Institute for
Metal and Lightweight Structures
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

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Comparative study on the influence of bolts preloaded in the plastic range vs. bolts preloaded in the elastic range only

Deliverable report D2.2

WP 2 – Task 2.2

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

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

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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

Slip-resistant connections are always used when slip and deformation in a bolted connection must be avoided at all costs, e.g. in radio masts and bridges. EN 1090-2 [1] defines a preload level of $F_{p,C} = 0.7\ f_{ub}\ A_s$ up to now. Preloading up to $F_{p,C}$ yields to plastic deformation in the bolt resp. in the thread combination of bolt and nut. For some reasons (e.g. reuse of the bolt), it might be useful to offer a second preload level, where the bolt is preloaded up to the elastic range only. $F_{p,C}* = 0.7\ f_{yb}\ A_s$ is such a reasonable second preload level. Currently available standards do not address the influence of a lower preload level on the slip resistance behaviour of the bolted connections. For this reason, three surface conditions were considered with different preload levels in order to investigate the influence of different preload levels on the determination of the slip factor.

2 State of the art

2.1 General

Slip of slip-resistant connections has to be prevented for either serviceability or ultimate limit state reasons. The slip resistance behaviour can be influenced by two main parameters; the condition of the faying surfaces and the preload level of the bolts. In Task 1.1 and 1.4, the influence of different surface conditions were investigated. All tests performed in these tasks were preloaded to $F_{p,C}$ level. In this task two smaller preload levels ($F_{p,C}*$ and 0.9 $F_{p,C}*$) were selected in order to investigate the influence of the preload level especially on the long-term behaviour of slip resistant connections.

2.2 Slip factor test procedure according to Annex G of EN 1090-2

The experimental investigations for the determination of the slip factor were performed according to the slip factor test procedure of EN 1090-2, Annex G. The test specimen geometry was chosen for the test specimen with M20 bolts as shown in Figure 1. EN 1090-2 prescribes a generalized experimental procedure to obtain the slip factor.

The experimental tests were carried out at the Institute for Metal and Lightweight Structures of the University of Duisburg-Essen. A universal testing machine with a capacity of ±600 kN was used for applying an incremental tensile load with a speed of 0.6 mm/min, see Figure 2.

According to EN 1090-2, the individual slip load F_{si} for a connection is defined as the load at a slip of 0.15 mm. In the presented investigations, the slip load was determined at the maximum load corresponding to a slip deformation lower than or equal to 0.15 mm.

The slip shall be taken as the relative displacement between adjacent points on an inner plate and a cover plate, in the direction of the applied load. It is measured for each end and each side of the specimen separately resulting in eight displacement values, see Figure 1b. The slip displacements were measured in the centre bolts group (CBG) of the specimens (LVDTs 1-8), as shown in Figure 1b. The slip was measured also on the upper and lower edges of the cover plates (PE: LVDTs 9-12).

In the present report, the slip factors are evaluated based on the measured slip displacement in CBG position for all four sliding planes.

Four static tests must be conducted under an incremental tensile loading condition at normal speed. The duration of the tests shall be 10 min to 15 min.

According to EN 1090-2, Annex G, the fifth test shall be a creep test with a constant load duration of at least 3 hours and a load level of 90% of the mean slip load F_{sm} resulting from the first four static tests. If the difference between the relative displacement between adjacent points on an inner plate and a cover plate at the end of 5 min and 3 hour after full load application does not exceed 0.002 mm, the slip load for the specimen under long term condition must be specified as for the previous four static tests. If the difference between the two slips at 5 min and 3 hour exceeds 0.002 mm, three extended creep tests must be performed.

The standard deviation s_{Fs} of the ten slip load values obtained from the five specimens should not exceed 8% of the mean value, otherwise additional specimens shall be tested.

In case that the difference between the slip at 5 min and 3 hours exceeds 0.002 mm, at least three extended creep tests are foreseen. The long term creep behaviour is evaluated by using a displacement-log time curve for the results of the extended creep tests. The slip displacement-log time curve may be extrapolated when a tangent can be determined with sufficient accuracy. For the extended creep tests the testing load has to be decreased (exemplary to 75 %, 60 %, 50 % of F_{sm}) in such a way, that a total displacement of 0.3 mm may not be exceeded in the service life of the structure by extrapolating the displacement-log time-curves.

The determination and the evaluation of the test results are carried out by the following equations.

Individual values of the slip factor μ_i

$$\mu_i = \frac{F_{Si}}{4 \cdot F_{p,C}} \tag{1}$$

F_{Si}: individual slip load,

$F_{p,C}$: specified preload level, in this investigation, for HV-M20 10.9 bolts, three different preload levels were selected:

$F_{p,C}$ = 172 kN

$F_{p,C}*$ = 160 kN

0.9 $F_{p,C}*$ = 144 kN

Mean value of the slip load F_{Sm} and standard deviation of the slip load s_{FS}

$$F_{Sm} = \frac{\sum F_{Si}}{n} \tag{2}$$

$$s_{FS} = \sqrt{\frac{\sum (F_{Si} - F_{Sm})^2}{n-1}} \tag{3}$$

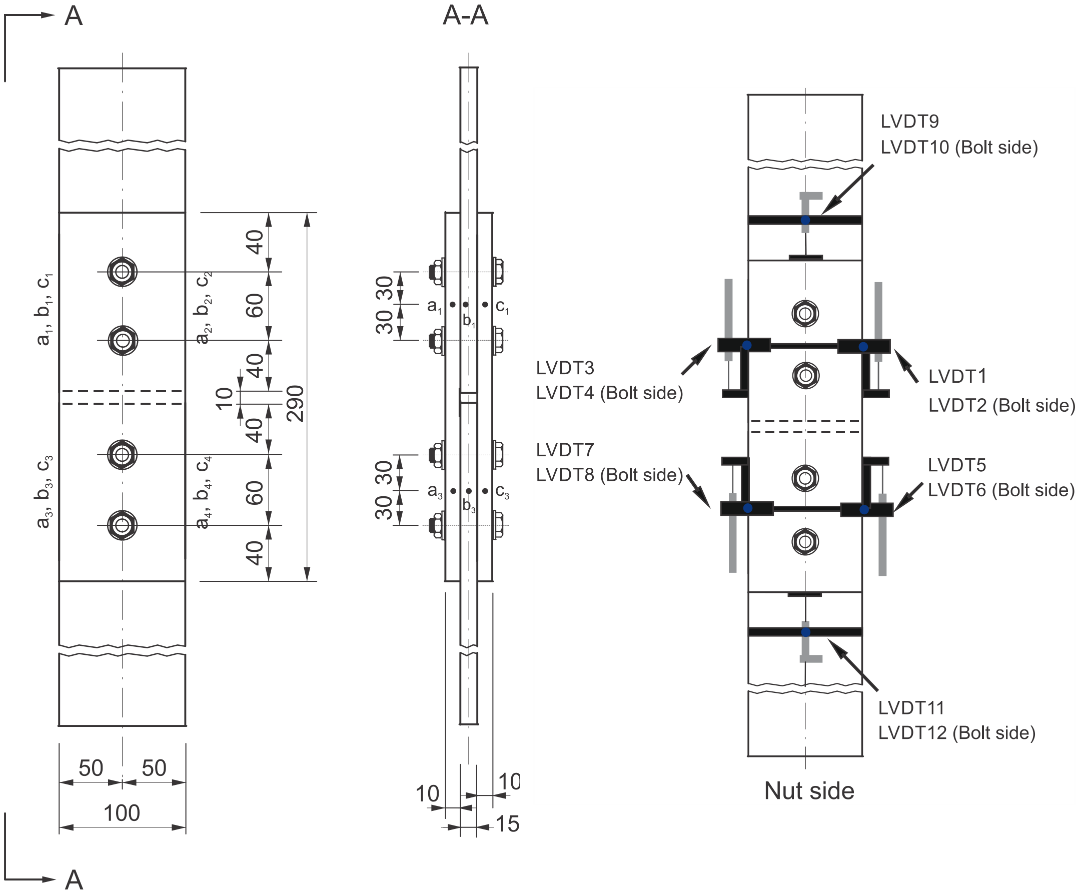
n: number of test specimens.

Mean value of the slip factor μ_m and standard deviation of the slip factor s_μ

$$\mu_m = \frac{\sum \mu_i}{n} \tag{4}$$

$$s_\mu = \sqrt{\frac{\sum(\mu_i - \mu_m)^2}{n-1}} \tag{5}$$

n: number of test specimens.



a) Test specimen geometry b) Positions of LVDTs

Figure 1 Test specimen geometry with M20 bolts for the determination of the slip factor and positions of displacement transducers (LVDTs)

If the creep test is passed, the characteristic value of the slip factor μ_k has to be calculated as the 5 % fractile value with a confidence level of 75 %.

Characteristic value of the slip-factor μ_k as 5 %-quantile from n = 10 results with a confidence level of 75 %

$$\begin{aligned} \mu_k &= \mu_m - 2{,}05 \cdot s_\mu \\ &= \mu_m \cdot (1 - 2{,}05 \cdot V) \end{aligned} \tag{6}$$

with $$V = \frac{s_\mu}{\mu_m} \tag{7}$$

V: coefficient of variation,
s_μ: standard deviation of the slip factor,
μ_m: mean value of the slip factor from ten measurements.

