Project

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

Deliverable 1.3

New criteria for the determination of

the slip load F_{Si}

Deliverable 1.4

Criteria for creep and extended creep test

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1 Introduction

This report describes Deliverable D 1.3 and D 1.4. D 1.3 evaluates the test results from slip load tests of the task 1.1 of the SIROCO Project [1]. D 1.4 contains experimental investigations based on these results.

Deliverable D 1.3

Existing test results reviewed from literature show that the slip load-displacement behaviour differs from the coating system of the faying surfaces. For this reason, the evaluation criterion for the slip load at a fixed value is questionable. Concerning a displacement criterion for the slip load, an analysis has to be performed

Deliverable D 1.4

The task 1.1 of work package WP 1 of this project [1] is the basis of the test campaign in task 1.4, which investigates the creep sensitivity of different coatings for the faying surfaces of slip-resistant connections acc. to EN 1993-1-8 [2] and the test procedure acc. to EN 1090-2, Annex G [3]. The investigation belongs also to a definition of a new creep criterion and to revise the current procedure of finding a sufficient load level for the mostly necessary extended creep tests. Therefore the following test strategy was invented within a close communication of all members from this work package. It could be shown that one new invented test procedure (long-term step test) does not give reasonable results and it was redesigned with quite good efficiency (short-term step test). This new test procedure simplifies the way and shortened the time to find a load level for the first extended creep test. This test will be more and more necessary during the test procedure of “determining the slip factor” acc. to EN 1090-2, Annex G [3] for slip-resistant connections.

2 Criteria for slip load (D1.3)

The individual slip load F_{Si} of a slip-resistant connections is defined as the load at a displacement of $\delta = 0.15$ mm acc. to EN 1090-2, Annex G [3]. This has to be questioned. Results of task 1.1 [1] show that the slip load F_{Si} should not always be taken at a fix value for the displacement. For different coatings, deviating slip load-displacement behaviours were detected. Figure 1 shows the characteristic slip load-displacement curves from slip load tests from task 1.1 of the SIROCO Project [1], [4], [5].

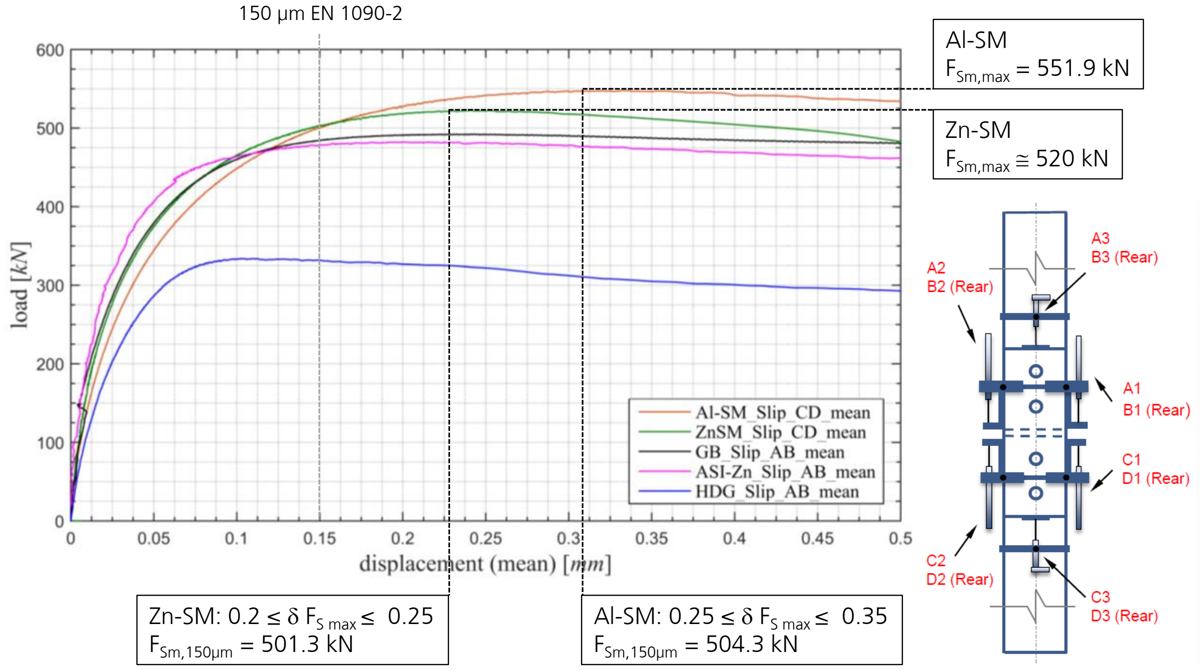


Figure 1: Influence of the coating system on the faying surfaces slip load-displacement [1]

For the final conclusion all tests - including the extended creep tests in task 1.4, need to be performed, analysed, evaluated and discussed in detail. A first idea is to take the maximum load as the slip load. This can be assumed in case of a decreasing slip load-displacement curve after reaching a maximum. Subsequently, the displacement δ has to be determined at the point of the maximum slip load. The displacement affects directly the procedure for the extended creep tests (task 1.4). It represents the point of failure of the connection under long term loads. Up to now EN 1090-2, Annex G [3] mentioned the value of $\delta = 0.3$ mm as failure criterion for the extended creep tests within a life of the structure of 50 years. Existing test results show that the slip load - displacement behaviour will differ from the size of the specimen and the coating system of the faying surfaces. For this reason, the evaluation criterion for the slip load at a fixed value is questionable. Concerning a reliable displacement criterion for the slip load, an analysis has to be performed. No experimental testing will be performed in this task 1.3. The main result is that the slip load should not be taken from a fix value of the displacement.

The applied coating system as a preparation for the faying surface of a slip-resistant connection has an influence onto the individual slip load–displacement behaviour (see Figure

1). The fix criterion with $\delta = 0.15$ mm for the evaluation of the slip load could underestimate the performance/slip load F_{Si} of the tested coating system, e. g. for Al-SM and Zn-SM. For Al-SM the mean slip load at $\delta = 150$ µm is $F_{Sm,150µm} = 504.3$ kN and the evaluated at the maximum $F_{Sm,max} = 551.9$ kN. The slip occurs between 0.25 and 0.35 mm in the slip load tests. Table 1 shows the results from task 1.1 [1] which are taken into account for evaluation.

