Project

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

RFSR-CT-2014-00024

Deliverable 3.1

Usability of lockbolts and H360 bolts
in slip-resistant joints including re-tightening of these
alternative fasteners and estimation of the loss of preload

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Beneficiaries:	Fraunhofer-Einrichtung für Großstrukturen in der Produktionstechnik IGP
Location:	Albert-Einstraße-Str. 30 18059 Rostock, Germany
Contact persons:	Dr.-Ing. Ralf Glienke (IWE) M.Sc. Wirt.-Ing. Andreas Ebert (IWE)

Abstract

HV bolts are often used for safe and durable connections in steel structures. However, this well-known and established bolting system has some disadvantages. Those include the scattering of the initial preload by the torque-controlled tightening process and the risk of self-loosening during fatigue loads due to lateral displacement of the components in connections with high loads. In this respect, the lockbolt technology has some advantages regarding initial preload and loss of preload; both will be discussed in detail in this report. The technology was invented in the 1940s and is mainly used in automotive, aviation, truck, trailer, rail, bus, agriculture, mining and military applications. Its use in structural steelwork, and especially for slip-resistant connections, has been mainly made possible through individual experimental investigations by users of the technology. Some applications call for its use in slip-resistant connections to EN 1090-2 and Eurocode 3, e.g. the wind industry for new tower concepts with higher hub heights, and steel girder bridges. These connections can be subjected to fatigue and/or significant load reversal. The loadbearing capacity (or slip resistance) of a slip-resistant connection is mainly determined by the level of preload in the bolt and the coating system applied to the faying surfaces. However, the preload is determined by the type of bolt, and lockbolts can be used as an alternative bolting system. This report describes a comparative study of lockbolts and H360 regarding their use in slip-resistant connections. The design and execution of lockbolts and H360 will be presented. Investigations will be presented which compare lockbolts and H360 regarding the assembly preload, re-tightening and the long-term behaviour with respect to loss of preload for maintenance-free connections. Furthermore, there is a discussion of the results of measuring the preload in lockbolts and H360.

In Deliverable D 3.1 (Task 3.1) the use of alternative fasteners in slip-resistant connections will be investigated. Therefore the potential of the installation (initial) preload ($F_{p,C,ini}$) of the bolted assemblies using Lockbolts, H360 and as the well-known reference HV bolts (EN 14399-4) will be tested. The preloading tests will be performed with specimen according to EN 1090-2, Annex G, Figure G.1, Type a) with M20 bolts of the same clamping length. The initial preload and the preload-time behaviour will be compared within the three mentioned high-strength fasteners (all of grade 10.9).

Keywords: HV bolts, Lockbolts, H360 bolts, Slip-resistant connection, loss of preload, slip factor, SIROCO-Project

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1 Introduction

An alternative to the classic bolted connection offers the lockbolt technology, developed in the 30s of the last century. With respect to their working functionality the lockbolts can be compared to high-strength bolts. They feature an extremely small spreading at friction independent prestressing and vibration resistance under shear loads. There has been prevalence in many technological branches, such as the utility vehicle industry, the rail vehicle industry, the aircraft industry and the mining industry. Lockbolts are available in metric and imperial dimensions with a nominal diameter range from 6.5 to 36 mm and the strength classes 5.8 to 10.9. The ability to prevent self-acting dismantling opens these technology new fields in steel construction.

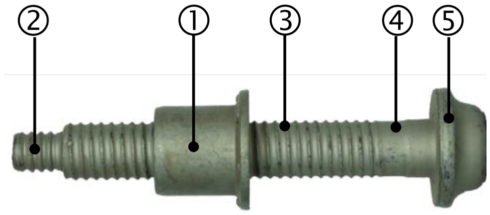
A further development of the lockbolt is the H360 (a nut and bolt fastening system [1]). This system offers quick installation and removal with convetional tools, delivers superior fatigue strength, and is engineered to be virtually maintenance free and resistant to vibration, even under extreme conditions. The Huck 360 System is available in metric and imperial dimensions with a nominal diameter range from 10 to 36 mm with a strength class of 10.9.

The installation process of the lockbolt and H360 fastener does not yet provide the ability to re-tight the fastener after setting effects. Therefore it could be possible that the assembly preload cannot be provided in its full scale by use of coated surfaces.

2 Technology

2.1 Lockbolt

Lockbolt systems are two-piece fasteners. Generally they consist of a high strength lockbolt and a matching collar. The collar is manufactured out of softer material. The required strength of the collar results of the cold-forming process during the tightening of the lockbolt. The term lockbolt system is similar to the term bolt assembly. In opposite to conventional HV bolt assemblies, additional washers are not required. Figure 1 shows the lockbolt system with a nominal diameter of 20 mm, which was used in the project [2] and is covered by the national technical approval Z-14.4-591 [3]. For assembly, double-sided accessibility to the components is required, but counteracting is unnecessary. Lockbolts made of carbon steel are available in strength classes 5.8, 8.8 and 10.9 in the sense of DIN EN ISO 898-1 [4]. They are also available made of aluminium and stainless steel. Lockbolts are produced in metric and imperial dimensions. The range for the nominal diameters is from 4.8 mm up to 36 mm. For further information, in particular on the production process, assembly and load bearing capacity of lockbolt connections please refer to [5], [6].



1 Collar
2 Pin tail
3 Locking grooves
4 Shank
5 Brazier or countersunk head

Figure 1: Lockbolt system type Bobtail according to Z-14.4-591 [3]

The load bearing behaviour of connections with lockbolts is closely related to connections with conventional bolts. Nevertheless connections with lockbolts show significant advantages. This is due to the installation principle. Lockbolts are being pretensioned without torsion and in small scatterings. It is also considered as an advantage that no special conditioning of the bolts or collars (e. g. lubrication) is necessary, quicker installation process and higher clamping range. After assembly, the collar is swaged form-fit into the locking grooves. This effectively prevents the collar from self-loosening, which can be caused by the loss of the self-locking and vibration. Further advantages result from the geometrical properties of the lockbolt. Lockbolts have a higher shear and tensile load capacity due to the higher cross sectional area compared to conventional bolts. The “softer” geometrical design of the shank and of the looking grooves results in higher fatigue strength for direct stress ranges $\Delta\sigma_C$. The fatigue resistance of lockbolts is classified by the detail category 63 [3]. The need of special installation tool for the assembly could be for small order quantity uneconomically. Also dismantling of lockbolts need a special cutting tool which could be part of the installation tool. Re-tightening of lockbolts is not possible to the state of the art, but also not needed in case of a correct installation process. Due to the request of the wind energy sector for steel towers with large hub heights and a segmentation of the tower in longitudinal direction, the lockbolt technology is increasingly used [7]. Figure 2 shows current fields of applications for high strength lockbolt connections.

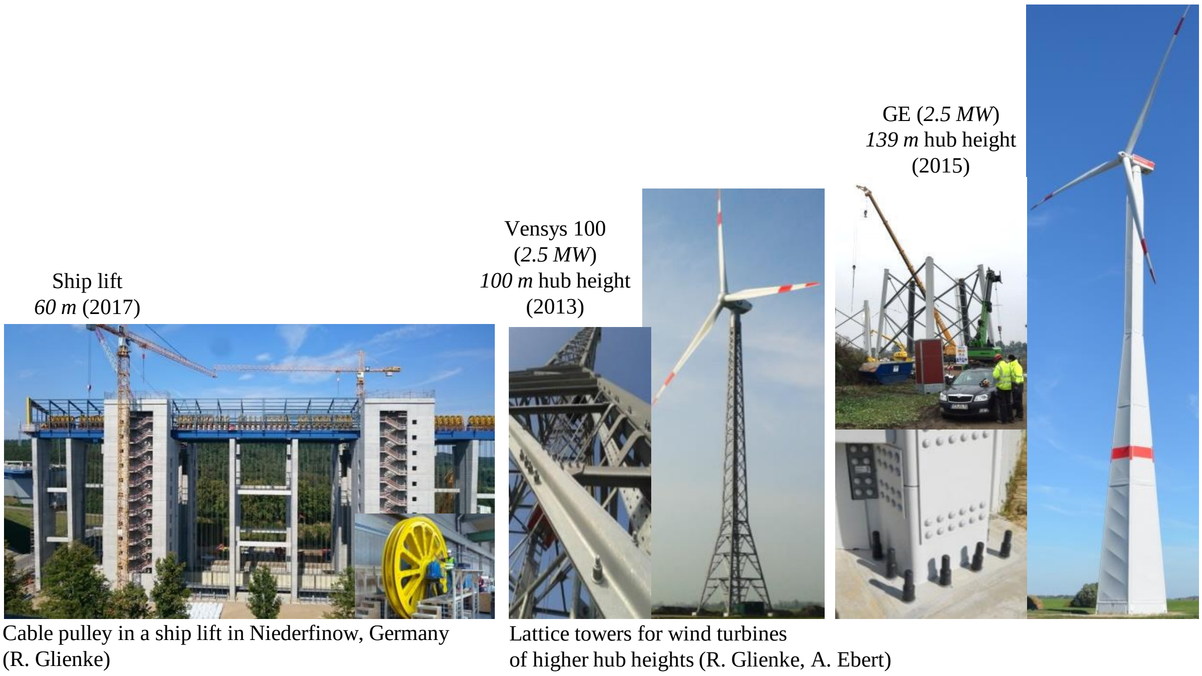


Figure 2: Current fields of applications of lockbolts in Germany

2.2 H360

The H360 is a removable & reusable nut and bolt system with lockbolt equivalent vibration resistance and high fatigue strength. Because of nut and bolt system the flexibility of the tightening method is comparable to a normal high strength bolt and nut system. This combination allows a tightening without a special installation tool. Additional the ductile hardness of the nut thread leads to a mechanical lock while tightening the system. [1]

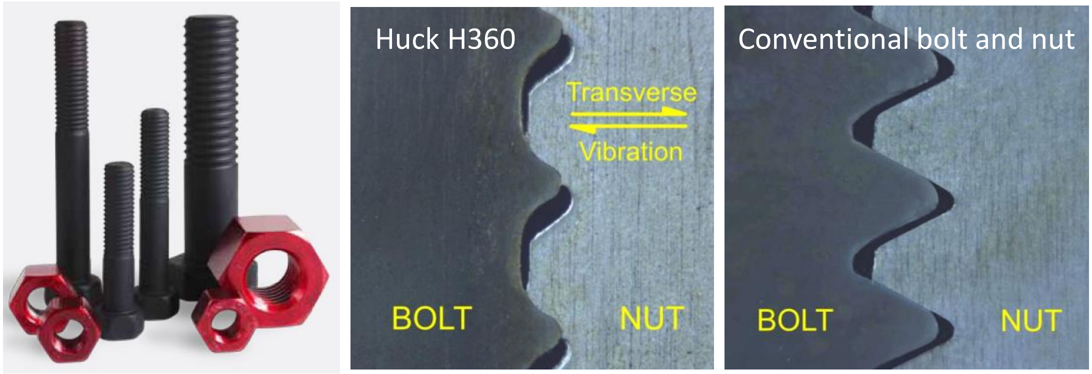


Figure 3: Comparison of cross-section between bolt and thread of H360 and conventional bolts [1]

Further advantages are smooth thread shapes and a bigger cross section area similar to the lockbolt system, which leads to high fatigue strength. It is also considered as an advantage that there is no initial interference between the bolt and the nut. With this free-spinning nut the damage to coatings can significantly reduce.

Figure 4 shows an example for usage of H360 [1]

Figure 4: Example for usage of H360 in mining industry, Grinder from Morbark Inc. [1]

The ideas behind this bolting system are the following advantages [1]:

- durable preload
- no special conditioning required (lubrication)
- no special installation tool required
- special suitability against automatic loosening

The Figure 5 shall show the suitability of H360 against automatic self-loosening compared to other nut designs [1].