Figure 2 Servo-hydraulic universal testing machine (load capacity ±600 kN)

The determination of the slip factor according to EN 1090-2 is based on the nominal preload level although the actual slip factor has to be determined with the level of preload at the moment when the slip occurs.

According to EN 1090-2, the preload in the bolts shall be directly measured with an equipment with an accuracy of ±5 %. Due to this requirement, the preloads in the bolts were measured continuously during the whole testing time by implanted and calibrated strain gauges in all bolts, see Figure 3.

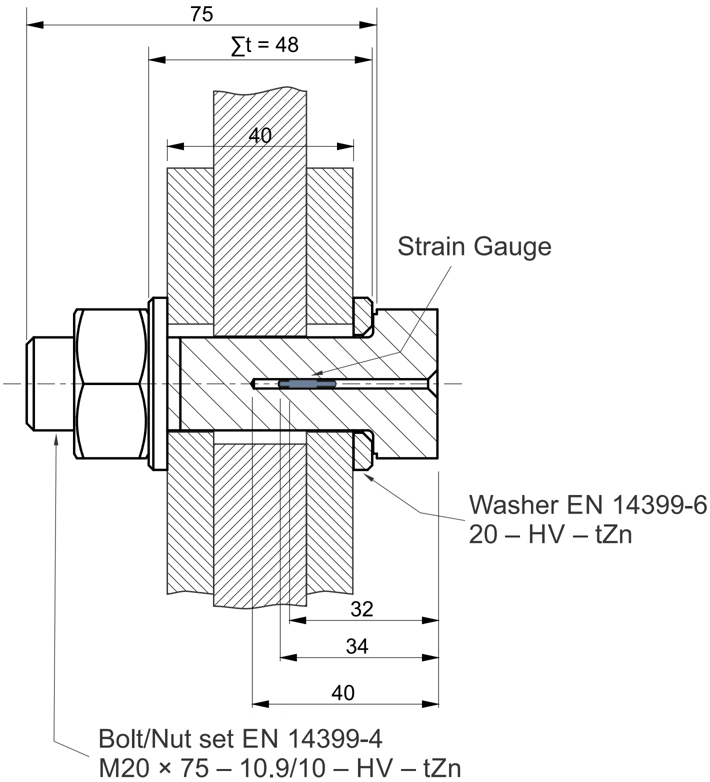


Figure 3 M20-bolt with implanted strain gauge

2.2.1 Bolts with implanted strain gauges

HV bolts of size M20 and strength 10.9 with implanted strain gauges were manufactured by drilling a centric hole of 2 mm diameter along the bolt shank. After drilling, the holes were cleaned and degreased. In a next step, two components of an adhesive were mixed to form the adhesive shortly before application. Afterwards, the mixed adhesive was injected into the hole by using a syringe, see Figure 4.

BTM-6C (produced by Tokyo Sokki Kenkyujo Co., Ltd.) strain gauges were used for instrumentation of the bolts. The gauge lead was marked according to the required length and bended rectangularly at the mark without injuring the installation material. The strain gauge was inserted gently into the hole to a certain depth while holding the upper part of the lead.

In the next step, the bolts were placed in a glass vacuum desiccator. For 15 to 20 minutes, a vacuum was created to get a level of 1 to 10 Pa. Thereafter, the bolts were placed in an electric furnace at 140 ° C for a period of three hours, see Figure 4.

The temperature was increased slowly to avoid appearance of air bubbles or cracks in the adhesive. Afterwards, each instrumented bolt was calibrated under stepwise tensile loading in a universal testing machine with a capacity of ±200 kN, see Figure 5.

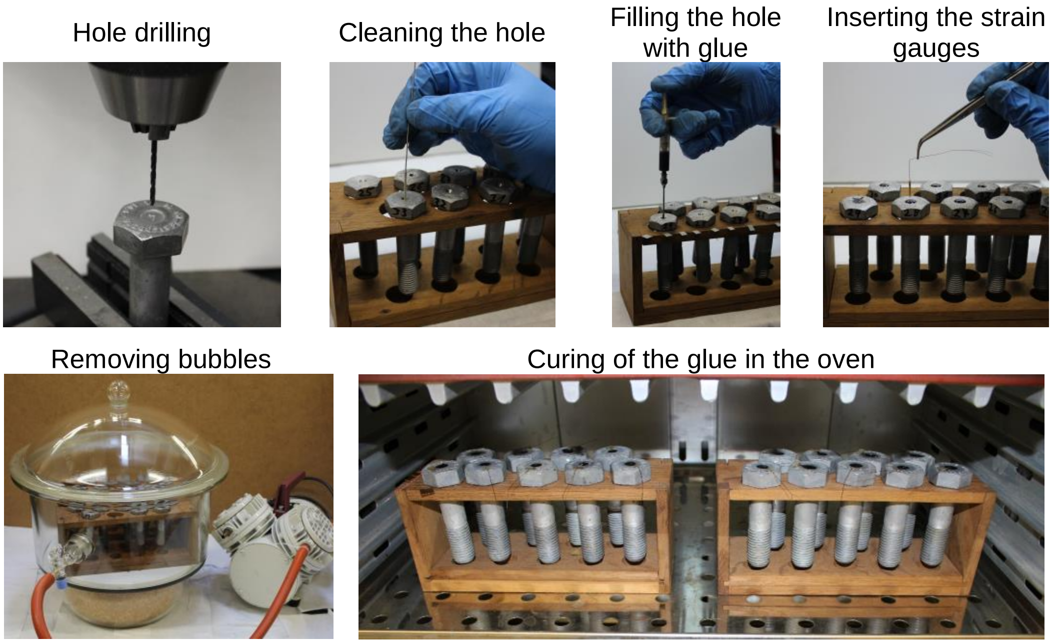


Figure 4 Production of the implanted strain gauges at UDE

Figure 6 shows an example of the load/strain-time curve of a bolt (number 2) instrumented with strain gauges, which has completed the calibration successfully. Figure 7 presents an unsuccessful calibration test for bolt number 12.

Those bolts which showed a linear load-strain behaviour, were selected for application within the slip tests, see Figure 8.

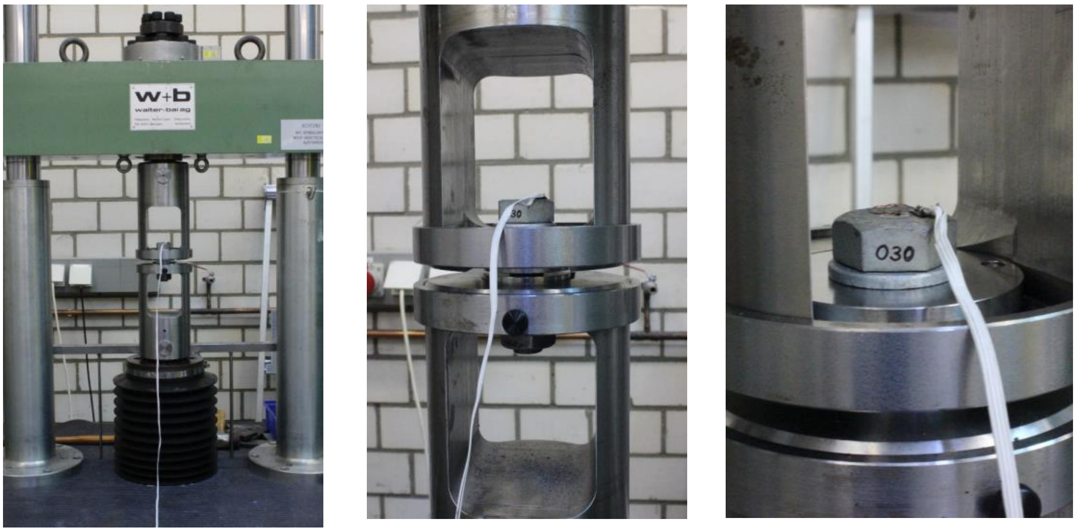


Figure 5 Calibration of instrumented bolts with strain gauge in the universal test machine (with a maximum load capacity of ±200 kN)

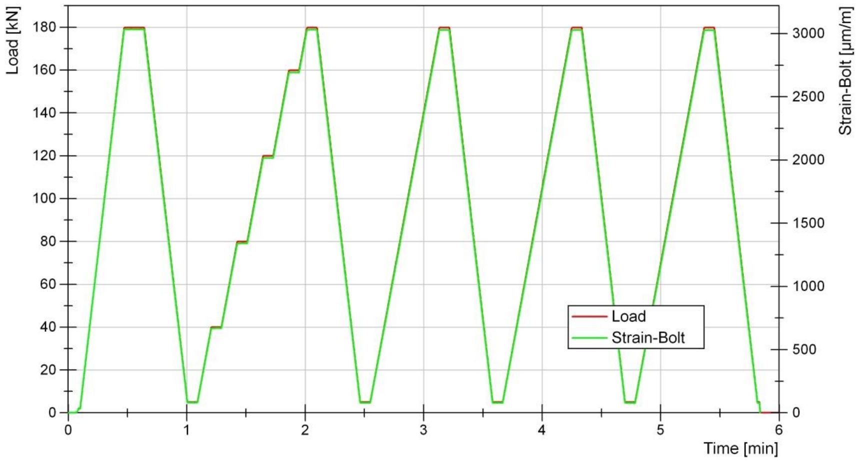


Figure 6 Example for a successful calibration test of a M20 x 75 instrumented bolt with a strain gauge: load/strain-time curve (bolt number 2)