Table 1: Results from test programme of task 1.1

Coating system (No. of results)	clamp length $\sum t$	$F_{Sm,150\,µm}$ (min. / mean / max.)	$F_{Sm,max}$ (min. / mean / max.)	$\mu_{start,150µm,5\%}$ (min./mean/max.)
	[mm]	[kN]	[kN]	[-]
Al-SM (8)	52 mm	487.5/504.3/528.8	536.2/551.9/572.2	0.71/0.73/0.76 (V_x = 2.5 %)
Zn-SM (4)	52 mm	485.3/501.2/508.8	493.6/512.0/522.7	0.71/0.73/0.75 (V_x = 2.1 %)
GB (4)	52 mm	484.5/507.4/525.3	492.4/513.1/525.6	0.71/0.74/0.77 (V_x = 3.7 %)
ASi-Zn (4)	52 mm	455.7/469.0/479.9	461.9/473.3/482.2	0.68/0.70/0.71 (V_x = 2.4 %)
HDG (8)	152 mm	278.2/323.6/355.8	290.9/326.0/355.8	0.40/0.47/0.52 (V_x = 9.0 %)

The restriction for evaluating the slip load strictly at $\delta = 0.15$ mm will be changed in the current draft prEN 1090-2:2017 [6], see Figure 2.

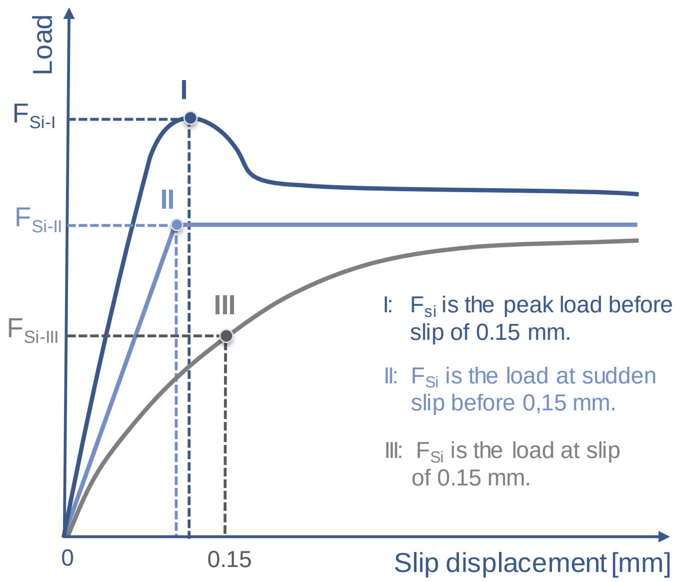


Figure 2: Criteria for evaluation of the slip load [5]

<u>Conclusion</u>

The maximum allowable displacement will be kept with $\delta = 0.15$ mm for the slip load (Figure 2, curve III). For taking the real physical failure of the slip-resistant connection (maximum of slip load curve) as slip load further investigations need to be performed. Incase the load will not decrease a maximum ca not be defined. [5]

3 Criteria for creep and extended creep test (D1.4)

There is a close link to the task 1.3 (Deliverable D 1.3) in which the slip load tests of 1.1 are evaluated regarding their different load-displacement behaviour comparing the slip load at δ = 150 µm and at maximum load $F_{Sm,max}$. The task 1.1 of work package WP 1 is the basis of the test campaign in this task, which investigates the creep sensitivity of different coatings for the faying surfaces of slip-resistant connections acc. to EN 1993-1-8 [2] and test procedure acc. to EN 1090-2, Annex G [3].

3.1 Test matrix and test setup

The mean values of the slip load F_{Sm} from the quasi-static slip load tests of task 1.1 is needed for determining relative load levels for the extended creep tests (ECT, acc. to EN 1090-2, Annex G.5 [3]) and step-tests. Table 2 shows the performed tests of each coating treatment.

Table 2: Overview of test campaign

Coating	Tests and test limitation	Comment
ASi-Zn	1. step test - long-term 2. ECT 90 % of F_{Sm} 3. ECT 80 % of F_{Sm} 4. step test - short-term 5. step test - short-term	- did not work, no slip occurred: max. $\delta \cong$ 0.17 mm - done, not passed the EN 1090-2, Annex G.5 - failed - in progress (~ 1000 d) → passed - did not work, no slip occurred until test load of 80 % F_{Sm} - slip/high creep rate at 90 %
HDG	1. step test - long-term 2. ECT 80 % of F_{Sm} 3. ECT 75 % of F_{Sm} 4. step test - short-term 5. slip load test	- did not work, no slip occurred: max. $\delta \cong$ 0.07 mm - done, not passed the EN 1090-2, Annex G.5 - failed - in progress (~ 500 d) → passed - ok, failed at 80 % - acc. to EN 1090-2, Annex G
Zn-SM	1. step test - long-term 2. ECT 80 % of F_{Sm} 3. ECT 75 % of F_{Sm} 4. step test - short-term 5. ECT 70 % of F_{Sm} 6. ECT 65 % of F_{Sm} 7. ECT 60 % of F_{Sm}	- slip/high creep rate at 80 % - done, not passed the EN 1090-2, Annex G.5 - failed - done, not passed the EN 1090-2, Annex G.5 - failed - slip/high creep rate at 70 % - done, not passed the EN 1090-2, Annex G.5 - failed - finished (ca. 318 d) – load limit→ test failed - in progress (ca. 450 d) → passed
Al-SM	1. step test - long-term 2. step test - short-term of $F_{Sm,150\mu m}$ 3. step test - short-term of $F_{Sm,max}$ 4. ECT 90 % of $F_{Sm,max}$ 5. ECT 80 % of F_{Sm}	- did not work, no slip occurred: max. δ = 0.07 mm - max. δ = 0.16 mm - done, slip/high creep rate at 90 % of $F_{Sm,max}$ (551.9 kN) - done, not passed the EN 1090-2, Annex G.5 - failed - in progress (~ 670 d) → passed
ASi-Zn – alkali-zinc silicate coating | GB – grit-blasted (Sa2½) | HDG - hot dip galvanized | Zn-SM – zinc spray metallized | Al-SM – aluminium spray metallized | ECT – extended creep test | F_{Sm} – mean slip load at a mean displacement of δ = 150 µm | $F_{Sm,max}$ – maximum slip load (see Figure 1, Al-SM slip load curve)		

Explanation of the Table 2: To investigate a new creep criterion and to revise the procedure of defining a sufficient load level for the mostly necessary ECT the following test were carried out:

1. *long-term* step test
2. *short-term* step test (later denoted as "step test")
3. extended creep tests with different load levels that will not pass
4. extended creep tests with a load levels that passes the criterion of EN 1090-2, Annex G.5

The step tests have been performed with two variations of time per load step, "long-term" (three days per load step for approximately six steps) and "short-term" (90 min per load step). The step test shall give a load level at which an ECT could pass the test. To verify the result of the step test a minimum of two ECTs is necessary. The first ECT was performed at the load level at which the step test shows a failure in connection. A failure criterion could not be quantified, yet. But it is possible to evaluate a qualitative criterion at that the connection seams to fail, e.g. reaching a maximum displacement, complete slip (approximately the hole clearance) or a displacement per time criterion. Afterwards an ECT has to be performed with a reduced load level that will pass the criterion of EN 1090-2, Annex G.5 (limit of δ = 0.3 mm of linear extrapolated displacements). This test is not restricted to minimum test duration. Therefore one ECT has to observe over the remaining project duration, to exclude long-term creep effects (tertiary creep). Therefore it was necessary to plan, calculate, manufacture, erect and calibrate autarkic test rigs that work without any electrical power to avoid bottlenecks at the hydraulic and electrical test machines. Figure 3 shows the test setup for the step tests at hydraulic test machine, the specimens, the instrumented bolts and the developed static test rig for the long-duration extended creep tests.

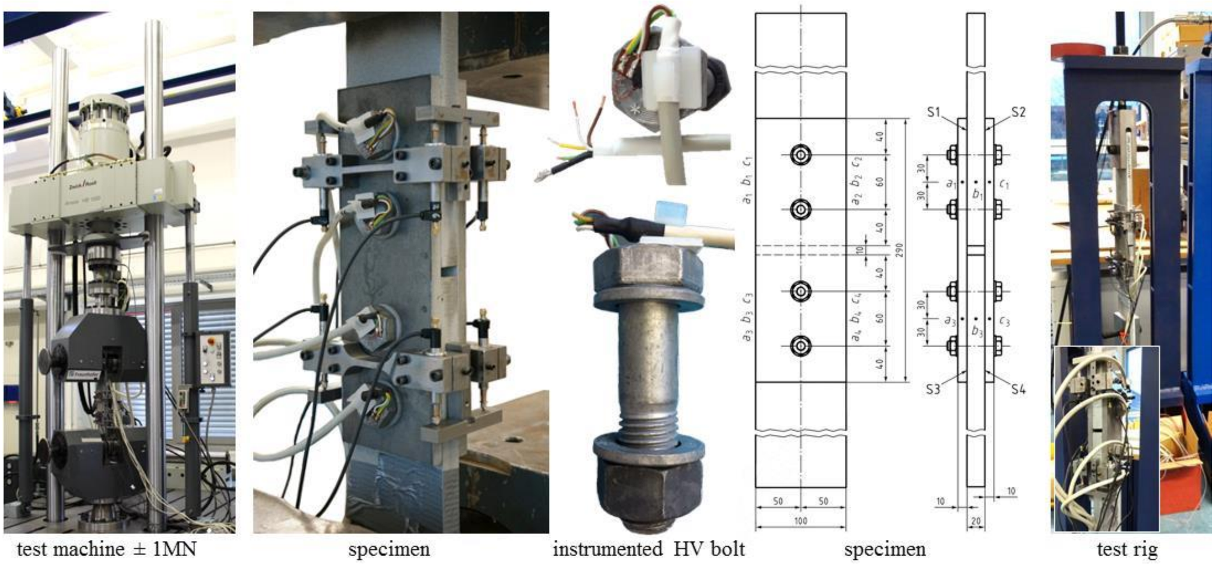
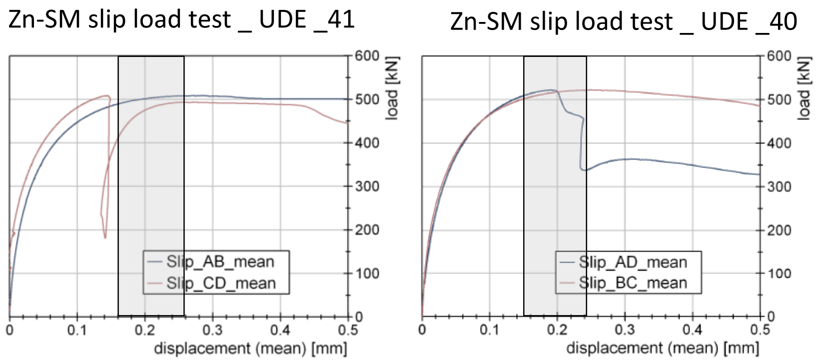


Figure 3: Test setup for step test in test machine and long duration ECT in test rig

Each test has instrumented bolts with strain gauges (BTM6C) like in task 1.1 and each specimen is equipped with eight LVDTs (LVDT: Linear Variable Differential Transformer; Company HBM Type: WI/5 mm), also the four ECTs in the test rigs. HV bolts were according to EN 14399-6 [7].

3.2 Test procedure

In the following the invented and investigated test procedure is explained. Therefore the graphs of the test results of the coating system Zn-SM (zinc spray metallized) will be shown and explained. At first the slip load tests from Task 1.1 has to be evaluated. The tests are shown in Figure 4.



previous tests in SIROCO (UDE)

specimen	$FS_{i,150\mu m}$ [kN]	LVDT-position
40_st	507,5	AB_mean
	503,4	CD_mean
41_st	508,8	AB_mean
	485,3	CD_mean
mean	501,3	

l_K/d = 52 mm/20 mm = 2.6

$\sum$ = 52 mm
$l_{K/d}$ = 2,6
2 tests
4 results
F_{Sm} = 501,2 kN
$\mu_{mean,start}$ = 0,73

Figure 4: Slip load tests of Zn-SM (task 1.1 University of Duisburg-Essen UDE)

The grey fields show the displacements where the slipping between inner and outer plates occurs. This field is around a displacement of δ > 0.15…0.2 mm. Based on the mean value of the individual slip loads F_{Si}, the load at a displacement of δ = 0.15 mm, the load levels for the step tests are calculated.

With these loads the first step test with long-term steps of a minimum with three days per step was performed. The specimen size, preparation and coating are all from the same batch as in task 1.1. The result of the long-term step test for the zinc spray metallized specimen is given in Figure 5.