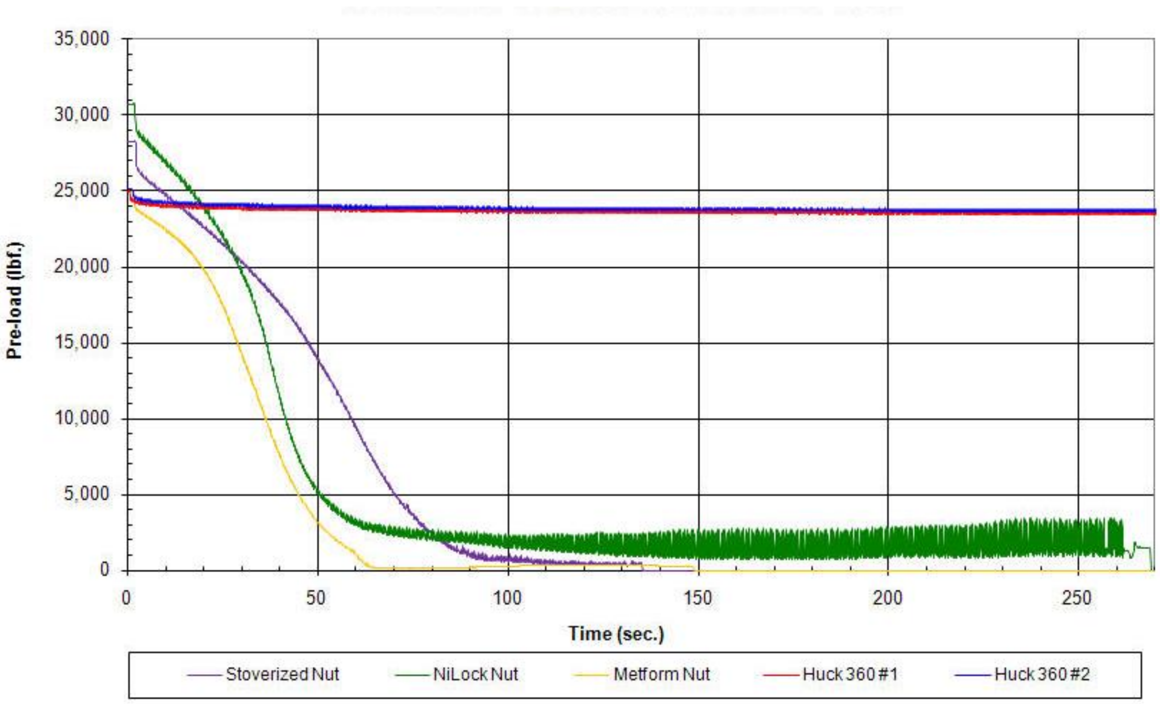


Figure 5: Comparison of H360 to other nut designs in Junker transverse vibration test [1]

States of the art are nominal diameters from 10 mm to 36 mm for this system, including imperial size. [1]

3 Design and execution of slip-resistant connections with lockbolts

The general load bearing behaviour of a slip-resistant connection is shown in Figure 6. Due to the applied preload $F_{p,C,SRB}$ (German: SRB – Schließringbolzen; English: LB – Lockbolt) during the installation process, the lockbolt is elongated and stressed in tension. The components are thereby compressed. The pressure-loaded zone widens from the bolt head towards the interface, taking the form of a rotation paraboloid, which is simplified to a deformation cone according to [8, p. 539] and [9, p. 43]. The joint is designed in such a way that the applied shear loads $F_{v,Ed(,ser)}$ are transmitted between the interfaces of the preloaded joint by static friction. EN 1993-1-8 [10] distinguishes between slip-resistant connections at ultimate limit state (Category C with γ_{M3}) and at serviceability limit state (Category B with $\gamma_{M3,ser}$).

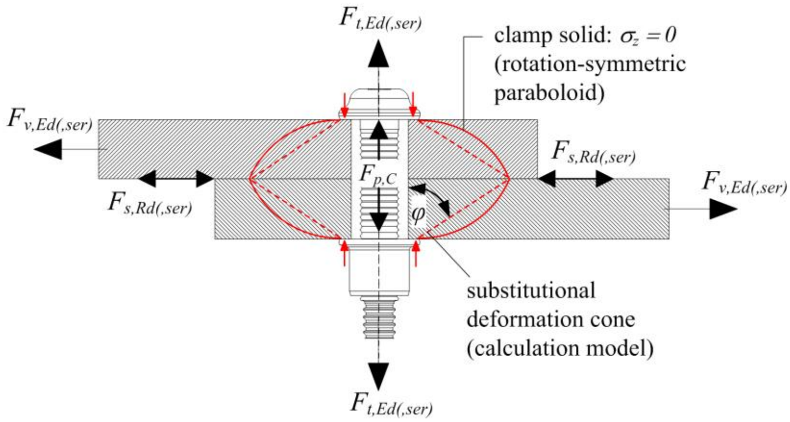


Figure 6: Load bearing behaviour of a slip-resistant connection

The slip resistance according to EN 1993-1-8 [10] is provided if the shear load $F_{v,Ed(,ser)}$ per bolt is smaller than the slip resistance $F_{s,Rd(,ser)}$ per bolt (Eq. 1):

$$F_{v,Ed(,ser)} \leq F_{s,Rd(,ser)} = \frac{k_s \cdot n \cdot \mu \cdot \left(F_{p,C} - 0{,}8 \cdot F_{t,Ed(,ser)}\right)}{\gamma_{M3(,ser)}} \qquad (1)$$

In this case, the factor k_s represents a geometric coefficient which results as a function of the selected hole clearance. Thus for a normal round hole k_s = 1.0 eliminates the reduction of the slip resistance. For oversized round holes (k_s = 0.85) and short slotted and long slotted holes (0.63 ≤ k_s ≤ 0.85) a reduced k_s has to be taken into account. The number of load-transmitting shear planes is denoted by n. The value of the slip factor μ depends on the pre-treatment and/or on the applied coating system for the faying surfaces. When an additional axial (tensile) load $F_{t,Ed(,ser)}$ is applied, the preload, and at the same time the remaining clamping load is reduced by the amount of 0.8 · $F_{t,Ed(,ser)}$. The magnitude of the preload was determined for a controlled level. The controlled preload level $F_{p,C}$ for conventional HV bolts according to EN 14399-4 [11] and EN 14399-6 [12] is obtained by the following equation (Eq.) (2).

$$F_{p,C} = 0{,}70 \cdot f_{ub} \cdot A_s \qquad (2)$$

To achieve the controlled preload level, standardized tightening methods according to EN 1090-2 [13] must be used as well as the required lubrication of the bolt assembly must be complied with.

The preload level for the use of HV bolts has to be reduced according to German regulations (DIN EN 1993-1-8/NA [14]) and is denoted as $F_{p,C}$*.

$$F_{p,C*} = 0{,}70 \cdot f_{yb} \cdot A_s \tag{3}$$

For the design of lockbolt connections there are two preload levels available. The nominal preload $F_{p,Cd}$ of the lockbolts type Bobtail, which are manufactured by ARCONIC FASTENING SYSTEMS AND RINGS and were used in the project, was taken from the national technical approval Z-14.4-591 [3] published by Deutsches Institut für Bautechnik. For all types of lockbolts the preload level $F_{p,C,SRB}$ according to the German guideline DVS-EFB 3435-2 [5] is determined by Eq. (4).

$$F_{p,C,SRB} = 0{,}62 \cdot f_{ub} \cdot A_{s,SRB} \tag{4}$$

In Eq. (1) γ is the partial safety factor and the numerical values are defined in the National Annex of EN 1993-1-8 [10] γ_{M3} is the partial safety factor for the design of slip-resistant connections at ultimate limit state (Category C) and $\gamma_{M3,ser}$ at serviceability limit state (Category B), recommended is $\gamma_{M3} = 1.25$ and $\gamma_{M3,ser} = 1.1$. In Category C connections slip should not occur at the ultimate limit state and for Category B at serviceability state.

The execution rules for slip-resistant connections according to EN 1090-2 [13] can be transferred to connections with lockbolts. These include the friction coefficient µ published in table 18 of EN 1090-2 [13] as well as the limit values for the hole clearance and the hole and edge distances.

The evolution of equivalent design rules for H360 is still in progress. [1]

4 Experimental investigation

The focus of the experimental investigation is on the usability of lockbolts and H360 in slip-resistant connections within three different surface treatments of the faying surfaces (slip planes). Figure 7 shows the test setup with the test machine and measurement equipment. The slip load tests were carried out in accordance with the Annex G of EN 1090-2 [13]. Details of the campaign and the procedure are explained in Workpackage 1 of this project and in [15], [16], [17].

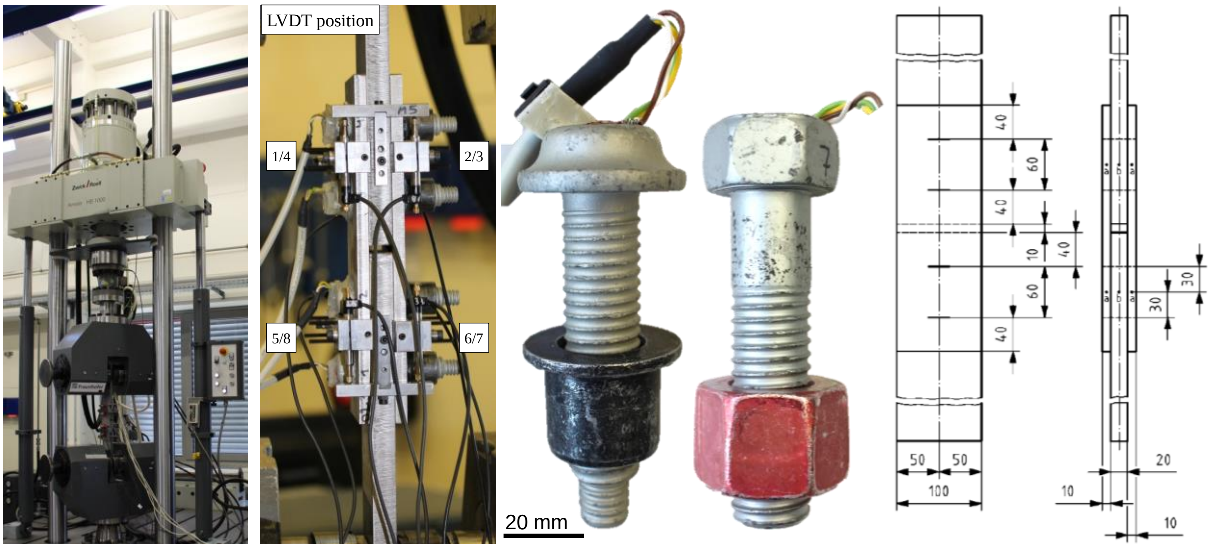


Figure 7: Test setup for experimental investigation acc. to EN 1090-2, Annex G, specimen type a) [13]

In Table 1 the test matrix is presented. According to the Technical Annex of this project there have to be performed 60 preload/tightening tests in specimens with three different surface treatments. The present test matrix shows in sum 27 slip load tests. Each includes 4 bolts that resulting in 108 results.

Table 1: Test matrix with specimen acc. EN 1090-2 (4 bolts [preload values] per test) [13]

Series ID	Bolt type	Steel grade	Surface preparation	Slip load test	Step test	Extended creep test (ECT)
01	"HV bolt" EN 14399-4-HV-M20x75-10.9/10-tZn-k1	S355J2+N	GB[1)]	3	-	-
02			HDG[2)]	2	1	1
03			Al-SM[3)]	2	1	2
04	"LB" Bobtail lockbolt M20-G40 J45/46 (Grade 10.9)		GB[1)]	2	-	-
05			HDG[2)]	4	1	-
06			Al-SM[3)]	3	1	1
07	"H360" H360-DT20-G40-D1 (Grade 10.9)		GB[1)]	3	-	-
08			HDG[2)]	4	1	1
09			Al-SM[3)]	4	1	1
			Σ:	27	6	6

1) Grit blasted surface Sa 2 ½ (Roughness Rz = 80 µm)
2) Hot dip galvanized steel plates (dry film thickness dft_mean = 67,8 µm (s = 4.5 µm), roughness (mean of 96 values) R_Z = 50.35 µm (s = 15.3 µm))
3) Aluminium spray metallized coating on grit blasted Sa 2 ½ (measurement of dry film thickness: mean m_x = 132 µm, s_x = 55.7 µm, n = 576, mean roughness Rz = 106.5 µm, s_x = 14.7, n = 336)

For reasons of reliability conventional HV bolts are also tested under the same conditions. This procedure makes the data from the different bolting systems evaluable.

