the bolt shank, see Figure 2. The preload level has been specified to $F_{p,C}$ = 110 kN.

According to Annex G of EN 1090-2, for each series four static tests were conducted displacement controlled at normal speed of 0.01 mm/s (see Figure 3) and one creep test to evaluate the long term effect of the slip-resistant connections. For the creep test, the fifth specimen was loaded with 90% of the average slip load from the first four static tests for at least 3 hours, see Table 11.4-1. The creep test is passed when the difference of the measured slip after five minutes and three hours after application of the constant load does not exceed 2 µm. When the difference exceeds 2 µm, at least three extended creep test have to be carried out. For the specimens made of austenitic steel two extended creep tests have been performed.

The individual slip factor μ_i, the mean slip factor μ_m are calculated as follows:

$$\mu_i = \frac{F_{si}}{4F_{P,c}}, \quad \mu_m = \frac{\sum \mu_i}{n}$$

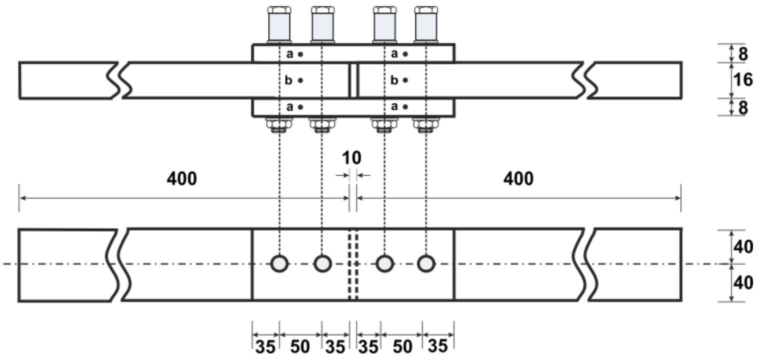


Figure 1 M16-test specimen according to Annex G of EN 1090-2

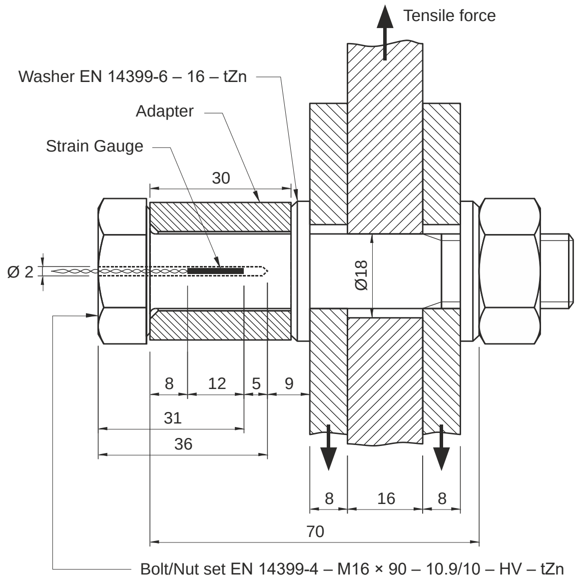


Figure 2 M16-Bolts with implanted strain gauges

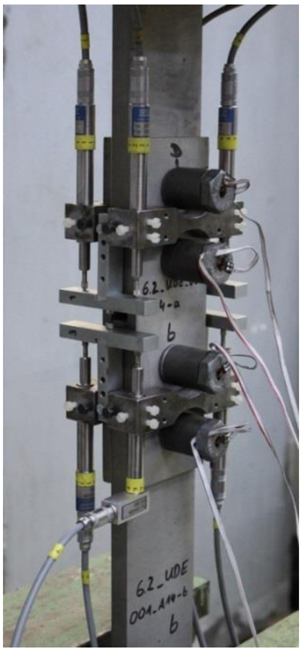
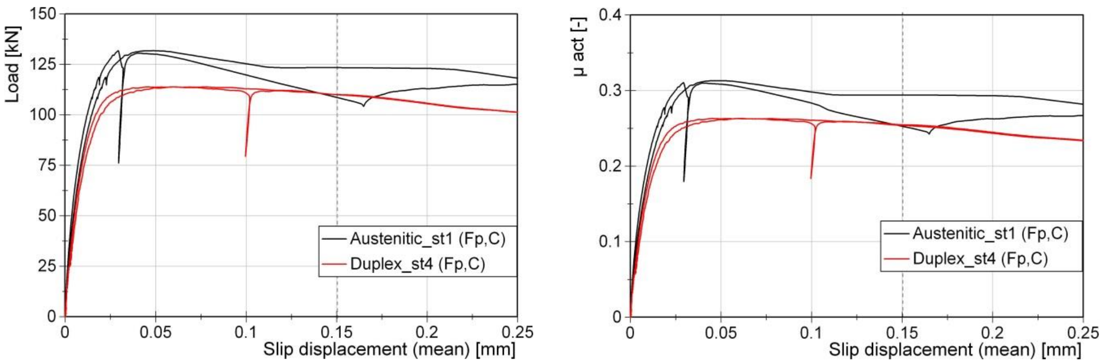


Figure 3 Test setup with eight LVDTs

Table 1 Test specimens and surface conditions

Series ID	Surface finish	Σt [1)] [mm]	$\Sigma t/d$ [2)] [-]	Preload [kN]	Number of tests st/ct/ect[3)]	$\mu_{ini,mean}$ [4)] st/st+ct [-]	$\mu_{act,mean}$ [5)] st/st+ct [-]	$V_{(\mu act)}$ [6)] st/st+ct [%]	Final slip factor $\mu_{5\%}$ [7)] / μ_{ect} [8)]
Austenitic-Pre	Hot rolled – 1D (as received)	70	4.4	$F_{p,C}/110$	4/1/2	0.31/-	0.32/-	2.1/-	-/0.15
Duplex-Pre					4/1/-	0.25/0.26	0.26/0.26	3.3/3.0	0.24/-

[1)] Σt: clamping length │ [2)] d = 16 mm (bolt diameter) │ [3)] st: static test/ct: creep-/ect: extended creep test │ [4)] $\mu_{ini,mean}$: calculated slip factors as mean values considering the initial preload when the tests started │ [5)] $\mu_{act,mean}$: calculated slip factors as mean values considering the actual preload at slip │ [6)] V: Coefficient of variation for μ_{act} │ [7)] $\mu_{5\%}$: slip factors as 5%-fractile calculated on the basis of the static tests and the passed creep test │ [8)] μ_{ect}: slip factor as the result from the passed extended creep test



a) load-slip-displacement-curve b) μ_{act}- slip-displacement-curve

Figure 4 Influence of different plate material on the slip-load behaviour and actual slip factors

It can be seen from Table 1 that the highest static initial and actual slip factors were achieved for austenitic specimens. Figure 4 shows typical load-slip-displacement- and μ_{act}- slip-displacement-curves. The higher slip factors for austenitic specimens cannot be explained only by the type of material. Some surface characteristics like e. g. the surface roughness play also an important role for slip resistance behaviour of the connection and the slip factor can be strongly influenced by the surface condition/treatment of the specimens. For this reason, more tests have to be performed to investigate the influence of the plate material on the slip resistance behaviour of the connection.

In the austenitic test series, the creep test was failed so that at least three extended creep tests were necessary to perform, see Figure 5.

The creep test was passed for the duplex test series, see Figure 6 and the characteristic value of the slip factor $\mu_{5\%}$ was calculated as the 5% fractile value equal to 0.24 with a confidence level of 75%.

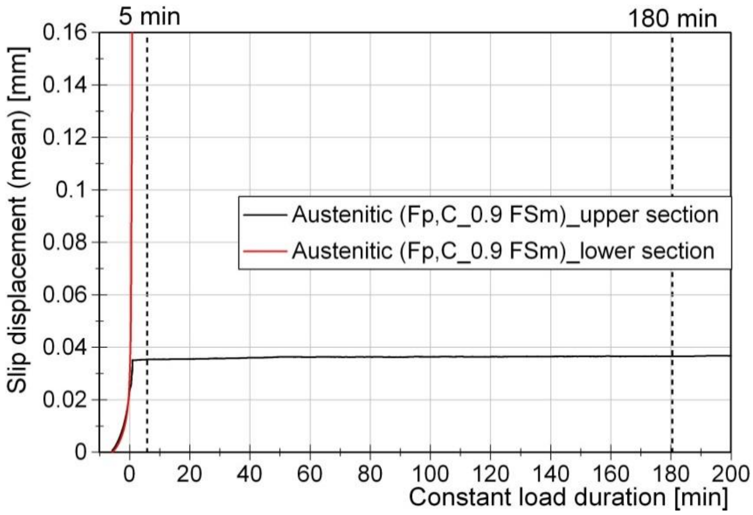


Figure 5 Time-displacement diagram of the creep test for the austenitic steel grade (A15 test specimen)

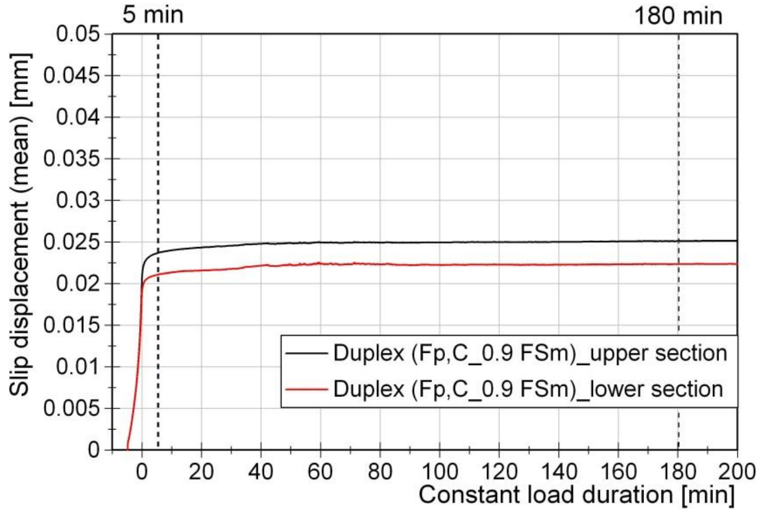


Figure 6 Time-displacement diagram of the creep test for the duplex steel grade (B15 test specimen)

For the austenitic specimens, it was necessary to perform at least three extended creep tests. Two extended creep tests have already been carried out .The specimens were loaded with 70 % and 50 % of the average slip force (F_{Sm}) obtained in the previous four static tests. One more extended creep test with 0.6 F_{Sm} will be carried out in future. The results of the tests are shown in the displacement - log time diagram in Figure 7. The extended creep test is passed for the load level of 0.5 F_{Sm}. The extrapolated displacement – log time curve shows less than 0.3 mm slip during 50 years. The nominal slip factor based on the passed extended creep test at 0.5 F_{Sm} is calculated as following:

$$\mu_{nom,Austenitic}(F_{p,C}) = \frac{0.5 \times F_{Sm}}{4 \times F_{v,nom}} = \frac{67.5\ kN}{4 \times 110\ kN} = 0.15\ [-].$$

It is still possible to achieve a higher slip factor by performing the third extended creep test with 0.6 F_{Sm}.

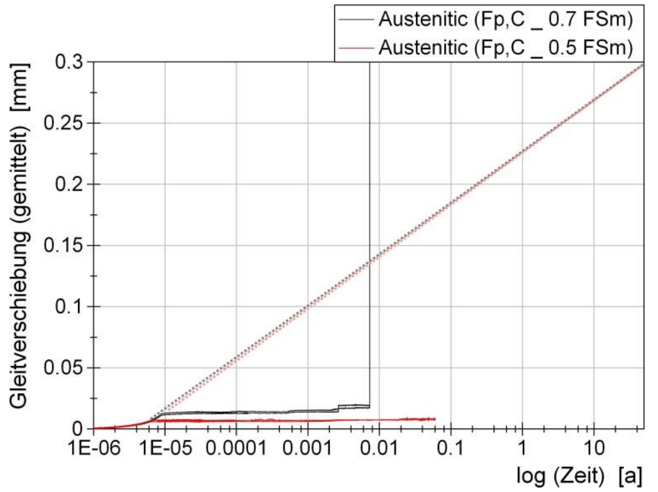


Figure 7 Extended creep tests for austenitic test specimens with different load level (0.7 F_{Sm} = 94.5 kN and 0.5 F_{Sm} = 67.5 kN)

3.1.2 Influence of different surface treatment

The results show that the slip resistant behaviour of both Austenitic and Duplex grades with 1D surfaces is poor (static slip factors of approx. 0.3 was found). It was decided to use the remaining specimens to examine:

- the effectiveness of grit / shot blasting
- Differences between Austenitic / Duplex grades
- Influence of blasting media

IKS performed the surface treatments and measurements of the resulting surface roughness of the plates, see Table 2.

Table 2 Test specimens and surface treatments

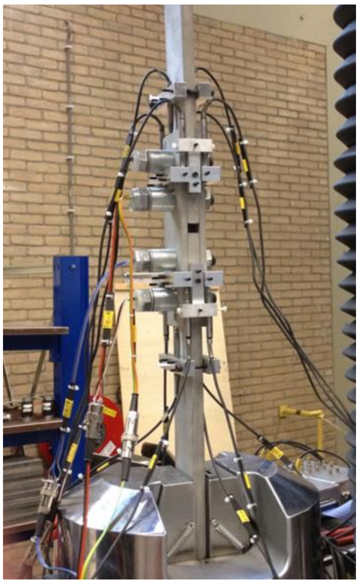
series ID	Stainless steel	Steel grade (centre / side plates)	Plate thickness (centre/side plates)	surface treatment	blasting abrasive	pressure	Rz Planned	Rz achieved (means)
A 1D	Austenitic	1.4307 / 1.4307	15.5 / 8.5	as rolled (1D)				
A T 50	Austenitic	1.4307 / 1.4307	15.5 / 8.5	grit blasted	Grittal GM30	2,0 bar	50	59
A 50	Austenitic	1.4307 / 1.4307	15.5 / 8.5	grit blasted	Grittal GM30	2,0 bar	50	58
D 50	(Super)Duplex	1.4462 / 1.4410	13.9 / 8.3	grit blasted	Grittal GM30	2,5 bar	50	44
D 40	(Super)Duplex	1.4462 / 1.4410	13.9 / 8.3	shot blasted	Chronital S40	4,5 bar	40	36

Remarks on the surface treatment results:

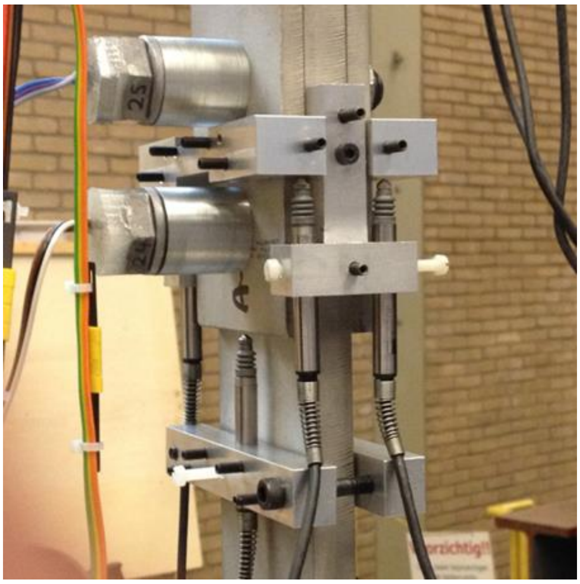
- Austenitic: Blasting chamber was used at minimum pressure, nevertheless Rz gets > 50 µm with Grittal GM30

- Duplex, despite high pressure, it was not possible to achieved Rz > 36 µm with the Chronital S40 shot

The geometry of the specimens was according to EN1090-2 annex G, for M16 bolts. Short term slip factor tests and creep tests were carried out on the specimens. Carbon steel bolts M16 HV10.9 were used, nominally preloaded to 100 kN. Through the use of protection sleeves the clamp length of the bolts was 70 mm. Slips were measured at both PE and CBG positions (Figure 8). Stroke controlled load application was used at a rate of 0.001 mm/s, which resulted in a test duration of 10 to 15 minutes.



Instrumented slip factor specimen in test rig. Slip was measured at both PE and CBG positions



Carbon steel M16 HV10.9 bolts with protection sleeves were used for the slip factor tests on the stainless steel plates

Figure 8 Test setup

The results of the short term slip factor tests for the various series stainless steel plates are presented in Table 3. An overview of all test results for the stainless steel plates can be found in Table 4. The result of the creep test indicate that the tested stainless steel plate materials are not creep sensitive (limited number of test results available, see Table 5)

Table 3 results preliminary slip factor tests on stainless steels with different surface treatments

Stainless steel			friction coefficient			preload $loss_{test}$		
grade	series	$F_{p,init}$	μ_{actual}	$\mu_{Fp,init}$	$\mu_{Fp,C}$	group	outer bolt	inner bolt
		[kN]	[-]	[-]	[-]	%	%	%
Austenitic (1.4307)	A 1D	98	0.31	0.30	0.29	3%	3%	3%
		97	0.31	0.30	0.29	3%	3%	4%
		96	0.32	0.31	0.30	3%	3%	3%
		96	0.32	0.31	0.30	3%	3%	3%
		97	0.32	0.30	0.29	4%	3%	5%
		97	0.31	0.30	0.29	4%	3%	4%
	mean	**97**	**0.31**	**0.30**	**0.29**	**3%**	**3%**	**4%**
	COV	1%	2%	2%	1%	14%	12%	15%

Stainless steel			friction coefficient			preload $loss_{test}$		
grade	series	$F_{p,init}$	μ_{actual}	$\mu_{Fp,init}$	$\mu_{Fp,C}$	group	outer bolt	inner bolt
		[kN]	[-]	[-]	[-]	%	%	%
Austenitic (1.4307)	AT50	98	0.54	0.50	0.49	7%	6%	8%
		99	0.50	0.47	0.46	6%	5%	6%
		99	0.59	0.54	0.54	8%	7%	9%
		98	0.64	0.58	0.57	9%	8%	10%
	mean	**99**	**0.57**	**0.52**	**0.52**	**7%**	**7%**	**8%**
	COV	0%	11%	9%	9%	20%	21%	20%
Austenitic (1.4307)	A50	98	0.46	0.43	0.42	6%	6%	6%
		98	0.57	0.51	0.49	11%	10%	13%
		97	0.60	0.55	0.53	9%	8%	10%
		98	0.64	0.57	0.56	11%	9%	13%
	mean	**98**	**0.57**	**0.51**	**0.50**	**9%**	**8%**	**10%**
	COV	0%	14%	12%	12%	26%	22%	31%

Stainless steel			friction coefficient			preload $loss_{test}$		
grade	series	$F_{p,init}$	μ_{actual}	$\mu_{Fp,init}$	$\mu_{Fp,C}$	group	outer bolt	inner bolt
		[kN]	[-]	[-]	[-]	%	%	%
Duplex (1.4462/1.4410)	D50	100	0.72	0.67	0.67	6%	5%	6%
		101	0.68	0.65	0.65	6%	5%	6%
		100	0.60	0.57	0.58	4%	4%	5%
		101	0.60	0.57	0.58	4%	4%	5%
	mean	**100**	**0.65**	**0.62**	**0.62**	**5%**	**4%**	**6%**
	COV	1%	9%	8%	8%	17%	19%	15%

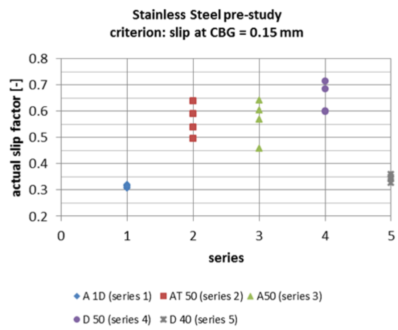
Stainless steel			friction coefficient			preload $loss_{test}$		
grade	series	$F_{p,init}$	μ_{actual}	$\mu_{Fp,init}$	$\mu_{Fp,C}$	group	outer bolt	inner bolt
		[kN]	[-]	[-]	[-]	%	%	%
Duplex (1.4462/1.4410)	D40	100	0.36	0.35	0.35	3%	3%	3%
		100	0.34	0.33	0.33	2%	2%	3%
		100	0.35	0.34	0.34	2%	2%	2%
		100	0.33	0.32	0.32	2%	2%	3%
	mean	**100**	**0.35**	**0.34**	**0.34**	**2%**	**2%**	**3%**
	COV	0%	4%	4%	4%	8%	13%	8%

Table 4 Overview results preliminary tests on stainless steel plates

Stainless series									
series	sample ID	EN 1090 suggested creep load (SCL)	load during creep test (CL)	CL/SCL	preload loss during creep test (3 hours)	slip at CBG	slip at PE	slip at PE - slip at CBG	result creep test
		[kN]	[kN]		[%]	[mm]	[mm]	[mm]	
AT 50	AT_02	186	150	0.81	1.4	0.2	3.6	3	passed
					1.5	0.5	3.4	3	passed
A50	A_50_04	181	180	0.99	1.4	1.8	6.3	5	passed
					1.3	2.1	6.2	4	failed
D50	D_50_03	223	195	0.87	0.4	0.6	2.5	2	passed
					0.4	0.6	2.2	2	passed
D40	D_40_03	121	110	0.91	1.4	1.2	1.7	1	passed
					1.5	1.1	1.9	1	passed

Table 5 Results of creep tests

Stainless Steel pre-study							
series	# tests		results short term tests		test results including creep test		characteristic value acc. to Annex G
	short term	creep	m_{actual}		m_{actual}		$m_{actual,k}$
			mean	COV	mean	COV	
A 1D	6	0	0.31	2%	-	-	-
AT 50	4	2	0.57	11%	0.55	10%	-
A 50	4	2	0.57	14%	0.57	11%	-
D 50	4	2	0.65	9%	0.67	8%	0.55
D 40	4	2	0.35	4%	0.35	4%	0.32



The results show that:

- The effectiveness of grit blasting with Grittal is significant for both Austenitic and Duplex grades
- Despite lower roughness of the surface, the slip resistance of grit blasted Duplex 1.4462/1.4410 plates is higher than Austenitic 1.4307 plate
- For Duplex 1.4462 / 1.4410 shot blasting with Chronital is hardly effective

Spread in results of the slip factor test for SS is larger than found for CS plates

3.2 Slip factor test according to Technical Annex

In the frame of SIROCO, slip factor tests were carried out to determine slip factors for different grades of stainless steel with different surface finishes. Four grades of stainless steel were tested: austenitic (1.4404) (A), duplex (1.4462) (D), lean-duplex (1.4162) (LD) and ferritic (1.4003) (F) stainless steel. Table 1 summarizes the measured material properties of the investigated stainless steel plates.

Table 6 Measured material properties of the stainless steel plates acc. to inspection certificate 3.1

Series	Grade	Part	Width [mm]	Thickness [mm]	$R_{p0.2}$ [N/mm²]	R_m [N/mm²]	A_5 %	HB HBW
Austenitic	1.4404	inner plate	80	15.4	266	585	61%	nm²⁾
		cover plate		7.95	284	592	52%	168
Ferritic	1.4003	inner plate ¹⁾		16.3	340	517	25%	85
				16.3	453	596	25%	82
		cover plate		8.07	362	488	28%	77
Lean Duplex	1.4162	inner plate		15.2	552	728	35%	238
		cover plate		8.65	570	730	38%	228
Duplex	1.4462	inner plate		15.4	538	788	34%	nm
		cover plate		8.06	638	712	33%	257

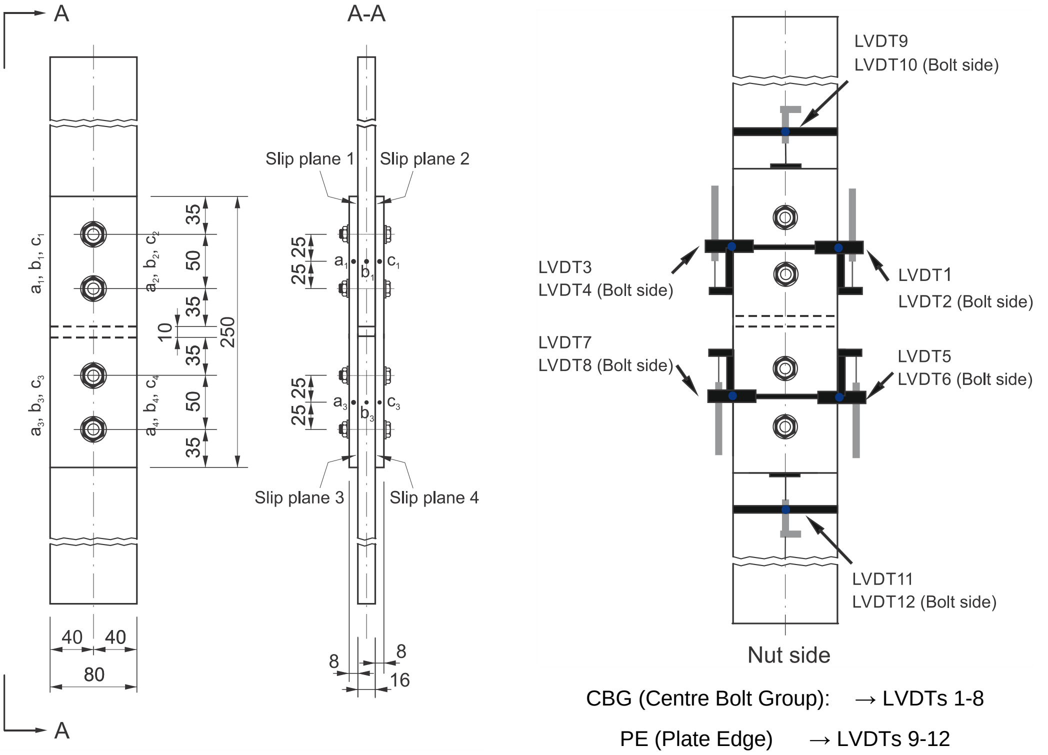
1) For the ferritic series, the specimens were cut from two different steel plates. The yield and ultimate stresses of both plates differed significantly. It is unclear which specimens originate from each plate
2) The surface hardness was not available on all material certificates.

The main focus of the investigations was on the influence of the different surface treatments on the resulting slip factor for the various stainless steel grades. Indicative tests series, carried out at the beginning of the test programme, had shown that grit blasting results in the highest slip factor. Therefore, it was decided to test the grit blasted (GB) surface condition for all four stainless steel grades. To compare the influence of different surface treatments, the austenitic series was tested additionally for two further surface conditions: as delivered/rolled (1D) and shot blasted (SB). Furthermore, additional investigations were carried out for an aluminium spray metalized coating (Al-SM), which was applied at all stainless steel grades in order to investigate its ability to achieve higher slip-factors.

3.2.1 Test procedure according to Annex G of EN 1090-2

The slip factor test of Annex G of EN 1090-2 consists of a three steps test procedure by using a predefined standard specimen (M16 or M20). The geometry of the test specimen used was according Annex G of EN 1090-2 for M16 bolts, see Figure 1(a). The specimen consists of two centre plates and two lap plates connected by four M16 bolts. Due to the limited range of available plate thicknesses in some stainless steel grades, the nominal plate thickness of some inner plates deviated from the M16-standard specimen inner plate thickness of 16 mm by max. 0.8 mm (see Table 1). As this difference is relatively small, it was accepted.

In the first step of the slip factor test procedure, four static slip factor tests have to be carried out and the slip has to be measured as the relative displacement between specific points of the inner (b) and cover plate (a and c), as shown in Figure 1(a). The stiffness of the slip-deformation-behaviour is much higher when measured with displacement transducers (LVDTs) 1-8 positioned in the centre of the bolt group (CBG position) than using the LVDTs 9-12 positioned at the plate edges (PE position), see Figure 1(b). Elastic elongation and possible creep deformation of the centre plates cause differences between the slip measurements at PE and CBG positions. Furthermore, large differences in the slip load can result when the 0.15 mm slip criterion is used for evaluation.



(a) Test specimen according to EN 1090-2, Annex G, for M16 bolts

(b) Position of the displacement transducers at CBG- and PE-position (LVDTs)

Figure 9 Test specimen geometry for determining the slip factor according to DIN EN 1090-2, Annex G; test specimens for M16 bolts as well as the positions of the displacement transducers (LVDTs)

Performing both CBG and PE measurements during the static slip factor tests serves two goals: firstly, to gain insight in the creep deformation behaviour of the centre plates and secondly, to determine the deviation between the CBG and PE measurements. Based on this deviation, relation coefficients could be determined which were used in the following for the interpretation of the results of the extended creep tests in which the slip deformations were only measured in PE positions in order to reduce the amount of LVDTs.