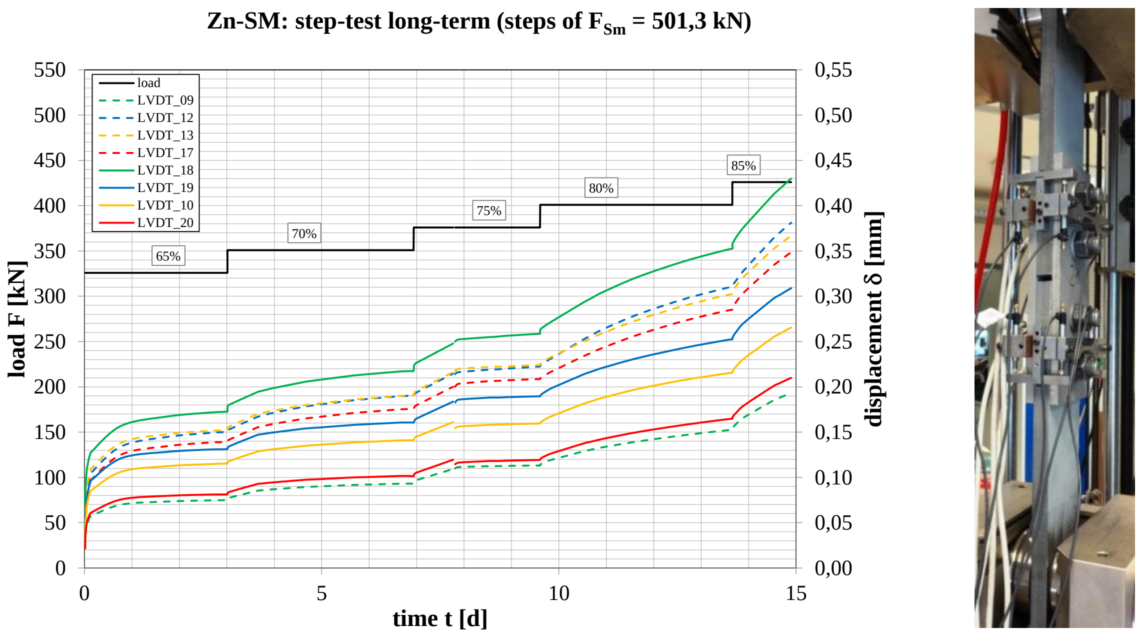


Figure 5: Result of long-term step test of zinc spray metallized (Zn-SM) specimen

During the 80 % step (test load F = 80 % of F_{Sm} = 401 kN) there is a high increase of the displacement (right ordinate). This increase seems to be the load level of failure. A quantitative criterion could not be given yet. In the next part of test campaign an ECT with 80 % load of F_{Sm} was performed. This is assumed as the load at that the specimen would not pass the test. Figure 6 shows the result of the ECT 80 %. As expected the test fails by exceeding δ > 0.3 mm immediately after application of the test load in the test rig.

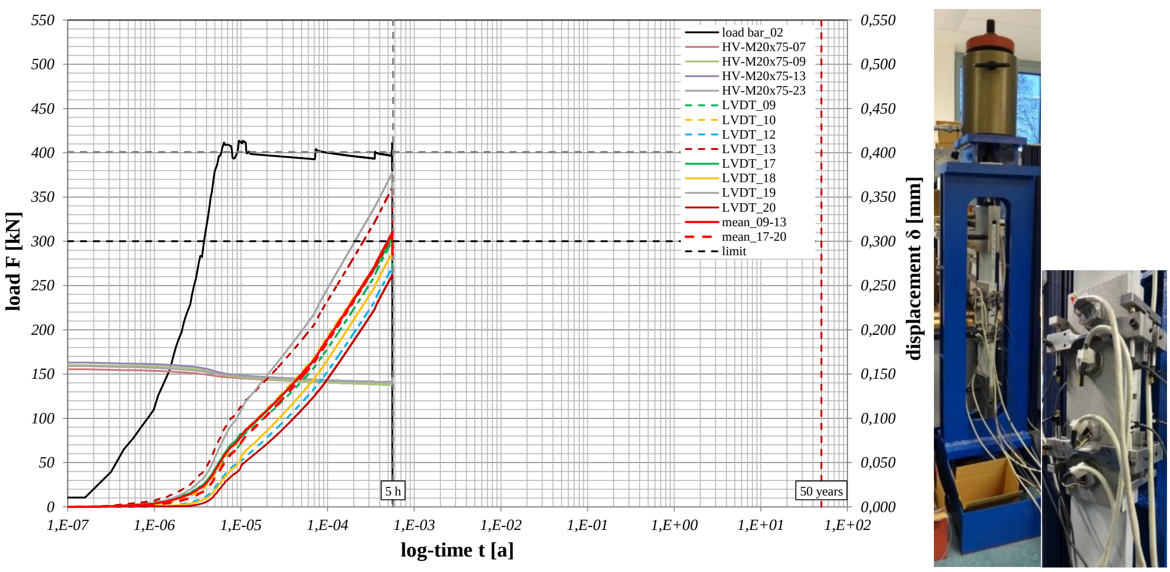


Figure 6: Load-time-displacement diagram of an extended creep test with load of 80 % of F_{Sm}

The criterion of EN 1090-2, Annex G.5 [3] for passing the test is an extrapolated displacement δ lower than 0.3 mm up to 50 years or the life-time of the structure. Therefore is log-time axis is used and scaled up to 50 years. The test needs to be repeated with a lower load level. Figure 7 shows the results of the ECT with a load level of 75 % of F_{Sm}.