For the grit-blasted (GB) surface treatment Figure 8 shows the three bolting systems in preloaded slip-resistant connections.

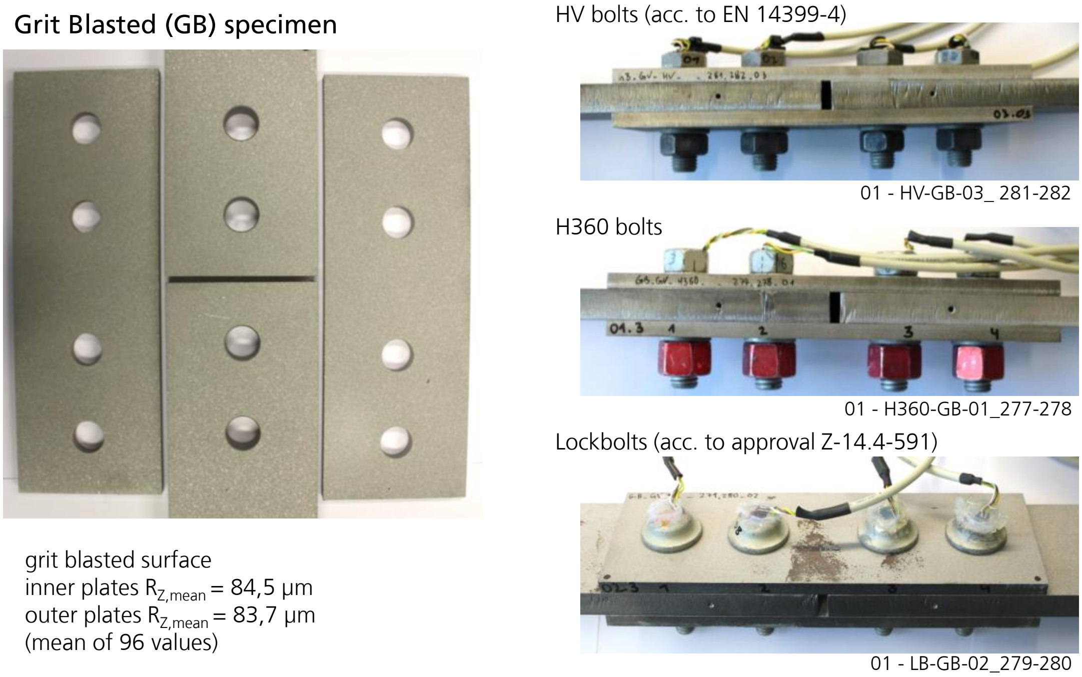


Figure 8: Specimens for testing the preloading behaviour

These types of specimens are designed according to EN 1090-2, Annex G for bolt size M20 [13] and part of the test campaign.

4.1 Preloading of lockbolts, H360 and HV bolts

The characteristic preload-time curves of the tightening process are shown in Figure 9. The exemplary curves of the three bolting system are compared to each other.

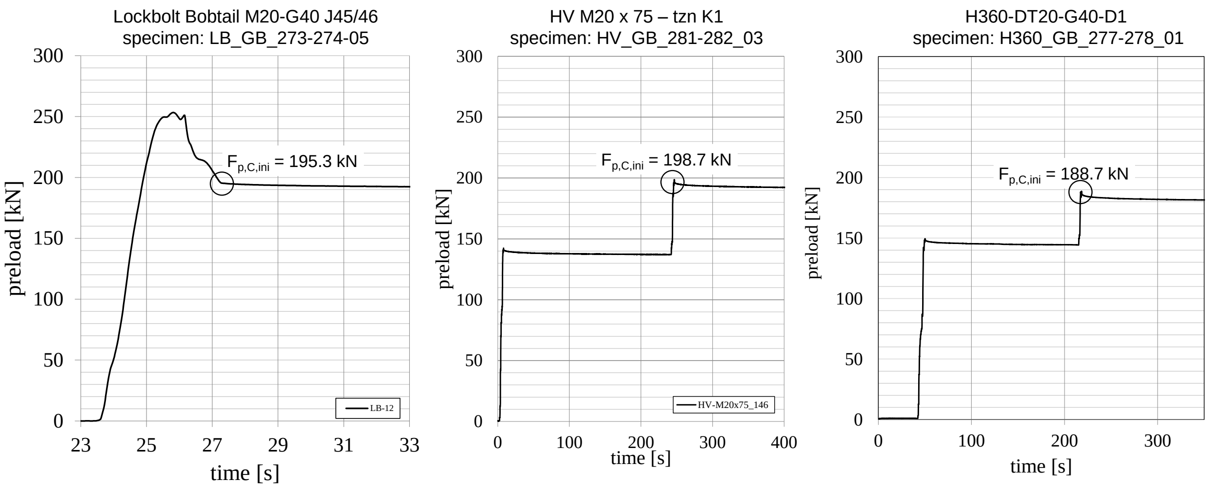


Figure 9: Characteristic preload-time curves of tightening process of Lockbolt, HV bolt and H360

Both tightening procedures those of the HV bolts and H360 are showing the same characteristic preload-time behaviour whereas the lockbolt is more different.

Figure 10 shows the preload-time curves for the assembly of the specimens with grit-blasted surfaces for HV bolts and lockbolts. The used HV bolts with nominal diameter M20 were tightened by the torque-controlled method according to the EN 1090-2 [13]. The tightening torque was applied continuously by a hydraulic wrench in two tightening steps. For the K1-lubricated HV bolts, M_A = 335.4 Nm (= 0.75 · k_m · $F_{p,C}$ · d) [13] was applied during the first tightening step. After about four minutes the HV bolts were preloaded in a second tightening step to the torque value of M_A = 492 Nm (= 1.1· $M_{r,1}$) [13]. The initialized preload $F_{p,C,ini}$ was determined one second after the tool has been removed (= peak), see Figure 10 (left). From this point, the reduction of the preload can be assumed as a result due to setting effects. During all tests with the grit-blasted (GB) surface, the target value of the preload with $F_{p,C}$ = 172 kN was achieved.

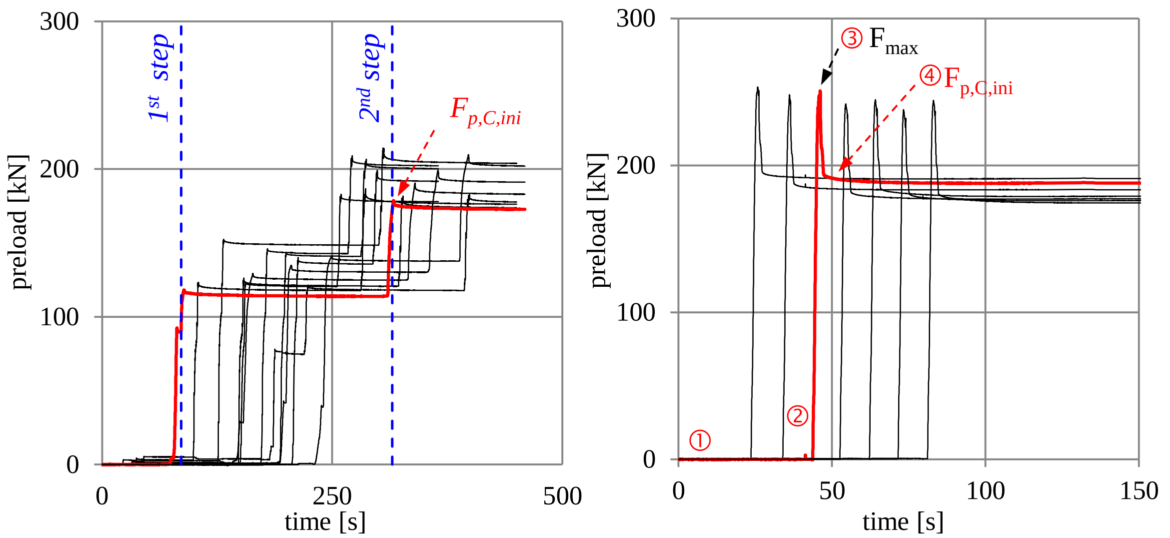


Figure 10: Tightening process Bobtail lockbolts in specimen with GB surface

The tightening process of lockbolts in comparison to HV bolts differ fundamentally. Figure 10 (right) preload-time curves for the Bobtail lockbolts of nominal diameter 20 mm in the same prepared slip load test specimens. The following steps describe the installation process:

① The installation process starts with placing the components, inserting the lockbolt into the hole and fitting the collar onto the pin from the opposite side by hand tightening.

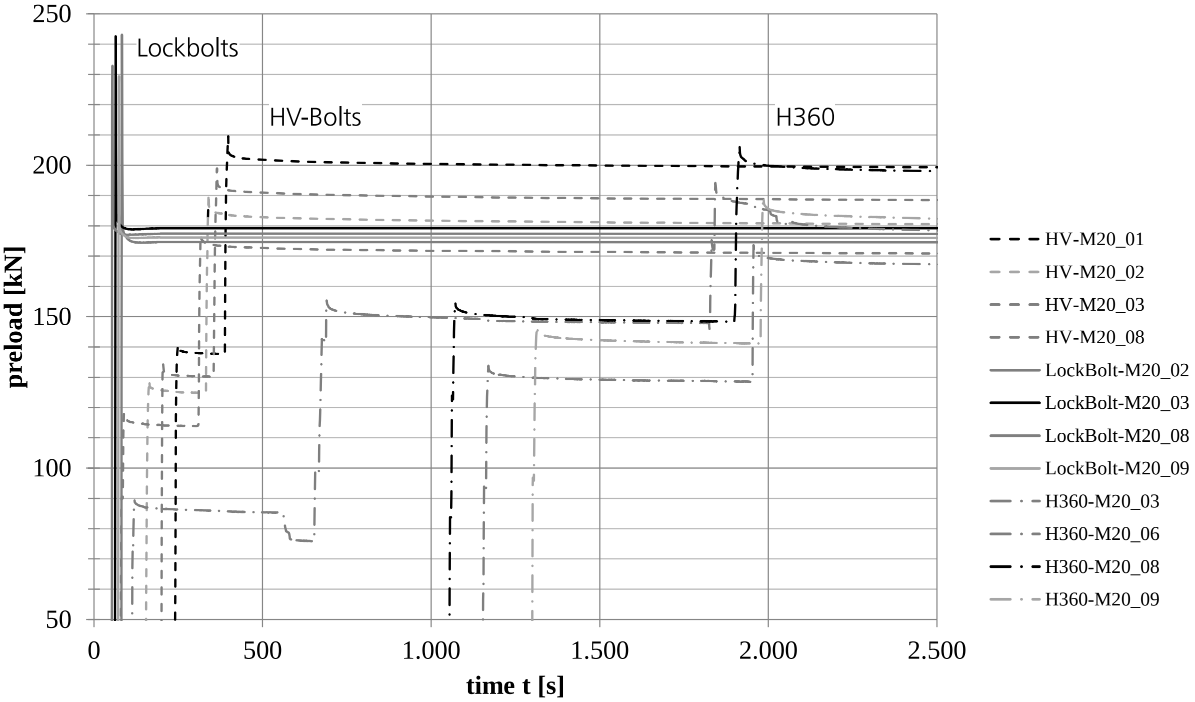
② The preload procedure starts with triggering the tightening process through the installation tool. From now, the preload increases until the maximum value (F_{max}) is reached. This process is a hydraulic frictionless and torsion-free tightening procedure.

③ The peak F_{max} marks the end of cold forming process of the collar material into the locking grooves of the lockbolt (mechanical locking).

