

Behaviour of Slip-resistant Stainless Steel Bolted Connections

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Abstract

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 paper 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.

Keywords

Slip-resistant connections, preloaded bolted connections, stainless steel, EN 1090-2, slip factor test, preload losses.

1 Introduction

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 standardised. 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.

2 Slip Factor Tests

In the frame of the presented investigation, slip factor tests were carried out to determine slip factors for different grades of stainless steel with typical 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). See Table 1 for material properties of the stainless steel plates.

Table 1 Material properties stainless steel plates

Series	Grade	Part	Width [mm]	Thickness [mm]	$R_{p0.2}$ [N/mm ²]	R_m [N/mm ²]	A_5 %	HB
Austenitic	1.4404	centre	80	15.4	266	585	61%	nm ⁽²⁾
		lap		7.95	284	592	52%	168
Ferritic	1.4003	centre ⁽¹⁾		16.3	340	517	25%	85
		lap		16.3	453	596	25%	82
Lean Duplex	1.4162	centre		8.07	362	488	28%	77
		lap		15.2	552	728	35%	238
Duplex	1.4462	centre		8.65	570	730	38%	228
		lap		15.4	538	788	34%	nm
				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 on the slip factor of the different surface treatments for the various stainless steel grades. Indicative tests series had shown that grit blasting results in the highest slip factor. It was therefore decided to test the grit blasted (GB) surface condition for all four grades. To compare the influence of the surface treatments the austenitic series was tested for two additional surface conditions: as delivered/rolled (1D) and shot blasted (SB). The resulting six test series were each executed with two different stainless steel bolt sets at different preload levels. 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.

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 ^{[3],[4]}. As currently comparable bolting assemblies made of stainless steel are not available on the market, for this investigation austenitic stainless steel bolt sets were used consisting of bolts according to EN ISO 4017 ^[5], nuts according to EN ISO 4032 ^[6] and washers according to EN ISO-7089 ^[7]. Six test series were assembled with austenitic bolts M16 A4-80, austenitic nuts M16 A4-80, and washers 17, HV 200, A4 (all Bumax88) with the mechanical properties according to EN ISO 3506-1 ^[8] and EN ISO 3506-2 ^[9]. For the other six series austenitic bolts M16 A4-100, austenitic nuts M16 A4-100 and washers 17-109, HV 300, A4 (all Bumax109) were used. Bumax88 and Bumax109 relate to property classes 8.8 and 10.9 according to EN ISO 898-1 ^[10] for carbon steel bolts, see ^[11]. The bolts of both Bumax88 and Bumax109 series were full thread.