In the current investigations, the slip loads F_{Si} were defined at 0.15 mm slip displacement or at the peak before 0.15 mm. The individual slip factor μ_i and the mean slip factor μ_m can be derived from Eq. (1) and (2), in which $F_{p,C}$ is the specified preload level ($F_{p,C} = 0.7 \cdot f_{ub} \cdot A_s$, with f_{ub}: tensile strength of the bolt and A_s: stress area of the bolt) and n the number of individual test results.

$$\mu_i = \frac{F_{Si}}{4 \cdot F_{p,C}}$$

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

Afterwards, the fifth test was carried out as a creep test with a constant load level of 0.9 F_{sm} (90 % of the mean slip load F_{sm} of the first four static tests). In case that the difference between the slip at 5 min and 3 hour exceed 0.002 mm, at least three extended creep tests are foreseen. For carbon steel specimens, the creep test is carried out to investigate the creep sensitivity of a coating or surface treatment. When the creep test is passed, no additional extended creep test is needed. As it is unclear if the EN 1090-2 criterion for judging the creep sensitivity also applies to slip-resistant connections made of stainless steel components, extended creep tests were conducted on all test series, independently of the outcome of the creep test.

In addition to the requirements of EN 1090-2, in the investigations presented here, the slip factors were also evaluated by considering the initial preload at the beginning of the test μ_{ini} and the measured actual preload at the onset of slip μ_{act}. All results are based on the slip measured in the centre bolt group (CBG) position.

3.2.2 Test program

Herewith, in total 20 test series with different stainless steel grades, surface treatments and preload levels were investigated. The test matrix is presented in Table 2. In this table all information regarding the surface preparation, clamp length of the bolting assemblies and preload levels can be found.

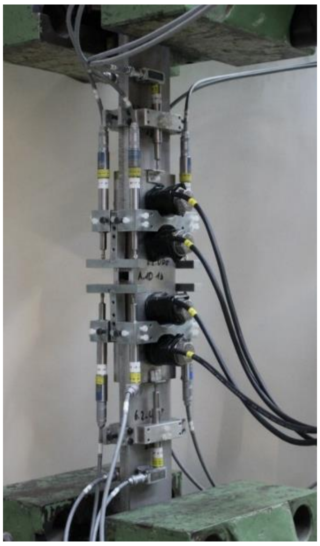
Table 7 Test programme

Series ID	Steel grade	Surface condition: Surface finish / Rz[1)] [µm]	Type of coating	Coating thickness [µm]	$\Sigma t^{2)}$ [mm]	Preload [kN]	Number of tests: st/ct/ect[3)]
M16 × 100 Bumax 88 (property class 8.8)							
A_1D_B88	1.4404	1D[4)] / 24	-	-	74	$F_{p,C}$/88	4/1/-
A_SB_B88	1.4404	SB[5)] / 38	-	-	74	$F_{p,C}$/88	4/-/-
A_GB_B88	1.4404	GB[6)] / 45	-	-	74	$F_{p,C}$/88	4/1/1
D_GB_B88	1.4462	GB / 47	-	-	74	$F_{p,C}$/88	4/1/1
LD_GB_B88	1.4162	GB / 41	-	-	74	$F_{p,C}$/88	4/-/-
F_GB_B88	1.4003	GB / 45	-	-	74	$F_{p,C}$/88	4/-/3
A_Al-SM_B88	1.4404	GB / 45	Al-SM	100[7)]	74	$F_{p,C}$/88	4/1/1
D_Al-SM_B88	1.4462	GB / 43	Al-SM	116[8)]	74	$F_{p,C}$/88	4/1/1
LD_Al-SM_B88	1.4162	GB / 51	Al-SM	105[8)]	74	$F_{p,C}$/88	4/1/1
F_Al-SM_B88	1.4003	GB / 44	Al-SM	91[8)]	74	$F_{p,C}$/88	4/1/1
M16 × 100 Bumax 109 (property class 10.9)							
A_1D_B109	1.4404	1D / 24	-	-	77	$F_{p,C}$/110	4/2/2
A_SB_B109	1.4404	SB / 34	-	-	77	$F_{p,C}$/110	4/2/1
A_GB_B109	1.4404	GB / 41	-	-	77	$F_{p,C}$/110	4/2/1
D_GB_B109	1.4462	GB / 47	-	-	77	$F_{p,C}$/110	4/2/2
LD_GB_B109	1.4162	GB / 40	-	-	77	$F_{p,C}$/110	4/2/1
F_GB_B109	1.4003	GB / 42	-	-	77	$F_{p,C}$/110	4/2/2
A_Al-SM_B109	1.4404	GB / 45	Al-SM	100[7)]	77	$F_{p,C}$/110	4/2/1
D_Al-SM_B109	1.4462	GB / 43	Al-SM	116[8)]	77	$F_{p,C}$/110	4/2/1
LD_Al-SM_B109	1.4162	GB / 51	Al-SM	105[8)]	77	$F_{p,C}$/110	4/2/1
F_Al-SM_B109	1.4003	GB / 44	Al-SM	91[8)]	77	$F_{p,C}$/110	4/2/1

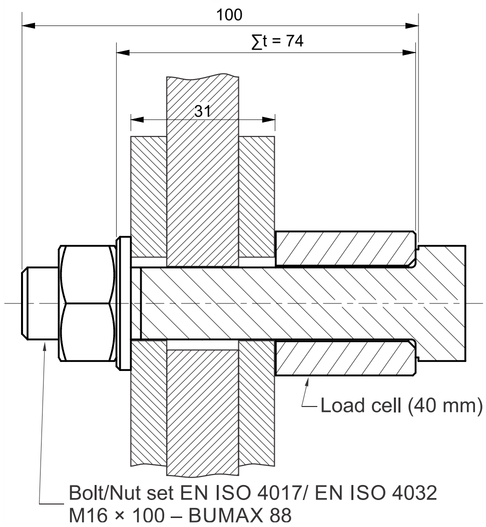
[1)] Rz: roughness | [2)] Σt: clamping length | [3)] st: static test/ct: creep-/ect: extended creep test | [4)] 1D surfaces | [5)] Shot blasted surfaces | [6)] Grit blasted surfaces | [7)] NDFT: nominal dry film thickness | [8)] DFT: dry film thickness (measured value)

The Al-SM test specimens were blasted and the surface roughness was measured according to EN ISO 4287 [3]. The measured roughness Rz of the faying surfaces before coating was determined to 43 µm to 51 µm. The nominal coating thickness for the austenitic (A_Al-SM) test series was 100 (NDFT). For the other test series, the coating thickness was measured according to ISO 2808 [4]. The measured coating thicknesses were about 116 µm, 105 µm and 91 µm for the duplex (D_Al-SM), lean-duplex (LD_Al-SM) and ferritic (F_Al-SM) test series respectively.

As the preload level is of great interest for the value of the final slip factor, two different kind of bolt classes and herewith preload levels were considered: bolt classes 8.8 and 10.9, austenitic stainless steel bolts. The bolt sets in slip-resistant connection have to be preloaded in order to activate the friction between the faying surfaces. For carbon steel connections, bolt sets that are especially developed for preloading are available within the series of EN 14399, e. g. HV- or HR-bolting assemblies [5], [6]. As currently comparable bolting assemblies made of stainless steel are neither standardized nor available on the market, for this investigation austenitic stainless steel bolting assemblies were used consisting of bolts according to EN ISO 4017 [7], nuts according to EN ISO 4032 [8] and washers according to EN ISO 7089 [9]. Ten test series were assembled with austenitic bolts M16 A4-88, austenitic nuts M16 A4-88, and washers 17-88, HV 200, A4 (all Bumax 88). For the other ten test series austenitic bolts M16 A4-109, austenitic nuts M16 A4-109 and washers 17-109, HV 300, A4 (all Bumax 109) were used. The Bumax 88 and Bumax 109 bolting assemblies are based on EN ISO 3506-1 [10] and EN ISO 3506-2 [11] but with property classes 8.8 and 10.9 according to EN ISO 898-1 [12] for carbon steel bolts, see [13]. All bolts were full threaded bolts. The resulting preload levels were $F_{p,C}$ = 88 kN for Bumax 88 and $F_{p,C}$ = 110 kN for Bumax 109. According to EN 1090-2, the preloads in the bolts have to be measured at the beginning of testing and adjusted to an accuracy of ± 5 %. In case of the presented slip factor tests, the preload in the bolts was measured by self-made small load cells instead of instrumented bolts in order to eliminate the influence of viscoplastic deformation on the measured preload level, see Figure 10.



(a) Test setup



(b) Clamped plates of a bolted connection with load cell

Figure 10 Test setup exemplary for the Bumax 88 and 109 – M16 specimens

To measure the preload in bolting assemblies, two common methods are available: (1) instrumented bolts (SG) and (2) load cells (LC). In previous studies it could be shown that the accuracy of instrumented bolts with implanted strain gauges for measuring the preload is very high for carbon steel bolting assemblies but they are not appropriable for stainless steel bolting assemblies. Due to the fact that in stainless steel bolting assemblies viscoplasticity occurs already during the preloading process of the stainless steel bolt. This leads to changes in the strain which are measured by the implanted strain gauges as well. That yields to deviating values in comparison to the real preload level. This phenomenon is not observed in carbon steel bolting assemblies due to the dynamic strain aging that occurs at room temperature. For this reason, it was decided to prepare special small load cells for stainless steel bolts for the measurement of the preload, see Figure 11 (a). The advantage of using load cells for stainless steel bolts is that the observed viscoplastic deformation has no influence on the measured preload level.

Each load cell was calibrated under stepwise tensile loading in a universal testing machine with a capacity of ±200 kN, see Figure 11 (b). Figure 12 shows an example of the load/strain-time curve of one exemplary load cell (number 06), which has completed the calibration successfully. Figure 13 presents an unsuccessful calibration test for load cell number 11 (which was not used for further testing). Those load cells, which showed a linear load-strain behaviour, were selected for application within the relaxation tests, see Figure 14.

The calibration procedure confirmed the expected robustness and accuracy of the load cells with an error < 1% of the full scale used in combination with M16 bolt.

(a) some production phases of load cells (LC) at the University of Duisburg-Essen

(b) calibration phases

Figure 11 Production calibration phases of load cells and test setup of relaxation test

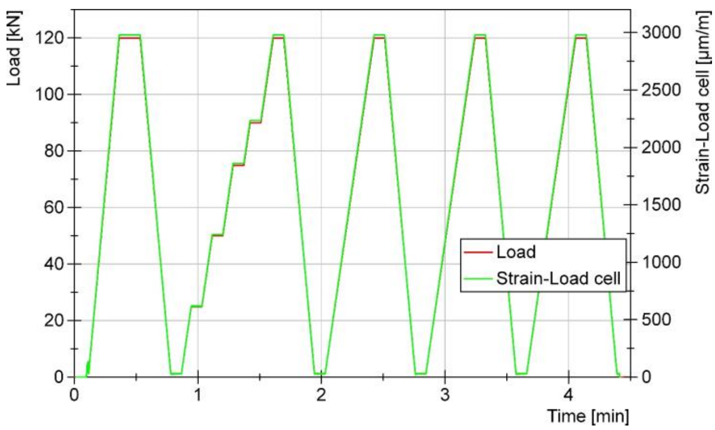


Figure 12 Example of a successful calibration test of a M16 x 40 instrumented load cell: load/strain-time curve (load cell number 01)

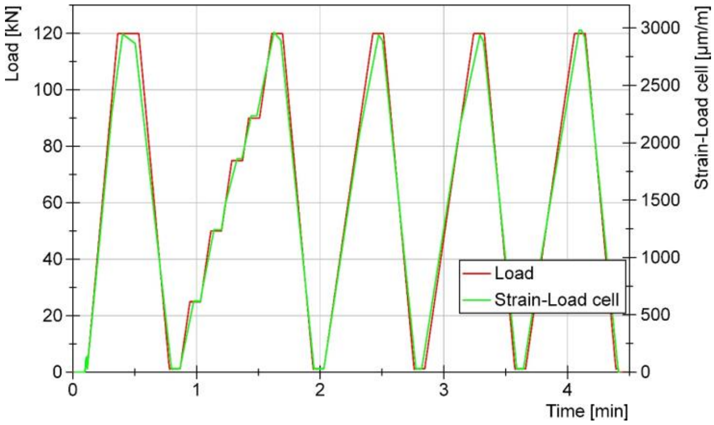


Figure 13 Example of an unsuccessful calibration test of a M16 x 40 instrumented load cell: load/strain-time curve (load cell number 05)

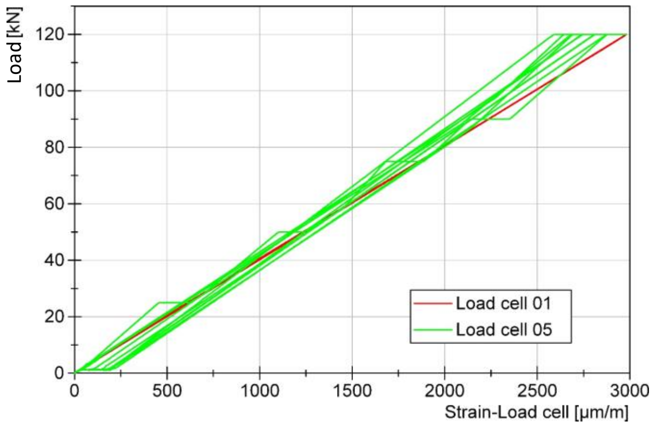


Figure 14 Example of a failed (load cell number 05) and passed (load cell number 01) calibration test of two M16 x 40 load cells: load-strain curve

EN 1090-2, Annex G does not explicitly prescribe the clamp length of the bolts that are used in slip factor tests. The clamp lengths of the bolts used during the slip factor tests were 74 mm and 77 mm respectively for the Bumax 88 and Bumax 109 series which is significantly longer than the clamp length of bolts that would be used in practical applications of a connection with plate thicknesses similar to those of the specimens. In that case, the clamp length would be (3+8+16+8+3=) 38 mm. This means that a correction might be needed in order to compare the results of the slip factor tests of this investigation with already known slip factors of other steel grades, see also [14], [16], [17], [18], [20].

3.3 Results and discussions

3.3.1 General

For each series of the stainless steel grades, firstly, four static tests were conducted in line with Annex G of EN 1090-2. Additionally, one creep test and extended creep tests were carried out. The mean values of the static slip factors ($\mu_{ini,mean}$ and $\mu_{act,mean}$) and characteristic values ($\mu_{5\%}$ for a passed creep test and μ_{ect} based on a passed extended creep test) are presented in Table 8.

Table 8 Test programme, mean slip factors based on static and creep tests ($\mu_{ini,mean}$ and $\mu_{act,mean}$) and characteristic values (final slip factors) calculated as 5%-fractile: $\mu_{5\%}$ or resulting from extended creep tests: μ_{ect}

Series ID	Surface condition			Number of tests	$\mu_{ini,mean}$ [3]	$\mu_{act,mean}$ [4]	V (μ_{act})[5]	Final slip factor
	Surface finish / Rz[1] [µm]	Type of coating	Coating thickness [µm]	st/ct/ect[2]	st/st+ct [-]	st/st+ct [-]	st/st+ct [%]	$\mu_{5\%}$[6] / μ_{ect}[7]
A_1D_B88	1D[8] / 24	-	-	4/1/2	0.21/0.21	0.21/0.21	4/4	0.2/0.14
A_SB_B88	SB[9] / 38	-	-	4/1/2	0.29/-	0.30/-	6/-	-/0.2
A_GB_B88	GB[10] / 45	-	-	4/1/1	0.56/0.55	0.60/59	6/7	0.49/0.51
D_GB_B88	GB / 47	-	-	4/1/1	0.60/0.6	0.63/0.62	6/5	0.54/0.54
LD_GB_B88	GB / 41	-	-	4/1/2	0.51/0.51	0.53/0.53	10/9	0.43/0.44
F_GB_B88	GB / 45	-	-	4/-/4	0.64/-	0.69/-	3/-	-/0.55
A_Al-SM_B88	GB / 45	Al-SM	100[11]	4/1/2	0.78/-	0.94/-	2/	-/0.71
D_Al-SM_B88	GB / 43	Al-SM	116[12]	4/1/2	0.85/-	0.98/-	2/-	-/0.79
LD_Al-SM_B88	GB / 51	Al-SM	105[12]	4/1/2	0.79/-	0.89/-	5/-	-/0.72
F_Al-SM_B88	GB / 44	Al-SM	91[12]	4/1/2	0.81/-	0.93/-	2/-	-/0.74
A_1D_B109	1D / 24	-	-	4/2/2	0.20/0.20	0.20/0.20	3/3	-/0.16
A_SB_B109	SB / 34	-	-	4/2/1	0.32/0.32	0.34/0.34	11/10	-/0.28
A_GB_B109	GB / 41	-	-	4/2/1	0.57/0.58	0.65/0.66	9/8	-/0.48
D_GB_B109	GB / 47	-	-	4/2/2	0.66/0.66	0.69/0.70	3/4	0.62/0.59
LD_GB_B109	GB / 40	-	-	4/2/1	0.62/0.62	0.65/0.64	4/5	0.56/0.49
F_GB_B109	GB / 42	-	-	4/2/2	0.68/0.68	0.74/0.75	4/4	0.64/0.59
A_Al-SM_B109	GB / 45	Al-SM	100[11]	4/2/1	0.70/-	0.84/-	3/-	-/0.63
D_Al-SM_B109	GB / 43	Al-SM	116[12]	4/2/1	0.81/-	0.90/-	4/-	-/0.73
LD_Al-SM_B109	GB / 51	Al-SM	105[12]	4/2/1	0.78/-	0.86/-	4/-	-/0.70
F_Al-SM_B109	GB / 44	Al-SM	91[12]	4/2/1	0.76/-	0.89/-	2/-	-/0.68

[1] Rz: roughness | [2] st: static test/ct: creep-/ect: extended creep test | [3] $\mu_{ini,mean}$: calculated slip factors as mean values considering the preload at the start of the tests | [4] $\mu_{act,mean}$: calculated slip factors as mean values considering the actual preload at 0.15 mm slip | [5] V: Coefficient of variation for μ_{act} | [6] $\mu_{5\%}$: slip factors as 5%-fractile calculated on the basis of the static tests and the passed creep test | [7] μ_{ect}: slip factor as the result from the passed extended creep test | [8] 1D surfaces | [9] Shot blasted surfaces | [10] Grit blasted surfaces | [11] NDFT: nominal dry film thickness | [12] DFT: dry film thickness (measured value)

3.3.2 Initial preload losses

To investigate the combined effect on the preload losses of settling, relaxation of the stainless steel bolted assemblies and creep of the stainless steel plates, a delay of at least 30 minutes was maintained between the end of the tightening procedure and the start of the slip tests. During the waiting period, the course of the preload was measured and analysed to get insight into the initial preload losses and to compare the preload losses of the four stainless steel grades and the different surface conditions. To compare the preload losses caused by the plate material, all static slip factor tests were conducted with the same bolt set.

When a bolt set is preloaded for the first time, viscoplastic deformation of the plate and bolted assemblies will cause preload losses. When the bolt is re-used at the same clamp length and load level (and is well lubricated), the additional viscoplastic deformation (creep/relaxation) in the components of the bolt set is negligible. Using re-used bolt sets, the recorded preload losses are mainly caused by the plate material. Table 9, Table 10 and Table 11 give the loss of preload at 15 and 30 minutes after applying the preload. A rough estimation of the expected losses after 50 years was made by linear extrapolation of the log-time course of the losses that was recorded over the first 30 minutes.

Table 9 shows that the estimated preload losses over 50 years caused by creep of the preloaded plate material vary between 2 % - 3 % for the grit blasted duplex, lean duplex and ferritic grades and lead to 6 % - 7 % for both shot and grit blasted austenitic plates. The higher preload losses found for the austenitic plates can be explained by the lower yield stress of these plates compared to the other grades (see Table 6). The preload losses given in Table 9 and Table 10 are not corrected for the longer clamp length, so in reality the preload losses will be larger (up to 1.1 times larger than the table values). Table 11 shows the results of similar preload loss measurements that were recorded for slip factor tests on grit blasted carbon steel plates of grade S355. Comparing the given preload losses in both tables indicates that the preload losses caused by creep are larger for the stainless steel plates but does not deviate significantly from what is found for carbon steel plates.

Table 9 Loss of preload for all stainless steel series (uncoated surfaces)

Spec ID	Bolts: D x L standard	Bolts: Class	Bolts: $F_{p,C}$ [kN]	Bolts: Clamp length [mm]	Bolts: Status	Plates: Grade	Plates: Rz [µm]	Preload: applic. Time [min]	Preload: Initial (P0) [kN]	Preload: delay [sec]	Preload: after delay (P1) [kN]	Preload Loss rel. to P1: after 15 min	Preload Loss rel. to P1: after 30 min	Preload Loss rel. to P1: extrapol. 50 y
Austenitic 1D surface														
A_1D_03	M16 x 100 / full thread	Bumax 109	110	77	re-used	1.4404	24	4.3	112.3	4	111.6	1.6%	1.8%	4% - 5%
A_1D_04								3.3	111.9	4	111.1	1.6%	1.7%	4% - 5%
A_1D_06					new			7.4	114.6	4	112.9	2.7%	3.1%	8% - 9%
A_1D_08								5.7	115.8	4	114.7	3.3%	3.6%	8% - 9%
A_1D_02		Bumax 88	88	74	re-used			2.1	88.3	3	87.3	1.7%	1.8%	6% - 7%
A_1D_03								1.9	88.8	3	88.1	1.8%	1.9%	6% - 7%
A_1D_05					new			1.3	89.7	3	88.2	2.8%	3.0%	8%
Austenitic shot blasted														
A_SB_02	M16 x 100 / full thread	Bumax 109	110	77	re-used	1.4404	34	5.7	111.0	4	109.5	1.9%	2.2%	6% - 7%
A_SB_04								8.5	111.0	4	109.3	1.8%	2.0%	6% - 7%
A_SB_06					new			4.2	112.3	4	110.3	3.0%	3.3%	9% - 10%
A_SB_10								5.7	115.7	4	113.5	2.8%	3.2%	9% - 10%
A_SB_01		Bumax 88	88	74	re-used			1.7	91.3	3	90.0	2.0%	2.2%	7%
A_SB_02								1.6	91.4	3	90.1	1.9%	2.0%	6% - 7%
A_SB_09					new			1.5	88.5	3	87.9	2.9%	3.2%	10%
Austenitic grit blasted														
A_GB_02	M16 x 100 / full thread	Bumax 109	110	77	re-used	1.4404	41	4.8	111.1	4	109.7	1.9%	2.1%	6%
A_GB_03								4.5	111.4	4	110.0	1.8%	2.0%	6%
A_GB_06					new			7.4	111.9	4	110.1	2.9%	3.2%	9%
A_GB_10								5.5	114.9	4	112.9	2.7%	3.1%	9%
A_GB_01		Bumax 88	88	74	re-used			1.7	92.3	3	91.3	1.8%	2.0%	6% - 7%
A_GB_02								1.5	91.6	3	90.2	1.9%	2.0%	6% - 7%
A_GB_06					new			3.9	91.5	3	90.6	2.7%	2.8%	8% - 9%
A_GB_07								2.7	94.2	3	92.4	2.9%	3.2%	9% - 11%
Duplex grit blasted														
D_GB_03	M16 x 100 / full thread	Bumax 109	110	77	re-used	1.4462	47	3.6	111.9	4	111.4	0.9%	1.0%	2% - 3%
D_GB_04								3.9	111.7	4	111.4	0.7%	0.8%	2% - 3%
D_GB_06					new			6.8	112.3	4	111.1	2.5%	2.7%	7% - 8%
D_GB_10								7.5	116.6	4	114.6	2.3%	2.6%	7% - 8%
D_GB_01		Bumax 88	88	74	re-used			1.9	89.6	3	89.4	1.1%	1.2%	4%
D_GB_02								2.2	90.5	3	90.0	1.1%	1.2%	4%
D_GB_05					new			2.3	92.8	3	92.1	2.1%	2.3%	7% - 8%
D_GB_06								2.5	94.6	3	92.6	2.4%	2.6%	8%
Lean duplex grit blasted														
LD_GB_03	M16 x 100 / full thread	Bumax 109	110	77	re-used	1.4162	40	4.6	111.3	4	110.5	0.9%	0.9%	2% - 3%
LD_GB_04								3.2	111.8	4	111.4	0.9%	1.0%	2% - 3%
LD_GB_06					new			4.6	112.6	4	111.0	2.3%	2.6%	7% - 8%
LD_GB_10								6.9	115.8	4	114.0	2.3%	2.6%	7% - 8%
LD_GB_01		Bumax 88	88	74	re-used			3.3	88.1	3	86.9	1.1%	1.9%	5%
LD_GB_02								2.2	88.5	3	87.7	1.3%	1.5%	4% - 5%
LD_GB_06					new			1.6	89.2	3	87.2	2.4%	2.6%	8% - 9%
Ferritic grit blasted														
F_GB_02	M16 x 100 / full thread	Bumax 109	110	77	re-used	1.4003	42	4.5	111.4	4	110.7	1.0%	1.1%	2% - 3%
F_GB_03								5.4	112.2	4	111.5	0.9%	1.0%	2% - 3%
F_GB_06					new			5.7	112.5	4	110.9	2.5%	2.8%	8%
F_GB_10								13.4	116.1	4	114.3	2.3%	2.6%	8%
F_GB_01		Bumax 88	88	74	re-used			1.2	91.1	3	90.2	1.0%	1.1%	3%
F_GB_02								2.0	91.0	3	90.2	1.0%	1.1%	3% - 4%
F_GB_07					new			1.7	93.9	3	91.7	2.3%	2.5%	8%

Table 10 Loss of preload for all stainless steel series (coated surfaces)

Spec ID	Bolts: D x L standard	Bolts: Class	Bolts: $F_{p,C}$ [kN]	Bolts: Clamp length [mm]	Bolts: Status	Plates: Grade	Plates: Rz [µm]	Preload: applic. Time [min]	Preload: Initial (P0) [kN]	Preload: delay [sec]	Preload: after delay (P1) [kN]	Preload Loss rel. to P1: after 15 min	Preload Loss rel. to P1: after 30 min	Preload Loss rel. to P1: extrapol. 50 y
Austenitic Al-SM														
A_AL-SM_01	M16 x 100 / full thread	Bumax 109	88	77	new	1.4404	-	4.8	116.0	4	113.7	2.7%	3.0%	9%
A_AL-SM_02								7.1	115.6	4	113.2	2.6%	2.9%	9%
A_AL-SM_05								6.0	115.7	4	113.4	2.7%	3.0%	9%
A_Al-SM_09								5.5	115.7	4	113.4	2.9%	3.2%	9%
A_Al-SM_05		Bumax 88	88	74	re-used			2.2	91.4	3	90.5	1.4%	1.5%*	4% - 5%
A_Al-SM_06								1.2	91.6	3	90.8	1.5%	1.7%*	5% - 6%
A_Al-SM_09					new			1.6	94.2	3	92.1	2.9%	3.2%	9% - 11%
A_Al-SM_10								1.1	93.9	3	92.3	2.9%	3.3%	10% - 11%
Duplex Al-SM														
D_Al-SM_01	M16 x 100 / full thread	Bumax 109	88	77	new	1.4462	-	4.5	116.0	4	114.1	2.4%	2.7%	8%
D_Al-SM_02								5.3	116.0	4	113.8	2.3%	2.6%	8%
D_Al-SM_05								5.5	115.8	4	113.5	2.3%	2.6%	8%
D_AL-SM_10								5.7	115.3	4	113.4	2.4%	2.7%	8%
D_Al-SM_05		Bumax 88	88	74	new			0.9	92.2	3	91.2	1.6%	1.8%	5% - 6%
D_Al-SM_06								0.7	92.7	3	91.9	1.4%	1.6%	5% - 6%
D_Al-SM_09								1.4	92.4	3	91.5	2.3%	2.6%*	8% - 9%
D_Al-SM_10								0.7	92.3	3	90.8	2.6%	2.8%*	9%-10%
Ferritic Al-SM														
F_AL-SM_01	M16 x 100 / full thread	Bumax 109	88	77	new	1.4003	-	4.8	115.6	4	113.6	2.5%	2.8%	9%
F_Al-SM_02								4.9	115.3	4	113.6	2.7%	3.0%	9%
F_Al-SM_05								4.8	116.3	4	114.0	2.3%	2.6%	8%
F_Al-SM_10								4.4	116.0	4	113.7	2.3%	2.6%	8%
F_Al-SM_03		Bumax 88	88	74	re-used			1.5	92.7	3	91.6	1.7%	1.9%*	6%
F_Al-SM_04								1.1	92.3	3	91.2	1.6%	1.8%*	6%
F_Al-SM_09					new			1.3	92.7	3	90.8	2.4%	2.6%*	8% - 9%
F_Al-SM_10								0.9	92.2	3	90.8	2.6%	2.9%*	9% - 10%
Lean duplex Al-SM														
L_Al-SM_01	M16 x 100 / full thread	Bumax 109	88	77	new	1.4162	-	4.8	115.7	4	113.5	2.3%	2.6%	8%
L_Al-SM_02								4.4	116.0	4	113.8	2.3%	2.6%	7%-8%
L_Al-SM_05								5.3	116.5	4	114.1	2.3%	2.6%	7% - 8%
L_Al-SM_10								5.2	116.3	4	114.0	2.2%	2.5%	7% - 8%
LD_Al-SM_05		Bumax 88	88	74	re-used			1.0	91.4	3	90.5	1.4%	1.5%*	5%
LD_Al-SM_06								0.8	91.6	3	90.8	1.5%	1.7%*	5%
LD_Al-SM_09					new			1.1	91.7	3	90.4	2.4%	2.6%*	8% - 9%
LD_Al-SM_10								0.8	91.5	3	90.2	2.4%	2.6%*	8% - 9%

* Preload loss after 25 min

In Figure 9 and Figure 10, also the initial preload losses are given for slip factor tests which were conducted with new bolt sets. The table shows that in this case the estimated preload losses in 50 years increase to approximately 10 % and 8 % respectively for the austenitic and the other grades.