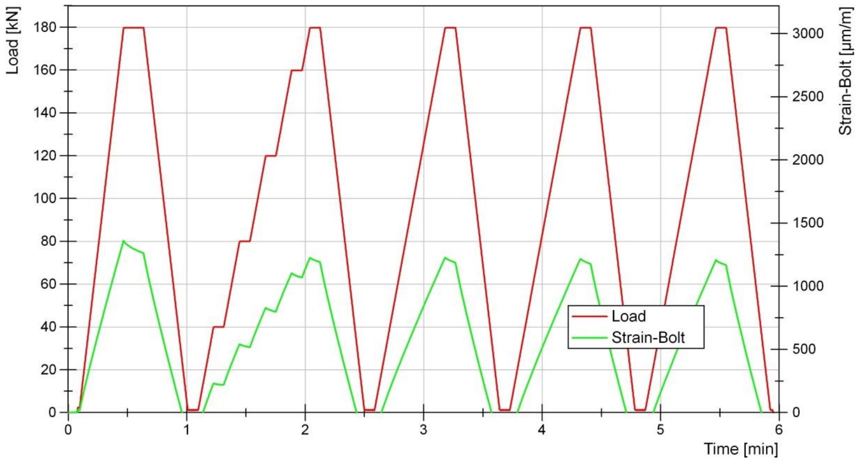


Figure 7 Example for an unsuccessful calibration test of a M20 x 75 instrumented bolt with a strain gauge: load/strain-time curve (bolt number 12)

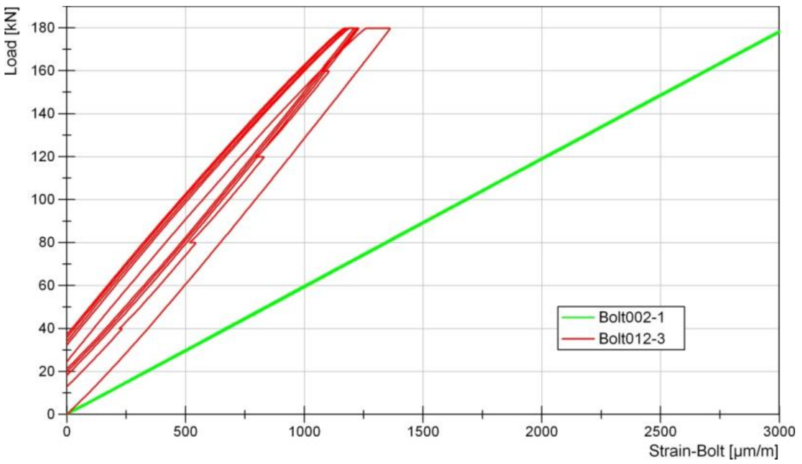


Figure 8 Example for a failed (bolt number 12) and passed (bolt number 2) calibration test of a M20 x 75 instrumented bolt with a strain gauge: load-strain curve

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3 Experimental investigations

3.1 General

In order to investigate the influence of different surface conditions and preload levels, three different surface conditions were considered, see Table 1: (1) alkali-zinc silicate (ASI-Zn)-coating, (2) spray metallized with zinc (SM-Zn) and (3) a combination of zinc metalized-alkali-zinc silicate coating (ASI – Zn-SM). The results of this task are compared with the results of Task 1.1 and 1.4 to investigate the influence of different preload levels on the determination of the slip factor. All static, creep and extended tests with preload level $F_{p,C}$ were covered in Task 1.1 and Task 1.4 and the results presented in this task too.

Table 1 Test programme

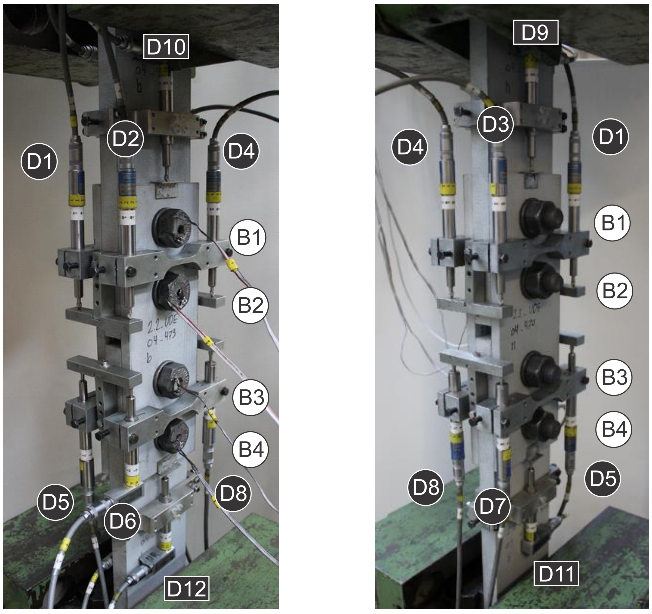
Series ID	Surface preparation		Σt[4)] [mm]	Bolt size (Md × l)[5)] [mm]	Preload [kN]	Number of tests
	Sa[1)] / Rz[2)] [µm]	DFT[3)] [µm]				st/(sp)ct/ ect[6)]
Alkali-zinc silicate coating (ASI)						
ASI-III	Sa 2½ / 80	60	52/48[7)]	M20 × 80/75[7)]	$F_{p,C}$/172	2/(3)/2
ASI-IV			48	M20 × 75	$F_{p,C}$*/160	4/1/3
Zinc spray metalized coating (Zn-SM)						
Zn-SM-II	Sa 3 / 100	140	52/48[7)]	M20 × 80/75[7)]	$F_{p,C}$/172	2/(2)/4
Zn-SM-III		164	48	M20 × 75	$F_{p,C}$*/160	4/-/4
Zn-SM-IV			48	M20 × 75	0.9 $F_{p,C}$*/144	4/-/3
Combination of alkali-zinc silicate and zinc spray metalized coating						
ASI – Zn-SM-I	Sa 2½/100 – Sa 3/100	55 – 170	48	M20 × 75	$F_{p,C}$/172	4/1/4
ASI – Zn-SM-II			48	M20 × 75	0.9 $F_{p,C}$*/144	4/1/3

1) Sa: surface preparation grade | 2) Rz: roughness | 3) DFT: dry film thickness (coating thickness) | 4) Σt: clamping length 5) d: bolt diameter, l: bolt length | 6) st: static test/ sp: step test/ ct: creep-/ect: extended creep test | 7) the extended creep tests were performed with only one washer under the bolt head (smaller bolt)

All specimens were made of steel S355J2+N. For each test specimen four M20 HV bolts class 10.9 were instrumented with a strain gauge, see section 2.2.1. Three different level of preloads ($F_{p,C}$, $F_{p,C}$* and 0.9 $F_{p,C}$*) were chosen. Herein, $F_{p,C}$* is defined as $F_{p,C}$* = 0.7 f_{yb} A_s = 160 kN (with f_{yb}: nominal yield strength of the bolt and A_s: tensile stress area of the bolt) and 0.9 $F_{p,C}$* = 144 kN. $F_{p,C}$ is defined as $F_{p,C}$ = 0.7 f_{ub} As = 172 kN (with f_{ub}: nominal tensile strength of the bolt and A_s: tensile stress area of the bolt).

Figure 9 shows the test setup used for the comparative study to investigate the influence of different preload levels. The slip load F_{Si} was determined at 0.15 mm slip or at the highest peak before. The mean values of the static slip factors by considering the initial preload when the tests started ($\mu_{ini,mean}$) as well as the actual preload at slip ($\mu_{act,mean}$) and the characteristic values ($\mu_{5\%}$ for a passed creep test and μ_{ect} based on a passed extended creep test) are presented in Table 2.

The influence of different preload levels for ASI-surface condition is shown in Figure 10. The results show that the slip load increases slightly with increasing preload. However, only a minor difference can be observed for the actual slip factor. The actual static slip factor for the specimens with preload level of 0.9 $F_{p,C}$* ($\mu_{act,mean}$ = 0.79) is slightly higher than the $\mu_{act,mean}$ value obtained from the specimens with $F_{p,C}$ ($\mu_{act,mean}$ = 0.77), see Table 2. The initial static slip factor was approximately the same for the specimens with the preload levels of 0.9 $F_{p,C}$* ($\mu_{ini,mean}$ = 0.69) and $F_{p,C}$ ($\mu_{ini,mean}$ = 0.70).