Table 2 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	Steel grade	Surface condition		$\Sigma t^{2)}$ [mm]	Preload [kN]	Number of tests	$\mu_{ini,mean}^{4)}$ st/st+ct [-]	$\mu_{act,mean}^{5)}$ st/st+ct [-]	V ($\mu_{act}^{6)}$ st/st+ct [%]	Final slip factor $\mu_{5\%}^{7)}) / \mu_{ect}^{8)}$
		Surface finish	Rz ¹⁾ [μm]							
M16 × 100 Bumax 88 (property class 8.8)										
A-1D_B88	1.4404	1D	24	74	F _{p,C} /88	4/1/-	0.21/0.21	0.21/0.21	4/4	0.2/-
A_SB_B88	1.4404	Shot blasted	38	74	F _{p,C} /88	4/-/-	0.29/-	0.30/-	6/-	-/-
A_GB_B88	1.4404	Grit blasted	45	74	F _{p,C} /88	4/1/1	0.56/0.55	0.60/59	6/7	0.49/0.51
D_GB_B88	1.4462	Grit blasted	47	74	F _{p,C} /88	4/1/1	0.60/0.6	0.63/0.62	6/5	0.54/0.54
LD_GB_B88	1.4162	Grit blasted	41	74	F _{p,C} /88	4/-/-	0.51/-	0.53/-	10/-	-/-
F_GB_B88	1.4003	Grit blasted	45	74	F _{p,C} /88	4/0/3 ⁹⁾	0.64/-	0.69/-	3/-	-/ ⁹⁾
M16 × 100 Bumax 109 (property class 10.9)										
A_1D_B109	1.4404	1D	24	77	F _{p,C} /110	4/2/2	0.20/0.20	0.20/0.20	3/3	- ¹⁰⁾ /0.16
A_SB_B109	1.4404	Shot blasted	34	77	F _{p,C} /110	4/2/1	0.32/0.32	0.34/0.34	11/10	- ¹¹⁾ /0.28
A_GB_B109	1.4404	Grit blasted	41	77	F _{p,C} /110	4/2/1	0.57/0.58	0.65/0.66	9/8	- ¹¹⁾ /0.48
D_GB_B109	1.4462	Grit blasted	47	77	F _{p,C} /110	4/2/2	0.66/0.66	0.69/0.70	3/4	0.62/0.59
LD_GB_B109	1.4162	Grit blasted	40	77	F _{p,C} /110	4/2/1	0.62/0.62	0.65/0.64	4/5	0.56/0.49
F_GB_B109	1.4003	Grit blasted	42	77	F _{p,C} /110	4/2/2	0.68/0.68	0.74/0.75	4/4	0.64/0.59

1) Rz: roughness | 2) Σt: clamping length | 3) st: static test/ct: creep-/ect: extended creep test | 4) μ_{ini,mean}: calculated slip factors as mean values considering the preload at the start of the tests | 5) μ_{act,mean}: calculated slip factors as mean values considering the actual preload at 0.15 mm slip | 6) V: Coefficient of variation for μ_{act} | 7) μ_{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 | 9) Three extended creep tests were performed but only one test was passed. For this reason no final conclusion can be drawn. | 10) creep test not passed. | 11) COV of static tests too large.

The preload in the bolts was measured by means of small load cells, see Fig. 1b. Details with respect to the design of the load cells are given [12]. The standard that was used to perform the slip factor tests, EN 1090-2, Annex G, does not explicitly prescribe the clamp length of the bolts that are used in slip factor tests. It is however clear that longer clamp lengths lead to higher slip factors. The clamp lengths of the bolts used during the slip factor tests were 73 mm and 77 mm respectively for the Bumax88 and Bumax109 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 is 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 [2], [13], [14], [15].

The geometry of the test specimen used was according Annex G of EN 1090-2 for M16 bolts, see Fig. 1.

The procedure to determine the slip factor consists of the following three steps: 1) four static tests, 2) a creep test and 3) extended creep tests. A detailed description of the procedure to determine the slip factor according to Annex G of EN 1090-2, more detail can be found in [2]. When the creep test is passed, no additional extended creep testing 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, independent of the outcome of the creep test.