④ The residual load level in the lockbolt after removing the installation tool is denoted as initialized preload $F_{p,C,ini}$ for the lockbolt system. Visual evidence of a successful installation process is provided by indicators and at least one of the dots need to be deformed.

The extremely low scattering of the preload is remarkable. The loss of preload in the bolt which can be observed subsequently to $F_{p,C,ini}$ depends on the structure of the interface area and the contact surfaces.

Figure 11 summarises the preload-time curves of the tightening processes from the three bolting systems in a single diagram.



HV bolts: torque method acc. to EN 1090-2, EN 14399-4:

- 1st step: $0{,}75 \cdot k_m \cdot F_{p,C} \cdot d$
  $= 0{,}75 \cdot 0{,}13 \cdot 172\ kN \cdot 20\ mm = 355{,}4\ Nm$
- 2nd step: $1{,}1 \cdot 0{,}13 \cdot 172\ kN \cdot 20\ mm = 492\ Nm$

H360: torque method acc. to EN 1090-2 and ARCONIC specification:

- 1st step: $0{,}75 \cdot torque = 0{,}75 \cdot 610\ Nm = 457{,}5\ Nm$
- 2nd step: $1{,}0 \cdot 610\ Nm = 610\ Nm$

Figure 11: Preload-time-diagram of the tightening procedures for HV, H360 and Lockbolts

The fast and one step installation process of the lockbolt is visible. For lockbolts a two-step tightening procedure for preloading is possible but not common in practice yet. As here are praxis-orientated tightening process shall be compared the two-step procedure is taken for preloading HV bolts and H360.

Figure 12 and Figure 13 show the preload-time diagram of the tightening processes for lockbolts and H360 in specimens with the three different surface treatments.

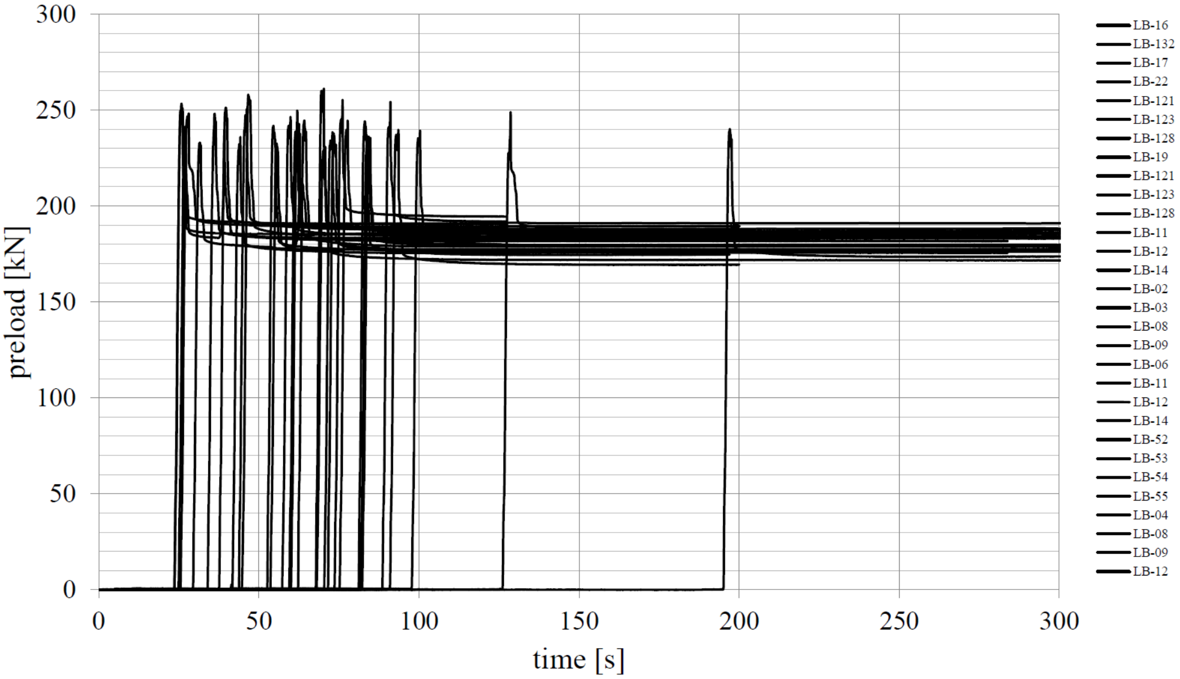


Figure 12: Preload-time diagram of tightening process of lockbolt Bobtail M20-G40 J45/46 of slip load tests with HDG, Al-SM and GB surface treatment

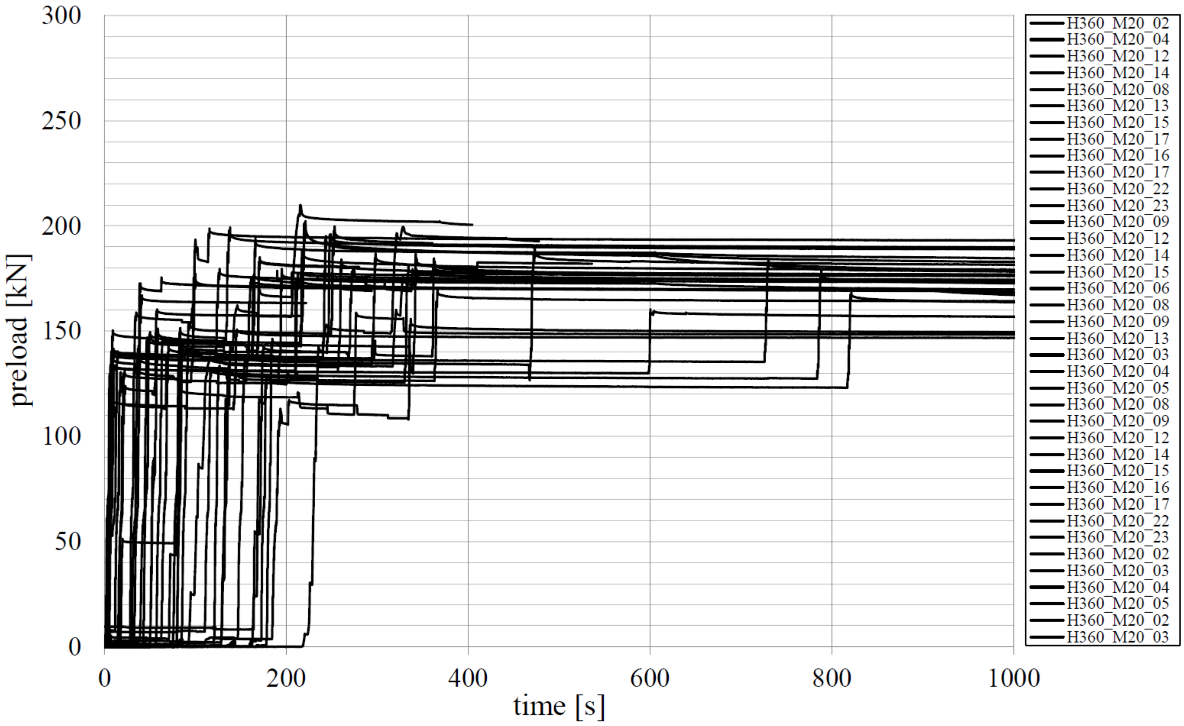


Figure 13: Preload-time diagram of tightening process of H360-DT20-G40-D1 of slip load tests with HDG, Al-SM and GB surface treatment

As a result it is obvious that the scatter of the initial preload $F_{p,C,ini}$ of H360 is higher compared to lockbolts.

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In the following, the reliability of the applied preload is evaluated for slip-resistant connections. The applied preload in bolted connections depends furthermore on the ratio of clamping length and bolt diameter, the selected tightening method, the tooling, the friction conditions under the nut / bolt head and in the threaded parts and as well on the material of the specimen including the surface conditions. As expected, the largest variation in the preload was obtained for the torque-controlled tightening method. At the same time, the influence of the component surface was worked out. Figure 14 shows the initial preloads $F_{p,C,ini}$ for Bobtail lockbolts, HV bolts and H360 for the three different surface preparations GB, HDG and Al-SM.

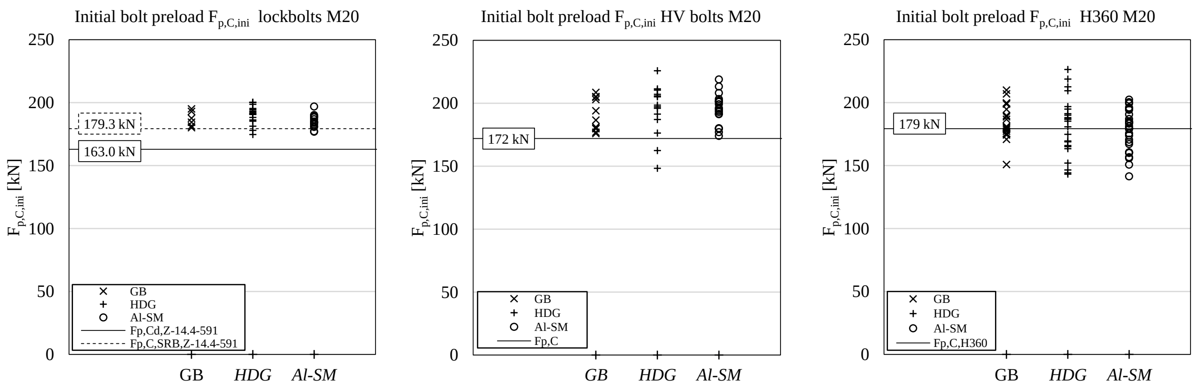

Figure 14: Comparison of the initial preload for lockbolts, HV bolts and H360

For M20 HV bolts a controlled preload level of $F_{p,C}$ = 172 kN is standardized. This level could be achieved reliably for the specimens with grit-blasted surface (GB) and with aluminium spray metallized faying surfaces (Al-SM). For the specimens with hot-dip galvanized surface (HDG), the highest deviations of the preload were observed. In addition, two HV bolts did not reach the target value (Figure 14). The VDI 2230 [9] regulates bolted connections in mechanical engineering. According to the VDI 2230, the “tightening factor” α_A is defined [9]. The tightening factor takes into account the scatter of the achievable assembly preload between F_{Mmin} and F_{Mmax}, takes into account the selected tightening method and is determined by Eq. (5). For torque-controlled tightening, a tightening factor between 1.4 and 1.6 is recommended and agrees very well with the observed experimental value $\alpha_{A,obs}$ of all 47 tests for HV bolts with $\alpha_{A,obs}$ = 1.52 (Table 2).

$$\alpha_A = \frac{F_{M\,max}}{F_{M\,min}} \tag{5}$$

For slip-resistant connections (Cat. B, C) the design value of the preload for lockbolts according to the national technical approval (Z-14.4-591) with the nominal diameter 20 mm is determined by Eq. (6).

$$F_{p,Cd} = \frac{F_{p,C,SRB}}{\gamma_{M7}} = \frac{179.3\,kN}{1.10} = 163\,kN \tag{6}$$

The target value of the preload for lockbolts $F_{p,Cd}$ could be achieved reliably for all of the 42 bolts. The HV bolts reached the target value of preload $F_{p,C}$ with a reliability of 95.7 %. This value is compared to [19] reasonable and a pleasing result (Table 2). The scattering of preload for lockbolts is considerably lower than for HV bolts because of the torsion-free tightening method without the influence of friction between bolt and nut. Despite the marginally lower mean value of the lockbolt preload, the 5 % quantile, with $F_{5\%}$ = 176.6 kN, is almost 9 kN higher compared to HV bolts. The tightening factor is slightly higher than recommended in DVS-EFB 3435-2 [5], due to the combined evaluation over the three different surface condition of the specimens. Taking into account only for GB surfaces the tightening factor is with α_A = 1.08 reliable to [5]. Similar to the HV bolts, the largest scattering of the lockbolt preload was observed for HDG surfaces. For H360 the target value is 62.0 % which leads to the assumption that the torque shall be increased (compare with results in chapter 4.5.2, page. 29). Here further investigations shall be performed. Table 2 shows the evaluation of initial preload $F_{p,C,ini}$.