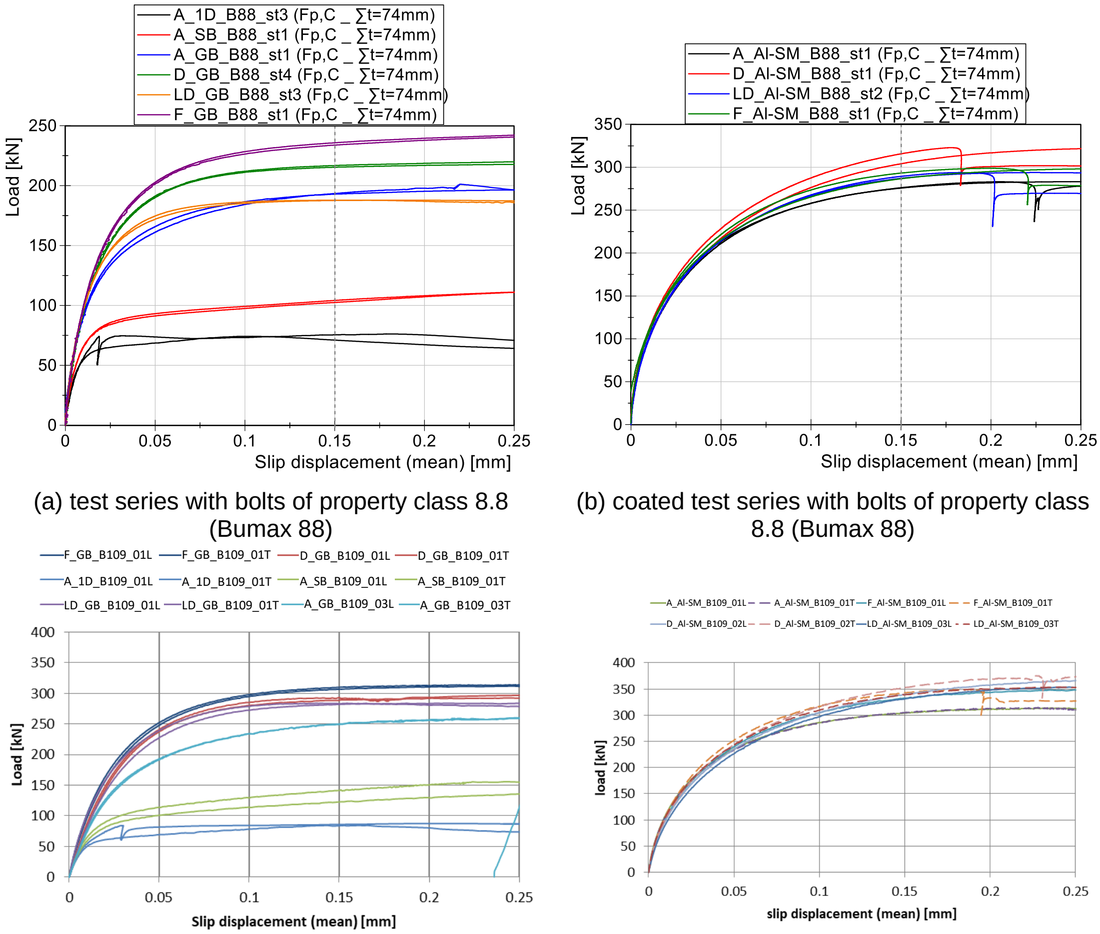
Table 11 Loss of preload for carbon steel series

Spec ID	Bolts: D x L standard	Bolts: Class	Bolts: $F_{p,C}$ [kN]	Bolts: Clamp length [mm]	Bolts: Status	Plates: Grade	Plates: Rz [µm]	Preload: applic. Time [min]	Preload: Initial (P0) [kN]	Preload: delay [sec]	Preload: after delay (P1) [kN]	Preload Loss rel. to P1: after 15 min	Preload Loss rel. to P1: after 30 min	Preload Loss rel. to P1: extrapol. 50 y
Grit blasted														
GB23	M20 x 85	HR8.8	138	48	re-used	S355	80	3.5	141.7	4	141.3	1.4%	1.6%	4% - 5%
GB22	EN13499-3							3.1	146.0	3	145.6	1.4%	1.6%	4% - 5%
GB06	M20 x 180	HV10.9	172	152	re-used	S355	80	2.0	170.4	4	170.4	0.8%	0.9%	2% - 3%
GB08	EN13499-4							2.4	169.1	4	169.0	0.8%	0.9%	2% - 3%
GB25	M20 x 80	HR10.9	172	48	re-used	S355	80	5.9	175.0	3	174.7	1.5%	1.6%	4% - 5%
GB26	EN13499-3							4.1	173.1	3	172.7	0.9%	1.1%	4% - 5%

3.3.3 Static tests

Figure 15 shows typical load - slip displacement curves that resulted from the static slip factor tests for the ten test series with Bumax 88 and Bumax 109 bolts. The figures show that the highest slip load for uncoated test series is achieved for the grit blasted ferritic grade, followed by grit blasted duplex, austenitic and lean duplex grades. As it can be seen in Table 8 the same results have been achieved for the uncoated test series with Bumax 109. With the surface that results from the shot blasting treatment and the as-rolled surface condition only very low slip factors are achieved compared to the grit blasted surfaces. Table 8 shows that the difference in the surface roughness that is achieved by the grit blasting compared to shot blasting is reflected by the results of the slip factor tests.

Table 8 and Figure 15 clearly show that the surface roughness plays an important role on the slip behaviour of the specimens. The slip factor can be strongly influenced by the surface treatment of the plates. The mean static slip factors were calculated based on 1) the initial preload in the bolts (μ_{ini}), 2) the actual preload at a slip deformation of 0.15 mm (μ_{act}) and 3) the nominal preload in the bolts (μ_{nom}). The achieved static slip factor values for all grit blasted surfaces were greater than 0.5, see Figure 16 and Figure 17. The high static slip factors for grit blasted surfaces in comparison to those of shot blasted specimens can be explained by the topography of the surfaces. The asperity of grit blasted faying surfaces is sharper than that of the shot blasted surfaces and consequently provides a better mechanical interlocking between the surfaces.



(a) test series with bolts of property class 8.8 (Bumax 88)

(b) coated test series with bolts of property class 8.8 (Bumax 88)

(c) test series with bolts of property class 10.9 (Bumax 109)

(d) coated test series with bolts of property class 10.9 (Bumax 109)

Figure 15 Typical load-slip-displacement curves for different surface conditions of the test series with bolts of property class 8.8 and 10.9 (Bumax 88 and Bumax 109) - each colour represent the upper and lower section of the specimen

As already mentioned above, the influence of an aluminium spray metalized surface (Al-SM) was examined as well. As shown in Table 7, eight different test series with two different preload levels were selected with approximately the same clamping length in order to eliminate the effect of clamping length on the loss of preload. The results show that the slip factor was significantly improved (greater than 0.7) by aluminium spray metalized coated surfaces for both preload levels in comparison to that of uncoated surfaces, see Table 8, Figure 16 and Figure 17.

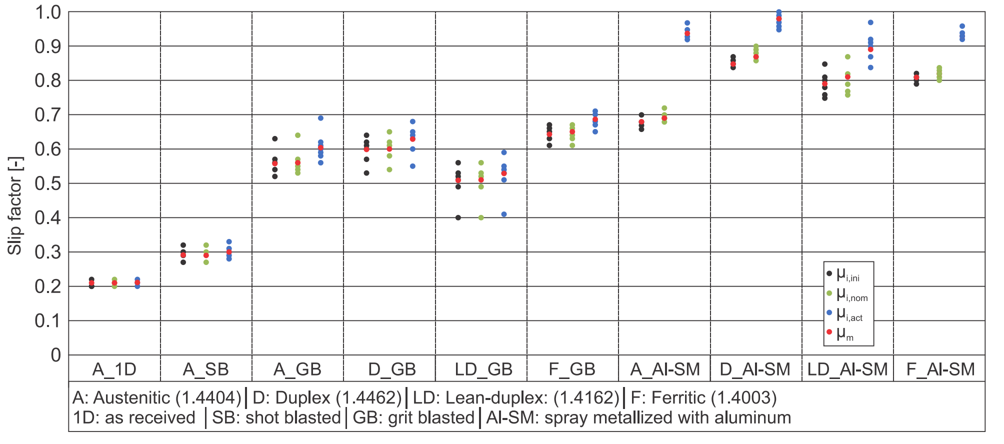


Figure 16 Influence of different stainless steel surface conditions on the static slip factors – test series with bolts of property class 8.8 (Bumax 88)

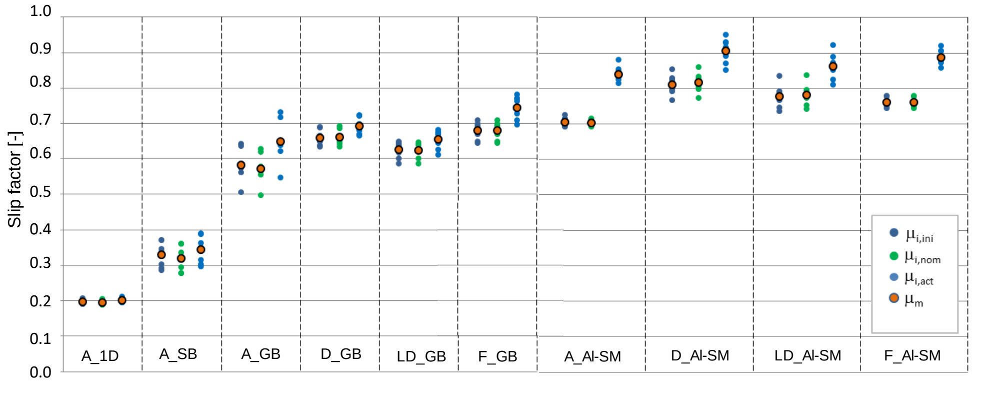
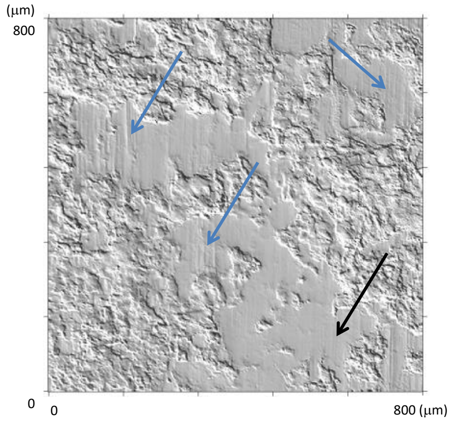
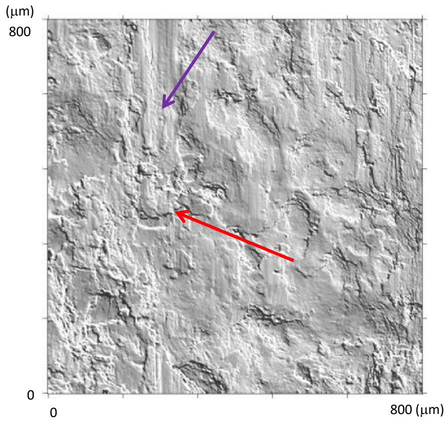


Figure 17 Influence of different stainless steel surface conditions on the static slip factors – test series with bolts of property class 10.9 (Bumax 109)

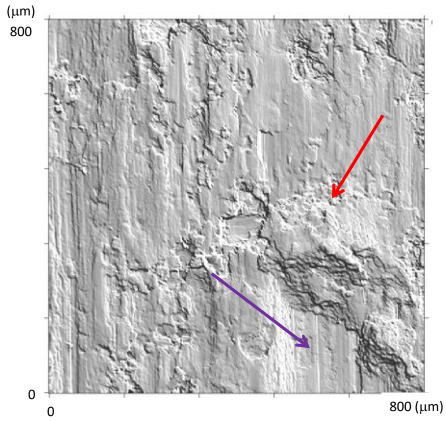
For all stainless steel grades that were preloaded with Bumax 88 ($F_{p,C}$ = 88 kN) static slip factors were achieved which are equal or lower to those resulting for the higher preload level with Bumax 109 bolts ($F_{p,C}$ = 110 kN). A possible explanation for this could be cold welding of the faying surfaces by the combined effect of the preload and slipping of the surfaces. Figure 18 (a) shows the faying surfaces after the slip factor test for the 1D surfaces. Flat and uniform contact spots (black arrow) can be observed on which sliding has occurred as demonstrated by the scratches on these contact spots (blue arrows). The shot blasted faying surfaces in Figure 18 (b) are much rougher after sliding and the contact spots are not that evident, probably due to cold welding (red arrow) and associated deep scratches made by the cold welds in the slip test (magenta arrow). The grit blasted faying surfaces in Figure 18 (c) are even more destroyed by heavy cold welding (red arrow) and associated deep scratches made by the cold welds in the slip test (magenta arrow). As the cold welding spots are caused by the combination of slip and preload, cold welding of the stainless steel surfaces could explain the higher slip factors that are found for Bumax 109 (preloaded to 110 kN, so potentially more cold welding spots) compared to Bumax 88 (preloaded to 88 kN). On the other hand, unlike the uncoated surfaces, the cold welding could not happen for the stainless steel bolted connection with aluminium spray metalized coated surfaces, because the contact surfaces are covered with aluminium and there was no direct contact between stainless steel surfaces. For this reason, like what is known for carbon steels [14], by increasing the preload level the slip load increase (see Figure 15) but slip factor decrease slightly, see Table 8, Figure 16 and Figure 17.



(a) Faying surfaces for 1D specimens



(b) Faying surfaces for shot blasted specimens



(c) Faying surfaces for grit blasted specimens

Figure 18 Topography between contact surfaces [15]

3.4 Creep tests

According to EN 1090-2, Annex G, a creep test shall be carried out on a load level of 90% of the average of the slip loads of the first four static slip tests (0.9 F_{Sm}). When the slip at CBG that is recorded between 5 min and 3 hours after application of the load does not exceed 0.002 mm, the coating or surface treatment is considered to be 'not creep sensitive'. The creep test was passed for all non-coated Bumax 88-series except for the A_SB_B88.

All Bumax 109 specimens passed the creep test, except for the A_1D_B109 and A_GB_B109 series. For the A_GB_B109 series the difference between slip that was recorded in 3 hours and the threshold value of 2 μm is negligible, so in fact all series with surface treatment can be considered to be non-creep sensitive.

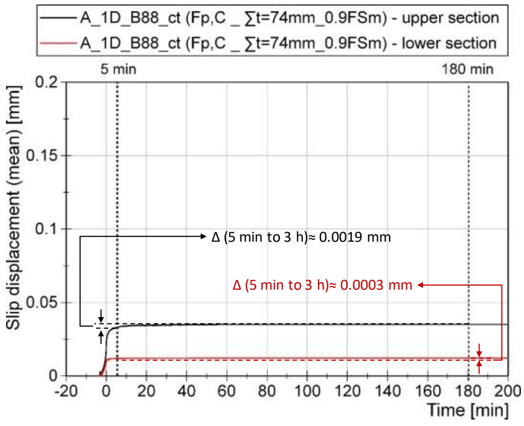
Once the load on the specimen has reached the required load for a creep test, the load remains constant. In this situation, the difference between slip measurements at CBG and PE position should be zero. An analyses of the difference between the slip measured at CBG and PE position shows that the stresses at the load level at which the AG series was tested caused creep effects in the steel plates. See Table 12.

Table 12 Results creep tests with B109 bolts

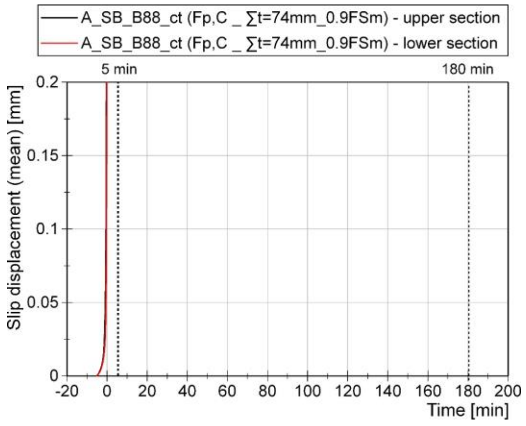
series	sample ID	Σt	time between pretensioning and start creep test	loading speed	$0.9F_{s,m}$ (SCL)	load during creep test (CL)	CL/SCL	preload loss during creep test (3 hours)	slip at CBG	slip at PE	slip at PE - slip at CBG	result creep test
		[mm]	[hour]	[kN/s]	[kN]	[kN]		[%]	µm	µm	µm	
A_1D_B109	A1D_06	78	0.5	0.1	76	76	1.00	0.8	10.1	11.0	1	failed
								0.9	x	x	x	slip thr
A_SB_B109	AS_06	78	0.5	0.3	126	126	1.00	1.0	1.4	4.2	3	passed
								1.0	1.7	3.8	2	passed
A_GB_B109	AG_06	78	0.5	0.3	226	226	1.00	1.3	1.6	9.6	8	passed
								1.3	3.1	14	11	failed
F_GB_B109	FG_06	78	0.5	0.3	269	269	1.00	0.8	1.6	2.9	1	passed
								0.8	1.6	3.2	2	passed
LD_GB_B109	LG_06	78	0.5	0.3	215	247	0.87	0.5	0.4	1.7	1	passed
								0.5	0.6	2.0	1	passed
D_GB_B109	DG_06	78	0.5	0.3	260	260	1.00	0.5	0.9	3.4	3	passed
								0.6	0.7	3.4	3	passed

The creep tests were also performed for all series with Al-SM coated surfaces. The results shows that all grades with Al-SM coating behave slightly, but not very creep sensitive according to the creep test criteria, see Figure 20. The difference between the recorded slip at the end of 5 min and 3 hours after full load application exceeded slightly the limit of 0.002 mm for both parts of the specimen. For this reason, the creep tests for all Al-SM test series were failed and consequently extended creep tests were necessary.

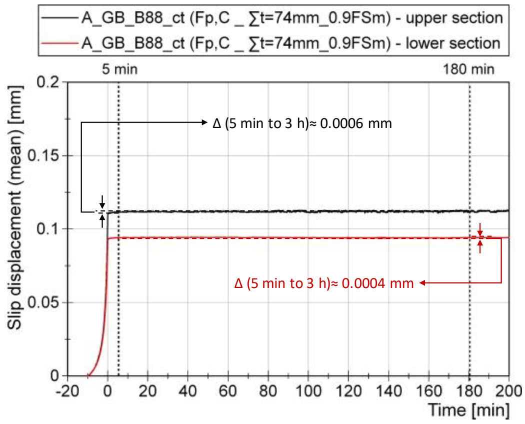
The creep tests on all Aluminium spray metallized surfaces with Bumax 109 bolts fail. Except for the F_Al-SM_B109 specimens the slip at CBG is less than 15 µm. Extended creep test are necessary. The results for the A_Al-SM_B109 specimen again show that the plate stresses during the creep tests cause creep of the stainless steel plates.



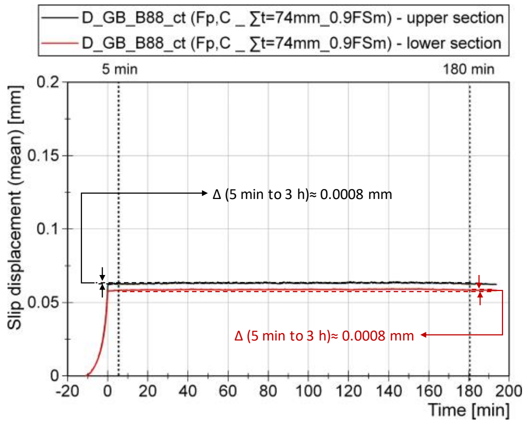
(a) Austenitic plates with 1D surfaces (A_1D_B88)



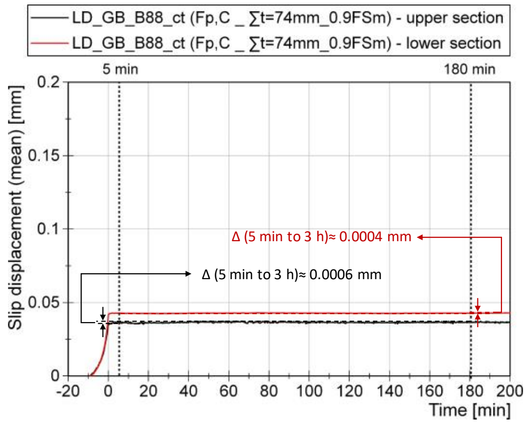
(b) Austenitic plates with shot blasted surfaces (A_SB_B88)



(c) Austenitic plates with grit blasted surfaces (A_GB_B88)

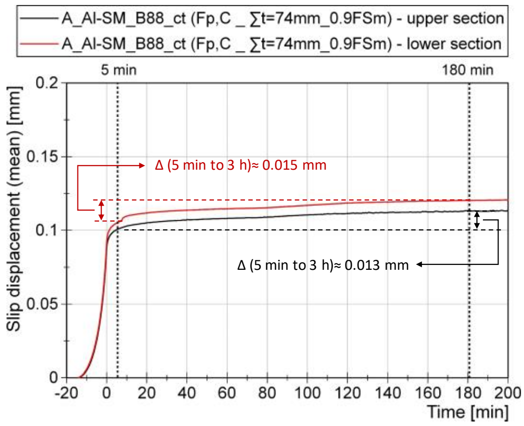


(d) Duplex plates with grit blasted surfaces (D_GB_B88)

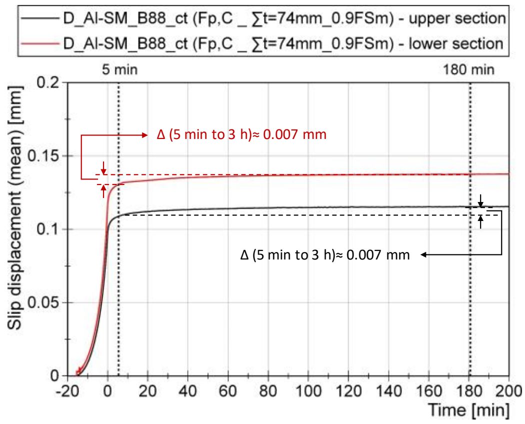


(e) Lean duplex plates with grit blasted surfaces (LD_GB_B88)

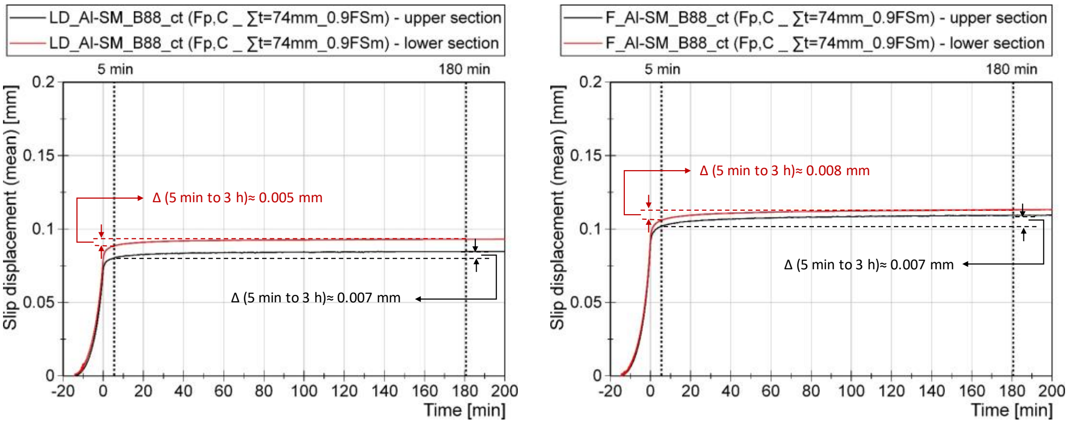
Figure 19 Results of creep tests considering different stainless steel grades and surface treatments - test series with bolts of property class 8.8 (Bumax88)



(a) Austenitic plates with Al-SM surfaces (A_Al-SM_B88)



(b) Duplex plates with Al-SM surfaces (D_Al-SM_B88)



(c) Lean duplex plates with Al-SM surfaces (LD_Al-SM_B88)

(d) Ferritic plates with Al-SM surfaces (F_Al-SM_B88)

Figure 20 Results of creep tests considering different stainless steel grades with aluminium spray metalized surfaces - test series with bolts of property class 8.8 (Bumax88)

Table 13 Results creep test on Aluminium spray metallized surfaces with B109 bolts

series	sample ID	Σt	time between pretensioning and start creep test	loading speed	0.9$F_{s,m}$ (SCL)	load during creep test (CL)	CL/SCL	preload loss during creep test (3 hours)	slip at CBG	slip at PE	slip at PE - slip at CBG	result creep test
		[mm]	[hour]	[kN/s]	[kN]	[kN]		[%]	µm	µm	µm	
A_Al-SM_B109	A_TSA_05	78	0.5	0.3	278	278	1.00	1.7	11	36	25	failed
								1.5	11	39	27	failed
F_Al-SM_B109	F_TSA_05	78	0.5	0.3	301	301	1.00	1.5	36	38	2	failed
								1.2	14	16	1	failed
LD_Al-SM_B109	L_TSA_05	78	0.5	0.3	309	309	1.00	0.7	9	11	2	failed
								0.6	7	9	2	failed
D_Al-SM_B109	D_TSA_05	78	0.5	0.3	323	323	1.00	0.7	11	15	4	failed
								0.6	8	11	3	failed

3.5 Extended creep tests

Where normally extended creep tests are only carried out on creep sensitive coatings, in this investigation for all test series extended creep tests were conducted although almost all creep tests were passed.

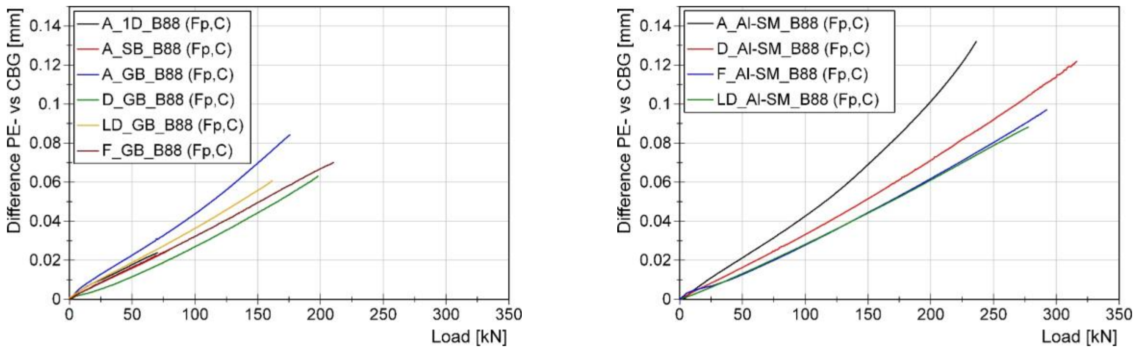
Extended creep tests are carried out in the long term test-rigs that were designed and erected at the Institute for Metal and Lightweight Structures of University of Duisburg-Essen and Department of Steel and Composite Structures of Delft University of Technology to determine the load level for which the slip does not exceed 0.3 mm over a period of 50 years – or the service life of the structure, see Figure 21and Figure 22. In an extended creep test, the load level is maintained at a constant level during the test and the slip deformations of the connections are continuously measured.