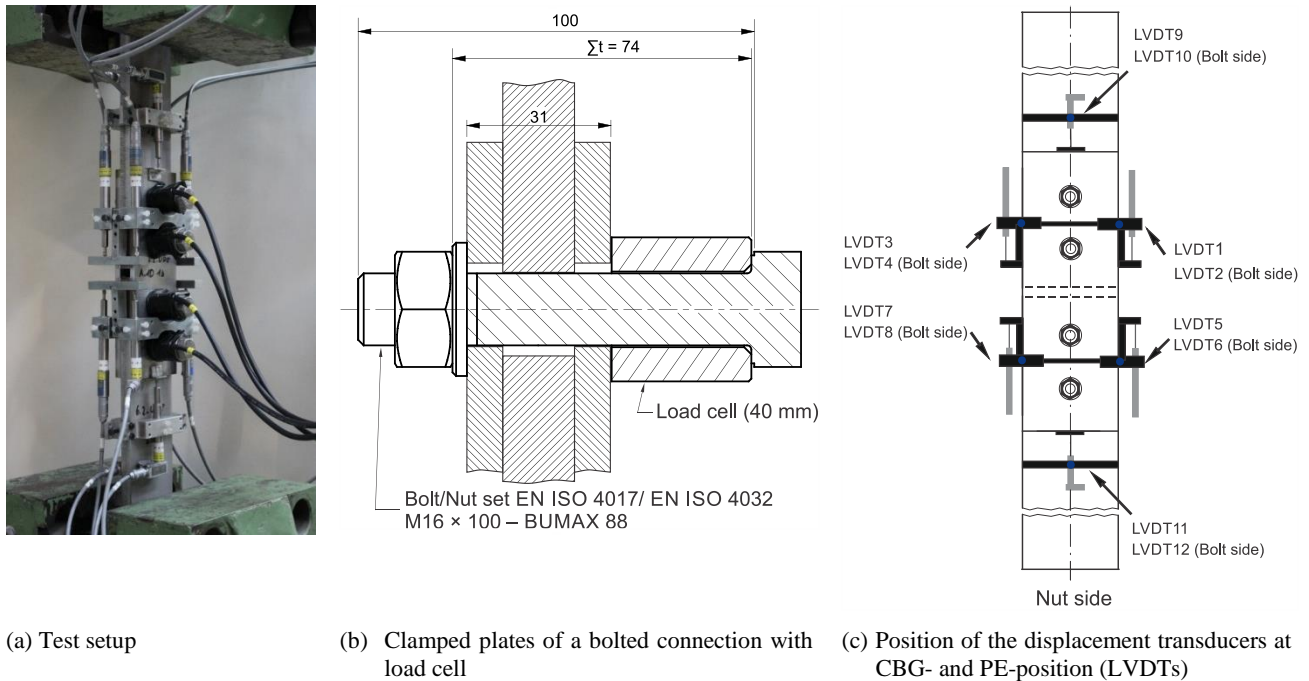


Fig. 1 Test setup exemplary for the Bumax 88 and 109 -test series – M16 test specimen

During the static slip factor tests, the slip displacements were measured in two positions: CBG (centre bolt group) and PE (plate edge), see Fig. 1. Elastic elongation and possible creep deformation of the centre plates causes differences between the slip measurements at PE and CBG positions.

3 Results and Final Slip Factors

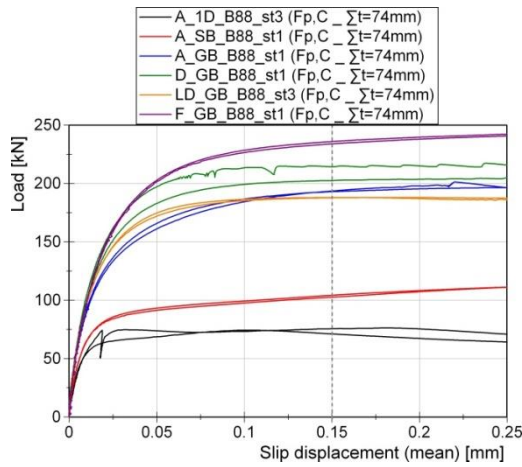
3.1 General

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 ($\mu_{\text{init,mean}}$ and $\mu_{\text{act,mean}}$) and characteristic values ($\mu_{5\%}$ for a passed creep test and μ_{ect} based on a passed extended creep test) are presented in Table 2. All results are based on the slip measured in the centre bolt group (CBG) position.