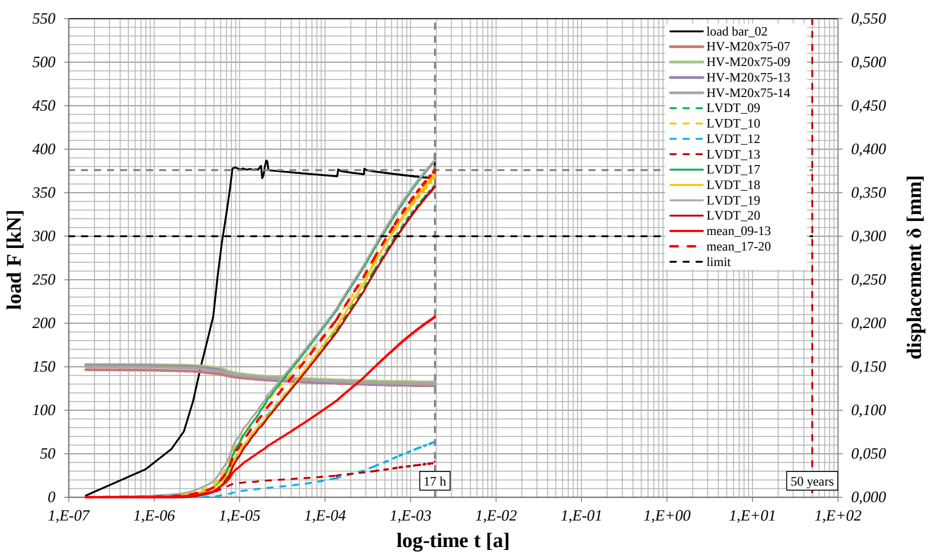


Figure 7: Load-time-displacement diagram of an extended creep test with load 75 % of F_{Sm}

The test fails within a longer time due to the reduced load. The test ended after 16.7 h. In the long-term step test a degressive curve of the displacements (slip) occurred at the load level of 75 %. That leads to the assumption that a load level of 75 % could pass the ECT. Nearly the same behaviour is also overserved during the test campaign regarding the other coating systems: ASi-Zn, HDG and Al-SM. As an example the long-term step test of HDG specimen is shown in Figure 8.

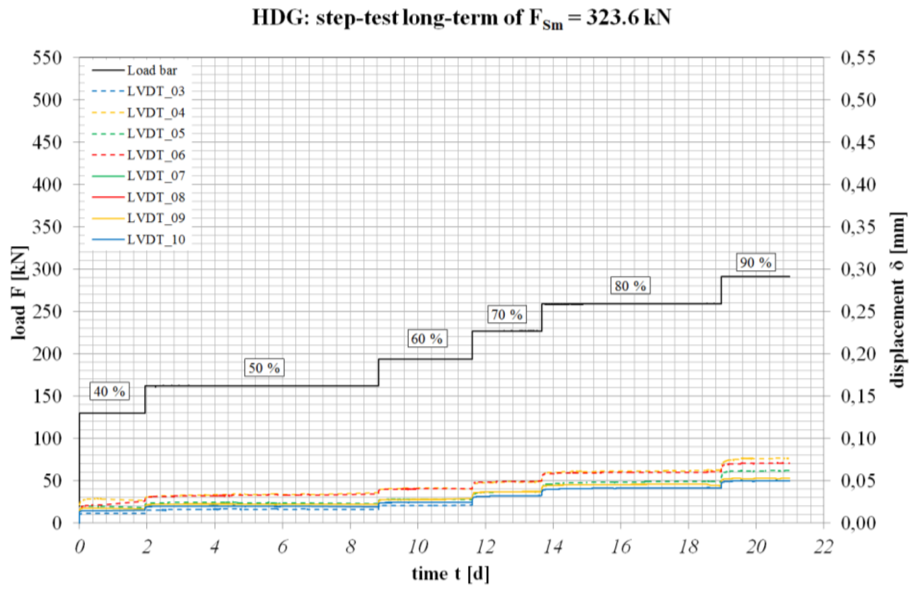


Figure 8: Long-term step test with hot dip galvanized specimen

The result does not show a slip in the connection, but the 80 % ECT fails after a few minutes, see Figure 9.

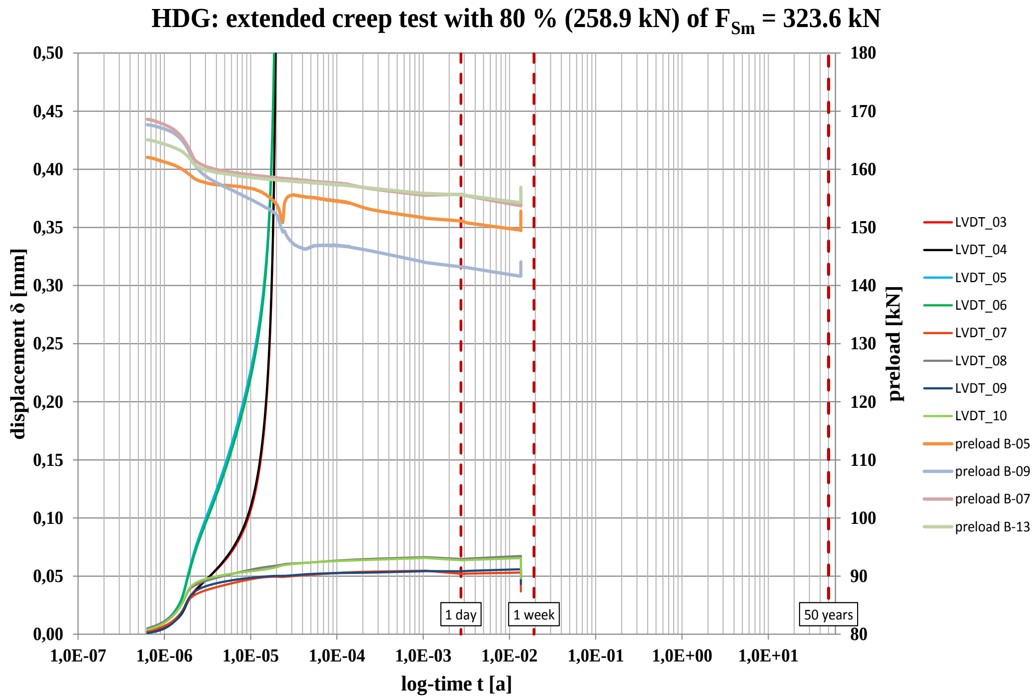


Figure 9: Extended creep test with load of 80 % of F_{Sm} for HDG specimen

To solve this issue the duration of the steps have been adapted and reduced to 90 min per step. The results are qualitative plausible and so the adaption is successful. In this way there could be saved a lot of time from 3 days to 90 min per step and the results are more reasonable. This *short-term step-test*, in the following *step test*, of the Zn-SM coating is shown in Figure 10.