Table 2: Results of praxis-orientated tightening procedure for HV bolts, H360 and lockbolts in the slip-resistant connections of the slip load tests with the surface treatment GB, HDG, Al-SM

	HV-M20 x75-tzn-k1	H360 M20-G40-D1	Bobtail Lockbolt M20-G40 J45/46
mean all $F_{p,C,ini}$ [kN]	192.8	182.7	187.8
deviation s $F_{p,C}$ [kN]	15.4	17.7	6.9
V_x $F_{p,C}$	8.0 %	9.7 %	3.7 %
lower 5% quantile [kN]	167.5	153.1	176.6
min [kN]	148.3	143.1	174.7
max [kN]	225.8	226.3	200.3
α_A (max/min)	1.52	1.58	1.15
n	47	71	42
Target value preload $F_{p,C}$ [kN]	172.0	179.0	163.0
Target value preload reached	95.7 % (45 of 47)	62.0 % (44 of 71)	100 % (42 of 42)

The min. value of $F_{p,C}$ can be below the nominal value of 172 kN because of the influence of the surface treatment of the specimens and the two interfaces of the double shear connection.

4.2 Re-tightening of H360

Figure 15 shows the results of the re-tightening tests on the H360 bolts. The first specimen has the grit-blasted surface treatment. The both below are prepared with the surface coating Al-SM. The left diagram shows the first full tightening process to initialise the preload by the torque method with 610 Nm. The right diagram shows the preload-time behaviour during the re-tightening process. A second time the toque of 610 Nm was initialised and the preload was measured. The used tool was a conventional hydraulic setting device as used for HV bolts. Some curves show a drop of preload. This is due to the fact that the head also rotates when the nut was tightened. In principle, re-tightening is possible to increase the preload. When tightening the bolt by turning the nut, the bolt head must be held in place otherwise the preload reduces.

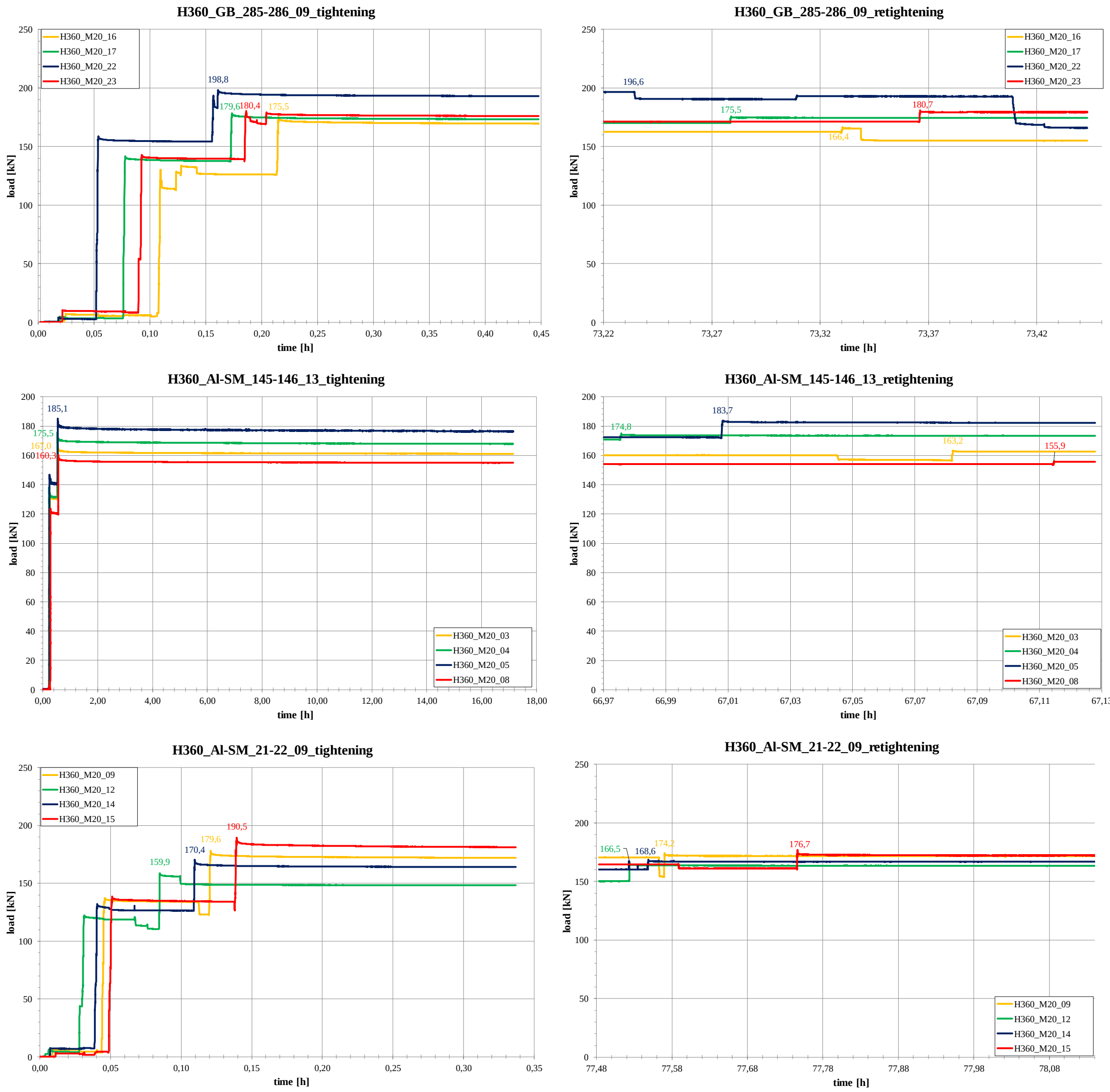

Figure 15: Re-tightening of H360 in slip-resistant connection with GB and HDG as surface treatment

4.3 Results of test with slip-resistant connection using Lockbolts, H360 and HV bolts

The following section describes the results of the slip load test campaign. Again, comparative investigations on HV bolts, lockbolts and H360 were conducted.

Figure 7 shows the used test setup with the testing machine and measurement equipment. The slip load tests were carried out in accordance with Annex G of EN 1090-2 [13]. Instead of tightening the HV bolts to the specified preload $F_{p,C}$ with a maximum deviation of ± 5 %, the torque method, as it is common practice for on-site installation, was used. The lockbolts were fully preloaded in one tightening step. The test procedure to determine the slip factor as well as the measurement of the preload, the dimensions of the used specimens, the execution and evaluation are not described at this point. The detailed procedure for carrying out the slip load test is given in the Annex G of EN 1090-2 [13]. Also more detailed information on the test procedure is given in [15], [17], [16].

This investigation focuses on the presentation and evaluation of the results of the slip load tests. The aim of the experimental investigations was not the determination of the slip factor for certain surface conditions, but rather to clarify whether the nominal slip resistance as characteristic or as design value can be reliably achieved.

Figure 16 shows the individual slip load-displacement curves for the specimens. Each specimen gives two results, one for the lower joint and one for the upper. The characteristic slip resistance was reliably achieved during all tests (HDG is not yet standardised in EN 1090-2). The resulting slip loads showed a bigger scattering for the HV bolts, which is attributed to the scattering of the preload and a result of the tightening method. The individual values of the slip factor μ_i can also be determined according to Eq. (7) which takes into account the preload $F_{p,C,start}$ at the beginning of each test. And $F_{p,C1}$ or $F_{p,C2}$ are the individual preload of the two bolts in one part of the connection.

$$\mu_i = \frac{F_{Si}}{2\left(F_{p,C1} + F_{p,C2}\right)} \tag{7}$$

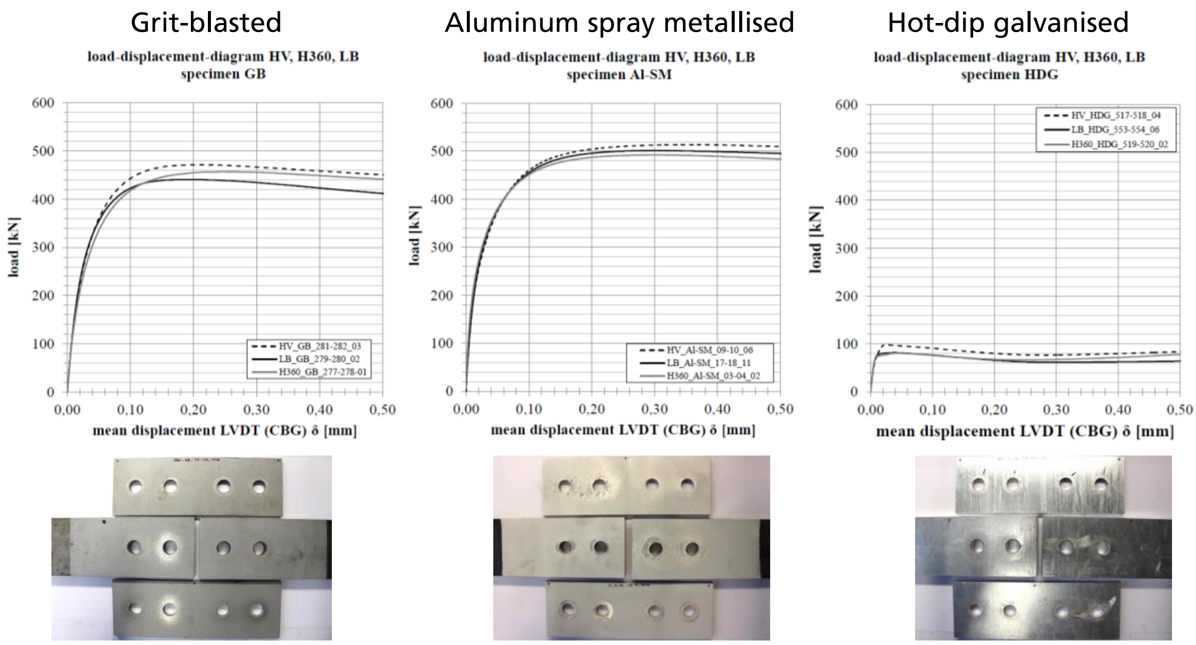

Figure 16: Exemplary slip load-displacement curves from results of the slip load tests

Table 3 shows all results of the slip load tests of HV bolts, lockbolts and H360.

Table 3: Results of the slip load tests

	GB			Al-SM			HDG		
	HV	H360	LB	HV	H360	LB	HV	H360	LB
	$F_{Si,max}$	$F_{Si,max}$	$F_{Si,max}$	$F_{Si,max}$	$F_{Si,max}$	$F_{Si,max}$	$F_{Si,max}$	$F_{Si,max}$	$F_{Si,max}$
	[kN]	[kN]	[kN]	[kN]	[kN]	[kN]	[kN]	[kN]	[kN]
$F_{S1,max}$	467.9	430.7	440.9	506.9	465.6	506.8	94.0 1)	80.8 1)	81.8 1)
$F_{S2,max}$	471.3	457.0	474.9	507.8	480.4	529.4	95.1 1)	86.1 1)	89.6 1)
$F_{S3,max}$	483.5	473.2	480.0	513.1	488.6	501.5	98.3 1)	122.0 2)	90.1 1)
$F_{S4,max}$	487.3	511.7	495.1	524.1	489.8	528.6	120.6 1)	123.7 2)	92.7 1)
$F_{S5,max}$	512.7	519.3			492.0	525.3		133.6 2)	155.3 2)
$F_{S6,max}$	562.0	523.0			493.3	545.0		139.4 2)	157.4 2)
$F_{S7,max}$					518.0			169.4 2)	198.1 2)
$F_{S8,max}$					521.1			174.1 2)	208.4 2)
$F_{Sm,max}$	497.5	485.8	472.7	513.0	493.6	522.8	102.0 1)	83.5 1)	88.5 1)
V_X	7.1%	7.8%	4.8%	1.5%	3.7%	3.1%	12.3% 1)	4.5% 1)	5.3% 1)
							$F_{Sm,max}$	143.7 2)	179.8 2)
							V_X	15.8% 2)	15.2% 2)
	GB			Al-SM			HDG		
$F_{Sm,max}$ (V_X)	$F_{Sm,max}$ = 486.9 kN (6.8 %)			$F_{Sm,max}$ = 507.6 kN (4.0 %)			1) $F_{Sm,max}$ = 92.9 kN (11.2 %) 2) $F_{Sm,max}$ = 158.1 kN (18.8 %)		
1) v = 0.01 mm/s (F_{Si} ~ 1.5 min) | 2) v = 0.003 mm/s (F_{Si} ~ 8 min)									

The achieved slip loads are in the same range. The design slip-resistant $F_{S,Rd}$ ([10], [13]) for grit-blasted surfaces of the tested connections with HV bolts is: $F_{S,Rd} = (\mu \cdot F_{p,C} \cdot k_s \cdot n)/\gamma_{M3}$ = (0.5 · 172 kN · 1 · 2)/1.25 = 137.6 kN per bolt. Two bolts are installed per connection: $F_{S,Rd,connection}$ = 275.2 kN. All tested configurations with grit-blasted surface treatment are beyond, which leads to the assumption that lockbolts and H360 can be used in slip-resistant.