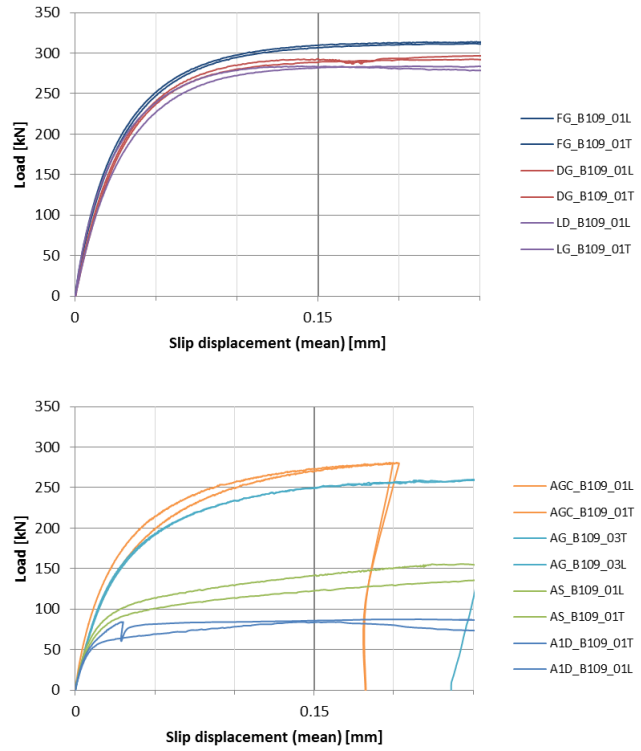
3.2 Slip loads

Fig. 2a and Fig. 2b show typical load-slip displacement curves that resulted from the static slip factor tests for the six test series with Bumax 88 and Bumax 109 bolts. The figures show that the highest slip load is achieved for the grit blasted ferritic grade, followed by grit blasted duplex, austenitic and lean duplex grades. With the surface that results from the shot blasting treatment and the as-rolled surface condition only very slow slip factors are achieved compared to the grit blasted surfaces.

Table 2 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.



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



b) Test series with bolts of property class 10.9 (Bumax 109, $\Sigma t = 78$ mm), top graph Ferritic, Duplex and Lean Duplex series, lower graph Austenitic series

Fig. 2 Typical load-slip-displacement curves for different surface conditions of the test series with bolts of property class 8.8 (Bumax 88) and property class 10.9 (Bumax 109) - each colour represent the upper and lower section of the specimen

The influence of the preload level on the slip factors is not evident. Contrary to what is experienced in slip factor tests on uncoated grit blasted carbon steels plates, except for the 1D surface the slip factor for all stainless steel grades that were preloaded with Bumax88 ($F_{p,C}=88$ kN) are equal or lower compared to the slip factors found in the experiments with the Bumax109 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. In Fig. 3 the faying surfaces after the slip factor test for the 1D surfaces are shown. Flat and uniform contact spots (black arrows) can be observed on which sliding has occurred as demonstrated by the scratches (blue arrows). The shot blasted faying surfaces in Fig. 4 are much rougher after sliding and the contact spots are not that evident, probably due to extensive cold welding (red arrows). The grit blasted faying surfaces in Fig. 5 are even more destroyed by extensive cold welding (red arrows). 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 Bumax109 (preloaded to 110 kN, so potentially more cold welding spots) compared to Bumax88 (preloaded to 88 kN).