(a) bolt head side (b) nut side

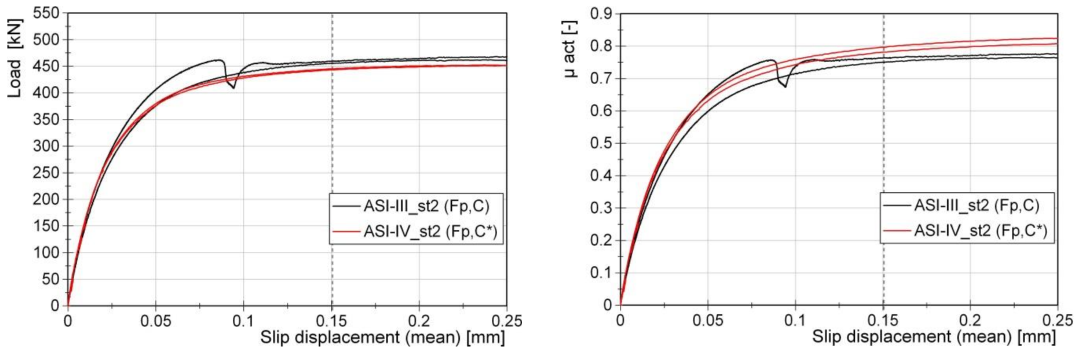
Figure 9 Positions of displacement transducers (LVDTs)
B: bolt | D: displacement transducers

It can also be seen in Figure 11 and Figure 12 that the highest actual static slip factor is achieved for Zn-SM-IV with a preload level of 0.9 $F_{p,C}$* ($\mu_{act,mean}$ = 0.92) in comparison to Zn-SM-III with a preload level of $F_{p,C}$* ($\mu_{act,mean}$ = 0.83) and Zn-SM-II with preload level of $F_{p,C}$ ($\mu_{act,mean}$ = 0.82). Table 2 shows that in this case, the initial static slip factors are following the same principle.

Table 2 Mean slip factors based on static and creep tests only ($\mu_{ini,mean}$ and $\mu_{act,mean}$) as well as final slip factors calculated as 5% fractile or determined in the extended creep test ($\mu_{5\%}$ or μ_{ect})

Series ID	DFT[1)] [µm]	Preload [kN]	Number of tests st/(sp)ct/ect[2)]	$\mu_{ini,mean}$[3)] st/st+ct [-]	$\mu_{act,mean}$[4)] st/st+ct [-]	V (μ_{act})[5)] st/st+ct [%]	Final slip factor [-] $\mu_{5\%}$[6)] / μ_{ect}[7)]
Alkali-zinc silicate coating (ASI)							
ASI-III	60	$F_{p,C}$	2/(3)/2	0.70/-	0.77/-	2.9/-	-/0.56
ASI-IV		$F_{p,C}$*	4/1/3	0.69/-	0.79/-	1.1/-	-/0.63
Zinc spray metalized coating (Zn-SM)							
Zn-SM-II	140	$F_{p,C}$	2/(2)/4	0.73/-	0.82/-	2.7/-	-/0.44
Zn-SM-III	164	$F_{p,C}$*	4/-/4	0.74/-	0.83/-	2.2/-	-/0.48
Zn-SM-IV		0.9 $F_{p,C}$*	4/-/3	0.80/-	0.92/-	1.3/-	-/0.48
Combination of alkali-zinc silicate and zinc spray metalized coating							
ASI – Zn-SM-I	55 – 170	$F_{p,C}$	4/1/4	0.63/-	0.71/-	3.9/-	-/0.44
ASI – Zn-SM-II		0.9 $F_{p,C}$*	4/1/3	0.69/-	0.77/-	3.7/-	-/0.55

[1)] DFT: dry film thickness (coating thickness) | [2)] st: static test/ sp: step test /ct: creep-/ect: extended creep test | [3)] $\mu_{ini,mean}$: calculated slip factors as mean values considering the initial preload when the tests started | [4)] $\mu_{act,mean}$: calculated slip factors as mean values considering the actual preload at 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 creep test passed | [7)] μ_{ect}: slip factor resulting from the extended creep test passed



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

Figure 10 Influence of different preload levels for ASI-surface condition

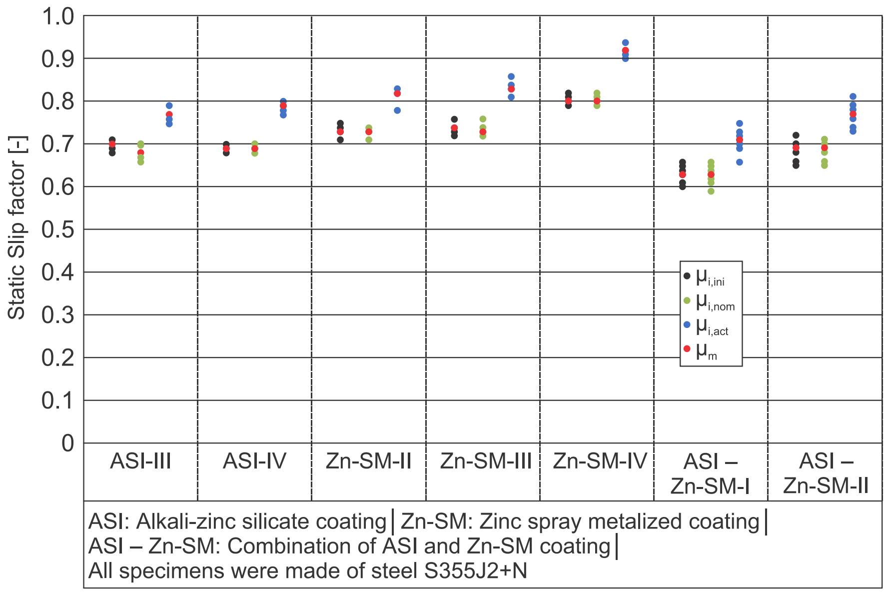
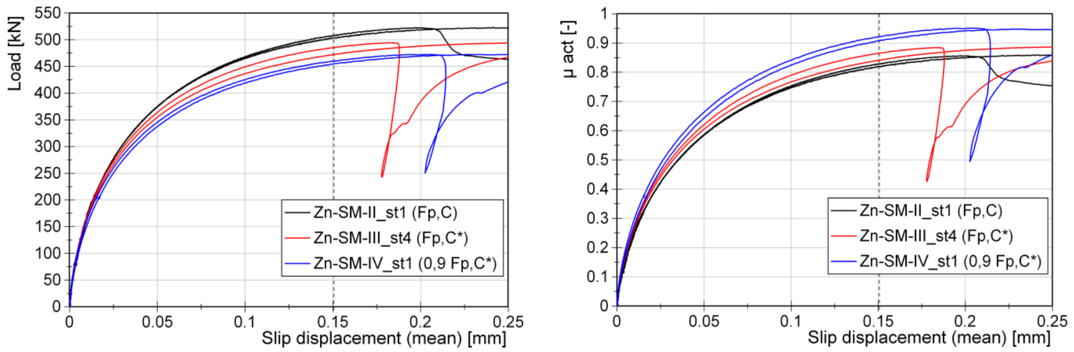


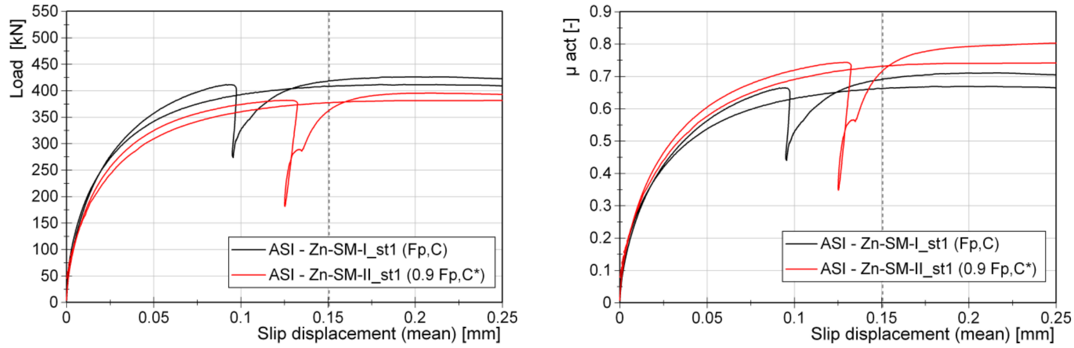
Figure 11 Influence of different preload level on the static slip factors



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

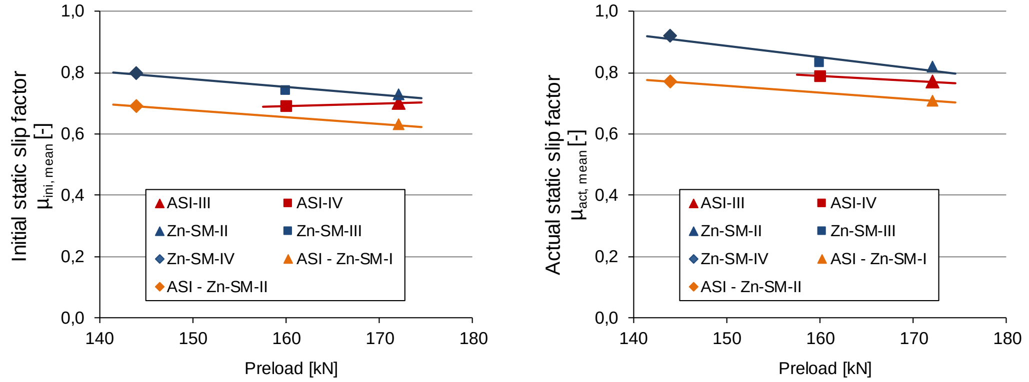
Figure 12 Influence of different preload levels for Zn-SM-surface condition

Figure 13 also confirms this phenomenon. The results show that in the ASI-Zn-SM series, $\mu_{act,mean}$ (0.9 $F_{p,C}$*) = 0.77 is higher than $\mu_{act,mean}$ ($F_{p,C}$) = 0.71. These behaviours confirm that a higher static slip factor can be achieved by a lower preload level (lower surface pressure), see Figure 14.