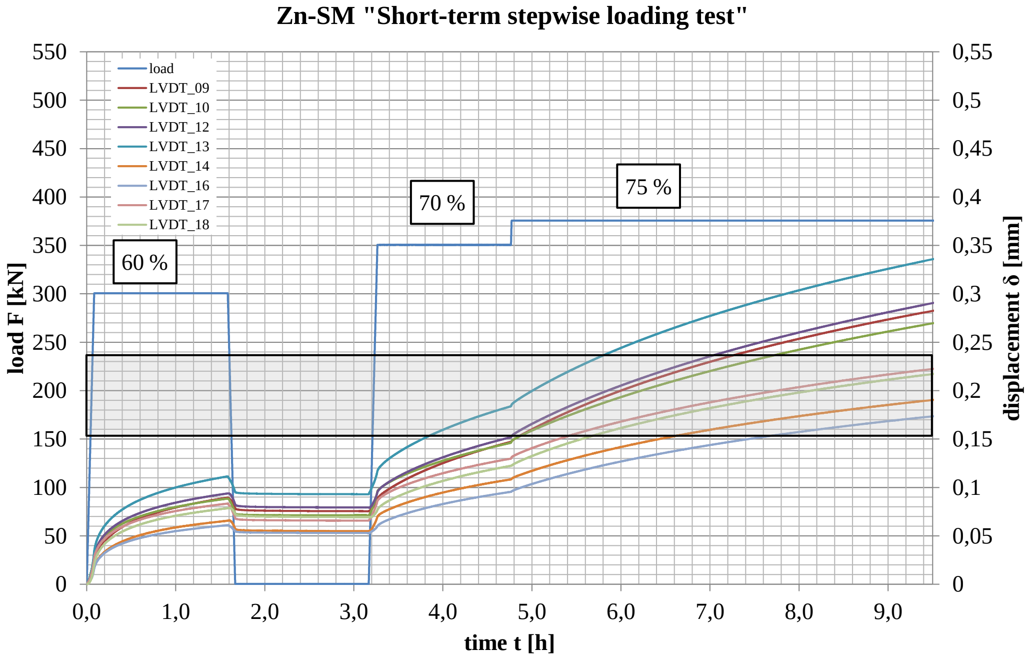


Figure 10: Short-term step-test of Zn-SM specimen

The load level starts with the step of 60 % of F_{Sm}, F = 300 kN. The next 65 % step is unfortunately without load that is caused by programming error of the test machine. But nevertheless it can be shown that in the next step with 70 % load of F_{Sm} the slip of the connection reaches the failure area (grey highlighted). The grey area is derived from the quasi-static slip load tests of Zn-SM in task 1.1, where in a range of about $\delta > 0.15 \ldots 0.2$ mm the slip-resistant connections fail during the slip load tests (Figure 4). This comparison was made after the performance of the long-term step tests of the other coating systems (Al-SM, ASi-Zn) which have shown a same less displacement like the in Figure 8 for HDG coatings. As a consequence 70 % load of the mean slip load F_{Sm} is the limit that cannot be hold permanently in the extended creep test for Zn-SM coatings. To prove the idea two more tests were performed at the load levels of 70 % and 65 % of F_{Sm}. Figure 11 shows the results of the extended creep tests.

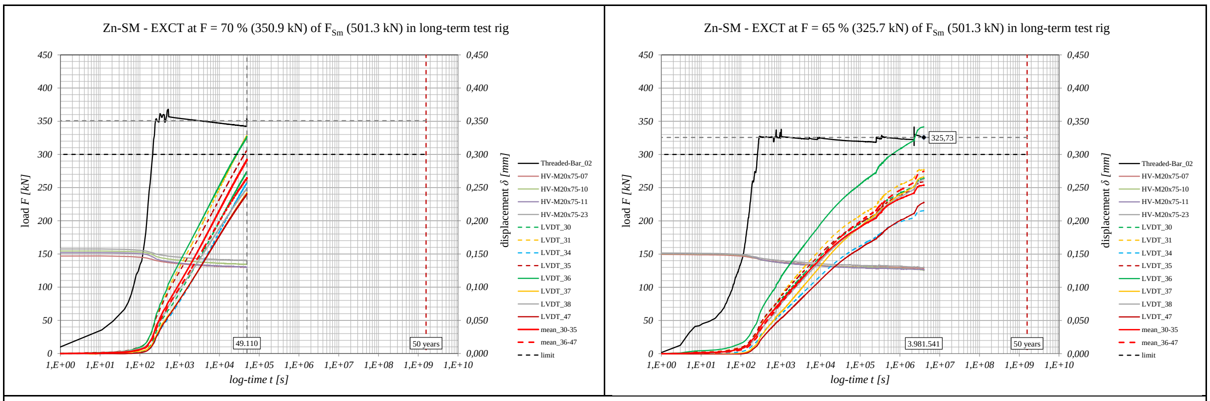


Figure 11: Extended creep test with load of 70 % and 65 % of F_{Sm} of Zn-SM specimens (failed)

In the long-term step-test at the load step of 70 % F_{Sm} no displacements up to δ < 0.3 mm occur (failure criterion of EN 1090-2, Annex G.5). Because of this it was assumed as the load, which will pass the extended creep test. But both specimen show a high slope of the displacement and the linear extrapolation will exceed the limit of 0.3 mm within 50 years. The connections do not pass the extended creep test. As a consequence a further test has been performed with a 60 % load level of F_{Sm}. Figure 12 shows the result.