Figure 21 Test rig for extended creep tests (UDE)

Figure 22 Test rig for extended creep tests (UDE)

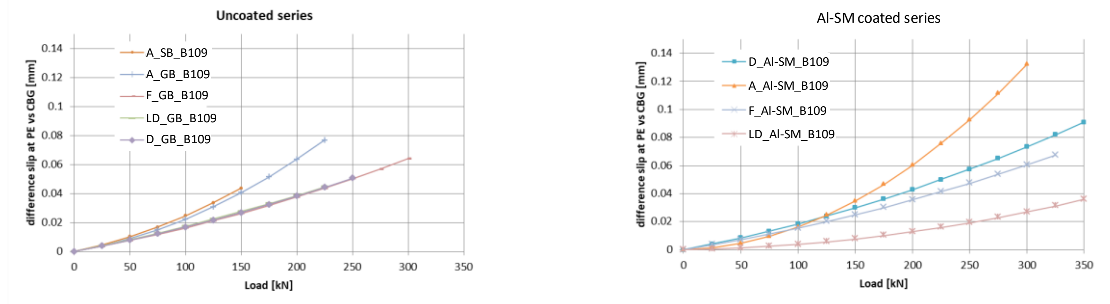
In all extended creep tests the displacement measured at PE (Plate Edges) position and the actual slip displacements at CBG position were calculated by using the correlation based on the results of the corresponding to first four static tests. Afterward the calculated actual slip displacements at CBG position were used for evaluation of all extended creep tests, for more information see [19].

Figure 23 and Figure 24 shows the PE-CBG conversion models used for all series in this task (valid for PE LVDTs fixed to inner plates at 12 mm distance of CBG position).



(a) different surfaces treatment without any coating (b) AL-SM coated test series

Figure 23 Relation between specimen load and difference between slip measured at PE and CBG position - with Bumax88



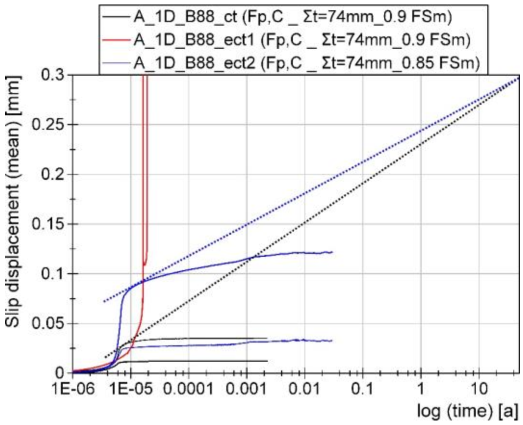
(a) different surfaces treatment without any coating (b) AL-SM coated test series

Figure 24 Relation between specimen load and difference between slip measured at PE and CBG position - with Bumax109

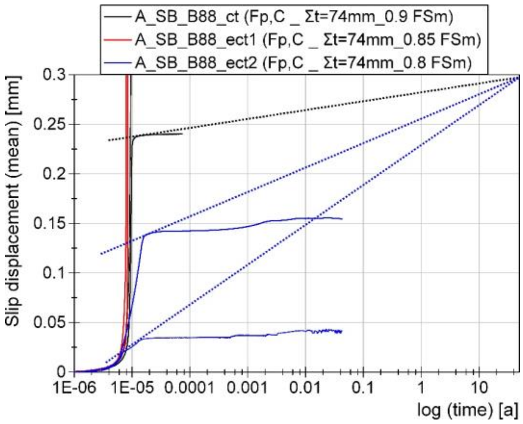
The slip over 50 years for a certain load level is estimated by plotting the course of the slip on a log-time scale and linear extrapolating this curve to t = 50 years. When the extrapolated line crosses the line on t = 50 years at a slip value less than or equal to 0.3 mm the load level can be used to calculate the slip factor.

All extended creep tests were conducted with new, unused bolting assemblies. By this, the combined effect of creep and relaxation of all stainless steel components of the connection could manifest during the tests.

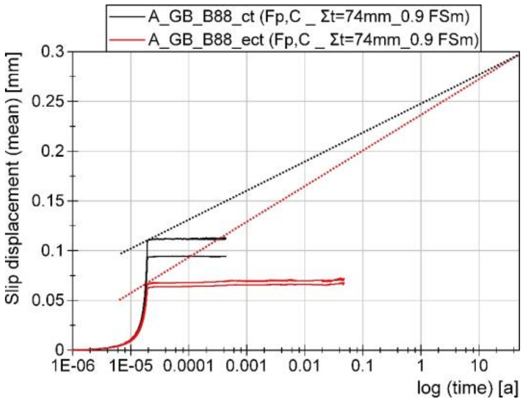
Figure 26 and **Error! Reference source not found.** show the results of the extended creep tests which were conducted on all series with Bumax 88 and Bumax 109 bolting assemblies. Figure 10 shows that for the load levels used during the extended creep test, the extrapolated slip at t = 50 years is significantly less than 0.3 mm. An increase of the load appeared to be not possible. Experiments with higher loads lead to sudden failure by slip through of one or both connections.



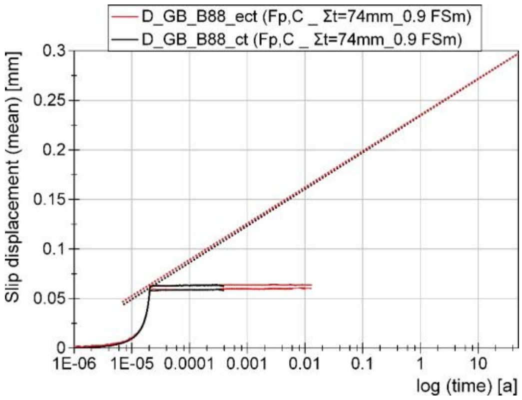
(a) Austenitic plates with 1D surfaces (A_1D_B88)



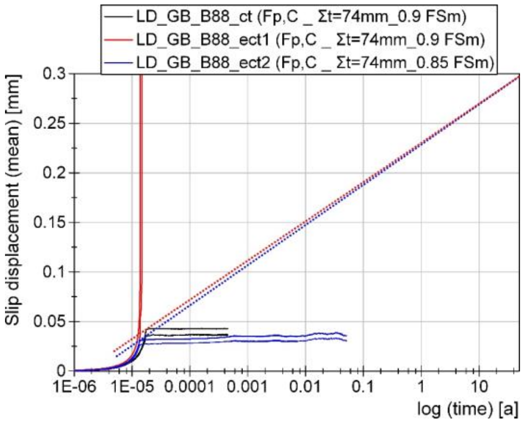
(b) Austenitic plates with shot blasted surfaces (A_SB_B88)



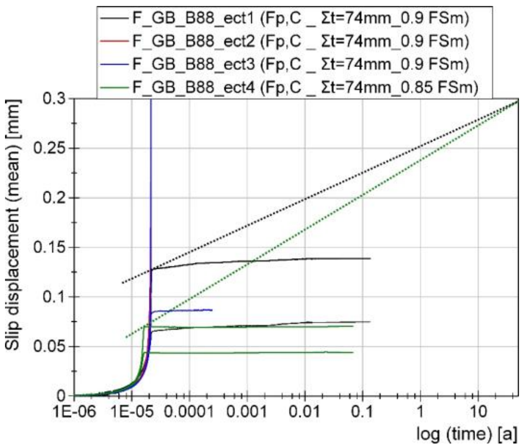
(c) Austenitic plates with grit blasted surfaces (A_GB_B88)



(d) Duplex plates with grit blasted surfaces (D_GB_B88)

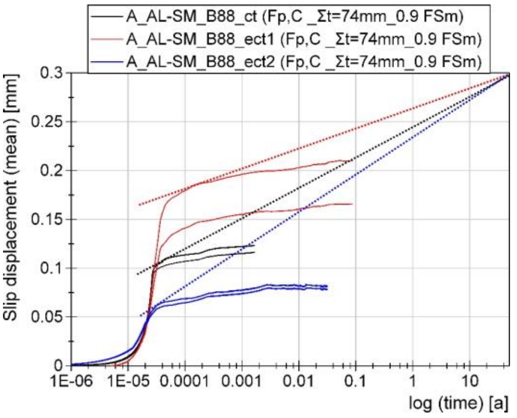


(e) Lean duplex plates with grit blasted surfaces (LD_GB_B88)

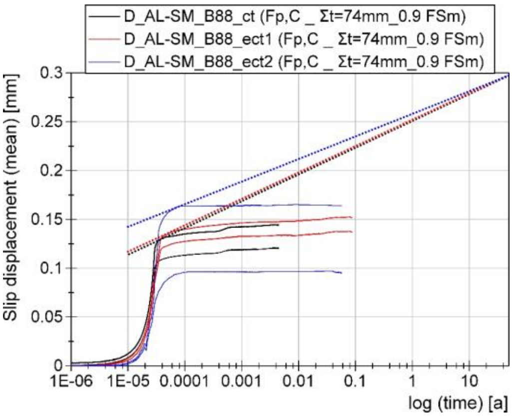


(f) Ferritic plates with grit blasted surfaces (F_GB_B88)

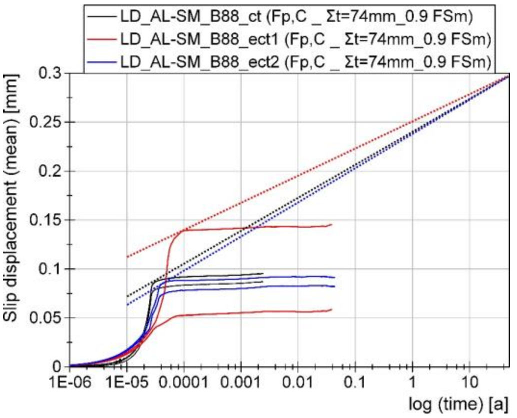
Figure 25 Results of extended creep tests considering different stainless steel grades and surface treatments - test series with bolts of property class 8.8 (Bumax88) (each colour represents the upper and lower section of the specimen)



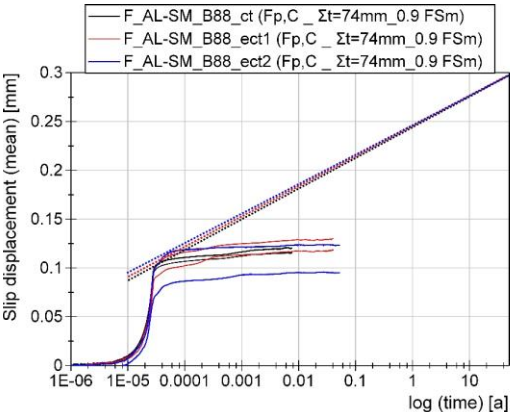
(a) Austenitic plates with Al-SM surfaces (A_Al-SM_B88)



(b) Duplex plates with Al-SM surfaces (D_Al-SM_B88)



(c) Lean duplex plates with Al-SM surfaces (LD_Al-SM_B88)



(d) Ferritic plates with Al-SM surfaces (F_Al-SM_B88)

Figure 26 Results of extended creep tests considering different stainless steel grades with aluminium spray metalized surfaces - test series with bolts of property class 8.8 (Bumax88) (each colour represents the upper and lower section of the specimen)

The load level during the extended creep tests (with new bolts) on the series with Bumax 109 bolts was chosen 3% lower than the load level of the creep tests (0.9 F_{Sm}, based on tests with re-used bolts). This reduction was carried out to compensate for the extra preload losses in the specimens with new bolts.

As it can be seen from Figure 25 (a) and (e), the extended creep tests on the A_1D_B88 and LD_GB_B88 series with Bumax 88 bolts do not passed with constant load level of 0.9 F_{Sm} however the creep tests with same load level were passed. This indicates that the chosen load level (0.9 F_{Sm}) is a critical load level for these series. For this reason, performing an extended creep test with lower load level is necessary.

Figure 25 (a) and (e) show that the extended creep tests with load level of 0.85 F_{Sm} were passed for both test series. Figure 25 (f) shows that for grit blasted ferritic plates, three extended creep tests were conducted on the same load level as the creep tests. However, from these tests only one passed. By considering these results, one more test with constant load level of 0.85 F_{Sm} was performed The extrapolated displacement – log time curve shows less than 0.3 mm slip when the curve is extrapolated to 50 years. For shot blasted Austenitic plates, the extended creep test were failed for load level of 0.9 F_{Sm} and 0.85 F_{Sm} and passed with 0.8 F_{Sm}, see Figure 25 (b). For the Austenitic and Duplex plates with grit blasted surfaces, the extended creep tests were passed on the same load level as the creep tests and the final slip factor can be calculated with 0.9 F_{Sm} load level.

Extended creep tests were performed on all Al-SM coated specimen that were preloaded with Bumax 109 bolts. The results of these tests show that in general the 90 % of F_{Sm} load level leads to an extrapolated slip at 50 years that is less than 0.3 mm. For the uncoated plates (Table 14) the percentages are just below 90%. This is caused by the fact that the average slip load F_{Sm} of the uncoated series was determined using bolt sets that were re-used, while the extended creep tests were performed on specimens with new bolts. Comparing the results of slip factor tests for new and re-used bolt sets shows a decrease of approximately 3% in observed when new bolts are used. The Al-SM coated plates perform exceptionally good. The average slip load F_{Sm} on the coated plates was determined with only specimens with new bolt sets. The results of the extended creep tests on the Al-SM coated plates (Table 15) show that the load level of 0.9 F_{Sm} leads to a passed test.

All test results (tables and graphs) on the coated and uncoated stainless steel plates preloaded with Bumax 109 bolts can be found in [20].

Table 14 Results extended creep tests uncoated stainless steel plates

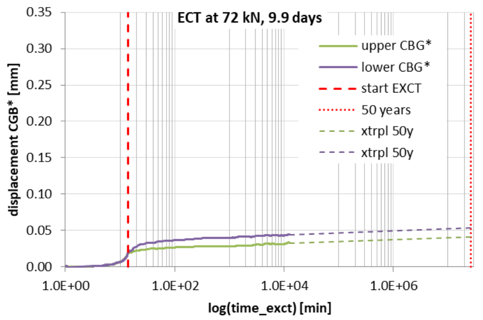
series	Fs,m	load levels / results				slip factor	long term slip load / Fs,m
		creep test (90% Fs,m)		extended creep test			
	[kN]	[kN]	result	[kN]	result[1)]	[-]	
A_1D_B109	84	76	p/f	72	p/p	0.16	85%
				72	p/p		
				-	-		
A_SB_B109	140	126	p/p	126	p/f	0.28	87%
				122	p/p		
				-	-		
A_GB_B109	251	226	p/p	226	p/p	0.48	84%
				226	p/f		
				210	p/p		
F_GB_B109	299	269	p/p	269	p/f	0.59	87%
				260	p/p		
				260	p/p		
LD_GB_B109	239	215	p/p	**215**	p/p	0.49	90%
				-	-		
				-	-		
D_GB_B109	290	261	p/p	**252**	p/p	0.57	87%
				260	p/p		
				-	-		

1) p:pass f:fail

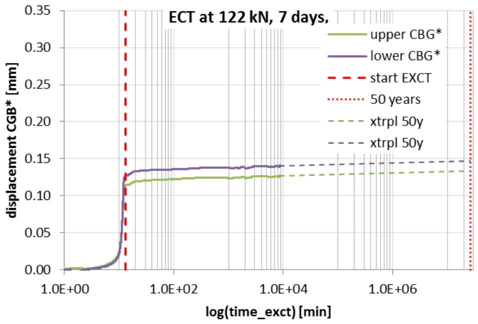
Table 15 Results extended creep tests AL-SM coated plates

series	Fs,m	load levels / results				slip factor	long term slip load / Fs,m
		creep test (90% Fs,m)		extended creep test			
	[kN]	[kN]	result	[kN]	result[1]	[-]	
A_Al-SM_B109	309	278	p/p	278	f/f	0.69	90%
				278	f/f		
				250[2]	p/p		
F_Al-SM_B109	334	301	p/p	301	p/p	0.68	90%
				301	p/p		
				-	-		
LD_Al-SM_B109	343	309	p/p	309	p/p	0.68	87%
				309	-		
				300	-		
D_Al-SM_B109	359	323	p/p	**322**	p/p	0.73	90%
				322	p/p		
				-	-		

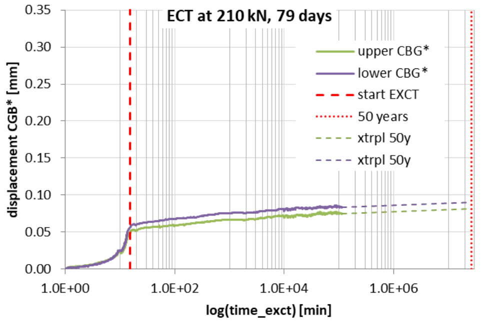
[1] p:pass f:fail
[2] tested at reduced preload level (90 kN)



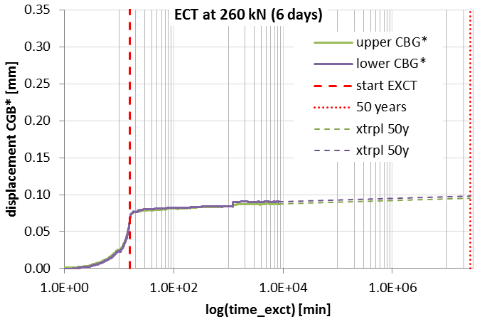
(a) Austenitic plates with 1D surface (A_1D_B109)



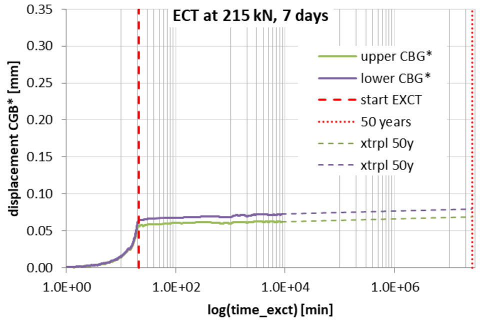
(b) Austenitic plates with Shot blasted surface (A_SB_B109)



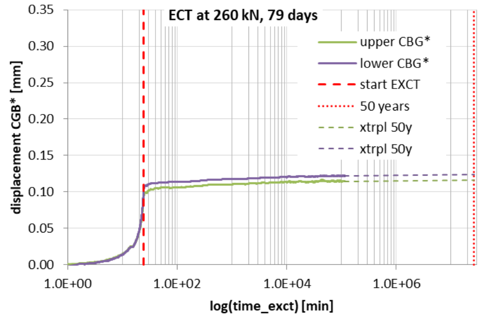
(c) Austenitic plates with Grit blasted surface (A_GB_B109)



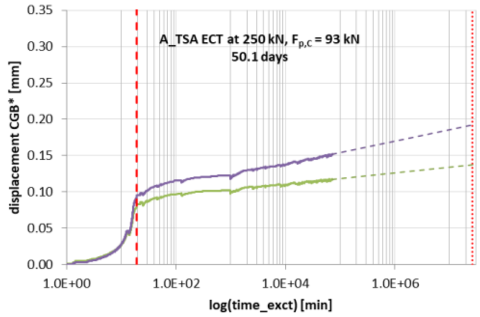
(d) Ferritic plates with Grit blasted surface (F_GB_B109)



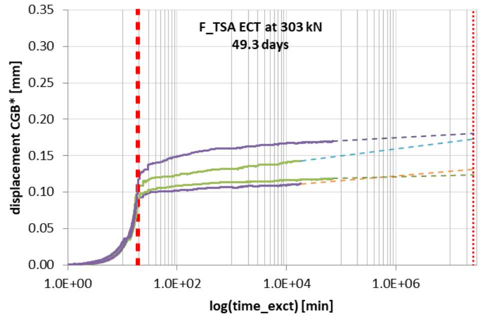
(e) Lean Duplex plates with Grit blasted surface (LD_GB_B109)



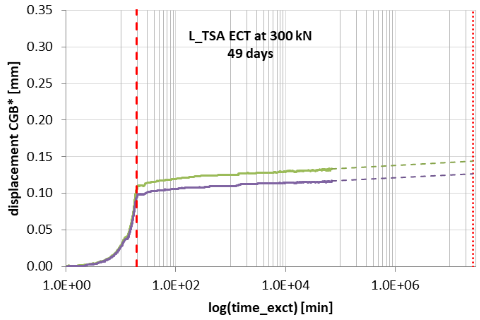
(f) Duplex plates with Grit blasted surface (D_GB_B109)



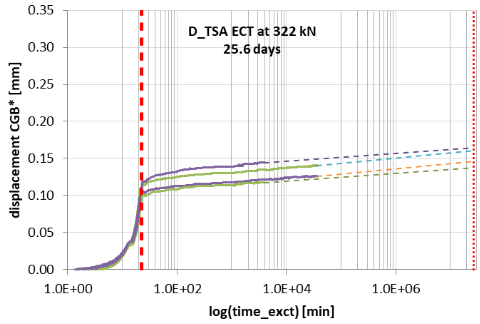
(g) Austenitic plates with Al-SM coating (A_Al-SM_B109)



(h) Ferritic plates with Al-SM coating (F_Al-SM_B109)



(i) Lean Duplex plates with Al-SM coating (LD_Al-SM_B109)



(j) Duplex plates with Al-SM coating (D_Al-SM_B109)

Figure 27 Results of extended creep tests considering different stainless steel grades and surface conditions - test series with bolts of property class 10.9 (Bumax109) - CBG* : During ECT tests slips were only measured at PE position, slip at CBG is calculated based on the relation between PE and CBG measurements found in the static tests.
The results of all slip factor tests (quasi static, creep and extended creep tests) for all series of stainless steel plates can be found in [20].

Evaluating the slip displacement – log time curve based on the results of the creep tests for Al-SM test series (on 0.9 F_{Sm}-level) is a valuable way to figure out the creep sensitivity level of the coated surfaces. Unfortunately, the duration of these two extended creep tests is quite short compared to a “normal” extended creep test and extended creep tests are necessary. Nevertheless, this method will help to estimate a more reasonable load level for extended creep tests. For the Al-SM test series, the results show that this type of coating is not very creep sensitive. For this reason, the same load level (0.9 F_{Sm}) was selected for performing the extended creep tests. As it can be seen in Figure 26, the extended creep tests can be considered as passed tests and the nominal slip factor can be calculated with the same load level (0.9 F_{Sm}). All extended creep tests were also passed with the same load level for test series with Bumax 109. As it can be seen in Figure 28, there is a tendency towards a slightly higher slip factor with higher preload level. This phenomenon can be explained by a better cold welding of the faying surfaces by having higher preload level.

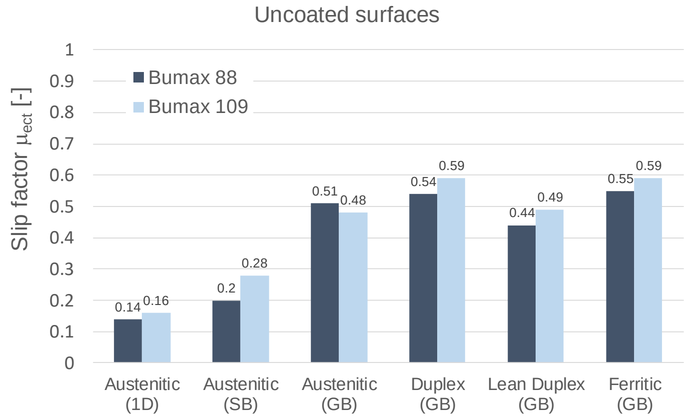


Figure 28 Final slip factor considering different stainless steel grades and surface treatments with bolts of property class 8.8 (Bumax88) and 10.9 (Bumax109)

Figure 29 shows that a higher preload level does not have this positive influence on slip resistance behaviour of the aluminium spray metalized coated surfaces. Because all surfaces are covered with aluminium and there is no contact between the stainless steel material any more. For this reason, there is no chance to have cold welding effects between the stainless steel faying surfaces.

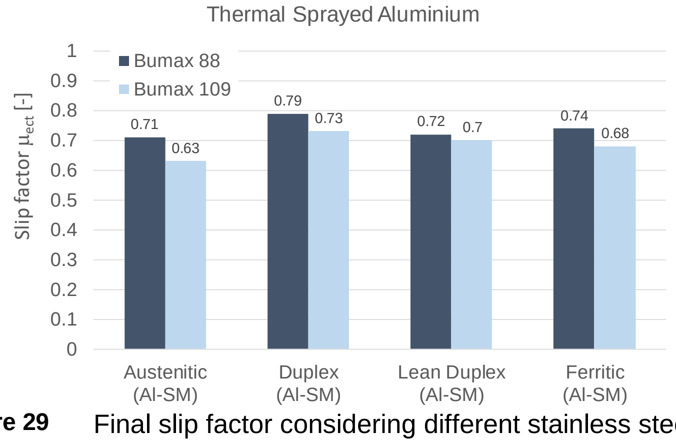


Figure 29 Final slip factor considering different stainless steel grades with aluminium spray metalized surfaces with bolts of property class 8.8 (Bumax88) and 10.9 (Bumax109)

It can be summarized that for all grit blasted surface conditions slip factors of around 0.5 could be achieved. Sometimes even much higher with values of about 0.6 to 0.7 for thermal spray metalized surfaces with aluminium. These are very promising results for carrying out long lasting and cost effective slip-resistant connections made of stainless steel.

4 Conclusions

For the investigated stainless steel plates and bolt sets, the preload losses during slip factor tests caused by viscoplastic deformation of the stainless steel material are not significantly higher than those found for preloaded bolted connections made of carbon steel components.

Grit blasting of stainless steel surfaces result in very high surface roughness and slip factors. For the investigated austenitic, duplex, lean duplex and ferritic stainless steel plates slip factors of about 0.5 and higher could be achieved. The results show that the slip factors for different grades of stainless steel with Al-SM-coating with Bumax 109 and Bumax 88 bolts were greater than 0.6 and 0.7 respectively. Stainless steel plates with untreated (1D) or shot blasted surfaces lead to comparable low slip factors of about 0.16 - 0.28 which might still be enough in some practical applications.

Opposite to what is known for carbon steels, uncoated slip-resistant connections made of stainless steel plates show with increasing preload levels higher slip factors. On the other hand, increasing the preload level in Al-SM-stainless steel slip-resistant connections lead to increased slip loads but slightly decreased slip factors comparable to the behaviour of coated carbon steel slip-resistant connections.

Essen, 23.03.2018

Univ.-Prof. Dr.-Ing. habil. Natalie Stranghöner　　　　Nariman Afzali M.Sc.

Peter de Vries M.Sc.

5 References

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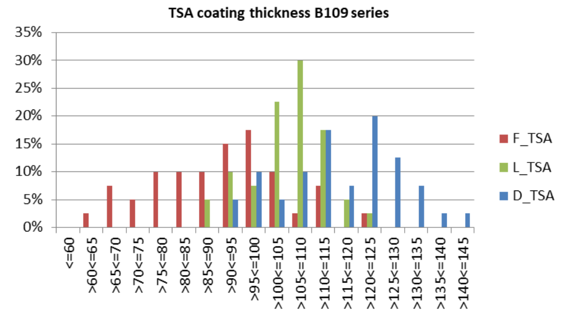
Appendix A: Coating thickness and roughness measurement

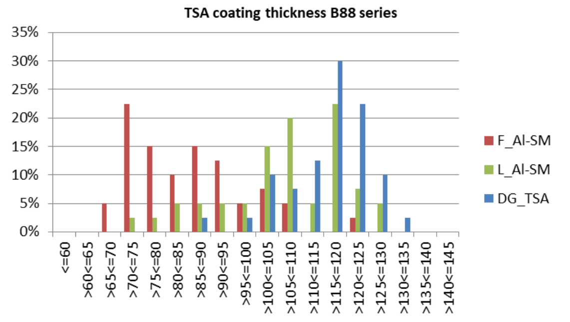
Coating thickness Thermal Sprayed Aluminium layers.

The coating thickness of the Austenitic series could not be determined.