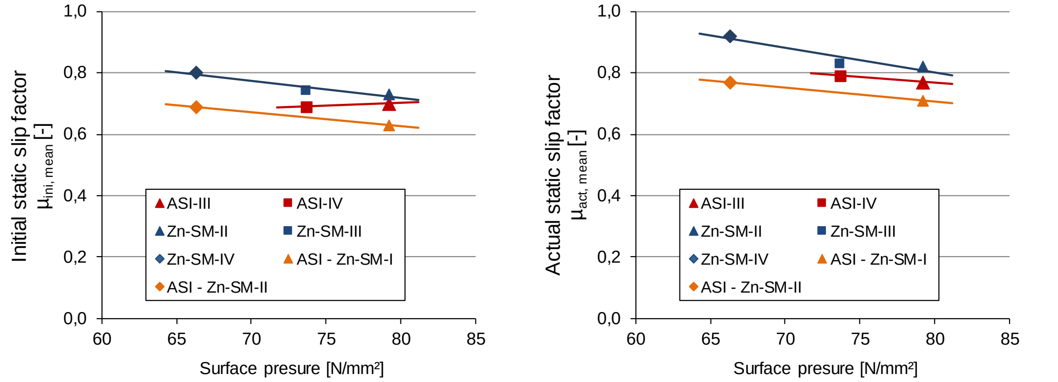


a) load-slip-displacement-curve b) μ_{act}- slip-displacement-curve

Figure 13 Influence of different preload levels for ASI-Zn-SM-surface condition



(a) intial static slip factor vs preload level (b) actual static slip factor vs preload level

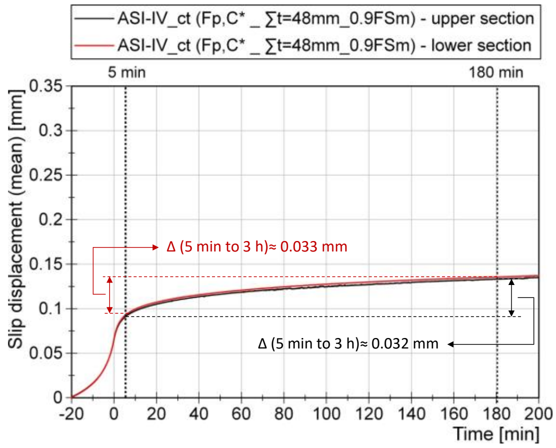


(c) intial static slip factor vs surface presure (d) actual static slip factor vs surface presure

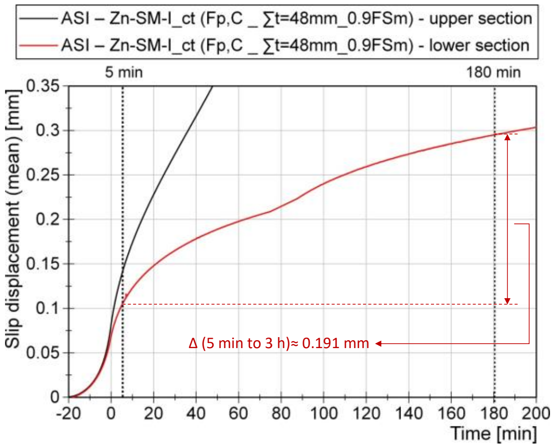
Figure 14 Influence of different preload levels and surface pressures

It can be observed from Figure 15 that for all coated test series the creep tests were failed for both upper and lower part of the specimens and performing extended creep tests were necessary to determine the final slip factor.

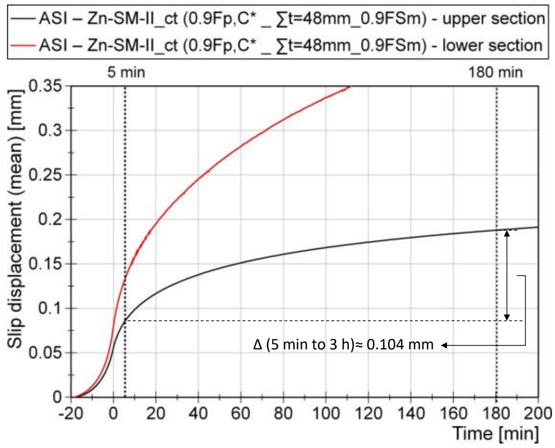
Figure 16 shows the detail of the long term test-rigs that were designed and erected at the Institute for Metal and Lightweight Structures of the University of Duisburg-Essen. Each test rig was made of a stiff steel frame, which consists of three positions for extended creep test specimens. Under each position a set of spring discs was installed to minimize the drop in the load level caused by slip in the specimen, see Figure 16 (d). Each specimen was connected to the fork connector on both ends and the whole package was mounted in the frame with a M36 threaded rod on both ends.



(a) coated surfaces with alkali-zinc silicate (ASI) – preload level: $F_{p,C}$*



(b) combination of ASI and Zn-SM – preload level: $F_{p,C}$*



(c) combination of ASI and Zn-SM – preload level: 0.9 $F_{p,C}$*

Figure 15 Results of creep tests considering different coating surfaces

The load was applied with a tensioner with a capacity of 600 kN, see Figure 16 (b). The threaded rod at the upper end of the specimens was instrumented with strain gauges in order to measure the actual load level in the specimens, see Figure 16 (c). By removing the tensioner a drop in the load level can be observed. For this reason a nut-style tensioner (Superbolt) was used in order to keep the load level constant. By turning the Jackbolt, it is possible to increase the load level slowly to reach the exact specified constant load level, see Figure 16 (e).

In the extended creep tests, the displacement transducers (LVDTs) were placed at PE (Plate Edges) position. The elongation of the centre plate between the located LVDTs at the PE and the CBG position may cause some differences regarding the measured slip values. This difference can be more critical by having higher level of constant load. The influence of location of displacement measurement is already investigated in Task 1.1. To solve this problem, the actual slip displacements at CBG position were calculated by using the correlation based on the results of the corresponding first four static tests. Afterwards, the calculated actual slip displacements at CBG position were used for evaluation of all extended creep tests. To be able to do this calculation all static test were performed including 12 LVDTs at CBG and PE positions, see Figure 9. Figure 17 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) UDE extended creep test rig

(b) tensioner with the capacity of 600 kN

(c) instrumented threaded rod for measuring the load level

(d) set of spring disc

(e) increasing the load level by using Superbolt

Figure 16 Test rig for extended creep tests

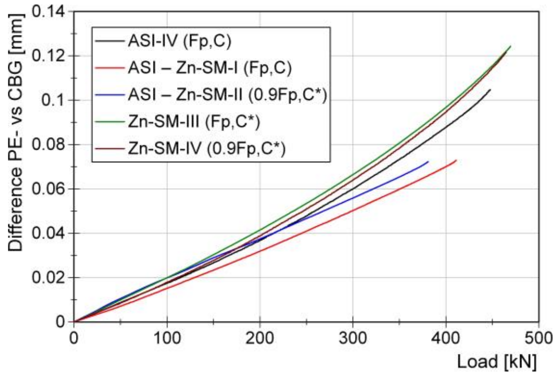


Figure 17 Relation between specimen load and difference between slip measured at PE and CBG position

Evaluating the slip displacement – log time curve based on the results of the creep tests is an effective way to get more information on the creep sensitivity of the coated surfaces. The result of the ECT at this load level is given in Figure 18 [4]. The extended creep test was performed for more than 707 days with a load level of 0.8 F_{Sm}. the results show that the slip is less than 0.3 mm when extrapolated to 50 years. Herewith, it is considered as passed extended creep test. As shown in Figure 19, for the ASI-surface conditions the slip displacement – log time curves are presented based on the results of creep and extended creep tests at 0.8, 0.85 and 0.9 F_{Sm}. The duration of the creep test is short in comparison to the extended creep test and it is not possible to consider these tests as passed extended creep tests. For this reason, to consider this load level as appropriate load level for extended creep test, an extended creep test with a constant load level of 0.9 F_{Sm} was performed. The result shows that the slip is less than 0.3 mm for this load level when extrapolated to 50 years and the tests are considered as passed extended creep tests so that the nominal slip factor can be calculated as follows:

$$\mu_{ect,ASI}(F_{p,C}) = 0.66 \text{ [-]} \tag{8}$$

$$\mu_{ect,ASI}(F_{p,C}*) = \frac{0.90 \cdot F_{Sm}}{4 \cdot F_{v,nom}} = \frac{400 \text{ kN}}{4 \cdot 160 \text{ kN}} = 0.63 \text{ [-]} \tag{9}$$