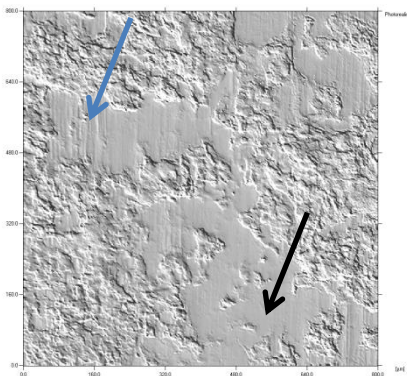


Fig. 3 Faying surfaces in the dimpled area for 1D

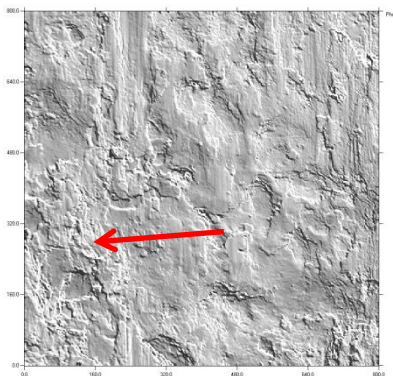


Fig. 4 Faying surfaces in the dimpled area for SB

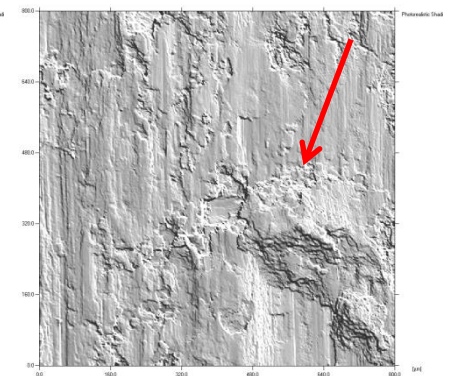


Fig. 5 Faying surfaces in the dimpled area for GB

3.3 Static slip factor tests, initial preload losses

Table 2 and Fig. 2 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 ($\mu_{i,ini}$), 2) the actual preload at a slip deformation of 0.15 mm ($\mu_{i,act}$) and 3) the nominal preload in the bolts ($\mu_{i,nom}$) and reached values for all grit blasted surfaces greater than 0.5, see Fig. 6 and Fig. 7. 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 of the shot blasted surfaces and consequently provides better mechanical interlocking between the surfaces.

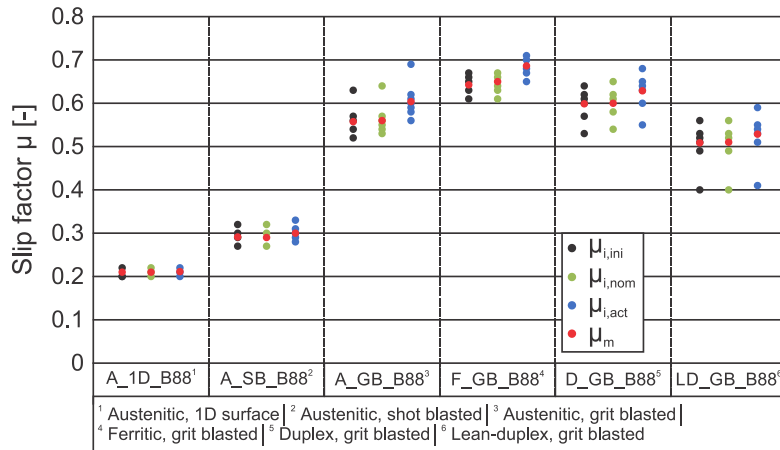


Fig. 6 Influence of different stainless steel surface conditions on the slip factors – test series with bolts of property class 8.8 (Bumax 88 – re-used bolts)

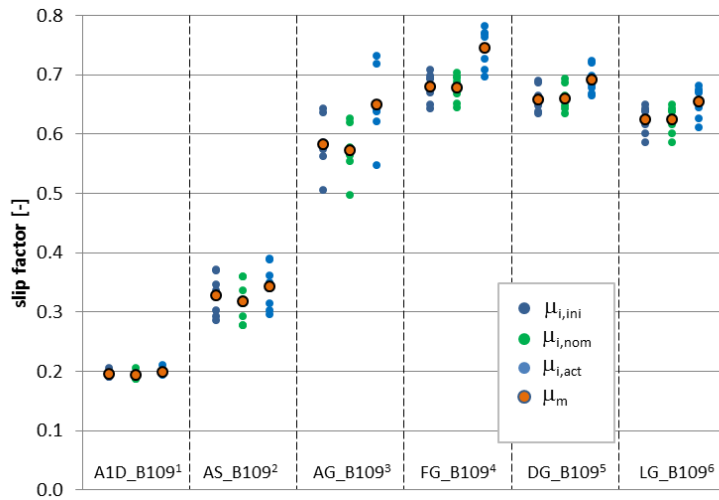


Fig. 7 Influence of different stainless steel surface conditions on the slip factors – test series with bolts of property class 10.9 (Bumax 109 – re-used bolts)

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, creep of the threads of bolt and nut and relaxation in the stress area of the bolt will cause preload losses. When the bolt is re-used at the same clamp length and load level (and is well lubricated), the additional creep/relaxation in the components of the bolt set is negligible. By using re-used bolt sets, the recorded preload losses are mainly caused by the plate material.