4.4 Loss of Preload

In this chapter HV bolts and lockbolts are compared regarding to their long-term behaviour and the extrapolated loss of preload. The knowledge about the long-term behaviour of a bolted connection regarding to the loss of preload is most important for slip-resistant connections, as the preload $F_{p,C}$ is, besides the slip factor µ, an essential design value. To obtain a maintenance free slip-resistant connection, all parts of the loss of preload (e. g. setting, transversal contraction, fatigue, sustainable loads) have to be considered experimentally and extrapolated. All losses of preload that have to be considered in slip-resistant connections are summarized in Eq. (8) acc. to [19]. The first addend $\Delta F_{p,C,setting}$ represents the loss of preload due to setting effects. Plastic flattening of surface roughness at the bearing areas under head and nut of bolt or collar of lockbolt, the loaded flanks of the mating threads between nut and bolt and other surfaces are designated as “setting” or “embedding”. [7] [20] [21]

$$\Delta F_{p,C,total} = \Delta F_{p,C,setting} + \Delta F_{p,C,relaxation} + \Delta F_{p,C,transvcontraction} + \Delta F_{p,C,tension} + \Delta F_{p,C,loosening} \quad (8)$$

In Figure 17 the results of four specimens including the extrapolated loss of preload are presented. The focus of the investigation is the comparison of the long-term preload-time behaviour of HV bolts and Bobtail lockbolts with specimens acc. to EN 1090-2, Annex G [13]. Figure 17 shows the results for the HV bolts on the left and for the lockbolts on the right diagram. The extrapolated (20 years) loss of preload due to setting $\Delta F_{p,C,setting}$ on grit-blasted surfaces can be compared between HV bolts and lockbolts. The loss of preload due to setting and superimposed by sustainable loads during extended creep tests (ECT) is investigated on specimens with aluminium-spray metallized (Al-SM) faying surfaces. The results of the loss of preload during the ECT for the specimen HV_Al-SM_289-290_15 and LB-Al-SM_291-292_16 are shown in Fig. 10 as well.

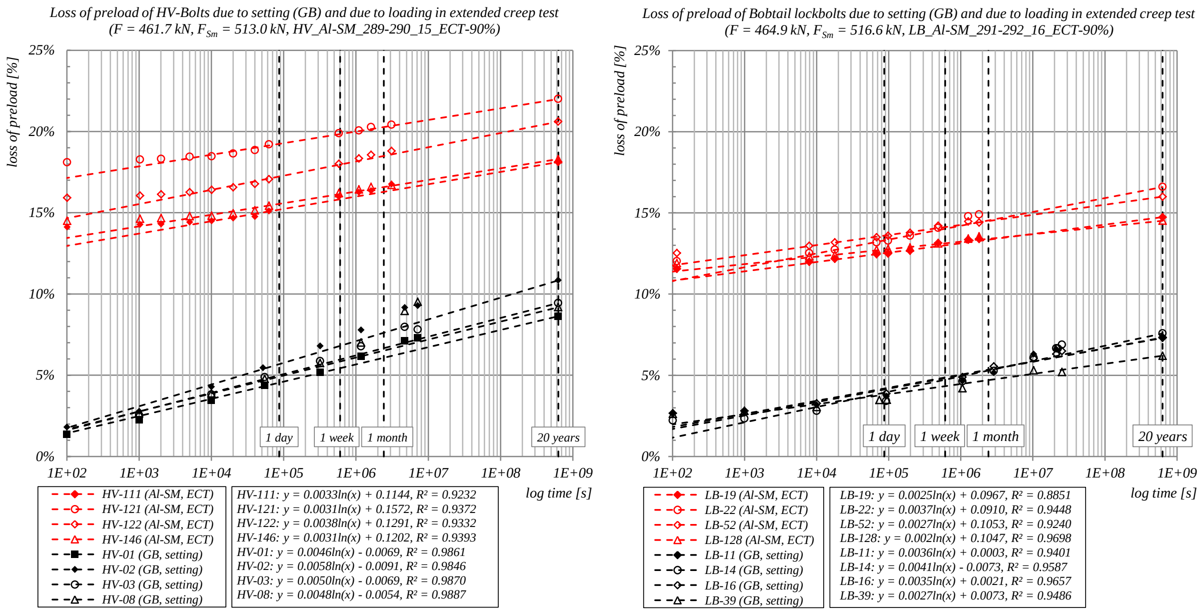

Figure 17: Extrapolated loss of preload due to setting (GB-specimen) and during ECT (Al-SM specimen) of slip-resistant connections HV bolts and Bobtail lockbolts

The pointed black lines in Figure 17 show the loss of preload due to setting effects $\Delta F_{p,C,setting}$ in surface condition GB. For the control of the preload the specimens are stored unloaded in an indoor laboratory with constant temperature. The evaluation is summarized in Table 4.

Table 4: Test results and evaluation of losses of preload due to setting effect for HV bolts and Bobtail lockbolts in grit-blasted faying surfaces

Series ID		HV_GB_281-282_031)				LB_GB_71-72_152)			
Bolt No.		01	02	03	08	11	14	16	39
$F_{p,C,ini}$	[kN]	204.7	186.5	175.9	194.3	183.0	187.5	184.6	186.9
$F_{p,C,setting}$	[kN]	189.7	169.2	162.2	175.8	171.1	174.6	172.7	177.2
$\Delta F_{p,C,setting}$	[kN]	15.0	17.3	13.7	18.5	11.9	12.9	11.9	9.7
		7.3%	9.3%	7.8%	9.5%	6.5%	6.9%	6.4%	5.2%
$F_{p,C,setting,20a}$	[kN]	187.0	166.3	159.3	176.5	169.6	173.3	171.2	175.3
$\Delta F_{p,C,setting,20a}$		8.6%	10.8%	9.4%	9.2%	7.3%	7.6%	7.3%	6.2%

setting time: 1) 83 d | 2) 294 d

The measured values for $\Delta F_{p,C,setting}$ of HV bolts range from 7.3 % to 9.5 % (mean $\Delta F_{p,C,setting}$ = 8.5 %) in 83 days. The extrapolated values showing losses of preload from 8.6 % to 10.8 % (mean $\Delta F_{p,C,setting,20a}$ = 9.5 %).

The losses of preload of lockbolts (in same surface preparation, GB) ranges from 5.2 % to 6.9 %, with a mean value of $\Delta F_{p,C,setting}$ = 6.3 % and a measuring time of 294 days. The extrapolated values for lockbolts show losses of preload from 6.2 % to 7.6 % with a mean value of $\Delta F_{p,C,setting,20a}$ = 7.1 %.

Both bolting systems show a similar long-time setting behaviour. This ensures the comparability of the test results. The Bobtail lockbolts have a lower mean value $\Delta F_{p,C,setting,20a}$ = 7.1 % compared to the HV bolts with a mean value of $\Delta F_{p,C,setting,20a}$ = 9.5.

To evaluate a specific coating system with regard to the creep sensitivity, extended creep tests have to be performed. In this way a maximum load is determined that can act on the connection without causing displacements of more than 300 µm (extrapolated to the life time of a structure or 50 years). For both bolting systems of specimens with Al-SM coating (Table 1) an ECT was performed. The load level for the ECT is based on the mean slip load F_{Sm}, evaluated as the maximum load that occurs during the slip load test, to consider the physics of the connection. The derived load level from the step test, which was developed in the research project SIROCO [2] and in [15], is 90 % of F_{Sm}. With this load level an ECT for both specimens HV_Al-SM_289-290_15 (test load F = 461.7 kN) and LB-Al-SM_291-292_16 (test load F = 464.9 kN) was performed and passed the requirements of EN 1090-2, Annex G.5 [13].

With regard to the preload for each of the four bolts per specimen, their loss of preload-log time-behaviour is shown in Figure 17 (red dashed lines). The evaluation of the losses of preload is shown in Table 5. The start value for determining the losses of preload is the value measured right at the beginning of the test. The lines in the diagram are plotted when the full shear load with 90 % of F_{Sm} is applied to the specimen. The HV bolts show losses of preload from 14.1 % to 18.2 % ($F_{p,C,full-load}/F_{p,C,start}$) and lockbolts from 11.5 % to 12.4 %. These losses are caused by setting effects and transversal contraction of the specimen. Concerning a comparison of the long-term log-time behaviour of the bolts the loss of preload $\Delta F_{p,C,ECT,20a}$ is considered. These are the losses while the sustainable load acts on the specimen. The calculation shows a mean value of $\Delta F_{p,C,ECT,20a}$ = 4.1 % (3.8 % - 4.6 %) for HV bolts and for the lockbolts a mean values of $\Delta F_{\mathbf{p,C,ECT,20a}}$ = 3.5 % (2.7 % - 4.6 %). These values seem reasonable as the losses of preload are due to setting of the coating under sustainable loads.

Table 5: Test results and evaluation of losses of preload due to setting and superimposed by sustained loads in an ECT for HV bolts and lockbolts in specimens with Al-SM faying surfaces

Series ID		HV_Al-SM_289-290_15				LB-Al-SM_291-292_16			
Bolt No.		111	121	122	146	19	22	52	128
$F_{p,C,ini}$	[kN]	196.2	179.7	202.0	194.2	186.7	196.8	184.6	188.3
$F_{p,C,start}$	[kN]	190.6	175.7	197.4	189.0	182.7	191.7	180.1	183.3
$F_{p,C,full-load}$	[kN]	163.7	143.8	165.9	161.6	161.7	168.7	157.7	161.6
$\Delta F_{p,C,full-load}$		14.1%	18.2%	16.0%	14.5%	11.5%	12.0%	12.4%	11.8%
$\Delta F_{p,C,ECT,20a}$ 1)		4.0%	3.8%	4.6%	3.8%	3.2%	4.6%	3.6%	2.7%
$\Delta F_{p,C,start,20a}$ 2)		18.1%	22.0%	20.6%	18.3%	14.7%	16.6%	16.0%	14.5%

1) loss of preload only due to sustainable loads during ECT (setting under load)
2) loss of preload extrapolated to 20 years during extended creep test (ECT) includes transversal contraction, setting and setting under sustainable load

The Bobtail lockbolts are showing a similar preload-time behaviour like the conventional and investigated HV bolts. As an advantage the lockbolts showing less losses of preload due to setting effects in the GB specimens and under sustainable load for Al-SM specimens. The slip load tests with Al-SM specimens of both bolting systems show also a similar load-displacement-behaviour and reach nearly the same mean slip load F_{Sm}. Both fastening systems pass the performed ECT at a load level of 90 % of F_{Sm}. The investigations showed that lockbolts can be used as alternative fasteners and are as well as HV bolts suitable for the use in slip-resistant connections for steel structures.