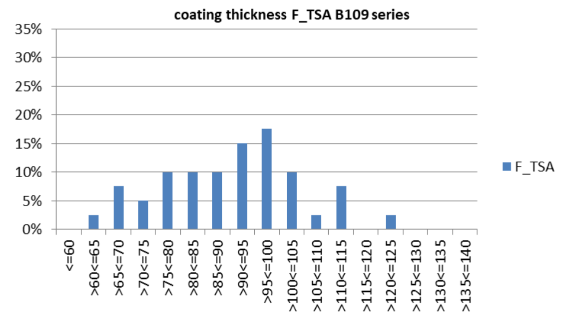
Al-SM metal coating thickness				
series	centre plates		lap plates	
	average	stdev	average	stdev
F_ Al-SM_B109	91	14	88	21
L_ Al-SM_B109	105	8	91	6
D_ Al-SM_B109	116	13	95	12
F_Al-SM_B88	85	13	83	15
L_Al-SM_B88	106	14	89	16
D_Al-SM_B88	116	10	111	11
total	103	12	93	13



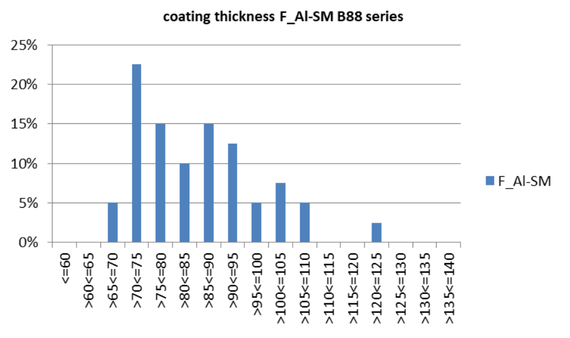
Distribution of Al-SM coating thickness on Ferritic, Duplex and Lean Duplex plates on series with B109 bolts



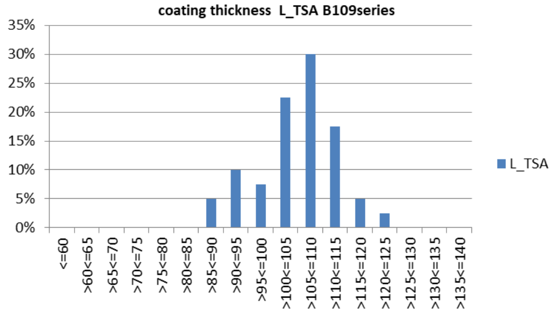
Distribution of Al-SM coating thickness on Ferritic, Duplex and Lean Duplex plates on series with B88 bolts



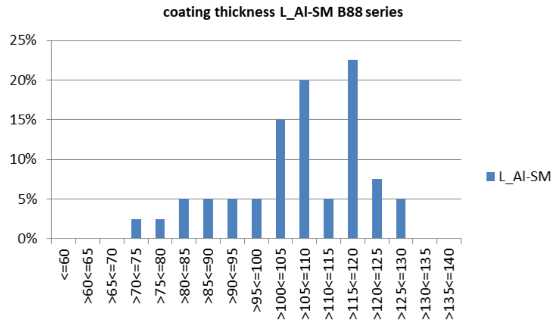
Distribution of Al-SM coating thickness on Ferritic B109 series



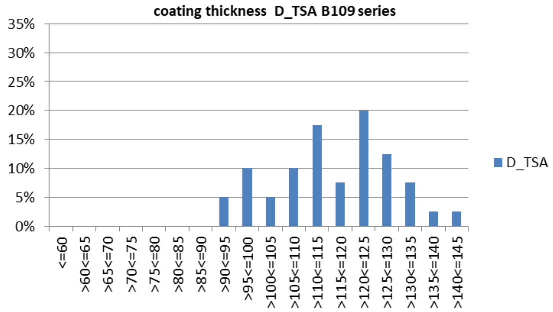
Distribution of Al-SM coating thickness on Ferritic B88 series



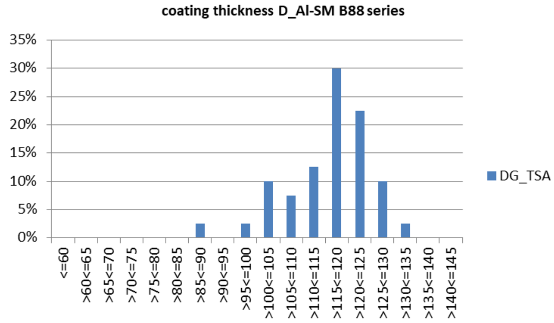
Distribution of Al-SM coating thickness on Lean Duplex B109 series



Distribution of Al-SM coating thickness on Lean Duplex B88 series



Distribution of Al-SM coating thickness on Duplex B109 series



Distribution of Al-SM coating thickness on Duplex B88 series

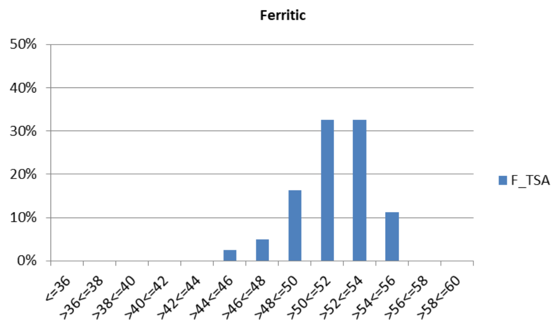
Al-SM Series

Plate roughness before metallizing.

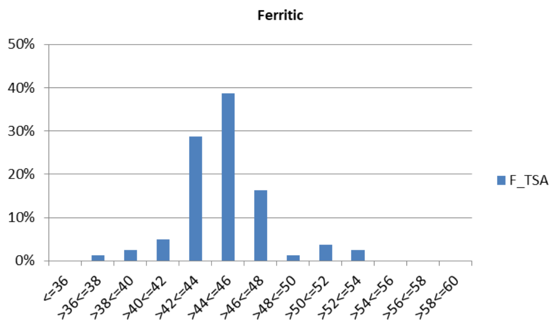
Notice the difference between the roughness of front and back side of the plates of the Lean Duplex series. This is observed on both centre and lap plates.

centre plates	front side		back side	
	average	stdev	average	stdev
F41-F60	50	2	51	3
F61-F80	52	2	52	1
A61-A80	54	1	48	3
A141-A160	55	2	49	3
D41-D60	41	1	41	1
D61-D80	41	2	41	1
L41-L60	63	3	40	2
L61-L80	64	3	42	2

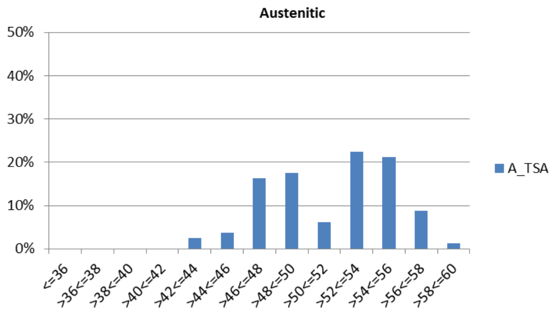
lap plates	front side		back side	
	average	stdev	average	stdev
F41-F60	44	2	45	2
F61-F80	45	3	46	2
A61-A80	45	2	46	1
A141-A160	46	2	45	2
D41-D60	43	2	44	2
D61-D80	43	2	43	2
L41-L60	44	3	59	3
L61-L80	44	3	58	3



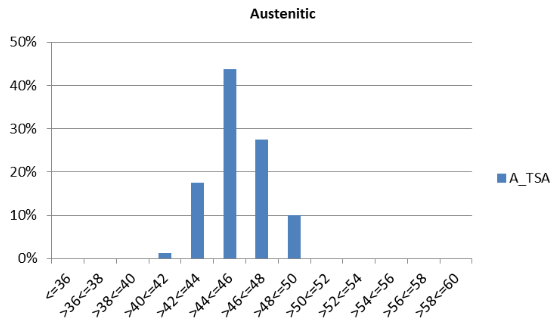
Centre plates (F_Al-SM)



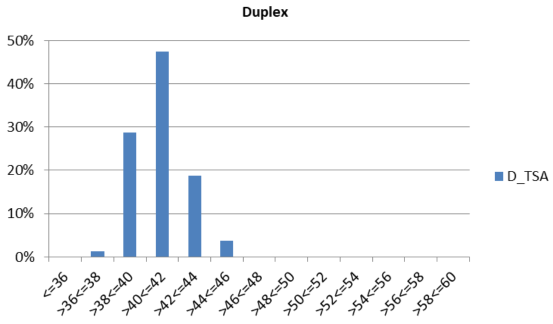
Lap plates (F_Al-SM)



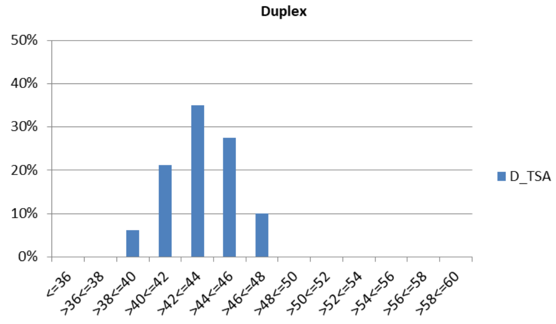
Centre plates (A_Al-SM)



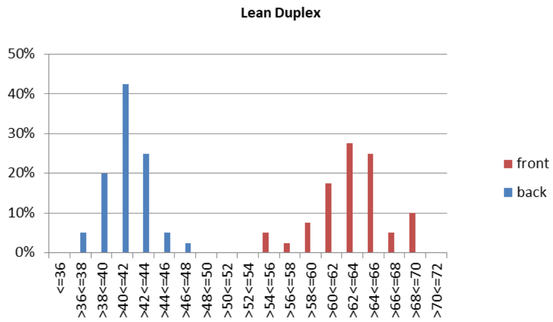
Lap plates (A_Al-SM)



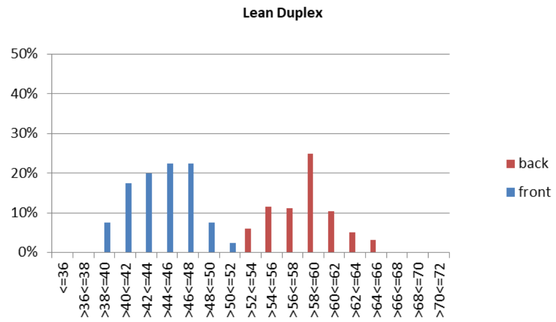
Centre plates (D_Al-SM)



Lap plates (D_Al-SM)



Centre plates (LD_Al-SM)



Lap plates (LD_Al-SM)

Appendix B: Slip factor test results (static and creep tests) – with Bumax 88 bolting assemblies

Table B1 Test protocol Austenitic test series

UNIVERSITÄT DUISBURG ESSEN Open-Minded
INSTITUTE FOR Metal and Lightweight Structures
Univ.-Prof. Dr.-Ing. habil. Natalie Stranghöner
Universitätsstr. 15, 45141 Essen
Fon: +49 (0)201 183-2757
Fax: +49 (0)201 183-2710
E-Mail: iml@uni-due.de
www.uni-due.de/iml

Test report

25/11/2014

Kenngrößen der Prüfung		
	Tested according to	DIN EN 1090-2:2011-10 – Annex G
	Test date	25.11.2014
	Test performed by	N. Afzali, M.Sc.
	Project No.	410410007 20003
	Quotation No.	RFSR-CT-2014-00024 (SIROCO)
	Steel grade	Austenitic (1.4307)
	Coating	–
	Coating composition	–
	Surface treatment	1D surface finish - Hot rolled
	Maximum coating thickness	–
	Mean coating thickness	–
	Minimum coating thickness	–
	Surface roughness (before coating)	–
	Surface roughness (after coating)	–
	Curing procedure	–
	Duration of curing	–
	Time between application of coating and testing	–
	Specimen size	Standard specimens M16 (EN 1090-2, Figure G.1 b)
	Bolt class, bolt type	10.9 (Set EN 14399-4 – HV – M16 x 90 – 10.9/10 – tZn)
	Nominal preload level	110 kN = $F_{p,C}$
	Preload measuring method	implanted SG, measured continuously, clamping length Σt = 70 mm
	Test speed	0.6 mm/min

	Specimens mark	plate ID's	Slip (average at CBG) u_i [mm]	Slip load F_{Si} [kN]	Preload at start of test (initial preload) Outer bolt $F_{bi,o,ini}$ [kN]	Mean value 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] 110 $\mu_i = \mu_{i,nom}$ [–]	based on preload at slip $\mu_{i,act}$ [–]	Preload at slip Outer bolt $F_{bi,o,act}$ [kN]	Mean value mean $F_{bi,act}$ [kN]	Inner bolt $F_{bi,i,act}$ [kN]	Test duration t [min]	Comment Eq. according to DIN EN 1090-2	Date of test Start of the test
Static test	6.2_UDE_Austenitic_11	a	0.029	132.1	110.0	109.8	109.5	0.30	0.30	0.31	106.9	106.1	105.3	6.1		25.11.14 10:55
		b	0.046	132.1	109.6	109.6	109.6	0.30	0.30	0.31	105.7	105.2	104.8	6.1		
	6.2_UDE_Austenitic_12	a	0.042	139.1	109.4	109.6	109.7	0.32	0.32	0.33	105.0	104.4	103.8	11.9		25.11.14 13:05
		b	0.045	134.8	109.5	109.6	109.7	0.31	0.31	0.32	105.2	104.6	104.0	6.4		
	6.2_UDE_Austenitic_13	a	0.044	136.0	109.6	109.3	109.0	0.31	0.31	0.33	105.8	104.5	103.2	6.2		25.11.14 14:10
		b	0.030	136.0	109.7	109.5	109.4	0.31	0.31	0.32	105.9	105.1	104.3	6.2		
	6.2_UDE_Austenitic_14	a	0.047	135.1	109.3	109.1	108.8	0.31	0.31	0.32	105.7	104.7	103.7	6.4		25.11.14 15:30
		b	0.034	135.1	109.4	109.5	109.5	0.31	0.31	0.32	105.4	104.9	104.4	6.4		
	Statistics (4 specimens, 8 test results)	n = 8	Number of tests													
		max	Maximum	139.1				0.32	0.32	0.33						
		min	Minimum	132.1				0.30	0.30	0.31						
		mean	Mean value F_{Sm} | μ_m	135.0				0.31	0.31	0.32					Eq. (2), Eq. (4)	
		R	Spread	6.9				0.02	0.02	0.02					$R = max - min$	
		s	Standard deviation s_{Fs}	2.2				0.005	0.005	0.007					Eq. (3), Eq. (5)	
		V	Coefficient of variation	1.7%				1.7%	1.7%	2.1%					$V = s / mean$	
		0.9 F_{Sm}		121.5											Load level for the creep test	
Creep test	6.2_UDE_Austenitic_15	a	Δ (5 min bis 3 h): 0,0012	121.5											Creep test failed Slip during the creep test > 0,002 mm (5 min to 3 h)	25.11.14 18:00
			0.049	136.3	108.9	108.9	108.9	0.31	0.31	0.34	102.6	101.6	100.7	875.4		
		b	Δ (5 min bis 3 h): 0,0017	121.5												
			0.150	121.5	108.9	108.9	109.0	0.28	0.28	0.29	103.1	103.4	103.7	7.0		
	Statistics (5 specimens, 10 test results)	n = 10	Number of tests													
		max	Maximum	139.1				0.32	0.32	0.34						
		min	Minimum	121.5				0.28	0.28	0.29						
		mean	Mean value F_{Sm} | μ_m	133.8				0.31	0.30	0.32					Eq. (2), Eq. (4)	
		R	Spread	17.6				0.04	0.04	0.04					$R = max - min$	
		s	Standard deviation s_{Fs}	4.8				0.011	0.011	0.012					Eq. (3), Eq. (5)	
		V	Coefficient of variation	3.6%				3.5%	3.6%	3.7%					$V = s / mean$ ≤ 8%	
		0.9 F_{Sm}		120.4												
	μ_k		Characteristic value of the slip factor					0.28	0.28	0.30					Eq. (6)	

Table B2 Test protocol Duplex test series

UNIVERSITÄT DUISBURG ESSEN Open-Minded
INSTITUTE FOR **Metal and Lightweight Structures**
Univ.-Prof. Dr.-Ing. habil. Natalie Stranghöner
Universitätsstr. 15
45141 Essen
Fon: +49 (0)201 183-2757
Fax: +49 (0)201 183-2710
E-Mail: iml@uni-due.de
www.uni-due.de/iml

Test report

26/11/2014

Technical characteristics of the test		
	Tested according to	DIN EN 1090-2:2011-10 – Annex G
	Test date	26.11.2014
	Test performed by	N. Afzali, M.Sc.
	Project No.	410410007 20003
	Quotation No.	RFSR-CT-2014-00024 (SIROCO)
	Steel grade	Duplex (1.4462 inner plate & 1.4401 cover plate)
	Coating	–
	Coating composition	–
	Surface treatment	1D surface finish - Hot rolled
	Maximum coating thickness	–
	Mean coating thickness	–
	Minimum coating thickness	–
	Surface roughness (before coating)	–
	Surface roughness (after coating)	–
	Curing procedure	–
	Duration of curing	–
	Time between application of coating and testing	–
	Specimen size	Standard specimens M16 (EN 1090-2, Figure G.1 b)
	Bolt class, bolt type	10.9 (Set EN 14399-4 – HV – M16 x 90 – 10.9/10 – tZn)
	Nominal preload level	110 kN = $F_{p,C}$
	Preload measuring method	implanted SG, measured continuously, clamping length Σt = 70 mm
	Test speed	0.6 mm/min

	Specimens mark	plate ID's	Slip (average at CBG) u_i [mm]	Slip load F_{Si} [kN]	Preload at start of test (initial preload) Outer bolt $F_{bi,o,ini}$ [kN]	Mean value 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] 110 $\mu_i = \mu_{i,nom}$ [–]	based on preload at slip $\mu_{i,act}$ [–]	Preload at slip Outer bolt $F_{bi,o,act}$ [kN]	Mean value mean $F_{bi,act}$ [kN]	Inner bolt $F_{bi,i,act}$ [kN]	Test duration t [min]	Comment Eq. according to DIN EN 1090-2	Date of test Start of the test
Static test	6.2_UDE_Duplex_11	a	0.071	106.9	110.1	110.0	109.9	0.24	0.24	0.25	108.4	108.2	108.0	5.6		26.11.14 11:00
		b	0.029	106.9	110.1	110.1	110.1	0.24	0.24	0.25	108.6	108.4	108.2	5.6		
	6.2_UDE_Duplex_12	a	0.095	116.3	110.2	110.1	110.0	0.26	0.26	0.27	109.5	109.1	108.6	5.8		26.11.14 12:25
		b	0.057	116.3	110.3	110.3	110.3	0.26	0.26	0.27	108.4	108.3	108.2	5.8		
	6.2_UDE_Duplex_13	a	0.072	111.7	110.3	110.1	109.9	0.25	0.25	0.26	108.7	108.1	107.5	5.6		26.11.14 14:05
		b	0.059	111.7	110.4	110.3	110.3	0.25	0.25	0.26	108.5	108.4	108.2	5.6		
	6.2_UDE_Duplex_14	a	0.045	114.2	110.3	110.1	110.0	0.26	0.26	0.26	108.3	108.2	108.2	5.9		26.11.14 16:20
		b	0.059	114.2	110.2	110.2	110.2	0.26	0.26	0.26	108.6	108.3	108.0	5.9		
	Statistics (4 specimens, 8 test results)	n = 8	Number of tests													
		max	Maximum	116.3				0.26	0.26	0.27						
		min	Minimum	106.9				0.24	0.24	0.25						
		mean	Mean value F_{Sm} | μ_m	**112.3**				**0.25**	**0.26**	**0.26**					Eq. (2), Eq. (4)	
		R	Spread	9.4				0.02	0.02	0.02					*R* = *max* – *min*	
		s	Standard deviation s_{Fs}	3.8				0.008	0.009	0.008					Eq. (3), Eq. (5)	
		V	Coefficient of variation	3.4%				3.3%	3.4%	3.3%					*V* = *s* / *mean*	
		0.9 F_{Sm}		**101.1**											Load level for the creep test	
Creep test	6.2_UDE_Duplex_15	a	Δ (5 min bis 3 h): **0,0015**	101.1											**Creep test is passed** Slip during the creep test < 0,002 mm (5 min to 3 h)	26.11.14 17:35
			0.039	113.5	110.4	110.2	110.0	0.26	0.26	0.26	107.8	107.3	106.9	929.0		
		b	Δ (5 min bis 3 h): **0,0013**	101.1												
			0.028	113.5	110.3	110.4	110.5	0.26	0.26	0.26	107.6	107.6	107.6	929.0		
	Statistics (5 specimens, 10 test results)	n = 10	Number of tests													
		max	Maximum	116.3				0.26	0.26	0.27						
		min	Minimum	106.9				0.24	0.24	0.25						
		mean	Mean value F_{Sm} | μ_m	112.5				0.26	0.26	0.26					Eq. (2), Eq. (4)	
		R	Spread	9.4				0.02	0.02	0.02					*R* = *max* – *min*	
		s	Standard deviation s_{Fs}	3.4				0.008	0.008	0.008					Eq. (3), Eq. (5)	
		V	**Coefficient of variation**	**3.0%**				**2.9%**	**3.0%**	**3.0%**					*V* = *s* / *mean* ≤ 8%	
		0.9 F_{Sm}		101.3												
	μ_k	Characteristic value of the slip factor						0.24	0.24	0.24					Eq. (6)	

Appendix C: Slip factor test results (static and creep tests) – with Bumax 88 bolting assemblies

Table C1 Test protocol A_1D test series

UNIVERSITÄT DUISBURG ESSEN Open-Minded

INSTITUTE FOR **Metal and Lightweight Structures**
Univ.-Prof. Dr.-Ing. habil. Natalie Stranghöner

Universitätsstr. 15
45141 Essen

Fon: +49 (0)201 183-2757
Fax: +49 (0)201 183-2710

E-Mail: iml@uni-due.de
www.uni-due.de/iml

Test report

13.10.2016

Technical characteristics of the test	Tested according to	DIN EN 1090-2:2011-10 – Annex G
	Test date	26.08.2016
	Test performed by	N. Afzali, M.Sc.
	Project No.	410410007 20003
	Quotation No.	RFSR-CT-2014-00024 (SIROCO)
	Steel grade	Austenitic Stainless Steel (1.4404)
	Coating	–
	Coating composition	–
	Surface treatment	1D surface finish - Hot rolled, heat treated, (shot blasted) and pickled
	Maximum coating thickness	
	Mean coating thickness	–
	Minimum coating thickness	–
	Surface roughness (before coating)	24 µm
	Surface roughness (after coating)	–
	Curing procedure	–
	Duration of curing	–
	Time between application of coating and testing	–
	Specimen size	Standard specimens M16 (EN 1090-2, Figure G.1 b)
	Bolt class, bolt type	Bolt: BUMAX 88 (EN ISO 4017 – M16 x 100) - Nut: BUMAX 88 (EN ISO 4032) - Washer: HV 200 (EN ISO 7089)
	Nominal preload level	88 kN = $F_{p,C}$
	Preload measuring method	Load cell (h = 40 mm), measured continuously, clamping length Σt = 75 mm
	Test speed	0.6 mm/min

	Specimens mark	plate ID's	Slip (average at CBG) u_i [mm]	Slip load F_{Si} [kN]	Preload at start of test (initial preload): Outer bolt $F_{bi,o,ini}$ [kN]	Mean value mean $F_{bi,ini}$ [kN]	Inner bolt $F_{bi,i,ini}$ [kN]	Slip factor based on initial $\mu_{i,ini}$ [–]	based on nominal $F_{p,C}$ [kN] 88: $\mu_i = \mu_{i,nom}$ [–]	based on preload at slip $\mu_{i,act}$ [–]	Preload at slip: Outer bolt $F_{bi,o,act}$ [kN]	Mean value mean $F_{bi,act}$ [kN]	Inner bolt $F_{bi,i,act}$ [kN]	Test duration t [min]	Comment Eq. according to DIN EN 1090-2	Date of test Start of the test
Static test	6.2_UDE_A_1D_1-2	1	0.084	78.0	88.7	88.8	88.9	0.22	0.22	0.22	87.1	86.9	86.7	4.2		26.08.16 13:05
		2	0.042	78.0	88.6	88.5	88.4	0.22	0.22	0.22	87.2	87.0	86.8	4.2		
	6.2_UDE_A_1D_3-4	3	0.094	70.7	89.7	89.2	88.7	0.20	0.20	0.20	88.2	87.4	86.6	3.8		29.08.16 12:05
		4	0.031	70.7	89.1	88.9	88.8	0.20	0.20	0.20	87.9	87.6	87.4	3.8		
	6.2_UDE_A_1D_5-6	5	0.150	75.5	89.6	89.8	90.0	0.21	0.21	0.22	87.8	87.6	87.3	8.9		29.08.16 14:15
		6	0.100	74.3	90.0	90.1	90.2	0.21	0.21	0.21	88.4	88.2	87.9	4.0		
	6.2_UDE_A_1D_7-8	7	0.071	73.2	90.2	90.0	89.8	0.20	0.21	0.21	88.8	88.5	88.1	3.8		29.08.16 15:40
		8	0.046	73.2	90.2	90.3	90.3	0.20	0.21	0.21	88.9	88.6	88.4	3.8		
	Statistics (4 specimens, 8 test results)	n = 8	Number of tests													
		max	Maximum	78.0				0.22	0.22	0.22						
		min	Minimum	70.7				0.20	0.20	0.20						
		$mean$	Mean value F_{Sm} | μ_m	74.2				0.21	0.21	0.21					Eq. (2), Eq. (4)	
		R	Spread	7.3				0.02	0.02	0.02					R = max – min	
		s	Standard deviation s_{FS}	2.8				0.009	0.008	0.009					Eq. (3), Eq. (5)	
		V	Coefficient of variation	3.8%				4.2%	3.8%	4.3%					V = s / $mean$	
		0,9 F_{Sm}		66.8											Load level for the creep test	
Creep test	6.2_UDE_A_1D_9-10	9	Δ (5 min to 3 h): 0,0019												Creep test is passed. Slip during the creep test < 0,002 mm (5 min to 3 h)	29.08.16 16:50
			0.039	75.7	90.2	90.3	90.5	0.21	0.21	0.22	87.2	87.0	86.9	1178.8		
		10	Δ (5 min to 3 h): 0,0003													
			0.103	78.2	90.3	90.4	90.4	0.22	0.22	0.22	87.6	87.6	87.6	1183.5		
	Statistics (5 specimens, 10 test results)	n = 10	Number of tests													
		max	Maximum	78.2				0.22	0.22	0.22						
		min	Minimum	70.7				0.20	0.20	0.20						
		$mean$	Mean value F_{Sm} | μ_m	74.7				0.21	0.21	0.21					Eq. (2), Eq. (4)	
		R	Spread	7.4				0.02	0.02	0.02					R = max – min	
		s	Standard deviation s_{FS}	2.8				0.008	0.008	0.009					Eq. (3), Eq. (5)	
		V	Coefficient of variation	3.8%				3.9%	3.8%	4.1%					V = s / $mean$ ≤ 8%	
		0,9 F_{Sm}		67.3												
	μ_k		Characteristic value of the slip factor					0.19	0.20	0.20					Eq. (6)	

Table C2 Test protocol A_SB test series

UNIVERSITÄT DUISBURG ESSEN Open-Minded
INSTITUTE FOR **Metal and Lightweight Structures**
Univ.-Prof. Dr.-Ing. habil. Natalie Stranghöner
Universitätsstr. 15
45141 Essen
Fon: +49 (0)201 183-2757
Fax: +49 (0)201 183-2710
E-Mail: iml@uni-due.de
www.uni-due.de/iml

Test report

20.11.2016

Technical characteristics of the test	Tested according to	DIN EN 1090-2:2011-10 – Annex G
	Test date	14.11.2016 - 15.11.2016
	Test performed by	N. Afzali, M.Sc.
	Project No.	410410007 20003
	Quotation No.	RFSR-CT-2014-00024 (SIROCO)
	Steel grade	Austenitic Stainless Steel (1.4404)
	Coating	–
	Coating composition	–
	Surface treatment	Shot blasted (using Chronital S40 particles of 40 µm particle size)
	Maximum coating thickness	–
	Mean coating thickness	–
	Minimum coating thickness	–
	Surface roughness (before coating)	38 µm
	Surface roughness (after coating)	–
	Curing procedure	–
	Duration of curing	–
	Time between application of coating and testing	–
	Specimen size	Standard specimens M16 (EN 1090-2, Figure G.1 b)
	Bolt class, bolt type	Bolt: BUMAX88 (EN ISO 4017 – M16 x 100) - Nut: BUMAX88 (EN ISO 4032) - Washer: HV 200 (EN ISO 7089)
	Nominal preload level	88 kN = $F_{p,C}$
	Preload measuring method	Load cell (h = 40 mm), measured continuously, clamping length Σt = 75 mm
	Test speed	0.6 mm/min