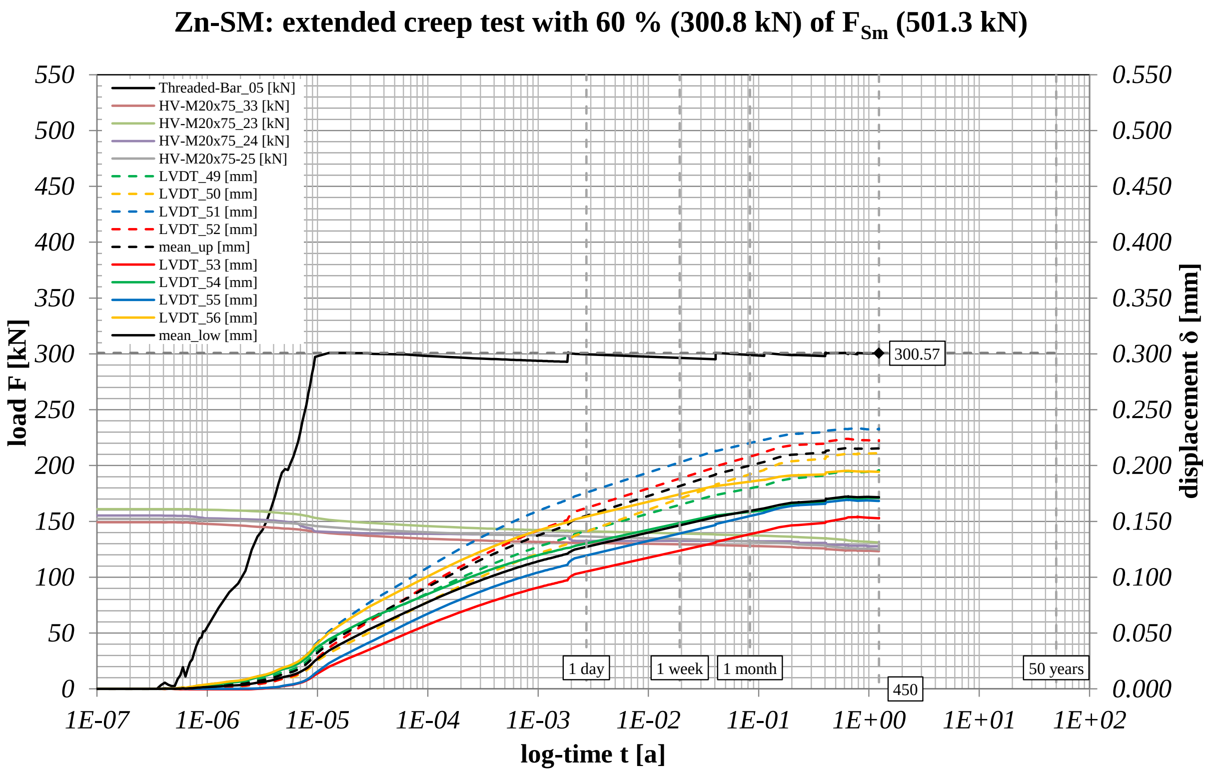


Figure 12: Extended creep test with 60 % of Zn-SM specimen (test duration: 450 d)

The procedure of *long-term* and *short-term* step test was performed for each coating system. The relative steps of the load levels calculated with F_{Sm} were given from the task 1.1. It can be shown that the *long-term* step test does not work well for defining a load level for the first extended creep test. No comparable displacements to the slip load tests will be achieved. For example during the long-term step test for HDG specimen in Figure 8 no slipping occurred during the 90 % load level, although the related extended creep test with the 80 % load level fails (see Figure 9).

Therefore the duration of each load step was reduced from testing time t = 3 d days to t = 90 min. This has also positive economical and practical effects on the test procedure. The *short-term* step test can be a new adaption of the current procedure of determining the slip factor acc. to EN 1090-2, Annex G [3] and could replace the creep test of Annex G.4 in EN 1090-2 [3]).

A main result is that this investigations show an alternative possibility to the current test procedure for determining slip factors µ of new coating systems for the faying surfaces of slip-resistant connections. The *short-term* step test could substitute the actual *creep test*. The *creep test* is only a ~ 3 h test at 90 % load of F_{Sm} and gives no answers for the mostly necessary extended creep test. As a result of the step test a first load level for the extremely time-consuming extended creep tests can be estimated quite quickly so that the specimen will pass the test. This procedure is summarised in [5].

3.3 Long-duration extended creep tests

Further results of this project are the long-term stability or creep behaviour of the investigated coatings for slip-resistant connections under permanent loading. This is possible because of the erection of autarkic static test rigs that are especially built for this project. Figure 13 shows the test rigs.

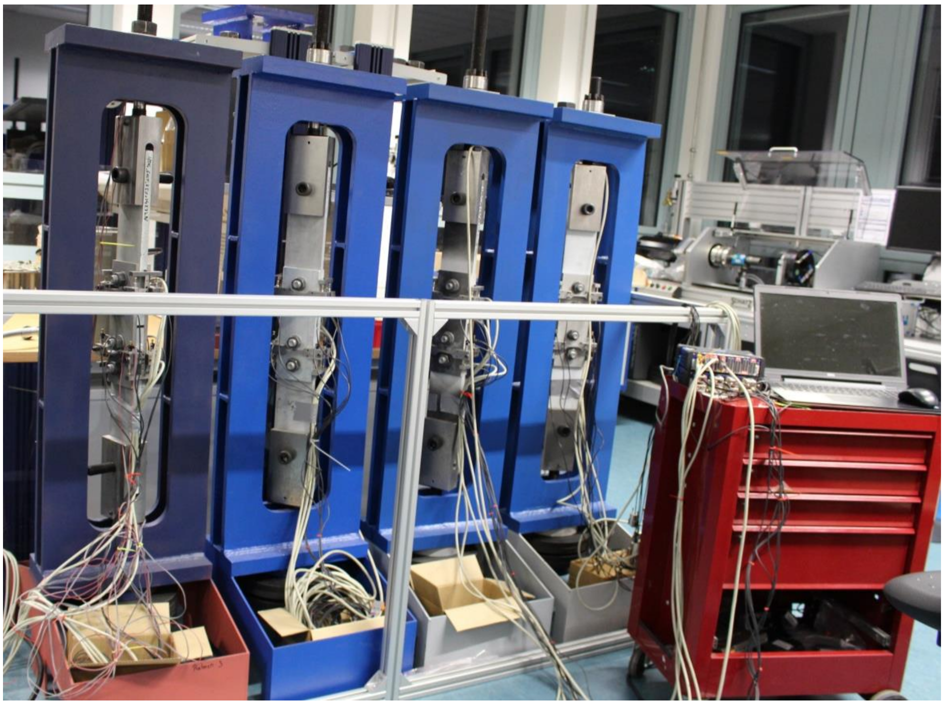


Figure 13: Autarkic test rigs for the investigation of the creep behaviour of the coating systems

The test rigs are equipped with a threaded bar. This bar is instrumented with strain gauges and calibrated in the tensile testing machine. The required load can applied exactly to the specimens by tensioning the bar with a hydraulic cylinder.

The results of the tested slip-resistant connections under sustained loading, extended creep tests, in these test rigs are summarized in a load-log time-displacement diagram in Figure 14.