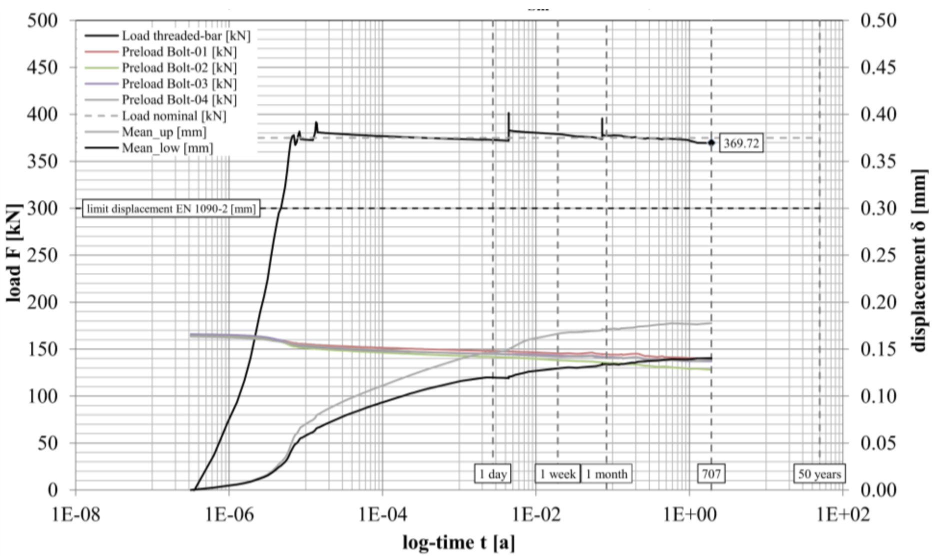


Figure 18 Results of the extended creep tests of the series ASI – the results from Task 1.4 [4]

In general, almost all coated surfaces will be considered as creep sensitive surfaces. However, this type of coating (ASI) shows a relatively good slip resistance behaviour with high loading levels under the long term extended creep test.

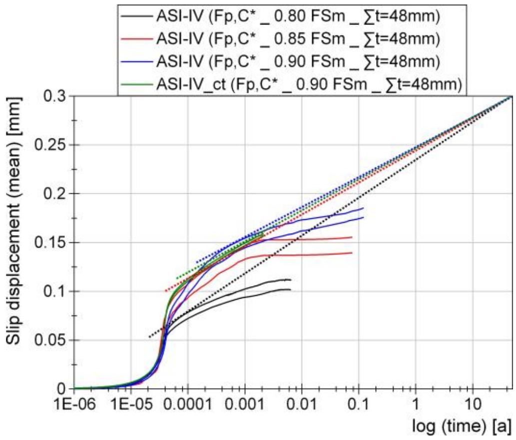


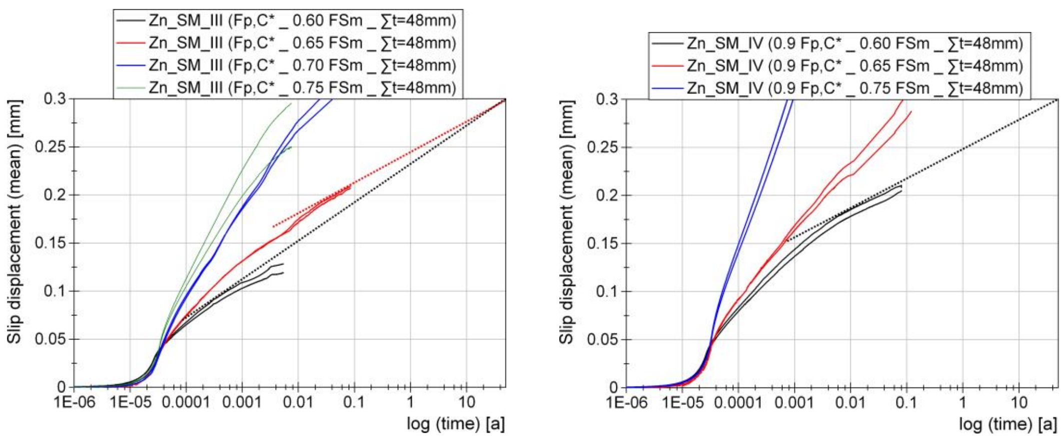
Figure 19 Results of the extended creep tests of the series ASI (each colour represents the upper/lower section of the specimen)

Seven extended creep tests were performed for Zn-SM-surface condition with two different preload levels of $F_{p,C}$* and 0.9 $F_{p,C}$*, see Figure 20. The extrapolated displacement – log time curves of the extended creep tests show that for a constant load level of 0.65 F_{Sm} for Zn-SM-III and for a constant load level of 0.60 F_{Sm} for Zn-SM-IV, the slip is less than 0.3 mm when extrapolated to 50 years. Herewith, they are considered as passed. The extended creep test also performed for Zn-Sm-surface condition with preload level of $F_{p,C}$ in Task 1.4 and the test was passed with load level of 0.60 F_{Sm} [4]. The nominal slip factor for Zn-SM-III and IV (with preload levels of $F_{p,C}$, $F_{p,C}$* and 0.9 $F_{p,C}$*) based on 0.60 F_{Sm}, 0.65 F_{Sm} and 0.60 F_{Sm} can be calculated respectively as follows:

$$\mu_{ect,Zn-SM}(F_{p,C}) = 0.44 \text{ [-]} \tag{10}$$

$$\mu_{ect,Zn-SM}(F_{p,C}*) = \frac{0.65 \cdot F_{Sm}}{4 \cdot F_{v,nom}} = \frac{304.2 \text{ kN}}{4 \cdot 160 \text{ kN}} = 0.48 \text{ [-]} \tag{11}$$

$$\mu_{ect,Zn-SM}(0.9F_{p,C}*) = \frac{0.60 \cdot F_{Sm}}{4 \cdot F_{v,nom}} = \frac{276.6 \text{ kN}}{4 \cdot 144 \text{ kN}} = 0.48 \text{ [-]} \tag{12}$$



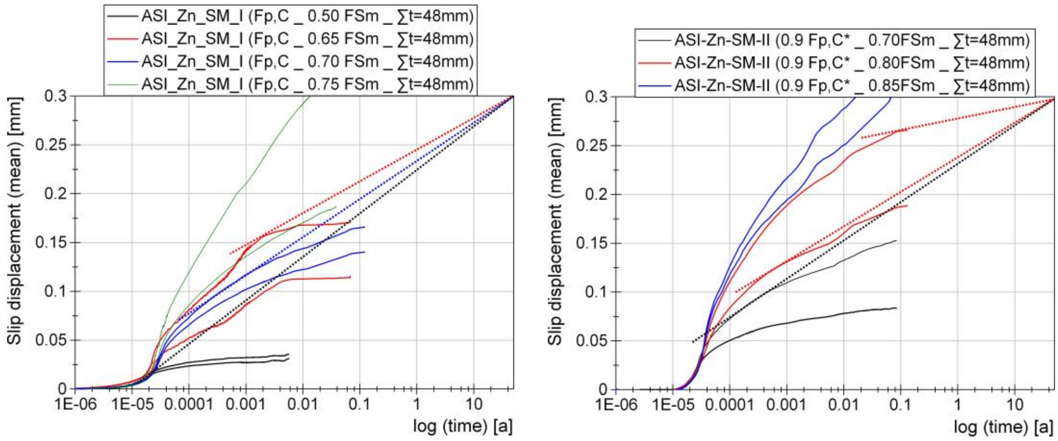
a) $F_{p,C}$* preload level b) 0.9 $F_{p,C}$* preload level

Figure 20 Results of the extended creep tests of the series Zn-SM (each colour represents the upper/lower section of the specimen)

The extended creep test for ASI - Zn-SM-I with a preload level of $F_{p,C}$ and 0.70 F_{Sm} was passed for both parts of the test specimen, see Figure 21 (a). The result also shows that the extended creep test for ASI - Zn-SM-II with a preload level of 0.9 $F_{p,C}$* and 0.80 F_{Sm} is clearly passed, see Figure 21 (b). The nominal slip factor for ASI - Zn-SM with preload levels of $F_{p,C}$ and 0.9 $F_{p,C}$* can be calculated as follows:

$$\mu_{nom,ASI-Zn-SM}(F_{p,C}) = \frac{0.70 \cdot F_{Sm}}{4 \cdot F_{v,nom}} = \frac{301.9\ kN}{4 \cdot 172\ kN} = 0.44\ [-] \tag{13}$$

$$\mu_{nom,ASI-Zn-SM}(0.9 F_{p,C}^*) = \frac{0.80 \cdot F_{Sm}}{4 \cdot F_{v,nom}} = \frac{316.7\ kN}{4 \cdot 144\ kN} = 0.55\ [-] \tag{14}$$



a) $F_{p,C}$ preload level b) 0.9 $F_{p,C}$* preload level

Figure 21 Results of the extended creep tests of the series ASI – Zn-SM (each colour represents the upper/lower section of the specimen)

4 Conclusions

In the present investigation, three different surface conditions (ASI, Zn-SM and combination of ASI and Zn-SM) and three different preload levels ($F_{p,C}$, $F_{p,C}$* and 0.9 $F_{p,C}$*) were selected, in order to investigate the influence of different preload levels. For the M20 bolts examined, this means that the preload levels result in $F_{p,C}$ = 172 kN, $F_{p,C}$* = 160 kN and 0.9 $F_{p,C}$* = 144 kN.