	Specimens		Slip	Slip load	Preload			Slip factor			Preload			Test duration	Comment	Date of test
	mark	plate ID's	(average at CBG)		at start of test (initial preload)			based on initial	based on nominal $F_{p,C}$ [kN] 88	based on preload at slip	at slip				Eq. according to DIN EN 1090-2	Start of the test
					Outer bolt	Mean value	Inner bolt				Outer bolt	Mean value	Inner bolt			
			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 test	6.2_UDE_A_SB_1-2	1	0.150	104.2	88.6	88.4	88.2	0.29	0.30	0.30	86.2	85.8	85.3	7.6		14.11.16 17:50
		2	0.150	102.5	87.2	87.2	87.2	0.29	0.29	0.30	84.7	84.3	84.0	7.4		
	6.2_UDE_A_SB_3-4	3	0.150	106.6	87.6	87.8	88.0	0.30	0.30	0.31	85.4	85.2	85.0	8.3		15.11.16 12:30
		4	0.150	95.1	88.9	88.4	87.9	0.27	0.27	0.28	87.1	86.0	85.0	7.2		
	6.2_UDE_A_SB_5-6	5	0.150	105.1	88.5	88.8	89.1	0.30	0.30	0.31	86.1	86.1	86.1	7.7		15.11.16 14:00
		6	0.150	95.8	88.7	89.1	89.6	0.27	0.27	0.28	86.4	86.6	86.7	6.9		
	6.2_UDE_A_SB_7-8	7	0.150	101.0	88.6	88.6	88.5	0.29	0.29	0.29	86.3	86.1	85.9	7.0		15.11.16 15:30
		8	0.150	112.4	87.8	88.2	88.6	0.32	0.32	0.33	85.2	85.1	85.1	7.9		
	Statistics (4 specimens, 8 test results)	*n* = 8	Number of tests													
		max	Maximum	112.4				0.32	0.32	0.33						
		min	Minimum	95.1				0.27	0.27	0.28						
		mean	Mean value F_{Sm} | μ_m	**102.8**				**0.29**	**0.29**	**0.30**					Eq. (2), Eq. (4)	
		R	Spread	17.3				0.05	0.05	0.05					*R* = *max* – *min*	
		s	Standard deviation s_{FS}	5.7				0.017	0.016	0.018					Eq. (3), Eq. (5)	
		V	Coefficient of variation	5.5%				5.8%	5.5%	6.0%					*V* = *s* / *mean*	
		0,9 F_{Sm}		**92.5**											Load level for the creep test	
Creep test	6.2_UDE_A_SB_9-10	9	Δ (5 min to 3 h): **–**												**Creep test failed** Slip during the creep test > 0,002 mm (5 min to 3 h)	15.11.16 17:30
				–	90.1	89.4	88.6	–	–	–	88.2	87.3	86.4	4.8		
		10	Δ (5 min to 3 h): **–**													
				–	88.0	88.7	89.4	–	–	–	86.4	86.6	86.8	5.0		

Table C3 Test protocol A_GB test series

UNIVERSITÄT DUISBURG ESSEN Open-Minded
INSTITUTE FOR **Metal and Lightweight Structures**
Univ.-Prof. Dr.-Ing. habil. Natalie Stranghöner
Universitätsstr. 15
45141 Essen
Fon: +49 (0)201 183-2757
Fax: +49 (0)201 183-2710
E-Mail: iml@uni-due.de
www.uni-due.de/iml

Test report

20.11.2016

Technical characteristics of the test		
	Tested according to	DIN EN 1090-2:2011-10 – Annex G
	Test date	16.11.2016
	Test performed by	N. Afzali, M.Sc.
	Project No.	410410007 20003
	Quotation No.	RFSR-CT-2014-00024 (SIROCO)
	Steel grade	Austenitic Stainless Steel (1.4404)
	Coating	–
	Coating composition	–
	Surface treatment	Grit blasted (using Grittal GM30 particles of 50 µm particle size)
	Maximum coating thickness	–
	Mean coating thickness	–
	Minimum coating thickness	–
	Surface roughness (before coating)	45 µm
	Surface roughness (after coating)	–
	Curing procedure	–
	Duration of curing	–
	Time between application of coating and testing	–
	Specimen size	Standard specimens M16 (EN 1090-2, Figure G.1 b)
	Bolt class, bolt type	Bolt: BUMAX88 (EN ISO 4017 – M16 x 100) - Nut: BUMAX88 (EN ISO 4032) - Washer: HV 200 (EN ISO 7089)
	Nominal preload level	88 kN = $F_{p,C}$
	Preload measuring method	Load cell (h = 40 mm), measured continuously, clamping length Σt = 75 mm
	Test speed	0.6 mm/min

	Specimens mark	plate ID's	Slip (average at CBG) u_i [mm]	Slip load F_{Si} [kN]	Preload at start of test (initial preload) Outer bolt $F_{bi,o,ini}$ [kN]	Mean value mean $F_{bi,ini}$ [kN]	Inner bolt $F_{bi,i,ini}$ [kN]	Slip factor based on initial $\mu_{i,ini}$ [–]	based on nominal $F_{p,C}$ [kN] 88 $\mu_i = \mu_{i,nom}$ [–]	based on preload at slip $\mu_{i,act}$ [–]	Preload at slip Outer bolt $F_{bi,o,act}$ [kN]	Mean value mean $F_{bi,act}$ [kN]	Inner bolt $F_{bi,i,act}$ [kN]	Test duration t [min]	Comment Eq. according to DIN EN 1090-2	Date of test Start of the test
Static test	6.2_UDE_A_GB_1-2	1	0.150	193.5	89.4	89.7	90.1	0.54	0.55	0.58	84.1	84.0	83.9	11.9		16.11.16 9:55
		2	0.150	193.0	89.2	89.2	89.2	0.54	0.55	0.58	83.5	82.8	82.1	11.9		
	6.2_UDE_A_GB_3-4	3	0.141	199.4	88.0	88.4	88.7	0.56	0.57	0.61	81.2	81.4	81.5	14.4		16.11.16 11:15
		4	0.150	191.5	88.2	88.1	88.0	0.54	0.54	0.59	82.3	81.4	80.4	10.9		
	6.2_UDE_A_GB_7-8	7	0.150	197.0	88.9	88.8	88.6	0.56	0.56	0.60	83.3	82.4	81.5	15.5		16.11.16 14:35
		8	0.150	186.1	89.6	88.9	88.2	0.52	0.53	0.56	84.5	82.8	81.1	11.1		
	6.2_UDE_A_GB_9-10	9	0.150	223.6	89.1	89.1	89.1	0.63	0.64	0.69	82.5	81.5	80.6	15.6		16.11.16 16:10
		10	0.150	200.5	89.2	88.6	88.0	0.57	0.57	0.62	83.0	81.4	79.7	11.4		
	Statistics (4 specimens, 8 test results)	n = 8	Number of tests													
		max	Maximum	223.6				0.63	0.64	0.69						
		min	Minimum	186.1				0.52	0.53	0.56						
		mean	Mean value F_{Sm} | μ_m	**198.1**				**0.56**	**0.56**	**0.60**					Eq. (2), Eq. (4)	
		R	Spread	37.4				0.10	0.11	0.12					*R* = *max* – *min*	
		s	Standard deviation s_{FS}	11.3				0.031	0.032	0.038					Eq. (3), Eq. (5)	
		V	Coefficient of variation	5.7%				5.6%	5.7%	6.3%					*V* = *s* / *mean*	
		0,9 F_{Sm}		**178.3**											Load level for the creep test	
Creep test	6.2_UDE_A_GB_13-14	13	Δ (5 min to 3 h): **0,0006**												**Creep test is passed** Slip during the creep test < 0,002 mm (5 min to 3 h)	16.11.16 18:00
			0.150	183.7	90.0	89.3	88.7	0.51	0.52	0.56	83.6	82.4	81.3	229.1		
		14	Δ (5 min to 3 h): **0,0004**													
			0.133	183.7	88.6	89.1	89.7	0.52	0.52	0.56	82.6	82.1	81.6	229.1		
	Statistics (5 specimens, 10 test results)	n = 10	Number of tests													
		max	Maximum	223.6				0.63	0.64	0.69						
		min	Minimum	183.7				0.51	0.52	0.56						
		mean	Mean value F_{Sm} | μ_m	195.2				0.55	0.55	0.59					Eq. (2), Eq. (4)	
		R	Spread	39.9				0.11	0.11	0.13					*R* = *max* – *min*	
		s	Standard deviation s_{FS}	11.7				0.033	0.033	0.038					Eq. (3), Eq. (5)	
		V	Coefficient of variation	**6.0%**				**6.0%**	**6.0%**	**6.5%**					*V* = *s* / *mean* ≤ 8%	
		0,9 F_{Sm}		175.7												
	μ_k		Characteristic value of the slip factor					0.48	0.49	0.51					Eq. (6)	

Table C4 Test protocol D_GB test series

UNIVERSITÄT DUISBURG ESSEN Open-Minded
INSTITUTE FOR Metal and Lightweight Structures
Univ.-Prof. Dr.-Ing. habil. Natalie Stranghöner
Universitätsstr. 15, 45141 Essen
Fon: +49 (0)201 183-2757
Fax: +49 (0)201 183-2710
E-Mail: iml@uni-due.de
www.uni-due.de/iml

Test report

20.11.2016

Technical characteristics of the test		
	Tested according to	DIN EN 1090-2:2011-10 – Annex G
	Test date	09.11.2016 - 10.11.2016
	Test performed by	N. Afzali, M.Sc.
	Project No.	410410007 20003
	Quotation No.	RFSR-CT-2014-00024 (SIROCO)
	Steel grade	Duplex Stainless Steel (1.4462)
	Coating	–
	Coating composition	–
	Surface treatment	Grit blasted (using Grittal GM30 particles of 50 µm particle size)
	Maximum coating thickness	–
	Mean coating thickness	–
	Minimum coating thickness	–
	Surface roughness (before coating)	47 µm
	Surface roughness (after coating)	–
	Curing procedure	–
	Duration of curing	–
	Time between application of coating and testing	–
	Specimen size	Standard specimens M16 (EN 1090-2, Figure G.1 b)
	Bolt class, bolt type	Bolt: BUMAX88 (EN ISO 4017 – M16 x 100) - Nut: BUMAX88 (EN ISO 4032) - Washer: HV 200 (EN ISO 7089)
	Nominal preload level	88 kN = $F_{p,C}$
	Preload measuring method	Load cell (h = 40 mm), measured continuously, clamping length Σt = 75 mm
	Test speed	0.6 mm/min

	Specimens mark	plate ID's	Slip (average at CBG) u_i [mm]	Slip load F_{Si} [kN]	Preload at start of test (initial preload) Outer bolt $F_{bi,o,ini}$ [kN]	Mean value mean $F_{bi,ini}$ [kN]	Inner bolt $F_{bi,i,ini}$ [kN]	Slip factor based on initial $\mu_{i,ini}$ [–]	based on nominal $F_{p,C}$ [kN] 88 $\mu_i = \mu_{i,nom}$ [–]	based on preload at slip $\mu_{i,act}$ [–]	Preload at slip Outer bolt $F_{bi,o,act}$ [kN]	Mean value mean $F_{bi,act}$ [kN]	Inner bolt $F_{bi,i,act}$ [kN]	Test duration t [min]	Comment Eq. according to DIN EN 1090-2	Date of test Start of the test
Static test	6.2_UDE_D_GB_1-2	1	0.138	215.0	88.6	88.3	88.0	0.61	0.61	0.64	84.7	84.3	83.9	12.6		09.11.16 10:05
		2	0.150	202.5	88.4	88.9	89.5	0.57	0.58	0.60	84.7	85.0	85.3	11.5		
	6.2_UDE_D_GB_3-4	3	0.150	189.0	88.5	88.7	88.9	0.53	0.54	0.55	84.9	85.3	85.6	11.5		09.11.16 12:35
		4	0.110	213.6	89.3	89.0	88.6	0.60	0.61	0.63	85.4	84.9	84.4	13.6		
	6.2_UDE_D_GB_5-6	5	0.150	228.4	88.6	88.6	88.6	0.64	0.65	0.68	84.5	84.5	84.5	12.4		10.11.16 9:55
		6	0.150	218.0	88.7	88.6	88.5	0.62	0.62	0.65	84.6	84.3	83.9	13.4		
	6.2_UDE_D_GB_7-8	7	0.150	216.8	88.7	88.6	88.5	0.61	0.62	0.64	84.7	84.7	84.7	13.0		10.11.16 12:10
		8	0.150	215.4	87.9	88.5	89.1	0.61	0.61	0.64	84.0	84.4	84.7	12.8		
	Statistics (4 specimens, 8 test results)	n = 8	Number of tests													
		max	Maximum	228.4				0.64	0.65	0.68						
		min	Minimum	189.0				0.53	0.54	0.55						
		mean	Mean value F_{Sm} | μ_m	**212.3**				**0.60**	**0.60**	**0.63**					Eq. (2), Eq. (4)	
		R	Spread	39.4				0.11	0.11	0.12					R = *max* – *min*	
		s	Standard deviation s_{FS}	11.8				0.034	0.033	0.037					Eq. (3), Eq. (5)	
		V	Coefficient of variation	5.5%				5.6%	5.5%	5.9%					$V = s$ / *mean*	
		0,9 F_{Sm}		**191.1**											Load level for the creep test	
Creep test	6.2_UDE_D_GB_9-10	11	Δ (5 min to 3 h): **0.0008**												**Creep test is passed** Slip during the creep test < 0,002 mm (5 min to 3 h)	
			0.150	207.9	90.1	89.5	88.8	0.58	0.59	0.61	85.8	85.1	84.3	205.1		
		12	Δ (5 min to 3 h): **0,0008**													
			0.150	209.7	89.5	89.7	89.9	0.58	0.60	0.61	85.5	85.4	85.3	205.3		
	Statistics (5 specimens, 10 test results)	n = 10	Number of tests													
		max	Maximum	228.4				0.64	0.65	0.68						
		min	Minimum	189.0				0.53	0.54	0.55						
		mean	Mean value F_{Sm} | μ_m	211.6				0.60	0.60	0.62					Eq. (2), Eq. (4)	
		R	Spread	39.4				0.11	0.11	0.12					R = *max* – *min*	
		s	Standard deviation s_{FS}	10.5				0.031	0.030	0.033					Eq. (3), Eq. (5)	
		V	Coefficient of variation	**5.0%**				**5.1%**	**5.0%**	**5.3%**					$V = s$ / *mean* ≤ 8%	
		0,9 F_{Sm}		190.5												
	μ_k		Characteristic value of the slip factor					0.53	0.54	0.56					Eq. (6)	

Table C 5 Test protocol LD_GB test series

UNIVERSITÄT DUISBURG ESSEN Open-Minded
INSTITUTE FOR **Metal and Lightweight Structures**
Univ.-Prof. Dr.-Ing. habil. Natalie Stranghöner
Universitätsstr. 15, 45141 Essen
Fon: +49 (0)201 183-2757
Fax: +49 (0)201 183-2710
E-Mail: iml@uni-due.de
www.uni-due.de/iml

Test report

20.11.2016

Technical characteristics of the test		
	Tested according to	DIN EN 1090-2:2011-10 – Annex G
	Test date	03.11.2016 - 04.11.2016
	Test performed by	N. Afzali, M.Sc.
	Project No.	410410007 20003
	Quotation No.	RFSR-CT-2014-00024 (SIROCO)
	Steel grade	Lean-Duplex Stainless Steel (1.4162)
	Coating	–
	Coating composition	–
	Surface treatment	Grit blasted (using Grittal GM30 particles of 50 µm particle size)
	Maximum coating thickness	–
	Mean coating thickness	–
	Minimum coating thickness	–
	Surface roughness (before coating)	41 µm
	Surface roughness (after coating)	–
	Curing procedure	–
	Duration of curing	–
	Time between application of coating and testing	–
	Specimen size	Standard specimens M16 (EN 1090-2, Figure G.1 b)
	Bolt class, bolt type	Bolt: BUMAX 88 (EN ISO 4017 – M16 x 100) - Nut: BUMAX 88 (EN ISO 4032) - Washer: HV 200 (EN ISO 7089)
	Nominal preload level	88 kN = $F_{p,C}$
	Preload measuring method	Load cell (h = 40 mm), measured continuously, clamping length Σt = 75 mm
	Test speed	0.6 mm/min

	Specimens mark	plate ID's	Slip (average at CBG) u_i [mm]	Slip load F_{Si} [kN]	Preload at start of test (initial preload): Outer bolt $F_{bi,o,ini}$ [kN]	Mean value mean $F_{bi,ini}$ [kN]	Inner bolt $F_{bi,i,ini}$ [kN]	Slip factor based on initial $\mu_{i,ini}$ [–]	based on nominal $F_{p,C}$ [kN] 88: $\mu_i = \mu_{i,nom}$ [–]	based on preload at slip $\mu_{i,act}$ [–]	Preload at slip: Outer bolt $F_{bi,o,act}$ [kN]	Mean value mean $F_{bi,act}$ [kN]	Inner bolt $F_{bi,i,act}$ [kN]	Test duration t [min]	Comment (Eq. according to DIN EN 1090-2)	Date of test (Start of the test)
Static test	6.2_UDE_LD_GB_3-4	3	0.150	185.5	88.7	89.4	90.0	0.52	0.53	0.54	85.4	86.0	86.6	13.3		03.11.16 15:35
		4	0.150	172.9	88.1	88.4	88.7	0.49	0.49	0.51	85.2	85.1	85.0	9.9		
	6.2_UDE_LD_GB_5-6	5	0.150	188.0	88.6	88.2	87.9	0.53	0.53	0.55	84.9	84.8	84.7	10.1		03.11.16 17:40
		6	0.150	198.5	89.0	88.7	88.5	0.56	0.56	0.59	85.3	84.7	84.2	14.0		
	6.2_UDE_LD_GB_7-8	7	0.150	187.7	88.1	88.7	89.4	0.53	0.53	0.55	84.9	85.5	86.1	10.4		04.11.16 10:25
		8	0.150	188.0	88.7	89.0	89.2	0.53	0.53	0.55	85.9	85.6	85.4	10.5		
	6.2_UDE_LD_GB_9-10	9	0.150	142.4	88.4	88.6	88.8	0.40	0.40	0.41	85.9	86.1	86.3	9.1		04.11.16 13:10
		10	0.132	183.0	88.8	88.9	89.0	0.51	0.52	0.53	85.8	85.7	85.6	12.7		
	Statistics (4 specimens, 8 test results)	n = 8	Number of tests													
		max	Maximum	198.5				0.56	0.56	0.59						
		min	Minimum	142.4				0.40	0.40	0.41						
		mean	Mean value F_{Sm} | μ_m	**180.8**				**0.51**	**0.51**	**0.53**					Eq. (2), Eq. (4)	
		R	Spread	56.1				0.16	0.16	0.17					*R = max – min*	
		s	Standard deviation s_{FS}	17.0				0.048	0.048	0.051					Eq. (3), Eq. (5)	
		V	Coefficient of variation	9.4%				9.3%	9.4%	9.7%					*V = s / mean*	
		0,9 F_{Sm}		**162.7**											Load level for the creep test	
Creep test	6.2_UDE_LD_GB_11-12	11	Δ (5 min to 3 h): **0,0006**	196.0	90.5	90.0	89.4	0.54	0.56	0.57	86.5	85.6	84.7	242.7	**Creep test is passed** Slip during the creep test < 0,002 mm (5 min to 3 h)	04.11.16 15:30
		12	Δ (5 min to 3 h): **0,0004**	184.8	90.6	89.8	89.0	0.51	0.53	0.54	87.1	86.0	84.9	239.2		
	Statistics (5 specimens, 10 test results)	n = 10	Number of tests													
		max	Maximum	198.5				0.56	0.56	0.59						
		min	Minimum	142.4				0.40	0.40	0.41						
		mean	Mean value F_{Sm} | μ_m	182.7				0.51	0.52	0.53					Eq. (2), Eq. (4)	
		R	Spread	56.1				0.16	0.16	0.17					*R = max – min*	
		s	Standard deviation s_{FS}	15.8				0.043	0.045	0.047					Eq. (3), Eq. (5)	
		V	Coefficient of variation	**8.6%**				**8.5%**	**8.6%**	**8.9%**					*V = s / mean* ≤ 8%	
		0,9 F_{Sm}		164.4												
	μ_k		Characteristic value of the slip factor					0.42	0.43	0.44					Eq. (6)	

Table C6 Test protocol F_GB test series

UNIVERSITÄT DUISBURG ESSEN Open-Minded
INSTITUTE FOR
Metal and Lightweight Structures
Univ.-Prof. Dr.-Ing. habil. Natalie Stranghöner
Universitätsstr. 15
45141 Essen
Fon: +49 (0)201 183-2757
Fax: +49 (0)201 183-2710
E-Mail: iml@uni-due.de
www.uni-due.de/iml

Test report

20.11.2016

Technical characteristics of the test		
	Tested according to	DIN EN 1090-2:2011-10 – Annex G
	Test date	10.11.2016 - 15.11.2016
	Test performed by	N. Afzali, M.Sc.
	Project No.	410410007 20003
	Quotation No.	RFSR-CT-2014-00024 (SIROCO)
	Steel grade	Ferritic Stainless Steel (1.4003)
	Coating	–
	Coating composition	–
	Surface treatment	Grit blasted (using Grittal GM30 particles of 50 µm particle size)
	Maximum coating thickness	–
	Mean coating thickness	–
	Minimum coating thickness	–
	Surface roughness (before coating)	45 µm
	Surface roughness (after coating)	–
	Curing procedure	–
	Duration of curing	–
	Time between application of coating and testing	–
	Specimen size	Standard specimens M16 (EN 1090-2, Figure G.1 b)
	Bolt class, bolt type	Bolt: BUMAX 88 (EN ISO 4017 – M16 x 100) - Nut: BUMAX 88 (EN ISO 4032) - Washer: HV 200 (EN ISO 7089)
	Nominal preload level	88 kN = $F_{p,C}$
	Preload measuring method	Load cell (h = 40 mm), measured continuously, clamping length Σt = 75 mm
	Test speed	0.6 mm/min

Static test	Specimens		Slip	Slip load	Preload			Slip factor			Preload			Test duration	Comment	Date of test
	mark	plate ID's	(average at CBG)		at start of test (initial preload)			based on initial	based on nominal $F_{p,C}$ [kN] 88	based on preload at slip	at slip				Eq. according to DIN EN 1090-2	
					Outer bolt	Mean value	Inner bolt				Outer bolt	Mean value	Inner bolt			Start of the 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]		
	6.2_UDE_F_GB_1-2	1	0.150	233.9	89.4	89.2	89.0	0.66	0.66	0.70	84.0	83.4	82.7	12.4		10.11.16 13:30
		2	0.150	235.8	89.0	89.3	89.5	0.66	0.67	0.71	84.0	83.4	82.8	12.6		
	6.2_UDE_F_GB_3-4	3	0.150	235.4	88.1	88.4	88.7	0.67	0.67	0.71	82.8	82.7	82.5	12.0		10.11.16 14:50
		4	0.150	233.2	89.8	89.8	89.8	0.65	0.66	0.70	84.5	83.6	82.6	11.8		
	6.2_UDE_F_GB_5-6	5	0.132	225.6	89.3	89.0	88.6	0.63	0.64	0.68	84.1	83.1	82.1	12.6		10.11.16 16:40
		6	0.150	222.1	89.1	88.8	88.5	0.63	0.63	0.67	84.1	82.9	81.7	11.7		
	6.2_UDE_F_GB_7-8	7	0.150	223.7	88.9	89.2	89.6	0.63	0.64	0.67	83.6	83.4	83.1	12.5		14.11.16 15:40
		8	0.150	216.4	89.3	89.1	88.9	0.61	0.61	0.65	84.3	83.3	82.2	11.7		
	Statistics (4 specimens, 8 test results)	*n* = 8	Number of tests													
		max	Maximum	235.8				0.67	0.67	0.71						
		min	Minimum	216.4				0.61	0.61	0.65						
		mean	Mean value F_{Sm} | μ_m	**228.3**				**0.64**	**0.65**	**0.69**					Eq. (2), Eq. (4)	
		R	Spread	19.4				0.06	0.06	0.06					*R* = *max* – *min*	
		s	Standard deviation s_{FS}	7.3				0.020	0.021	0.022					Eq. (3), Eq. (5)	
		V	Coefficient of variation	3.2%				3.2%	3.2%	3.2%					*V* = *s* / *mean*	
		0,9 F_{Sm}		**205.4**											Load level for the creep test	

Table C 7 Test protocol A_Al-SM test series

UNIVERSITÄT DUISBURG ESSEN Open-Minded

INSTITUTE FOR **Metal and Lightweight Structures**
Univ.-Prof. Dr.-Ing. habil. Natalie Stranghöner

Universitätsstr. 15
45141 Essen

Fon: +49 (0)201 183-2757
Fax: +49 (0)201 183-2710

E-Mail: iml@uni-due.de
www.uni-due.de/iml

Test report

06.12.2017

Technical characteristics of the test		
	Tested according to	DIN EN 1090-2:2011-10 – Annex G
	Test date	05.12.2017
	Test performed by	N. Afzali, M.Sc.
	Project No.	410410007 20003
	Quotation No.	RFSR-CT-2014-00024 (SIROCO)
	Steel grade	Austenitic Stainless Steel (1.4404)
	Coating	**Thermally sprayed with aluminium (Al-SM)**
	Coating composition	–
	Surface treatment	–
	Maximum coating thickness	–
	Mean coating thickness	100 µm (NDFT)
	Minimum coating thickness	–
	Surface roughness (before coating)	45 µm
	Surface roughness (after coating)	–
	Curing procedure	–
	Duration of curing	–
	Time between application of coating and testing	–
	Specimen size	Standard specimens M16 (EN 1090-2, Figure G.1 b)
	Bolt class, bolt type	Bolt: BUMAX 88 (EN ISO 4017 – M16 x 100) - Nut: BUMAX 88 (EN ISO 4032) - Washer: HV 200 (EN ISO 7089)
	Nominal preload level	88 kN = $F_{p,C}$
	Preload measuring method	Load cell (h = 40 mm), measured continuously, clamping length Σt = 75 mm
	Test speed	0.6 mm/min

	Specimens		Slip	Slip load	Preload			Slip factor			Preload			Test duration	Comment	Date of test
	mark	plate ID's	(average at CBG)		at start of test (initial preload)			based on initial	based on nominal $F_{p,C}$ [kN] 88	based on preload at slip	at slip				Eq. according to DIN EN 1090-2	Start of the test
					Outer bolt	Mean value	Inner bolt				Outer bolt	Mean value	Inner bolt			
			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 test	6.3_UDE_A_Al-SM_01-02	1	0.150	276.1	88.7	88.7	88.7	0.78	0.78	0.93	74.5	73.9	73.4	15.0		05.12.17 11:05
		2	0.150	275.7	88.9	88.7	88.6	0.78	0.78	0.93	75.4	73.9	72.4	15.0		
	6.3_UDE_A_Al-SM_03-04	3	0.150	281.5	90.6	90.7	90.9	0.78	0.80	0.93	76.3	75.5	74.6	13.8		05.12.17 12:30
		4	0.150	278.4	89.7	89.9	90.2	0.77	0.79	0.93	76.5	75.1	73.6	14.0		
	6.3_UDE_A_Al-SM_05-06	5	0.150	276.2	89.9	90.8	91.7	0.76	0.78	0.92	76.7	75.4	74.1	13.9		05.12.17 13:55
		6	0.150	288.2	88.9	90.1	91.2	0.80	0.82	0.97	75.0	74.4	73.7	14.6		
	6.3_UDE_A_Al-SM_07-08	7	0.150	275.9	88.5	89.7	90.8	0.77	0.78	0.93	74.2	74.5	74.8	13.7		05.12.17 15:20
		8	0.150	278.2	89.1	89.1	89.0	0.78	0.79	0.95	74.9	73.3	71.7	13.8		
	Statistics (4 specimens, 8 test results)	n = 8	Number of tests													
		max	Maximum	288.2				0.80	0.82	0.97						
		min	Minimum	275.7				0.76	0.78	0.92						
		mean	Mean value F_{Sm} | μ_m	**278.8**				**0.78**	**0.79**	**0.94**					Eq. (2), Eq. (4)	
		R	Spread	12.5				0.04	0.04	0.05					*R = max – min*	
		s	Standard deviation s_{FS}	4.3				0.011	0.012	0.016					Eq. (3), Eq. (5)	
		V	Coefficient of variation	1.5%				1.5%	1.5%	1.7%					*V = s / mean*	
		0,9 F_{Sm}		**250.9**											Load level for the creep test	
Creep test	6.3_UDE_A_Al-SM_09-10	9	Δ (5 min to 3 h): **0,013**												**Creep test failed** Slip during the creep test > 0,002 mm (5 min to 3 h)	05.12.17 16:30
			0.150	278.6	89.1	89.1	89.1	0.78	0.79	0.95	75.3	73.6	72.0	946.4		
		10	Δ (5 min to 3 h): **0,015**													
			0.150	276.6	89.7	89.4	89.2	0.77	0.79	0.94	75.2	73.8	72.4	946.3		
	Statistics (5 specimens, 10 test results)	n = 10	Number of tests													
		max	Maximum	288.2				0.80	0.82	0.97						
		min	Minimum	275.7				0.76	0.78	0.92						
		mean	Mean value F_{Sm} | μ_m	278.5				0.78	0.79	0.94					Eq. (2), Eq. (4)	
		R	Spread	12.5				0.04	0.04	0.05					*R = max – min*	
		s	Standard deviation s_{FS}	3.8				0.010	0.011	0.015					Eq. (3), Eq. (5)	
		V	Coefficient of variation	**1.4%**				**1.3%**	**1.4%**	**1.6%**					*V = s / mean* ≤ 8%	
		0,9 F_{Sm}		250.7												
	μ_k		Characteristic value of the slip factor					0.76	0.77	0.91					Eq. (6)	