4.5 H360 Torque/clamp force test

Since the H360 systems according to categories B and C will be used in shear connections and category E in tension connections, the suitability for preloading according to DIN EN 14399-2 [22] and DIN EN ISO 16047 [23] must be investigated. The suitability for preloading is determined on the basis of torque/preloading force tests. For reasons against self-loosening it must be ensured that the H360 nut forms into the bolt thread. While this it must be ensured that the preload $F_{p,Ck}$ is achieved with the specified tightening torque T_{H360} by using the torque method. The bolt sets used in the experimental investigations consist of H360 bolts, H360 nuts and washers according to DIN EN 14399-6 [24]. For the performance of the torque/clamp force tests a *Schatz Analyse* horizontal test bench was used. Aim of the torque/clamp force tests was the determination of the characteristic torque/clamp load behavior of the H360 system during installation. Figure 18 shows on the left hand side a schematic drawing of an installed H360, on the right hand side the used test bench is shown. The torque/clamp force tests were performed in accordance with DIN EN ISO 16047 [23].

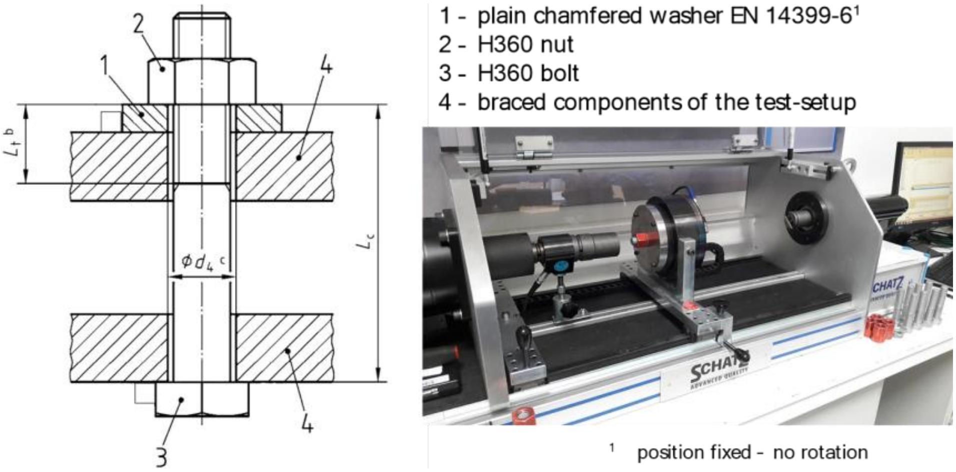

Figure 18: Test bench for torque/clamp force testing acc. to DIN EN ISO 16047:2013-01

The H360 set used for the tests consisted of a H360 bolt (strength class 10.9) with a nominal diameter of 20 mm (360H-DT20-G100-D1) and a H360 nut (R20RX). The H360 system will be delivered without washers. For each test an unused plain chamfered washer acc. to DIN EN 14399-6:2015-04 [24] was placed under the nut.

The clamp length in the test setup was l_k = 66 mm. Each fastener set was manually installed into the test rig. The hexagon H360 bolt head was fixed to the test rig to avoid turning during the pre-load procedure. To determine the bearing surface and friction coefficient μ_b in the contact area between the nut and the washer, the washer was also fixed to the test rig. Due to the non-standard thread geometry the determination of the friction coefficient for the thread μ_{th} was impossible.

Before applying the torque, the nut was placed hand-tight onto the bolt. The H360 bolt sets were installed as delivered without additional lubrication. The torque was applied continuously through the nut with a turning speed of 5 rpm (rotations per minute).

In a first step the mechanism of the H360 system was tested in torque/clamp force testing machine to evaluate the forming effect of the nut. The nut is made of a softer material compared to the bolt. This shall provide that the material of the nut forms into the grooves (thread) of the bolt. The torque to achieve the full preload of the H360 system was preassigned by the manufacturer with T_{H360} = 610 Nm. For the stepwise installation, the maximum level of torque had to be determined where the plastic deformation of the nut begins. With increasing deformation of the nut and destruction of the surface coating in the thread, the coefficient of friction μ_{th} increases. Beyond this point loosing and retightening inhibits the risk that the designed preload will not be achieved due to the increased μ_{th}. To define the point of beginning deformation, macro-examination specimens were evaluated. The results and cross-sections at three different torque steps are shown in Figure 19.

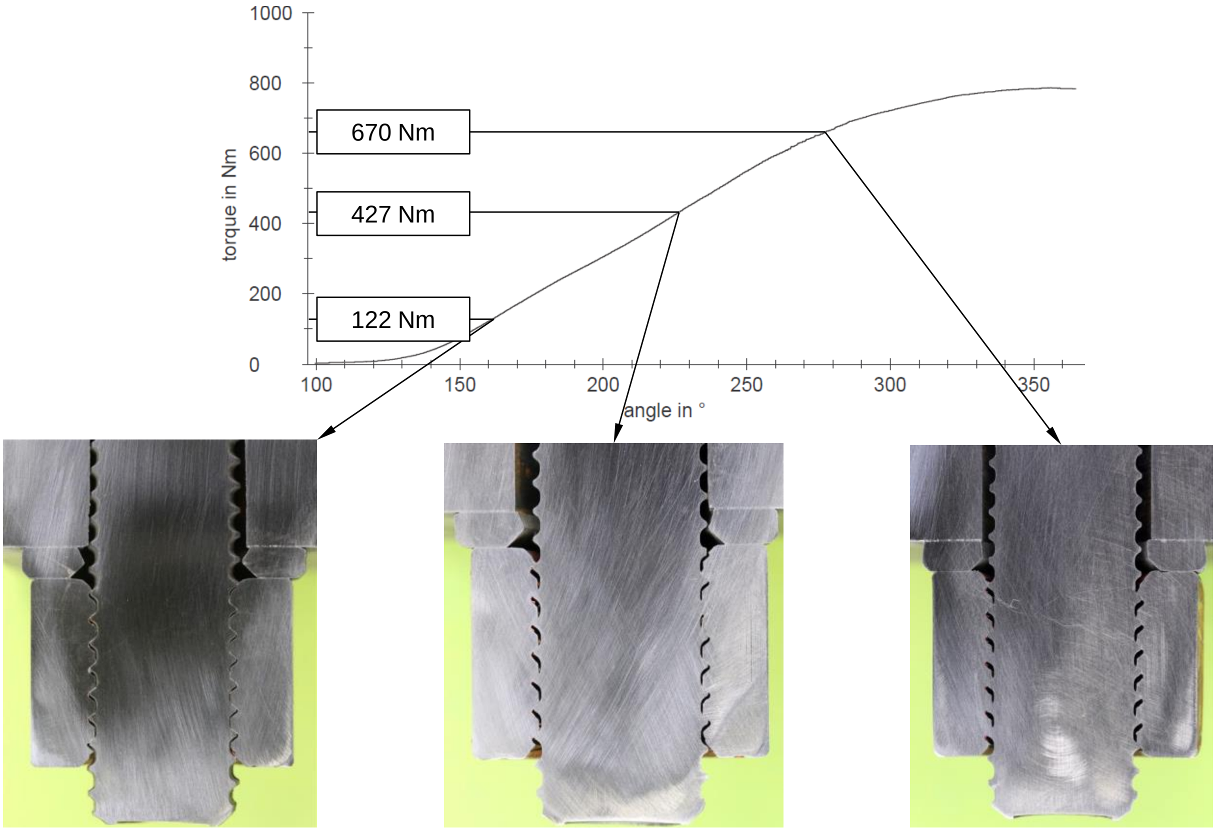

Figure 19: Forming effect of the nut by tightening up to the nominal torque H360 size M20

This effect of forming the nut into the grooves of the bolt shall provide that the nut does not loosen under vibration loads. By the cold forming process of the nut the material will be strengthen and the friction between nut and bolt will increase. This increasing friction can be preventing the ability to preload the bolt up to a defined preload $F_{p,C}$. The preload $F_{p,C}$ is besides the slip factor µ the essential parameter to design slip-resistant connection. Therefore torque/clamp force test were performed to evaluate the preloadability of this bolting system.

The investigation of the torque/clamp force behavior of the H360 system was divided into four sections. In Table 6 the performed test sections are listed.

Table 6: Description of test sections

Test section	Description of test procedure
I	Determination of effective diameter D_b for the friction moment of nut bearing area
II	Torque/clamp force for testing the ability to preload H360 bolting system
III	Torque/clamp force test for stepwise tightening (two steps)
IV	Torque/clamp force test for reusability of bolt with same nut

4.5.1 Test section I: Determination of effective diameter D_b for the friction moment of nut bearing area

In test section I the H360 were tightened to the defined preload acc. to DIN EN ISO 16047 [23] with 0.75 F_p and to the preload level, which was given by ARCONIC. In Figure 20 the tightening process is shown. After the tightening is finished, the bolts have been loosed. Finally the diameters d_a and d_i (Figure 20) were measured to determine the real effective diameter $D_{b,real}$ for the friction moment at the nut bearing area (see Figure 20).

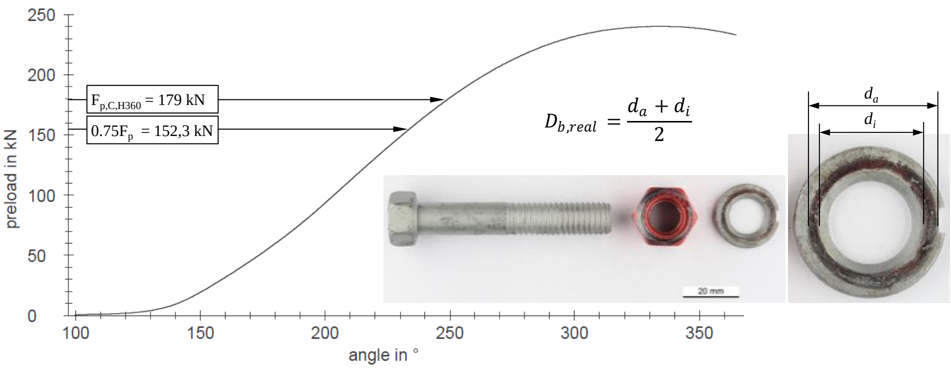

Figure 20: Tightening process to determine μ_b, d_a and d_i

Table 7 summarises the results. With the measured bearing area it is possible to compute the coefficient of friction μ_b in the bearing surface more exactly, which is necessary for the evaluation of test section II

Table 7: Measured bearing surfaces

test load	d_a [mm]	d_i [mm]	$D_{b,real}$ [mm]	$D_{b,theor}$ [mm]
0.75 F_p 1)	33.1	27.0	30.05	min. 27.74 max. 29.16
$F_{p,C,H360}$ 2)	33.5	26.5	30.00	

1) 0.75 F_p = 152.3 kN – F_p according to DIN EN ISO 898-1:2013-05
2) preload H360 $F_{p,C,H360}$ = 179 kN (defined by ARCONIC [1])

4.5.2 Test section II: Torque/clamp force test to evaluate the ability to preload

From the continuous torque/clamp test, the achievable preload level $F_{p,Ck}$ and the scattering range are determined. The tightening process was performed, as usual in steel constructions, by turning the. The washer has to be fixed during these tests, to ensure that the relative movement takes place only between washer and nut. This movement leads to under-head friction. To evaluate the tightening behaviour of the H360 systems, the following parameters shall be determined from the continuous torque/preload test:

- preload $F_{p,Ck}$ for the specified tightening torque T_{H360} (deviation and tightening factor α_A)
- maximum preload, tightening torques and angles of rotation.

The following points of analysis in Table 8 will be used for evaluating the ability to preload.

Table 8: Description of points of analysis

points	description	measured value
#1	0.75 F_p = 152.3 kN – F_p according to DIN EN ISO 898-1 [4]	$T_{0.75\ Fp}$ [Nm]
#2	preload national F_{p,C^*} = 160 kN	T_{Fp,C^*} [Nm]
#3	preload international $F_{p,C}$ = 172 kN	$T_{Fp,C}$ [Nm]
#4	torque ARCONIC T_{H360} = 610 Nm	$F_{p,C,H360}$ [kN]
#5	yield point (thread deformation nut)	F_{yield} [kN] and T_{yield} [Nm]

Figure 21 shows the points for the analysis.