It becomes obvious that the actual and initial static slip factor increases slightly with decreasing preload level. Only by ASI-coated surfaces, the initial static slip factor remains approximately the same but the actual static slip factor increases by decreasing preload level. By comparing the actual static slip factors μ_{act} with those calculated with the initial preload μ_{ini} and the final slip factor μ_{ect}, it can be seen that this behaviour can also be observed for the final slip factors including the extended creep tests – at least for the surface conditions and tests in the present investigations.

Essen, 23.03.2018

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

5 References

[1] EN 1090-2:2008+A1:2011: Execution of steel structures and aluminium structures — Part 2: Technical requirements for steel structures.

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

[3] EN 14399-4:2015: High-strength structural bolting assemblies for preloading – Part 4: System HV – Hexagon bolt and nut assemblies.

[4] Stranghöner, N., Afzali, N., de Vries, P., Glienke, R., Ebert, A.: Optimization of the test procedure for slip factor tests according to EN 1090-2, Steel Construction 10 (2017), Issue 4, p. 267-281.

Appendix A: Slip factor test results (static and creep tests)

Table A1 Test protocol ASI-IV 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

24.07.2015

Technical characteristics of the test		
	Tested according to	DIN EN 1090-2:2011-10 – Annex G
	Test date	21.07.2015 - 22.07.2015
	Test performed by	N. Afzali, M.Sc. – Dipl.-Ing. M. Schiborr – J. Berg, M.Sc.
	Project No.	410410007 20003
	Quotation No.	RFSR-CT-2014-00024 (SIROCO)
	Steel grade	Structural Steel EN 10025-2 – S355J2C +N (hot rolled)
	Coating	**Alkali-zinc silicate coating (ASI), Type 2K-Interzinc 697**
	Coating composition	–
	Surface treatment	**Blasted** Sa 2 1/2, Hartguss, edged
	Maximum coating thickness	–
	Mean coating thickness	60 µm (DFT)
	Minimum coating thickness	–
	Surface roughness (before coating)	about 80 µm
	Surface roughness (after coating)	–
	Curing procedure	–
	Duration of curing	–
	Time between application of coating and testing	–
	Specimen size	Standard specimens M20 (EN 1090-2, Figure G.1 b)
	Bolt class, bolt type	10.9 (Set EN 14399-4 – HV – M20 x 75 – 10.9/10 – tZn)
	Nominal preload level	172 kN = $F_{p,C}$
	Preload measuring method	implanted SG, measured continuously, clamping length Σt = 48 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] 160 $\mu_i = \mu_{i,nom}$ [–]	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	2.2_UDE_02_245-246	245	0.150	449.6	160.6	160.4	160.3	0.70	0.70	0.79	145.2	143.0	140.7	16.3		21.07.15 15:50
		246	0.150	446.4	161.0	160.3	159.6	0.70	0.70	0.79	145.0	141.6	138.2	16.1		
	2.2_UDE_02_247-248	247	0.150	443.2	162.4	162.0	161.7	0.68	0.69	0.78	143.6	141.8	140.1	15.6		21.07.15 17:35
		248	0.150	445.0	159.6	160.0	160.5	0.70	0.70	0.80	141.6	139.6	137.7	15.7		
	2.2_UDE_02_249-250	249	0.150	436.9	161.2	161.1	161.0	0.68	0.68	0.77	143.7	141.9	140.0	15.7		22.07.15 10:55
		250	0.150	445.9	160.2	160.2	160.2	0.70	0.70	0.79	142.6	140.5	138.5	16.3		
	2.2_UDE_02_251-252	251	0.150	445.2	159.8	159.8	159.7	0.70	0.70	0.80	142.2	140.0	137.8	15.9		22.07.15 12:35
		252	0.150	443.5	160.0	160.0	160.1	0.69	0.69	0.79	142.9	140.8	138.6	15.8		
	Statistics (4 specimens, 8 test results)	n = 8	Number of tests													
		max	Maximum	449.6				0.70	0.70	0.80						
		min	Minimum	436.9				0.68	0.68	0.77						
		mean	Mean value F_{Sm} | μ_m	**444.5**				**0.69**	**0.69**	**0.79**					Eq. (2), Eq. (4)	
		R	Spread	12.7				0.02	0.02	0.03					*R = max – min*	
		s	Standard deviation s_{FS}	3.6				0.008	0.006	0.009					Eq. (3), Eq. (5)	
		V	Coefficient of variation	0.8%				1.1%	0.8%	1.1%					*V = s / mean*	
		0.9 F_{Sm}		**400.0**											Load level for the creep test	
Creep test	2.2_UDE_02_253-254	253	Δ (5 min to 3 h): **0.032**												**Creep test failed** Slip during the creep test > 0.002 mm (5 min to 3 h)	22.07.15 14:34
				–	161.8	160.9	160.0	–	–	–	140.7	138.4	136.2	649.7		
		254	Δ (5 min to 3 h): **0.033**													
				–	160.0	160.1	160.3	–	–	–	136.8	135.6	134.3	541.5		

Table A2 Test protocol Zn-SM-III 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

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

Test report

17.08.2015

Technical characteristics of the test		
	Tested according to	DIN EN 1090-2:2011-10 – Annex G
	Test date	14.08.2015
	Test performed by	N. Afzali, M.Sc. – Dipl.-Ing. M. Schiborr – J. Berg, M.Sc.
	Project No.	410410007 20003
	Quotation No.	RFSR-CT-2014-00024 (SIROCO)
	Steel grade	Structural Steel EN 10025-2 – S355J2C +N (hot rolled)
	Coating	**Thermally sprayed with zinc (Zn-SM)**
	Coating composition	–
	Surface treatment	**Blasted** Sa 3, Hartguss, edged
	Maximum coating thickness	–
	Mean coating thickness	164 µm (DFT)
	Minimum coating thickness	–
	Surface roughness (before coating)	about 100 µm
	Surface roughness (after coating)	–
	Curing procedure	–
	Duration of curing	–
	Time between application of coating and testing	–
	Specimen size	Standard specimens M20 (EN 1090-2, Figure G.1 b)
	Bolt class, bolt type	10.9 (Set EN 14399-4 – HV – M20 x 75 – 10.9/10 – tZn)
	Nominal preload level	160 kN = $F_{p,C}$*
	Preload measuring method	implanted SG, measured continuously, clamping length Σt = 48 mm
	Test speed	0.6 mm/min

	Specimens mark	plate ID's	Slip (average at CBG) mean slip planes	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] 160 $\mu_i = \mu_{i,nom}$ [–]	based on preload at slip $\mu_{i,act}$ [–]	Preload at slip, upper part: Outer bolt $F_{bi,1,act}$ [kN]	upper part: Inner bolt $F_{bi,2,act}$ [kN]	Mean value mean $F_{bi,act}$ [kN]	lower part: Inner bolt $F_{bi,3,act}$ [kN]	lower part: Outer bolt $F_{bi,4,act}$ [kN]	Test duration t [min]	Comment (Eq. according to DIN EN 1090-2)	Date of test (Start of the test)
Static test	2.2_UDE_04_431-432	431	A | B	0.150	464.7	157.1	157.3	157.6	0.74	0.73	0.83	143.0	138.3	140.6			19.4		14.08.15 10:35
		432	C | D	0.150	457.9	157.3	157.1	157.0	0.73	0.72	0.81			141.4	139.4	143.5	19.1		
	2.2_UDE_04_433-434	433	A | B	0.150	469.2	158.5	158.7	158.9	0.74	0.73	0.83	141.8	139.7	140.7			19.4		14.08.15 13:00
		434	C | D	0.150	463.1	159.5	159.1	158.7	0.73	0.72	0.81			142.2	139.9	144.4	19.1		
	2.2_UDE_04_435-436	435	A | D	0.150	470.1	158.5	159.5	160.5	0.74	0.73	0.83	142.7	140.7	141.9	139.8	144.4	19.0		14.08.15 15:15
		436	B | C	0.150	462.8	160.1	159.6	159.1	0.72	0.72	0.81	143.0	141.3	142.3	140.3	144.7	18.7		
	2.2_UDE_04_437-438	437	A | B	0.150	471.9	158.9	158.9	159.0	0.74	0.74	0.84	142.3	138.5	140.4			19.1		14.08.15 17:00
		438	C | D	0.150	485.0	158.7	158.5	158.3	0.76	0.76	0.86			140.3	139.0	141.5	19.6		
	Statistics (4 specimens, 8 test results)	n = 8	Number of tests																
		max	Maximum		485.0				0.76	0.76	0.86								
		min	Minimum		457.9				0.72	0.72	0.81								
		mean	Mean value F_{Sm} | μ_m		**468.1**				**0.74**	**0.73**	**0.83**							Eq. (2), Eq. (4)	
		R	Spread		27.1				0.04	0.04	0.05							*R* = *max* – *min*	
		s	Standard deviation s_{FS}		8.2				0.013	0.013	0.018							Eq. (3), Eq. (5)	
		V	Coefficient of variation		1.8%				1.7%	1.8%	2.2%							*V* = *s* / *mean*	
		0.9 F_{Sm}			**421.3**													Load level for the creep test	
Creep test	2.2_UDE_04_439-440	439	Δ (5 min to 3 h): **0.113**															**Creep test failed** Slip during the creep test > 0.002 mm (5 min to 3 h)	14.08.15 18:50
			A | B		–	160.3	160.2	160.1	–	–	–	141.3	137.9	141.3			109.5		
		440	Δ (5 min to 3 h): **0.098**																
			C | D		–	160.0	159.9	159.9	–	–	–			140.9	139.2	140.9	149.6		