3.4 Creep tests

According to EN 1090-2, Annex G, a creep test should be carried out on a load level of 90% of the average of the slip loads of the first four static slip tests ($0.9 F_{s,m}$). 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’.

For Bumax88 the creep test was passed for all series. For Bumax109 all series except the 1D surface passed the creep test.

3.5 Extended creep tests

Where normally extended creep tests are only carried out on creep sensitive coatings, in this investigation extended creep tests were additionally conducted on all series for both Bumax88 and Bumax109 bolt sets although almost all the creep tests were passed.

Extended creep tests are carried out 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. 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. 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 bolt sets. By this, the combined effect of creep and relaxation of all stainless steel components of the connection could manifest during the tests.

For the series with Bumax88 bolt sets, so far only the austenitic, duplex and ferritic grit blasted plates were tested (see Fig. 8a, b and c). Fig. 9 shows the results of the extended creep tests which were conducted on all series with the Bumax109 bolts. Fig. 8 and Fig. 9 show 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. Still an increase of the load appeared to be not possible.

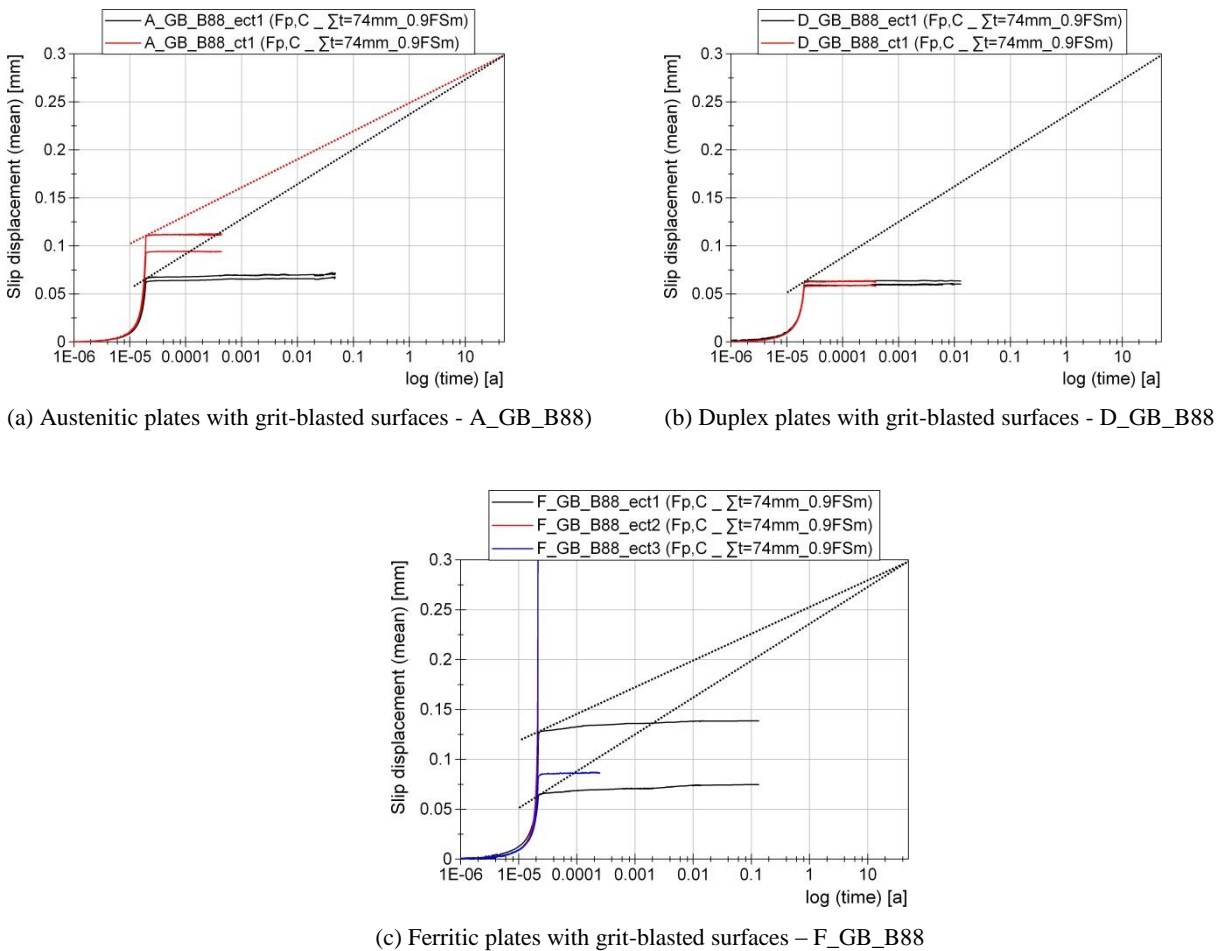
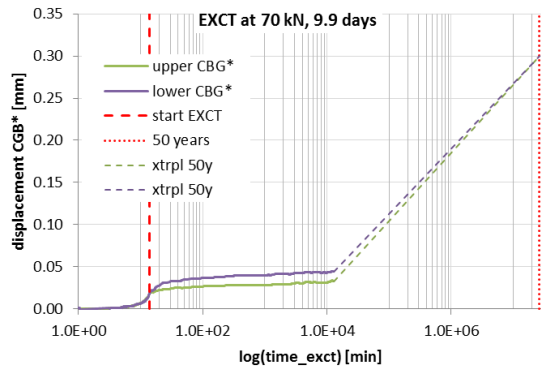