Table C8 Test protocol D_Al-SM test series

UNIVERSITÄT DUISBURG ESSEN Open-Minded
INSTITUTE FOR **Metal and Lightweight Structures**
Univ.-Prof. Dr.-Ing. habil. Natalie Stranghöner
Universitätsstr. 15, 45141 Essen
Fon: +49 (0)201 183-2757
Fax: +49 (0)201 183-2710
E-Mail: iml@uni-due.de
www.uni-due.de/iml

Test report

06.12.2017

Technical characteristics of the test		
	Tested according to	DIN EN 1090-2:2011-10 – Annex G
	Test date	06.12.2017
	Test performed by	N. Afzali, M.Sc.
	Project No.	410410007 20003
	Quotation No.	RFSR-CT-2014-00024 (SIROCO)
	Steel grade	Duplex Stainless Steel (1.4462)
	Coating	**Thermally sprayed with aluminium (Al-SM)**
	Coating composition	–
	Surface treatment	–
	Maximum coating thickness	–
	Mean coating thickness	116 µm (DFT)
	Minimum coating thickness	–
	Surface roughness (before coating)	43 µm
	Surface roughness (after coating)	–
	Curing procedure	–
	Duration of curing	–
	Time between application of coating and testing	–
	Specimen size	Standard specimens M16 (EN 1090-2, Figure G.1 b)
	Bolt class, bolt type	Bolt: BUMAX 88 (EN ISO 4017 – M16 x 100) - Nut: BUMAX 88 (EN ISO 4032) - Washer: HV 200 (EN ISO 7089)
	Nominal preload level	88 kN = $F_{p,C}$
	Preload measuring method	Load cell (h = 40 mm), measured continuously, clamping length Σt = 75 mm
	Test speed	0.6 mm/min

	Specimens: mark	plate ID's	Slip (average at CBG) u_i [mm]	Slip load F_{Si} [kN]	Preload at start of test (initial preload): Outer bolt $F_{bi,o,ini}$ [kN]	Mean value: mean $F_{bi,ini}$ [kN]	Inner bolt $F_{bi,i,ini}$ [kN]	Slip factor based on initial: $\mu_{i,ini}$ [–]	based on nominal $F_{p,C}$ [kN] 88: $\mu_i = \mu_{i,nom}$ [–]	based on preload at slip: $\mu_{i,act}$ [–]	Preload at slip: Outer bolt $F_{bi,o,act}$ [kN]	Mean value: mean $F_{bi,act}$ [kN]	Inner bolt $F_{bi,i,act}$ [kN]	Test duration t [min]	Comment (Eq. according to DIN EN 1090-2)	Date of test (Start of the test)
Static test	6.3_UDE_D_Al-SM_01-02	1	0.150	304.0	91.3	91.0	90.7	0.84	0.86	0.95	80.3	79.6	79.0	12.9		06.12.17 9:10
		2	0.150	315.6	90.6	90.8	90.9	0.87	0.90	1.00	79.2	78.9	78.5	13.4		
	6.3_UDE_D_Al-SM_03-04	3	0.150	301.3	90.2	90.1	90.0	0.84	0.86	0.96	79.2	78.9	78.5	12.7		06.12.17 10:10
		4	0.150	307.8	90.8	90.6	90.3	0.85	0.87	0.98	80.0	78.8	77.6	13.0		
	6.3_UDE_D_Al-SM_05-06	5	0.150	302.2	89.9	89.5	89.1	0.84	0.86	0.97	78.7	77.9	77.1	13.0		06.12.17 11:15
		6	0.150	310.5	89.9	90.4	90.9	0.86	0.88	0.99	78.8	78.7	78.6	13.4		
	6.3_UDE_D_Al-SM_07-08	7	0.150	311.2	89.7	89.6	89.6	0.87	0.88	0.99	78.4	78.3	78.1	13.1		06.12.17 12:15
		8	0.150	306.5	90.6	90.5	90.4	0.85	0.87	0.97	79.6	79.3	79.0	12.9		
	Statistics (4 specimens, 8 test results)	n = 8	Number of tests													
		max	Maximum	315.6				0.87	0.90	1.00						
		min	Minimum	301.3				0.84	0.86	0.95						
		mean	Mean value F_{Sm} | μ_m	**307.4**				**0.85**	**0.87**	**0.98**					Eq. (2), Eq. (4)	
		R	Spread	14.3				0.03	0.04	0.05					*R = max – min*	
		s	Standard deviation s_{FS}	4.9				0.013	0.014	0.017					Eq. (3), Eq. (5)	
		V	Coefficient of variation	1.6%				1.6%	1.6%	1.8%					*V = s / mean*	
		0,9 F_{Sm}		**276.7**											Load level for the creep test	
Creep test	6.3_UDE_D_Al-SM_09-10	9	Δ (5 min to 3 h): **0,007**												**Creep test failed** Slip during the creep test > 0,002 mm (5 min to 3 h)	06.12.17 14:15
			0.150	306.7	89.1	89.1	89.0	0.86	0.87	1.00	76.5	76.6	76.8	2516.9		
		10	Δ (5 min to 3 h): **0,007**													
			0.150	298.7	87.7	88.1	88.5	0.85	0.85	0.99	74.9	75.1	75.2	2516.5		
	Statistics (5 specimens, 10 test results)	n = 10	Number of tests													
		max	Maximum	315.6				0.87	0.90	1.00						
		min	Minimum	298.7				0.84	0.85	0.95						
		mean	Mean value F_{Sm} | μ_m	306.5				0.85	0.87	0.98					Eq. (2), Eq. (4)	
		R	Spread	16.9				0.03	0.05	0.05					*R = max – min*	
		s	Standard deviation s_{FS}	5.1				0.012	0.015	0.018					Eq. (3), Eq. (5)	
		V	**Coefficient of variation**	**1.7%**				**1.4%**	**1.7%**	**1.8%**					*V = s / mean* ≤ 8%	
		0,9 F_{Sm}		275.8												
	μ_k	Characteristic value of the slip factor						0.83	0.84	0.94					Eq. (6)	

Table C9 Test protocol LD_Al-SM test series

UNIVERSITÄT DUISBURG ESSEN *Open-Minded*

INSTITUTE FOR **Metal and Lightweight Structures**
Univ.-Prof. Dr.-Ing. habil. Natalie Stranghöner

Universitätsstr. 15
45141 Essen

Fon: +49 (0)201 183-2757
Fax: +49 (0)201 183-2710

E-Mail: iml@uni-due.de
www.uni-due.de/iml

Test report

12.12.2017

Technical characteristics of the test		
	Tested according to	DIN EN 1090-2:2011-10 – Annex G
	Test date	11.12.2017
	Test performed by	N. Afzali, M.Sc.
	Project No.	410410007 20003
	Quotation No.	RFSR-CT-2014-00024 (SIROCO)
	Steel grade	Lean-Duplex Stainless Steel (1.4162)
	Coating	**Thermally sprayed with aluminium (Al-SM)**
	Coating composition	–
	Surface treatment	–
	Maximum coating thickness	–
	Mean coating thickness	105 µm (DFT)
	Minimum coating thickness	–
	Surface roughness (before coating)	51 µm
	Surface roughness (after coating)	–
	Curing procedure	–
	Duration of curing	–
	Time between application of coating and testing	–
	Specimen size	Standard specimens M16 (EN 1090-2, Figure G.1 b)
	Bolt class, bolt type	Bolt: BUMAX 88 (EN ISO 4017 – M16 x 100) - Nut: BUMAX 88 (EN ISO 4032) - Washer: HV 200 (EN ISO 7089)
	Nominal preload level	88 kN = $F_{p,C}$
	Preload measuring method	Load cell (h = 40 mm), measured continuously, clamping length Σt = 75 mm
	Test speed	0.6 mm/min

	Specimens mark	plate ID's	Slip (average at CBG) u_i [mm]	Slip load F_{Si} [kN]	Preload at start of test (initial preload) Outer bolt $F_{bi,o,ini}$ [kN]	Mean value mean $F_{bi,ini}$ [kN]	Inner bolt $F_{bi,i,ini}$ [kN]	Slip factor based on initial $\mu_{i,ini}$ [–]	based on nominal $F_{p,C}$ [kN] 88 $\mu_i = \mu_{i,nom}$ [–]	based on preload at slip $\mu_{i,act}$ [–]	Preload at slip Outer bolt $F_{bi,o,act}$ [kN]	Mean value mean $F_{bi,act}$ [kN]	Inner bolt $F_{bi,i,act}$ [kN]	Test duration t [min]	Comment Eq. according to DIN EN 1090-2	Date of test Start of the test
Static test	6.3_UDE_LD_Al-SM_01-02	1	0.150	290.3	91.2	90.6	90.0	0.80	0.82	0.91	81.5	79.9	78.3	12.3		11.12.17 11:45
		2	0.148	305.4	90.0	89.9	89.9	0.85	0.87	0.97	79.5	78.7	77.9	13.1		
	6.3_UDE_LD_Al-SM_03-04	3	0.150	287.1	89.4	89.5	89.5	0.80	0.82	0.90	79.3	79.6	79.9	12.6		11.12.17 12:40
		4	0.150	289.3	89.0	89.0	89.0	0.81	0.82	0.92	79.0	78.8	78.5	12.7		
	6.3_UDE_LD_Al-SM_05-06	5	0.150	269.3	88.6	89.1	89.5	0.76	0.77	0.84	79.6	79.9	80.2	11.8		11.12.17 13:35
		6	0.112	279.2	89.0	89.3	89.6	0.78	0.79	0.87	80.6	80.0	79.5	12.4		
	6.3_UDE_LD_Al-SM_07-08	7	0.150	268.1	90.1	89.5	88.9	0.75	0.76	0.84	81.1	80.0	78.9	11.8		11.12.17 14:30
		8	0.150	278.6	88.8	89.1	89.5	0.78	0.79	0.87	80.8	80.1	79.3	12.3		
	Statistics (4 specimens, 8 test results)	n = 8	Number of tests													
		max	Maximum	305.4				0.85	0.87	0.97						
		min	Minimum	268.1				0.75	0.76	0.84						
		mean	Mean value F_{Sm} | μ_m	**283.4**				**0.79**	**0.81**	**0.89**					Eq. (2), Eq. (4)	
		R	Spread	37.3				0.10	0.11	0.13					*R = max – min*	
		s	Standard deviation s_{FS}	12.3				0.032	0.035	0.044					Eq. (3), Eq. (5)	
		V	Coefficient of variation	4.3%				4.1%	4.3%	4.9%					*V = s / mean*	
		0,9 F_{Sm}		**255.1**											Load level for the creep test	
Creep test	6.3_UDE_LD_Al-SM_09-10	9	Δ (5 min to 3 h): **0,007**												**Creep test failed** Slip during the creep test > 0,002 mm (5 min to 3 h)	11.12.17 15:25
			0.150	301.4	87.8	88.0	88.2	0.86	0.86	0.99	76.5	76.4	76.2	1263.6		
		10	Δ (5 min to 3 h): **0,005**													
			0.151	298.5	87.5	87.8	88.1	0.85	0.85	0.98	76.8	76.2	75.6	1263.4		
	Statistics (5 specimens, 10 test results)	n = 10	Number of tests													
		max	Maximum	305.4				0.86	0.87	0.99						
		min	Minimum	268.1				0.75	0.76	0.84						
		mean	Mean value F_{Sm} | μ_m	286.7				0.80	0.81	0.91					Eq. (2), Eq. (4)	
		R	Spread	37.3				0.11	0.11	0.15					*R = max – min*	
		s	Standard deviation s_{FS}	12.9				0.038	0.037	0.055					Eq. (3), Eq. (5)	
		V	**Coefficient of variation**	**4.5%**				**4.8%**	**4.5%**	**6.1%**					*V = s / mean* ≤ 8%	
		0,9 F_{Sm}		258.0												
	μ_k		Characteristic value of the slip factor					0.73	0.74	0.80					Eq. (6)	

Table C10 Test protocol F_Al-SM test series

INSTITUTE FOR
Metal and Lightweight Structures
Univ.-Prof. Dr.-Ing. habil. Natalie Stranghöner
Universitätsstr. 15, 45141 Essen
Fon: +49 (0)201 183-2757
Fax: +49 (0)201 183-2710
E-Mail: iml@uni-due.de
www.uni-due.de/iml

Test report

11.12.2017

Technical characteristics of the test	
Tested according to	DIN EN 1090-2:2011-10 – Annex G
Test date	06.12.2017 and 08.12.2017
Test performed by	N. Afzali, M.Sc.
Project No.	410410007 20003
Quotation No.	RFSR-CT-2014-00024 (SIROCO)
Steel grade	Ferritic Stainless Steel (1.4003)
Coating	**Thermally sprayed with aluminium (Al-SM)**
Coating composition	–
Surface treatment	–
Maximum coating thickness	–
Mean coating thickness	91 µm (DFT)
Minimum coating thickness	–
Surface roughness (before coating)	44 µm
Surface roughness (after coating)	–
Curing procedure	–
Duration of curing	–
Time between application of coating and testing	–
Specimen size	Standard specimens M16 (EN 1090-2, Figure G.1 b)
Bolt class, bolt type	Bolt: BUMAX 88 (EN ISO 4017 – M16 x 100) - Nut: BUMAX 88 (EN ISO 4032) - Washer: HV 200 (EN ISO 7089)
Nominal preload level	88 kN = $F_{p,C}$
Preload measuring method	Load cell (h = 40 mm), measured continuously, clamping length Σt = 75 mm
Test speed	0.6 mm/min

	Specimens mark	plate ID's	Slip (average at CBG) u_i [mm]	Slip load F_{Si} [kN]	Preload at start of test (initial preload) Outer bolt $F_{bi,o,ini}$ [kN]	Mean value mean $F_{bi,ini}$ [kN]	Inner bolt $F_{bi,i,ini}$ [kN]	Slip factor based on initial $\mu_{i,ini}$ [–]	based on nominal $F_{p,C}$ [kN] 88 $\mu_i = \mu_{i,nom}$ [–]	based on preload at slip $\mu_{i,act}$ [–]	Preload at slip Outer bolt $F_{bi,o,act}$ [kN]	Mean value mean $F_{bi,act}$ [kN]	Inner bolt $F_{bi,i,act}$ [kN]	Test duration t [min]	Comment Eq. according to DIN EN 1090-2	Date of test Start of the test
Static test	6.3_UDE_F_Al-SM_01-02	1	0.150	286.5	89.7	89.8	89.9	0.80	0.81	0.92	79.0	78.1	77.1	12.5		06.12.17 13:15
		2	0.150	293.2	90.8	90.6	90.4	0.81	0.83	0.94	79.8	78.2	76.7	12.8		
	6.3_UDE_F_Al-SM_03-04	3	0.150	283.3	90.2	89.8	89.5	0.79	0.80	0.92	78.5	77.2	75.9	12.8		08.12.17 9:05
		4	0.129	292.1	89.4	89.5	89.6	0.82	0.83	0.94	78.8	77.5	76.2	13.4		
	6.3_UDE_F_Al-SM_05-06	5	0.150	294.8	89.3	89.4	89.4	0.82	0.84	0.96	78.1	76.8	75.4	13.5		08.12.17 10:00
		6	0.150	292.0	90.4	90.2	90.0	0.81	0.83	0.94	79.8	77.5	75.3	13.4		
	6.3_UDE_F_Al-SM_07-08	7	0.150	282.8	89.3	89.5	89.7	0.79	0.80	0.92	78.4	76.8	75.1	13.0		08.12.17 10:55
		8	0.150	290.0	90.2	89.9	89.6	0.81	0.82	0.93	79.6	77.7	75.7	13.3		
	Statistics (4 specimens, 8 test results)	n = 8	Number of tests													
		max	Maximum	294.8				0.82	0.84	0.96						
		min	Minimum	282.8				0.79	0.80	0.92						
		$mean$	Mean value F_{Sm} | μ_m	**289.3**				**0.81**	**0.82**	**0.93**					Eq. (2), Eq. (4)	
		R	Spread	12.0				0.04	0.03	0.04					$R = max – min$	
		s	Standard deviation s_{FS}	4.6				0.012	0.013	0.015					Eq. (3), Eq. (5)	
		V	Coefficient of variation	1.6%				1.6%	1.6%	1.6%					$V = s / mean$	
		0,9 F_{Sm}		**260.4**											Load level for the creep test	
Creep test	6.3_UDE_F_Al-SM_09-10	9	Δ (5 min to 3 h): **0,008**												**Creep test failed** Slip during the creep test > 0,002 mm (5 min to 3 h)	08.12.17 11:55
			0.150	289.2	88.1	88.4	88.6	0.82	0.82	0.97	76.1	74.8	73.4	4262.6		
		10	Δ (5 min to 3 h): **0,007**													
			0.150	287.6	87.8	88.1	88.3	0.82	0.82	0.97	76.1	74.4	72.6	4262.5		
	Statistics (5 specimens, 10 test results)	n = 10	Number of tests													
		max	Maximum	294.8				0.82	0.84	0.97						
		min	Minimum	282.8				0.79	0.80	0.92						
		$mean$	Mean value F_{Sm} | μ_m	289.2				0.81	0.82	0.94					Eq. (2), Eq. (4)	
		R	Spread	12.0				0.04	0.03	0.05					$R = max – min$	
		s	Standard deviation s_{FS}	4.1				0.012	0.012	0.019					Eq. (3), Eq. (5)	
		V	Coefficient of variation	**1.4%**				**1.5%**	**1.4%**	**2.0%**					$V = s / mean$ ≤ 8%	
		0,9 F_{Sm}		260.2												
	μ_k	Characteristic value of the slip factor						0.78	0.80	0.90					Eq. (6)	

Appendix D: Slip factor test results (static and creep tests) – with Bumax 109 bolting assemblies

Table D1 Test protocol A_1D test series

TU Delft | SIROCO RFSR-CT-2014-00024 | Delft University of Technology, Department of Civil Engineering and Geosciences, MacroLab | Stevinweg 1, 2628 CN Delft, The Netherlands | Phone: +31 (0)15 2784034, E-Mail: p.a.devries@tudelft.nl

A1D	0,001	CBG	**Test protocol**	28.03.2018

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	Stainless, Austenitic
Coating	**No coating**
Coating composition	
Surface treatment	1D surface, no treatment
Maximum coating thickness	
Curing procedure	
Duration of curing	
Time between application coating and testing	
Specimen	Standard test piece M16 (EN 1090-2, drawing Annex G.1 b)
Bolt class, bolt type	BUMAX 109, full thread
Nominal Preload level	110 kN = $F_{p,C}$
Measuring of the preload level	Load cell M16, clamping length Σt = 78 mm
load head speed	0,001 mm/sec

Static load

specimen mark	plate ID's	slip (average at CBG) u_i [mm]	Slip load F_{Si} [kN]	Pre loading at start test (initial pre load): outer Bolt $F_{bi,o,ini}$ [kN]	average mean $F_{bi,ini}$ [kN]	inner Bolt $F_{bi,i,ini}$ [kN]	slip factor based on initial preload $\mu_{i,ini}$ [-]	based on nominal preload $F_{p,C}$ [kN] 110; $\mu_i = \mu_{i,nom}$ [-]	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
A1D_01	0	0,150	84	108	109	109	0,19	0,19	0,20	107	107	107	10,6	0,00	12.12.16 10:50
	0	0,150	86	108	109	109	0,20	0,19	0,20	106	106	106	23,4	0,00	
A1D_02	0	0,082	82	109	108	108	0,19	0,19	0,19	107	106	105	12,9	0,00	12.12.16 12:41
	0	0,133	82	108	108	108	0,19	0,19	0,19	106	106	106	12,9	0,00	
A1D_03	0	0,150	86	109	109	110	0,20	0,20	0,20	107	107	107	21,6	0,00	12.12.16 14:14
	0	0,150	85	109	109	110	0,20	0,19	0,20	108	108	108	10,4	0,00	
A1D_04	0	0,150	90	110	110	109	0,21	0,21	0,21	108	107	106	25,0	0,00	13.12.16 10:58
	0	0,150	85	109	109	108	0,20	0,19	0,20	107	107	107	10,1	0,00	
Statistics (4 specimen, 8 test results)	n=8	number of tests													
	max	Maximum	90				0,21	0,21	0,21				25,0		
	min	Minimum	82	SSWL test	dF (5%)		0,19	0,19	0,19				10,1		
	mean	Average F_{Sm} | μ_m	**85**	**51**	**4**		**0,20**	**0,19**	**0,20**				**15,9**	Eq. (2), Eq. (4)	
	R	spread	7,9				0,02	0,02	0,02				14,9	*R = max – min*	
	s	standard deviation	2,5				0,005	0,006	0,005				6,3	Eq. (3), Eq. (5)	
	V	coefficient of variation	2,9%				2,6%	2,9%	2,7%				40%	*V = s / mean*	
creep test	0,9 F_{Sm}		77										slip [μm]	Load level creep test [kN]	
A1D_05	0	0,150	85	109	109	109	0,20	0,19	0,20	108	107	107	5,5	**76**	12.12.16 16:34
	0	0,029	87	109	109	108	0,20	0,20	0,21	106	105	104	1,4	passed	
Statistics (5 specimen, 10 test results)	n=10	number of tests											**result**		
	max	Maximum	90				0,21	0,21	0,21				failed	Δ slip < 2 μm in 3 h.	
	min	Minimum	82				0,19	0,19	0,19						
	mean	Average F_{Sm} | μ_m	90				0,20	0,19	0,20					Eq. (2), Eq. (4)	
	R	spread	7,9				0,02	0,02	0,02					*R = max – min*	
	s	standard deviation	2,3				0,005	0,005	0,005					Eq. (3), Eq. (5)	
	V	coefficient of variation	**2,7%**				**2,4%**	**2,7%**	**2,7%**					*V = s / mean* ≤ 8%	
μ_k		Characteristic value slip factor					-	-	-					Eq. (6)	

Table D2 Test protocol A_SB test series

TU Delft SIROCO RFSR-CT-2014-00024
Delft University of Technology, Department of Civil Engineering and Geosciences, MacroLab
Stevinweg 1, 2628 CN Delft, The Netherlands
Phone: +31 (0)15 2784034
E-Mail: p.a.devries@tudelft.nl

AS | 0,001 | CBG **Test protocol** 28.03.2018

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	Stainless, Austenitic
	Coating	**No coating**
	Coating composition	
	Surface treatment	shot blasted
	Maximum coating thickness	
	Curing procedure	
	Duration of curing	
	Time between application coating and testing	
	Specimen	Standard test piece M16 (EN 1090-2, drawing Annex G.1 b)
	Bolt class, bolt type	BUMAX 109, full thread
	Nominal Preload level	110 kN = $F_{p,C}$
	Measuring of the preload level	Load cell M16, clamping length Σt = 77 mm
	load head speed	0,001 mm/sec

	specimen mark	plate ID's	slip (average at CBG) u_i [mm]	Slip load F_{Si} [kN]	Pre loading at start test (initial pre load): outer Bolt $F_{bi,o,ini}$ [kN]	average mean $F_{bi,ini}$ [kN]	inner Bolt $F_{bi,i,ini}$ [kN]	slip factor based on initial preload $\mu_{i,ini}$ [–]	based on nominal preload $F_{p,C}$ [kN] 110 $\mu_i = \mu_{i,nom}$ [–]	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
sted																
Static load	AS_01	0	0,150	141	105	105	105	0,34	0,32	0,35	102	101	100	26,5	0,00	16.11.16 14:12
		0	0,150	122	105	105	105	0,29	0,28	0,30	102	101	101	18,5	0,00	
	AS_02	0	0,150	148	107	107	107	0,35	0,34	0,36	103	102	101	19,6	0,00	16.11.16 16:15
		0	0,150	159	107	107	107	0,37	0,36	0,39	103	102	102	21,2	0,00	
	AS_03	0	0,150	129	106	107	108	0,30	0,29	0,31	103	103	102	18,0	0,00	17.11.16 10:15
		0	0,150	138	106	106	107	0,33	0,31	0,34	102	102	101	19,4	0,00	
	AS_04	0	0,150	122	106	107	108	0,29	0,28	0,30	103	103	103	16,9	0,00	17.11.16 12:20
		0	0,150	158	106	107	107	0,37	0,36	0,39	102	101	101	32,1	0,00	
	Statistics (4 specimen, 8 test results)	n=8	number of tests													
		max	Maximum	159				0,37	0,36	0,39				32,1		
		min	Minimum	122	SSWL test	dF (5%)		0,29	0,28	0,30				16,9		
		mean	Average F_{Sm} | μ_m	**140**	**84**	**7**		**0,33**	**0,32**	**0,34**				**21,5**	Eq. (2), Eq. (4)	
		R	spread	36,3				0,09	0,08	0,09				15,3	*R = max – min*	
		s	standard deviation	14,6				0,033	0,033	0,036				5,2	Eq. (3), Eq. (5)	
		V	coefficient of variation	10,4%				10,2%	10,4%	10,6%				24%	*V = s / mean*	
	creep test	0,9 F_{Sm}		**126**										slip [μm]	Load level creep test [kN]	
	AS_05	0	0,150	142	109	109	109	0,33	0,32	0,35	104	103	101	2,3	**126**	17.11.16 16:34
		0	0,150	133	109	109	108	0,31	0,30	0,33	104	103	102	1,7	passed	
	Statistics (5 specimen, 10 test results)	n=10	number of tests											**result**		
		max	Maximum	159				0,37	0,36	0,39				failed	Δ slip < 2 μm in 3 h.	
		min	Minimum	122				0,29	0,28	0,30						
		mean	Average F_{Sm} | μ_m	159				0,33	0,32	0,34					Eq. (2), Eq. (4)	
		R	spread	36,3				0,09	0,08	0,09					*R = max – min*	
		s	standard deviation	13,0				0,030	0,030	0,033					Eq. (3), Eq. (5)	
		V	coefficient of variation	**9,4%**				**9,3%**	**9,4%**	**9,5%**					*V = s / mean* ≤ 8%	
	μ_k	Characteristic value slip factor						-	-	-					Eq. (6)	

Table D3 Test protocol A_GB test series

TU Delft SIROCO RFSR-CT-2014-00024

Delft University of Technology
Department of Civil Engineering and Geosciences
MacroLab

Stevinweg 1
2628 CN Delft
The Netherlands

Phone: +31 (0)15 2784034
E-Mail: p.a.devries@tudelft.nl

AG	0,001	CBG	Test protocol	28.03.2018

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	Stainless, Austenitic
Coating	**No coating**
Coating composition	
Surface treatment	grit blasted
Maximum coating thickness	
Curing procedure	
Duration of curing	
Time between application coating and testing	
Specimen	Standard test piece M16 (EN 1090-2, drawing Annex G.1 b)
Bolt class, bolt type	BUMAX 109, full thread
Nominal Preload level	110 kN = $F_{p,C}$
Measuring of the preload level	Load cell M16, clamping length Σt = 77 mm
load head speed	0,001 mm/sec