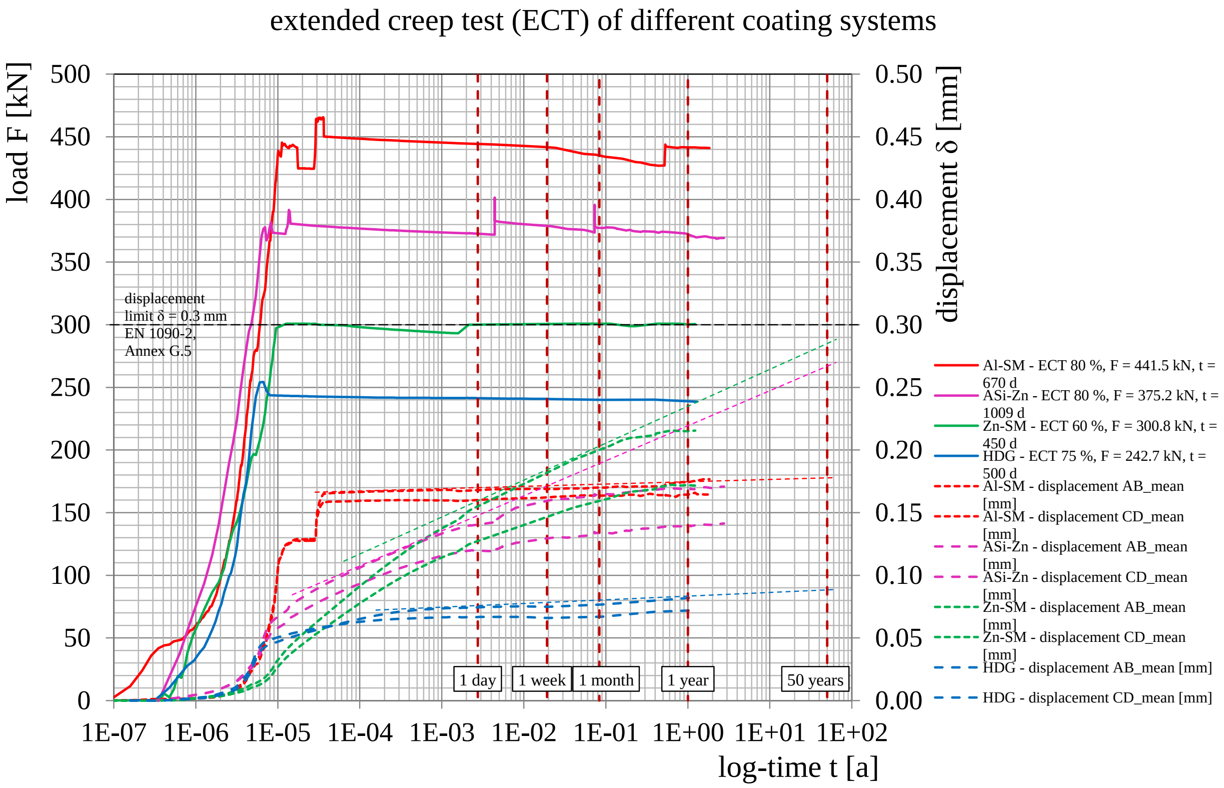


Figure 14: Results of long-term observation of the ECT for the four tested coating systems

Figure 14 shows the load and displacement curves of the long-duration extended creep tests for the investigated coating systems ASi-Zn (alkali-zinc silicate coating), HDG (hot-dip galvanised), Zn-SM (zinc spray metallized) and Al-SM (aluminium spray metallized). The results of Figure 14 show no tertiary creep effects. The displacement measurements were stable over the whole test duration and did not show high deviations or scatters. Therefore the measured values seem reasonable. The same procedure is applied in [8] and task 3.1 [1].

4 Summary

This report to the Deliverable D 1.3 and D1.4 of task 1.3 and 1.4 of the SIRCOCO Project (RFSR-CT-2014-00024) describes the evaluation of the slip load and the procedure to determine a load level for an extended creep.

The main objective is the comparison of the different slip load-displacement behaviours of slip-resistant connections with different coating systems for the faying surfaces. Tests from Task 1.1 of the SIROCO Project [1] were evaluated. The background is that the individual slip load for a slip-resistant connection, F_{Si}, is defined in EN 1090-2 [3] as the load at that a slip of $\delta = 0.15$ mm occurs. This fix criterion was questioned. Different surfaces (e.g. surfaces as rolled, grit-blasted, spray-metallized or hot-dip galvanized surfaces) show different slip load-displacement behaviours. To improve the cost effectiveness of slip-resistant connections, different coating systems have been investigated in accordance with the procedure prescribed in the Annex G of EN 1090-2 [3]. During the test campaign some questions arise: Is the given criterion for the slip load F_{Si} applicable and logically? Are there differences in the slip load-displacement behaviour of miscellaneous coating systems? The evaluation of the test results show that there are differences that shall to be considered. These results are linked to the deliverable D1.4 (Task 1.4 in the SIROCO Project [1]) in which the long-term stability of the coating systems were tested.

A main result is that this investigations show an alternative possibility to the current test procedure for determining slip factors μ of new coating systems for the faying surfaces of slip-resistant connections. The *short-term* step test could substitute the actual *creep test*. The *creep test* is only a ~ 3 h test at 90 % load of F_{Sm} and gives no answers for the mostly necessary extended creep test. As a result of the step test a first load level for the extremely time-consuming extended creep tests can be estimated quite quickly so that the specimen will pass the test.

List of references

[1] RFCS, Research Programme of the Research Fund for Coal and Steel – Technical Group: TG 8: "Execution and Reliability of slip resistant connections for steel structures using CS and SS" (SIROCO), Project Coordinator, Prof. Natalie Stranghöner, Universität Duisburg-Essen, 2014-2017.

[2] EN 1993-1-8:2005 + AC:2009, *Design of steel structures – Part 1-8: Design of joints..*

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

[4] Stranghöner, N.; Afzali, N.; Berg, J.; Schiborr, M.; Bijlaard, F.; Gresnigt, N.; de Vries, P.; Glienke, R.; Ebert, A., *Influence of different testing criteria on the slip factor of slip-resistant connections,* Tampere (Finnland), 2015.

[5] 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), No. 4,* pp. 267 - 281, 2017.

[6] prEN 1090-2:2017, *Execution of steel structures and aluminium structures - Part 2: Technical requirements for steel structures; German and English version prEN 1090-2:2017.*

[7] EN 14399-4:2015-04, *High-strength structural bolting assemblies for preloading – Part 4: System HV – Hexagon bolt and nut assemblies.*

[8] Ebert, A.; Dörre, M.; Glienke, R., „Behaviour of lockbolts in slip-resistant connections for steel structures," *Steel Construction Vol. 10 (2017), No. 4,* pp. 295 - 309, 2017.