Fig. 8 Results of extended creep tests considering different stainless steel grades and surface conditions - test series with bolts of property class 8.8 (Bumax88) (each colour represents the upper and lower section of the specimen)

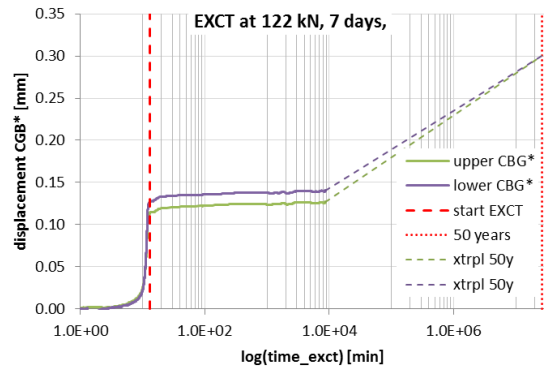
Experiments with higher loads lead to sudden failure by slip through of one or both connections. The load level during the extended creep tests (with new bolts) on the series with Bumax109 bolts was chosen 3% lower than the load level of the creep tests ($0.9 F_{sm}$, based on tests with re-used bolts). This reduction was necessary to compensate for the extra preload losses in the specimens with new bolts.

As it can be seen from Fig. 8a and b, the extended creep tests on the austenitic and duplex series with Bumax88 bolts pass, which were conducted on the same load level as the creep tests. However, Fig. 8c shows that from the three extended creep tests on the grit blasted ferritic plates only one passed. This indicates that also for these series the chosen load levels ($0.9 F_{sm}$) are at a critical level. By considering Fig. 8c, it can be seen that the available extended creep test

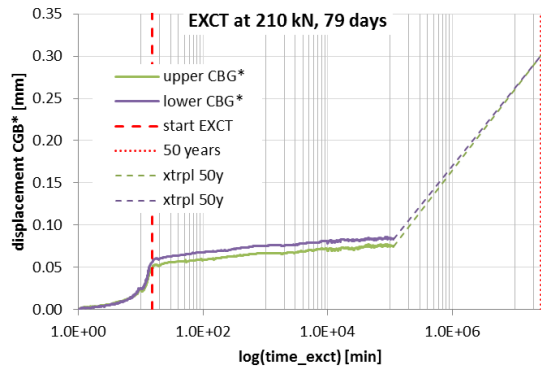