Static load

specimen mark	plate ID's	slip (average at CBG) u_i [mm]	Slip load F_{Si} [kN]	Pre loading at start test (initial pre load): outer Bolt $F_{bi,o,ini}$ [kN]	average mean $F_{bi,ini}$ [kN]	inner Bolt $F_{bi,i,ini}$ [kN]	slip factor based on initial preload $\mu_{i,ini}$ [–]	based on nominal preload $F_{p,C}$ [kN] 110 $\mu_i = \mu_{i,nom}$ [–]	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
AG_01	0	0,150	244	108	109	109	0,56	0,55	0,62	99	98	97	59,7	0,00	21.11.16 10:33
	0	0,150	218	108	108	109	0,51	0,50	0,55	100	100	100	27,1	0,00	
AG_02	0	0,150	276	107	107	107	0,64	0,63	0,73	97	94	92	41,8	0,00	21.11.16 12:37
	0	0,150	273	108	107	107	0,64	0,62	0,72	98	95	92	40,3	0,00	
AG_03	0	0,150	249	107	108	108	0,58	0,57	0,64	98	98	97	33,7	0,00	21.11.16 14:27
	0	0,150	250	108	108	108	0,58	0,57	0,64	98	97	96	35,6	0,00	
AG_04	0	0,150	254	108	109	109	0,59	0,58	0,65	99	98	96	35,2	0,00	21.11.16 16:14
	0	0,150	248	108	108	109	0,57	0,56	0,64	98	97	96	33,2	0,00	
Statistics (4 specimen, 8 test results)	n=8	number of tests													
	max	Maximum	276				0,64	0,63	0,73				59,7		
	min	Minimum	218	SSWL test	dF (5%)		0,51	0,50	0,55				27,1		
	mean	Average F_{Sm} | μ_m	**252**	**151**	**12,58**		**0,58**	**0,57**	**0,65**				**38,3**	Eq. (2), Eq. (4)	
	R	spread	57,2				0,14	0,13	0,19				32,6	*R = max – min*	
	s	standard deviation	17,7				0,043	0,040	0,057				9,7	Eq. (3), Eq. (5)	
	V	coefficient of variation	7,0%				7,3%	7,0%	8,8%				25%	*V = s / mean*	
creep test	0,9 F_{Sm}		**226**										slip [μm]	Load level creep test [kN]	
AG_05	0	0,150	272	109	109	108	0,63	0,62	0,71	98	96	94	2,3	**226**	22.11.16 15:38
	0	0,150	266	108	108	108	0,61	0,60	0,69	98	97	95	2,6	NOT passed	
Statistics (5 specimen, 10 test results)	n=10	number of tests											**result**		
	max	Maximum	276				0,64	0,63	0,73				failed	Δ slip < 2 μm in 3 h.	
	min	Minimum	218				0,51	0,50	0,55						
	mean	Average F_{Sm} | μ_m	276				0,59	0,58	0,66					Eq. (2), Eq. (4)	
	R	spread	57,2				0,14	0,13	0,19					*R = max – min*	
	s	standard deviation	17,3				0,041	0,039	0,055					Eq. (3), Eq. (5)	
	V	coefficient of variation	**6,8%**				**7,0%**	**6,8%**	**8,3%**					*V = s / mean ≤ 8%*	
μ_k	Characteristic value slip factor						-	-	-					Eq. (6)	

Table D4 Test protocol D_GB test series

TU Delft SIROCO RFSR-CT-2014-00024
Delft University of Technology
Department of Civil Engineering and Geosciences
MacroLab
Stevinweg 1
2628 CN Delft
The Netherlands
Phone: +31 (0)15 2784034
E-Mail: p.a.devries@tudelft.nl

DG	0,002	CBG	**Test protocol**	28.03.2018

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	Stainless, Duplex
Coating	**No coating**
Coating composition	
Surface treatment	grit blasted
Maximum coating thickness	
Curing procedure	
Duration of curing	
Time between application coating and testing	
Specimen	Standard test piece M16 (EN 1090-2, drawing Annex G.1 b)
Bolt class, bolt type	BUMAX 109, full thread
Nominal Preload level	110 kN = $F_{p,C}$
Measuring of the preload level	Load cell M16, clamping length Σt = 77 mm
load head speed	0,002 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] 110 $\mu_i = \mu_{i,nom}$ [–]	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
DG_01	0	0,150	288	110	110	110	0,66	0,66	0,69	105	105	104	16,5	0,00	23.11.16 9:58
	0	0,150	293	110	110	110	0,66	0,67	0,70	105	105	104	18,1	0,00	
DG_02	0	0,150	288	111	111	110	0,65	0,65	0,68	106	105	104	21,0	0,00	23.11.16 11:18
	0	0,150	279	110	110	110	0,63	0,63	0,66	106	105	105	15,3	0,00	
DG_03	0	0,150	305	111	110	110	0,69	0,69	0,72	106	105	104	18,3	0,00	23.11.16 12:58
	0	0,150	302	110	110	110	0,69	0,69	0,72	105	105	104	18,1	0,00	
DG_04	0	0,150	285	110	110	110	0,65	0,65	0,68	106	105	105	16,1	0,00	23.11.16 14:33
	0	0,150	283	111	111	111	0,64	0,64	0,67	106	106	105	15,9	0,00	
Statistics (4 specimen, 8 test results)	n=8	number of tests													
	max	Maximum	305				0,69	0,69	0,72				21,0		
	min	Minimum	279	SSWL test	dF (5%)		0,63	0,63	0,66				15,3		
	mean	Average F_{Sm} | μ_m	**290**	**174**	**14,5**		**0,66**	**0,66**	**0,69**				**17,4**	Eq. (2), Eq. (4)	
	R	spread	25,8				0,06	0,06	0,06				5,7	*R = max – min*	
	s	standard deviation	9,0				0,021	0,020	0,022				1,8	Eq. (3), Eq. (5)	
	V	coefficient of variation	3,1%				3,2%	3,1%	3,2%				11%	*V = s / mean*	
creep test	0,9 F_{Sm}		**261**										slip [μm]	Load level creep test [kN]	
DG_05	0	0,150	309	110	110	109	0,71	0,70	0,75	104	103	102	1,0	**261**	24.11.16 12:00
	0	0,150	289	109	110	110	0,66	0,66	0,70	104	104	104	1,2	passed	
Statistics (5 specimen, 10 test results)	n=10	number of tests											**result**		
	max	Maximum	309				0,71	0,70	0,75				passed	Δ slip < 2 μm in 3 h.	
	min	Minimum	279				0,63	0,63	0,66						
	mean	Average F_{Sm} | μ_m	309				0,66	0,66	0,70					Eq. (2), Eq. (4)	
	R	spread	30,4				0,07	0,07	0,09					*R = max – min*	
	s	standard deviation	10,0				0,024	0,023	0,027					Eq. (3), Eq. (5)	
	V	coefficient of variation	**3,4%**				**3,6%**	**3,4%**	**3,9%**					*V = s / mean* ≤ 8%	
μ_k	Characteristic value slip factor						0,61	0,62	0,64					Eq. (6)	

Table D5 Test protocol LD_GB test series

TU Delft SIROCO RFSR-CT-2014-00024

Delft University of Technology
Department of Civil Engineering and Geosciences
MacroLab

Stevinweg 1
2628 CN Delft
The Netherlands

Phone: +31 (0)15 2784034
E-Mail: p.a.devries@tudelft.nl

LG	0,002	CBG

Test protocol

28.03.2018

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	Stainless, Lean Duplex
Coating	**No coating**
Coating composition	
Surface treatment	grit blasted
Maximum coating thickness	
Curing procedure	
Duration of curing	
Time between application coating and testing	
Specimen	Standard test piece M16 (EN 1090-2, drawing Annex G.1 b)
Bolt class, bolt type	BUMAX 109, full thread
Nominal Preload level	110 kN = $F_{p,C}$
Measuring of the preload level	Load cell M16, clamping length Σt = 77 mm
load head speed	0,002 mm/sec

sted

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
LG_01	0	0,150	281	109	109	110	0,64	0,64	0,68	105	104	104	16,2	0,00	28.11.16 12:21
	0	0,137	284	109	109	110	0,65	0,65	0,68	105	104	104	17,3	0,00	
LG_02	0	0,150	264	110	110	110	0,60	0,60	0,63	106	105	105	15,0	0,00	28.11.16 13:41
	0	0,150	257	110	110	110	0,59	0,59	0,61	106	105	105	14,2	0,00	
LG_03	0	0,150	276	110	110	110	0,62	0,63	0,65	106	105	105	16,5	0,00	28.11.16 15:03
	0	0,150	272	110	110	110	0,62	0,62	0,64	106	106	105	15,8	0,00	
LG_04	0	0,150	281	110	110	111	0,64	0,64	0,67	105	105	105	16,3	0,00	28.11.16 16:26
	0	0,150	281	110	110	111	0,64	0,64	0,67	105	105	105	16,5	0,00	
Statistics (4 specimen, 8 test results)	n=8	number of tests													
	max	Maximum	284				0,65	0,65	0,68				17,3		
	min	Minimum	257	SSWL test	dF (5%)		0,59	0,59	0,61				14,2		
	mean	Average F_{Sm} | μ_m	**275**	**165**	**13,7**		**0,62**	**0,62**	**0,65**				**16,0**	Eq. (2), Eq. (4)	
	R	spread	26,5				0,06	0,06	0,07				3,1	*R = max – min*	
	s	standard deviation	9,6				0,022	0,022	0,026				1,0	Eq. (3), Eq. (5)	
	V	coefficient of variation	3,5%				3,6%	3,5%	3,9%				6%	*V = s / mean*	
creep test	**0,9 F_{Sm}**		**247**										slip [μm]	Load level creep test [kN]	
LG_05	0	0,150	259	110	110	110	0,59	0,59	0,62	106	105	104	1,5	**247**	29.11.16 9:38
	0	0,150	254	111	111	111	0,57	0,58	0,60	106	106	105	1,3	passed	
Statistics (5 specimen, 10 test results)	n=10	number of tests											**result**		
	max	Maximum	284				0,65	0,65	0,68				passed	Δ slip < 2 μm in 3 h.	
	min	Minimum	254				0,57	0,58	0,60						
	mean	Average F_{Sm} | μ_m	284				0,62	0,62	0,64					Eq. (2), Eq. (4)	
	R	spread	29,6				0,08	0,07	0,08					*R = max – min*	
	s	standard deviation	11,4				0,027	0,026	0,030					Eq. (3), Eq. (5)	
	V	coefficient of variation	**4,2%**				**4,4%**	**4,2%**	**4,6%**					*V = s / mean* ≤ 8%	
μ_k	Characteristic value slip factor						0,56	0,56	0,58					Eq. (6)	

Table D6 Test protocol F_GB test series

TU Delft | SIROCO RFSR-CT-2014-00024 | Delft University of Technology, Department of Civil Engineering and Geosciences, MacroLab | Stevinweg 1, 2628 CN Delft, The Netherlands | Phone: +31 (0)15 2784034, E-Mail: p.a.devries@tudelft.nl

FG	0,002	CBG	**Test protocol**	28.03.2018

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	Stainless, Ferretic
Coating	**No coating**
Coating composition	
Surface treatment	grit blasted
Maximum coating thickness	
Curing procedure	
Duration of curing	
Time between application coating and testing	
Specimen	Standard test piece M16 (EN 1090-2, drawing Annex G.1 b)
Bolt class, bolt type	BUMAX 109, full thread
Nominal Preload level	110 kN = $F_{p,C}$
Measuring of the preload level	Load cell M16, clamping length Σt = 77 mm
load head speed	0,002 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
FG_01	0	0,150	310	109	109	110	0,71	0,70	0,78	102	99	96	18,8	0,00	22.11.16 9:04
	0	0,150	306	110	110	109	0,70	0,70	0,77	102	100	97	18,1	0,00	
FG_02	0	0,150	303	109	109	109	0,69	0,69	0,76	102	99	96	19,1	0,00	22.11.16 10:31
	0	0,150	294	109	110	110	0,67	0,67	0,73	103	101	99	16,7	0,00	
FG_03	0	0,150	300	110	110	111	0,68	0,68	0,74	103	101	98	17,5	0,00	22.11.16 11:56
	0	0,150	306	110	110	110	0,69	0,69	0,77	102	100	97	19,6	0,00	
FG_04	0	0,150	283	110	110	110	0,64	0,64	0,70	104	102	100	16,0	0,00	22.11.16 13:21
	0	0,150	286	110	110	111	0,65	0,65	0,71	103	101	100	17,4	0,00	
Statistics (4 specimen, 8 test results)	n=8	number of tests													
	max	Maximum	310				0,71	0,70	0,78				19,6		
	min	Minimum	283	SSWL test	dF (5%)		0,64	0,64	0,70				16,0		
	mean	Average F_{Sm} | μ_m	**298**	**179**	**15**		**0,68**	**0,68**	**0,74**				**17,9**	Eq. (2), Eq. (4)	
	R	spread	26,4				0,06	0,06	0,09				3,7	*R = max – min*	
	s	standard deviation	9,8				0,023	0,022	0,031				1,2	Eq. (3), Eq. (5)	
	V	coefficient of variation	3,3%				3,5%	3,3%	4,2%				7%	*V = s / mean*	
creep test	**0,9 F_{Sm}**		**269**										slip [μm]	Load level creep test [kN]	
FG_05	0	0,150	305	111	110	109	0,69	0,69	0,77	102	99	96	1,5	**269**	23.11.16 16:04
	0	0,150	299	110	110	110	0,68	0,68	0,75	101	100	98	1,7	passed	
Statistics (5 specimen, 10 test results)	n=10	number of tests											**result**		
	max	Maximum	310				0,71	0,70	0,78				passed	Δ slip < 2 μm in 3 h.	
	min	Minimum	283				0,64	0,64	0,70						
	mean	Average F_{Sm} | μ_m	310				0,68	0,68	0,75					Eq. (2), Eq. (4)	
	R	spread	26,4				0,06	0,06	0,09					*R = max – min*	
	s	standard deviation	8,9				0,021	0,020	0,029					Eq. (3), Eq. (5)	
	V	coefficient of variation	**3,0%**				**3,1%**	**3,0%**	**3,9%**					*V = s / mean* $\leq$ 8%	
μ_k	Characteristic value slip factor						0,64	0,64	0,69					Eq. (6)	

Table D7 Test protocol A_AL-SM test series

TU Delft SIROCO RFSR-CT-2014-00024
Delft University of Technology
Department of Civil Engineering and Geosciences
MacroLab
Stevinweg 1
2628 CN Delft
The Netherlands
Phone: +31 (0)15 2784034
E-Mail: p.a.devries@tudelft.nl

A_TSA	0,002	CBG

Test protocol

28.03.2018

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	Stainless, Austenitic
	Coating	**TSA**
	Coating composition	
	Surface treatment	grit blasted
	Maximum coating thickness	
	Curing procedure	
	Duration of curing	
	Time between application coating and testing	
	Specimen	Standard test piece M16 (EN 1090-2, drawing Annex G.1 b)
	Bolt class, bolt type	BUMAX 109, full thread
	Nominal Preload level	110 kN = $F_{p,C}$
	Measuring of the preload level	Load cell M16, clamping length Σt = 77 mm
	load head speed	0,002 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] 110 $\mu_i = \mu_{i,nom}$ [–]	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	A_TSA_02	0	0,150	310	110	110	110	0,71	0,70	0,85	94	91	89	26,6	0,00	07.11.17 9:39
		0	0,150	307	110	110	110	0,70	0,70	0,84	95	92	89	25,0	0,00	
	A_TSA_03	0	0,150	312	110	110	109	0,71	0,71	0,85	92	92	91	26,5	0,00	07.11.17 12:02
		0	0,150	314	109	110	111	0,71	0,71	0,83	93	94	95	26,8	0,00	
	A_TSA_04	0	0,150	306	110	110	110	0,70	0,70	0,83	95	92	90	23,6	0,00	14.11.17 9:32
		0	0,150	314	108	108	108	0,72	0,71	0,88	90	89	88	27,5	0,00	
	A_TSA_01	0	0,150	305	110	110	111	0,69	0,69	0,82	95	92	90	24,0	0,00	14.11.17 12:13
		0	0,150	304	110	110	110	0,69	0,69	0,81	95	94	92	23,4	0,00	
	Statistics (4 specimen, 8 test results)	n=8	number of tests													
		max	Maximum	314				0,72	0,71	0,88				27,5		
		min	Minimum	304	SSWL test	dF (5%)		0,69	0,69	0,81				23,4		
		mean	Average F_{Sm} | μ_m	**309**	**185**	**15,46**		**0,70**	**0,70**	**0,84**				**25,4**	Eq. (2), Eq. (4)	
		R	spread	9,9				0,03	0,02	0,07				4,2	*R = max – min*	
		s	standard deviation	4,0				0,012	0,009	0,021				1,6	Eq. (3), Eq. (5)	
		V	coefficient of variation	1,3%				1,7%	1,3%	2,5%				6%	*V = s / mean*	
	creep test	0,9 F_{Sm}		**278**										slip [μm]	Load level creep test [kN]	
	A_TSA_05	0	0,115	278	109	110	111	0,64	0,63	0,75	93	93	93	11,3	**278**	16.11.17 14:43
		0	0,124	278	109	109	110	0,64	0,63	0,73	95	95	95	11,2	NOT passed	
	Statistics (5 specimen, 10 test results)	n=10	number of tests											**result**		
		max	Maximum	314				0,72	0,71	0,88				failed	Δ slip < 2 μm in 3 h.	
		min	Minimum	278				0,64	0,63	0,73						
		mean	Average F_{Sm} | μ_m	314				0,69	0,69	0,82					Eq. (2), Eq. (4)	
		R	spread	35,9				0,09	0,08	0,15					*R = max – min*	
		s	standard deviation	13,5				0,031	0,031	0,046					Eq. (3), Eq. (5)	
		V	coefficient of variation	**4,4%**				**4,5%**	**4,4%**	**5,6%**					*V = s / mean* ≤ 8%	
	μ_k	Characteristic value slip factor						-	-	-					Eq. (6)	

Table D8 Test protocol D_AL-SM test series

TU Delft SIROCO RFSR-CT-2014-00024
Delft University of Technology
Department of Civil Engineering and Geosciences
MacroLab
Stevinweg 1
2628 CN Delft
The Netherlands
Phone: +31 (0)15 2784034
E-Mail: p.a.devries@tudelft.nl

D_TSA	0,002	CBG

Test protocol

28.03.2018

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	Stainless, Duplex
	Coating	**TSA**
	Coating composition	
	Surface treatment	grit blasted
	Maximum coating thickness	
	Curing procedure	
	Duration of curing	
	Time between application coating and testing	
	Specimen	Standard test piece M16 (EN 1090-2, drawing Annex G.1 b)
	Bolt class, bolt type	BUMAX 109, full thread
	Nominal Preload level	110 kN = $F_{p,C}$
	Measuring of the preload level	Load cell M16, clamping length Σt = 77 mm
	load head speed	0,002 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] 110 $\mu_i = \mu_{i,nom}$ [-]	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															
D_TSA_01	0	0,150	378	111	111	111	0,85	0,86	0,95	100	99	99	22,9	0,00	15.11.17 13:58
	0	0,150	364	111	111	111	0,82	0,83	0,91	99	99	100	22,1	0,00	
D_TSA_02	0	0,150	353	111	111	111	0,80	0,80	0,90	98	98	98	21,9	0,00	15.11.17 15:54
	0	0,150	340	111	111	111	0,77	0,77	0,85	100	100	100	20,6	0,00	
D_TSA_03	0	0,150	365	110	110	111	0,83	0,83	0,93	98	98	98	21,7	0,00	16.11.17 9:45
	0	0,150	355	111	111	110	0,80	0,81	0,89	99	100	100	21,5	0,00	
D_TSA_04	0	0,150	366	111	111	110	0,83	0,83	0,93	99	99	98	23,1	0,00	16.11.17 11:57
	0	0,150	351	111	111	111	0,79	0,80	0,87	100	101	102	21,0	0,00	
Statistics (4 specimen, 8 test results)	n=8	number of tests													
	max	Maximum	378				0,85	0,86	0,95				23,1		
	min	Minimum	340	SSWL test	dF (5%)		0,77	0,77	0,85				20,6		
	mean	Average F_{Sm} | μ_m	**359**	**215**	**17,9**		**0,81**	**0,82**	**0,90**				**21,8**	Eq. (2), Eq. (4)	
	R	spread	38,4				0,09	0,09	0,10				2,5	*R = max – min*	
	s	standard deviation	11,8				0,027	0,027	0,033				0,9	Eq. (3), Eq. (5)	
	V	coefficient of variation	3,3%				3,3%	3,3%	3,7%				4%	*V = s / mean*	
creep test	0,9 F_{Sm}		**323**										slip [μm]	Load level creep test [kN]	
D_TSA_05	0	0,150	340	109	110	111	0,77	0,77	0,87	97	98	99	11,2	**323**	23.11.17 14:09
	0	0,150	358	110	110	110	0,81	0,81	0,91	99	99	99	7,6	NOT passed	
Statistics (5 specimen, 10 test results)	n=10	number of tests											**result**		
	max	Maximum	378				0,85	0,86	0,95				failed	Δ slip < 2 μm in 3 h.	
	min	Minimum	340				0,77	0,77	0,85						
	mean	Average F_{Sm} | μ_m	378				0,81	0,81	0,90					Eq. (2), Eq. (4)	
	R	spread	38,4				0,09	0,09	0,10					*R = max – min*	
	s	standard deviation	11,9				0,026	0,027	0,032					Eq. (3), Eq. (5)	
	V	coefficient of variation	**3,3%**				**3,3%**	**3,3%**	**3,5%**					*V = s / mean* ≤ 8%	
μ_k	Characteristic value slip factor						-	-	-					Eq. (6)	

Table D9 Test protocol LD_AL-SM test series

TU Delft | SIROCO RFSR-CT-2014-00024 | Delft University of Technology, Department of Civil Engineering and Geosciences, MacroLab | Stevinweg 1, 2628 CN Delft, The Netherlands | Phone: +31 (0)15 2784034, E-Mail: p.a.devries@tudelft.nl

L_TSA | 0,002 | CBG **Test protocol** 28.03.2018

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	Stainless, Lean Duplex
	Coating	**TSA**
	Coating composition	
	Surface treatment	grit blasted
	Maximum coating thickness	
	Curing procedure	
	Duration of curing	
	Time between application coating and testing	
	Specimen	Standard test piece M16 (EN 1090-2, drawing Annex G.1 b)
	Bolt class, bolt type	BUMAX 109, full thread
	Nominal Preload level	110 kN = $F_{p,C}$
	Measuring of the preload level	Load cell M16, clamping length Σt = 77 mm
	load head speed	0,002 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] 110: $\mu_i = \mu_{i,nom}$ [–]	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
L_TSA_01	0	0,150	344	111	110	110	0,78	0,78	0,87	100	99	97	21,6	0,00	28.11.17 9:42
	0	0,150	369	110	111	111	0,83	0,84	0,92	99	100	100	22,8	0,00	
L_TSA_02	0	0,150	349	111	110	110	0,79	0,79	0,89	100	98	96	46,2	0,00	29.11.17 9:50
	0	0,150	326	111	111	111	0,73	0,74	0,81	101	101	100	19,0	0,00	
L_TSA_03	0	0,150	340	111	111	111	0,77	0,77	0,85	101	100	99	20,5	0,00	29.11.17 13:22
	0	0,150	331	111	111	111	0,75	0,75	0,82	101	100	100	19,6	0,00	
L_TSA_04	0	0,150	343	111	111	111	0,77	0,78	0,86	101	100	99	19,7	0,00	29.11.17 15:08
	0	0,150	350	111	111	111	0,79	0,79	0,87	101	100	100	20,4	0,00	
Statistics (4 specimen, 8 test results)	n=8	number of tests													
	max	Maximum	369				0,83	0,84	0,92				46,2		
	min	Minimum	326	SSWL test	dF (5%)		0,73	0,74	0,81				19,0		
	mean	Average **F_{Sm} | μ_m**	**344**	**206**	**17,2**		**0,78**	**0,78**	**0,86**				**23,7**	Eq. (2), Eq. (4)	
	R	spread	42,5				0,10	0,10	0,11				27,2	*R = max – min*	
	s	standard deviation	13,0				0,031	0,030	0,035				9,2	Eq. (3), Eq. (5)	
	V	coefficient of variation	3,8%				3,9%	3,8%	4,1%				39%	*V = s / mean*	
creep test	**0,9 F_{Sm}**		**309**										slip [μm]	Load level creep test [kN]	
L_TSA_05	0	0,150	344	111	111	111	0,77	0,78	0,86	101	100	99	8,6	**309**	30.11.17 14:00
	0	0,150	355	112	111	110	0,80	0,81	0,88	102	101	100	6,7	NOT passed	
Statistics (5 specimen, 10 test results)	n=10	number of tests											**result**		
	max	Maximum	369				0,83	0,84	0,92				failed	Δ slip < 2 μm in 3 h.	
	min	Minimum	326				0,73	0,74	0,81						
	mean	Average **F_{Sm} | μ_m**	369				0,78	0,78	0,86					Eq. (2), Eq. (4)	
	R	spread	42,5				0,10	0,10	0,11					*R = max – min*	
	s	standard deviation	12,0				0,028	0,027	0,032					Eq. (3), Eq. (5)	
	V	coefficient of variation	**3,5%**				**3,6%**	**3,5%**	**3,7%**					*V = s / mean* ≤ 8%	
μ_k	Characteristic value slip factor						-	-	-					Eq. (6)	

Table D10 Test protocol F_AL-SM test series

TU Delft SIROCO RFSR-CT-2014-00024
Delft University of Technology
Department of Civil Engineering and Geosciences
MacroLab
Stevinweg 1
2628 CN Delft
The Netherlands
Phone: +31 (0)15 2784034
E-Mail: p.a.devries@tudelft.nl

F_TSA | 0,002 | CBG — **Test protocol** — 28.03.2018

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	Stainless, Ferretic
Coating	**TSA**
Coating composition	
Surface treatment	grit blasted
Maximum coating thickness	
Curing procedure	
Duration of curing	
Time between application coating and testing	
Specimen	Standard test piece M16 (EN 1090-2, drawing Annex G.1 b)
Bolt class, bolt type	BUMAX 109, full thread
Nominal Preload level	110 kN = $F_{p,C}$
Measuring of the preload level	Load cell M16, clamping length Σt = 77 mm
load head speed	0,002 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] 110 $\mu_i = \mu_{i,nom}$ [–]	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
F_TSA_01	0	0,150	343	111	110	110	0,78	0,78	0,92	96	93	90	21,8	0,00	20.11.17 12:34
	0	0,150	332	110	110	110	0,75	0,76	0,87	97	95	94	20,3	0,00	
F_TSA_02	0	0,150	336	110	110	111	0,76	0,76	0,91	95	93	90	20,9	0,00	21.11.17 12:05
	0	0,150	329	109	110	110	0,75	0,75	0,87	96	94	93	20,1	0,00	
F_TSA_03	0	0,150	334	109	110	111	0,76	0,76	0,88	97	94	92	20,7	0,00	27.11.17 10:52
	0	0,150	343	110	110	110	0,78	0,78	0,91	97	95	92	22,1	0,00	
F_TSA_04	0	0,150	335	112	111	111	0,75	0,76	0,88	98	95	92	21,4	0,00	27.11.17 12:54
	0	0,150	328	110	110	111	0,74	0,75	0,86	97	96	94	20,5	0,00	
Statistics (4 specimen, 8 test results)	n=8	number of tests													
	max	Maximum	343				0,78	0,78	0,92				22,1		
	min	Minimum	328	SSWL test	dF (5%)		0,74	0,75	0,86				20,1		
	mean	Average F_{Sm} | μ_m	**335**	**201**	**17**		**0,76**	**0,76**	**0,89**				**21,0**	Eq. (2), Eq. (4)	
	R	spread	14,6				0,04	0,03	0,06				2,1	*R = max – min*	
	s	standard deviation	5,6				0,013	0,013	0,021				0,7	Eq. (3), Eq. (5)	
	V	coefficient of variation	1,7%				1,7%	1,7%	2,4%				3%	*V = s / mean*	
creep test	0,9 F_{Sm}		**301**										slip [μm]	Load level creep test [kN]	
F_TSA_05	0	0,150	301	111	111	111	0,68	0,68	0,77	100	98	96	35,5	**301**	28.11.17 11:48
	0	0,150	314	110	111	111	0,71	0,71	0,82	97	96	95	14,1	NOT passed	
Statistics (5 specimen, 10 test results)	n=10	number of tests											**result**		
	max	Maximum	343				0,78	0,78	0,92				failed	Δ slip < 2 μm in 3 h.	
	min	Minimum	301				0,68	0,68	0,77						
	mean	Average F_{Sm} | μ_m	343				0,75	0,75	0,87					Eq. (2), Eq. (4)	
	R	spread	41,6				0,10	0,09	0,15					*R = max – min*	
	s	standard deviation	12,9				0,031	0,029	0,045					Eq. (3), Eq. (5)	
	V	coefficient of variation	**3,9%**				**4,1%**	**3,9%**	**5,1%**					*V = s / mean* ≤ 8%	
μ_k	Characteristic value slip factor						-	-	-					Eq. (6)	