Table A3 Test protocol Zn-SM-IV 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

24.08.2015

Technical characteristics of the test	Tested according to	DIN EN 1090-2:2011-10 – Annex G
	Test date	21.08.2015
	Test performed by	N. Afzali, M.Sc. – Dipl.-Ing. M. Schiborr – J. Berg, M.Sc.
	Project No.	410410007 20003
	Quotation No.	RFSR-CT-2014-00024 (SIROCO)
	Steel grade	Structural Steel EN 10025-2 – S355J2C +N (hot rolled)
	Coating	**Thermally sprayed with zinc (Zn-SM)**
	Coating composition	–
	Surface treatment	**Blasted** Sa 3, Hartguss, edged
	Maximum coating thickness	–
	Mean coating thickness	164 µm (DFT)
	Minimum coating thickness	–
	Surface roughness (before coating)	about 100 µm
	Surface roughness (after coating)	–
	Curing procedure	–
	Duration of curing	–
	Time between application of coating and testing	–
	Specimen size	Standard specimens M20 (EN 1090-2, Figure G.1 b)
	Bolt class, bolt type	10.9 (Set EN 14399-4 – HV – M20 x 75 – 10.9/10 – tZn)
	Nominal preload level	144 kN = 0.9 $F_{p,C}$*
	Preload measuring method	implanted SG, measured continuously, clamping length Σt = 48 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] 144 $\mu_i = \mu_{i,nom}$ [–]	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	2.2_UDE_04_469-470	469	0.150	459.5	142.0	141.8	141.6	0.81	0.80	0.92	127.3	124.8	122.3	18.9		20.08.15 9:25
		470	0.150	454.4	142.7	142.2	141.8	0.80	0.79	0.91	127.7	125.2	122.7	18.6		
	2.2_UDE_04_471-472	471	0.150	466.8	145.1	145.6	146.2	0.80	0.81	0.91	128.7	127.9	127.1	18.8		20.08.15 10:55
		472	0.150	463.5	144.9	144.5	144.2	0.80	0.80	0.91	129.1	127.2	125.3	18.7		
	2.2_UDE_04_473-474	473	0.150	455.5	143.6	143.8	144.1	0.79	0.79	0.91	126.6	124.7	122.9	18.7		20.08.15 12:35
		474	0.150	462.6	143.8	143.9	143.9	0.80	0.80	0.92	127.9	125.9	123.9	19.0		
	2.2_UDE_04_475-476	475	0.150	471.4	143.1	143.5	143.8	0.82	0.82	0.94	126.8	125.3	123.8	19.0		20.08.15 14:55
		476	0.150	454.1	143.9	143.7	143.4	0.79	0.79	0.90	127.9	126.3	124.7	18.3		
	Statistics (4 specimens, 8 test results)	*n* = 8	Number of tests													
		max	Maximum	471.4				0.82	0.82	0.94						
		min	Minimum	454.1				0.79	0.79	0.90						
		mean	Mean value F_{Sm} | μ_m	**461.0**				**0.80**	**0.80**	**0.92**					Eq. (2), Eq. (4)	
		R	Spread	17.3				0.03	0.03	0.04					*R* = *max* – *min*	
		s	Standard deviation s_{FS}	6.3				0.010	0.011	0.012					Eq. (3), Eq. (5)	
		V	Coefficient of variation	1.4%				1.3%	1.4%	1.3%					*V* = *s* / *mean*	
		0.9 F_{Sm}		**414.9**											Load level for the creep test	
Creep test	2.2_UDE_04_478-479	478	Δ (5 min to 3 h): **0.150**												**Creep test failed** Slip during the creep test > 0.002 mm (5 min to 3 h)	20.08.15 16:50
			0.150	–	143.8	144.7	145.7	–	–	–	125.9	126.1	126.2	60.0		
		479	Δ (5 min to 3 h): **0.160**													
			0.150	–	146.3	146.0	145.8	–	–	–	129.6	129.2	128.9	52.9		

Table A4 Test protocol ASI – Zn-SM-II 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

30.07.2014

Technical characteristics of the test	Tested according to	DIN EN 1090-2:2011-10 – Annex G
	Test date	29.07.2015
	Test performed by	N. Afzali, M.Sc. – Dipl.-Ing. M. Schiborr – J. Berg, M.Sc.
	Project No.	410410007 20003
	Quotation No.	RFSR-CT-2014-00024 (SIROCO)
	Steel grade	Structural Steel EN 10025-2 – S355J2C +N (hot rolled)
	Coating	**Inner plate: thermally sprayed with zinc - Zn-SM; cover plate: alkali-zinc silicate (ASI)**
	Coating composition	–
	Surface treatment	**Zn-SM: blasted** Sa 3, Hartguss, edged; **ASI: blasted** Sa 2 1/2, Hartguss, edged
	Maximum coating thickness	–
	Mean coating thickness	Zn-SM: 170 µm (DFT); ASI: 55 µm (DFT)
	Minimum coating thickness	–
	Surface roughness (before coating)	about 100 µm
	Surface roughness (after coating)	–
	Curing procedure	–
	Duration of curing	–
	Time between application of coating and testing	–
	Specimen size	Standard specimens M20 (EN 1090-2, Figure G.1 b)
	Bolt class, bolt type	10.9 (Set EN 14399-4 – HV – M20 x 75 – 10.9/10 – tZn)
	Nominal preload level	144 kN = 0.9 $F_{p,C}$*
	Preload measuring method	implanted SG, measured continuously, clamping length Σt = 48 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 $\mu_{i,ini}$ [–]	Slip factor based on nominal preload $F_{p,C}$ [kN] = 144; $\mu_i = \mu_{i,nom}$ [–]	Slip factor 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	2.2_UDE_06_21-22	21	0.126	381.7	144.9	144.8	144.7	0.66	0.66	0.74	130.2	128.5	126.8	16.1		29.07.15 10:10
		22	0.150	377.2	145.2	144.9	144.6	0.65	0.65	0.73	132.5	129.0	125.5	15.9		
	2.2_UDE_06_23-24	23	0.127	403.9	144.1	143.9	143.6	0.70	0.70	0.78	132.9	129.6	126.3	16.5		29.07.15 11:50
		24	0.127	403.9	144.1	144.3	144.5	0.70	0.70	0.79	130.3	128.3	126.3	16.5		
	2.2_UDE_06_25-26	25	0.132	392.8	143.9	143.7	143.5	0.68	0.68	0.76	132.1	128.5	124.9	16.3		29.07.15 13:25
		26	0.150	389.1	144.0	143.9	143.7	0.68	0.68	0.76	130.3	127.3	124.4	16.1		
	2.2_UDE_06_27-28	27	0.150	410.3	142.7	142.6	142.4	0.72	0.71	0.81	128.4	126.3	124.2	17.1		29.07.15 15:40
		28	0.150	407.9	142.6	142.6	142.6	0.72	0.71	0.81	130.1	126.4	122.8	17.0		
	Statistics (4 specimens, 8 test results)	*n* = 8	Number of tests													
		max	Maximum	410.3				0.72	0.71	0.81						
		min	Minimum	377.2				0.65	0.65	0.73						
		mean	Mean value F_{Sm} | μ_m	**395.9**				**0.69**	**0.69**	**0.77**					Eq. (2), Eq. (4)	
		R	Spread	33.1				0.07	0.06	0.08					*R* = *max* – *min*	
		s	Standard deviation s_{Fs}	12.4				0.025	0.022	0.029					Eq. (3), Eq. (5)	
		V	Coefficient of variation	3.1%				3.7%	3.1%	3.7%					*V* = *s* / *mean*	
		0.9 F_{Sm}		**356.3**											Load level for the creep test	
Creep test	2.2_UDE_06_29-30	29	Δ (5 min to 3 h): **0.104**	–	144.4	144.5	144.6	–	–	–	129.5	126.8	124.2	76.3	**Creep test failed** Slip during the creep test > 0.002 mm (5 min to 3 h)	29.07.15 17:15
		30	Δ (5 min to 3 h): **0.280**	–	144.4	144.5	144.7	–	–	–	129.9	126.8	123.7	26.7		