results for the ferritic grade do not allow a conclusion regarding the final slip factor for this test series. Herewith, additional testing at a reduced load level is needed.



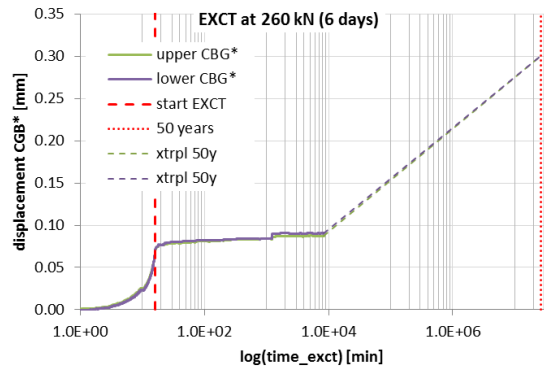
(a) Austenitic plates with 1D surface: A_1D_B109



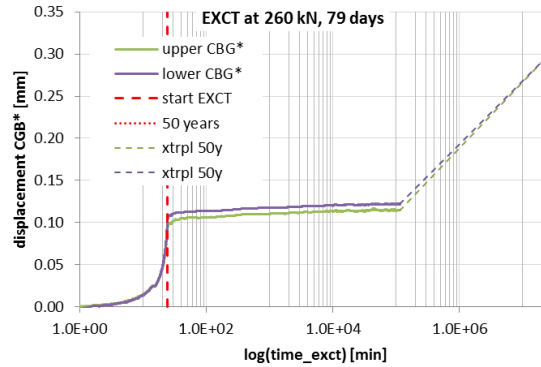
(b) Austenitic plates with Shot blasted surface A_SB_B109



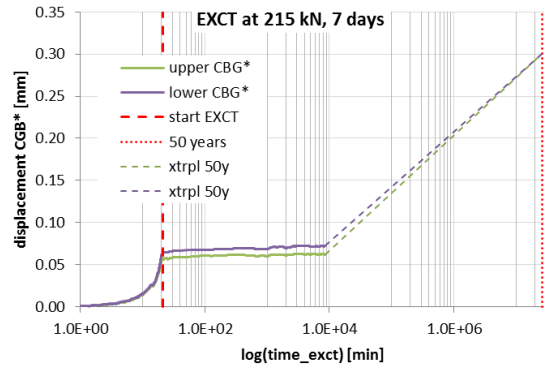
(c) Austenitic plates Grit Blasted surface: A_GB_B109



(d) Ferritic plates with Grit blasted surface F_GB_B109



(e) Duplex plates with Grit blasted surface D_GB_B109



(f) Lean Duplex plates with Grit blasted surface LD_GB_B109

Fig. 9 Results of extended creep tests considering different stainless steel grades and surface conditions - test series with bolts of property class 10.9 (Bumax109)

4 Conclusions

Grit blasting of stainless steel surfaces result in the highest surface roughness and slip factors. For the investigated stainless steel plates slip factors of more than 0.5 could be achieved.

Stainless steel plates with untreated (1D) or shot blasted surfaces are effectively unusable to transfer load by friction grip.

Opposite to what is known for carbon steels, in slip-resistant connections made of stainless steel plates higher preload levels result in higher slip factors.

Acknowledgements

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