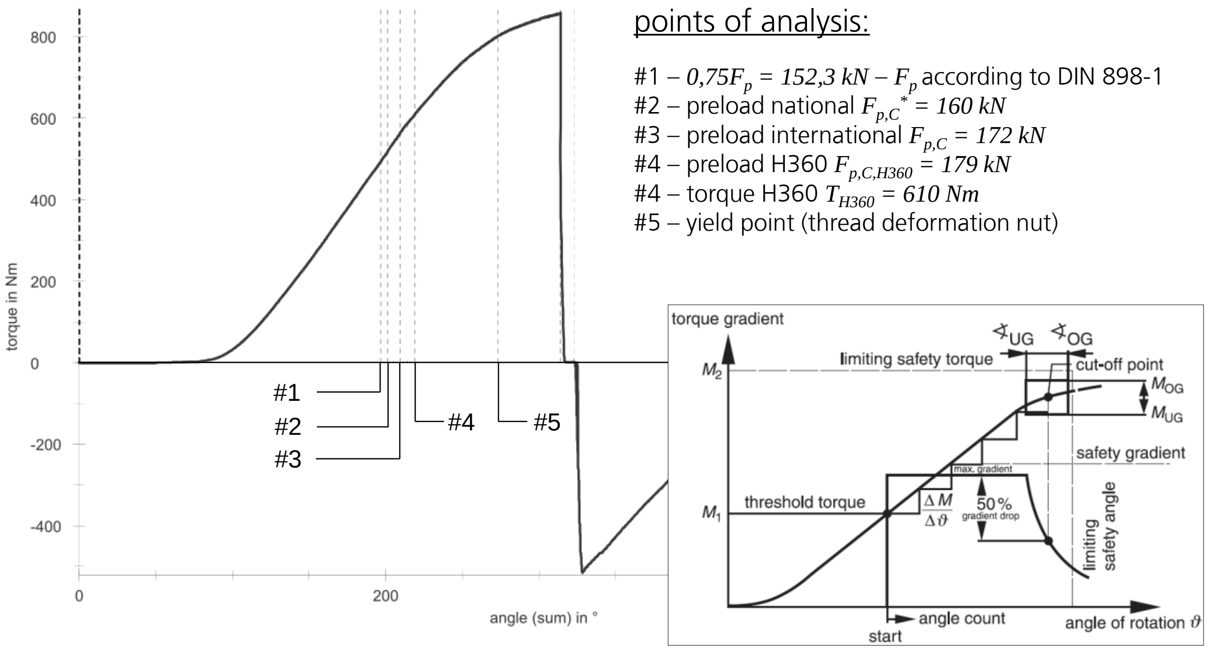

Figure 21: Points of analysis for torque/clamp force test

In Figure 22 shows a preload/torque-angle curve with different points of evaluation.

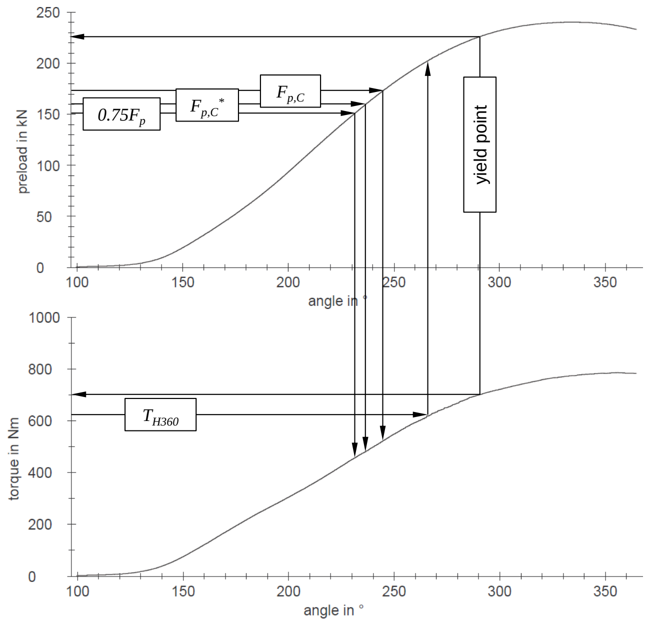

Figure 22: Evaluation points

There are different points of the tightening curve which are evaluated. In Figure 22 a continuously tightening curve is shown. In the upper chart the preload is plotted over the angle. The three loads of interest are marked (0.75 F_p, F_{p,C^*} and $F_{p,C}$). The torque, which belongs to the preload is determined in the lower chart, as shown in Figure 22. Another evaluation point is the torque, which is given by ARCONIC. In this case the preload is picked in the point where the torque T_{H360} is reached. The yield point indicates the yield strength of the bolting system. In test section II H360 bolts were tested with washers acc. to DIN EN 14399-6 [24] from manufacturers FUCHS and PEINER. The results are given in Table 9 and Table 10. For the calculation it is necessary that the area of the thread keeps the same and the thread of the H360 deforms as planned by the manufacturer ARCONIC during the tightening process [1].

Table 9: Results of torque/ clamp load tests with washers from company FUCHS

Point	#1	#1	#2	#2	#3	#3	#4	#4	#5	#5
No.	$T_{0.75\,Fp}$ [Nm]	$\mu_{b,0.75Fp}$	T_{Fp,C^*} [Nm]	μ_{b,Fp,C^*}	$T_{Fp,C}$ [Nm]	$\mu_{b,\,Fp,C}$	$F_{p,C,H360}$ [kN]	$\mu_{b,Fp,C,H360}$	T_{yield} [Nm]	F_{yield} [kN]
1	476.93	0.075	504.15	0.08	548.07	0.08	187.76	0.08	825.66	226.52
2	561.66	0.070	589.93	0.07	632.10	0.07	166.04	0.07	911.59	228.98
3	546.11	0.079	572.98	0.08	617.00	0.08	170.05	0.08	892.17	232.27
4	646.18	0.100	680.85	0.10	740.42	0.10	142.54	0.10	1064.04	229.33
5	588.47	0.078	621.18	0.08	675.12	0.08	157.30	0.08	969.96	224.09
6	628.88	0.077	661.58	0.08	717.13	0.08	147.34	0.08	978.81	218.83
7	533.73	0.072	560.35	0.07	604.17	0.07	173.50	0.07	858.56	229.75
8	566.34	0.075	594.26	0.08	638.34	0.08	164.51	0.08	951.39	232.35
9	489.41	0.075	515.22	0.08	556.02	0.08	186.53	0.08	874.11	237.13
10	568.30	0.087	597.83	0.09	644.57	0.09	163.34	0.09	982.03	231.87
mean	560.60	0.079	589.83	0.08	637.29	0.08	165.89	0.08	930.83	229.11
s_x	53.60	0.009	56.33	0.01	62.00	0.01	14.72	0.01	71.48	5.06
V_x [%]	9.56	10.98	9.55	11.11	9.73	12.09	8.87	12.24	7.68	2.21

Table 10 shows the results of the torque/clamp test with washer from PEINER.

Table 10: Results of torque/ clamp load tests with washers from company PEINER

Point	#1	#1	#2	#2	#3	#3	#4	#4	#5	#5
No.	$T_{0.75\ Fp}$ [Nm]	$\mu_{b,0.75Fp}$	$T_{Fp,C*}$ [Nm]	$\mu_{b,Fp,C*}$	$T_{Fp,C}$ [Nm]	$\mu_{b,Fp,C}$	$F_{p,C,H360}$ [kN]	$\mu_{b,Fp,C,H360}$	T_{yield} [Nm]	F_{yield} [kN]
1	494.01	0.060	519.97	0.06	562.69	0.06	185.23	0.06	801.41	222.67
2	441.31	0.057	465.25	0.06	499.37	0.06	207.71	0.06	763.01	237.69
3	535.49	0.056	559.90	0.06	600.35	0.06	175.01	0.06	846.84	229.89
4	745.76	0.100	790.13	0.10	856.75	0.10	126.77	0.10	980.07	192.70
5	565.93	0.069	593.05	0.07	635.92	0.07	164.63	0.07	864.50	224.02
6	480.45	0.066	503.14	0.07	540.37	0.06	191.78	0.06	831.39	234.81
7	603.42	0.076	630.24	0.08	674.56	0.08	154.32	0.08	928.35	225.29
8	461.13	0.069	482.71	0.07	519.04	0.07	200.34	0.07	755.01	238.63
9	516.53	0.071	545.41	0.07	592.75	0.07	176.06	0.07	913.15	233.16
10	562.97	0.060	589.48	0.06	635.77	0.06	165.28	0.06	891.32	227.96
mean	540.70	0.068	567.93	0.07	611.76	0.07	174.71	0.07	857.51	226.68
s_x	88.03	0.013	93.82	0.01	102.39	0.01	23.70	0.01	72.80	13.18
V_x [%]	16.28	19.05	16.52	19.61	16.74	19.72	13.56	20.37	8.49	5.81

As mentioned before, it is necessary to deform the thread of the nut, this could not clearly explained by these tests. On this topic more detailed investigation including analysis of cross-sections have to be performed. For the estimation of the scatter of the preload the tightening factor is calculated acc. to VDI 2230 [9]. The tightening factor for the torque T_{H360} is $\alpha_A = 1.32$ with the FUCHS washers and $\alpha_A = 1.35$ with PEINER washers, when trial number 4 in Table 10 is declared as an outliner (Figure 23).

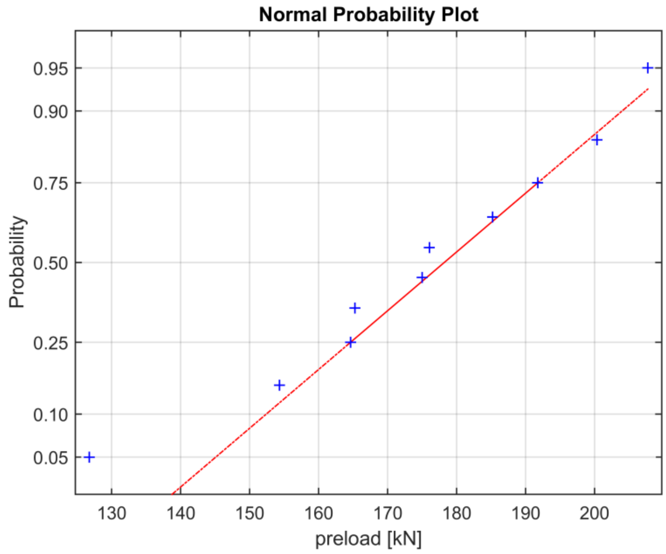

Figure 23: normal probability plot from $F_{p,C,H360}$ with PEINER washers

As it is shown in Figure 23 trial number 4 with PEINER washers can be declared as an outliner, because it is not following the normal distribution.

The scatter is not significantly depending on the used washers and the tightening factors of both configurations. They are comparable with the tightening factor of conventional bolts with α_A = 1.4 … 1.6 acc. to VDI 2230 [9].

According to DIN EN ISO 16047 [23] the friction coefficients are evaluated at 0.75 F_p. The only coefficient of these tests that is analysable for the H360 is the friction coefficient for the bearing surface $\mu_{b,\,0.75Fp}$. The mean value by using FUCHS washers is $\mu_{b,\,0.75Fp}$ = 0.079 and with PEINER washers the average is $\mu_{b,\,0.75Fp}$ = 0.068. The scatter of both configurations is small. The necessary torque to reach the international European preload level $F_{p,C}$ = 172 kN is (evaluation point #3) is much higher than the defined torque by the manufacturer ARCONIC with T_{H360} = 610 Nm. The mean value is 611.76 Nm and 637.29 Nm. The evaluation of the preload by applying the given torque of 610 Nm (evaluation point #4 [kN]) shows mean values of $F_{p,C,H360}$ = 174.71 kN and 165.89 kN.

As a conclusion H360:

- can be preloaded,
- the scatter of the preload is comparable to HV bolts,
- the use in slip-resistant connections (Cat. B, C acc. to EN 1993-1-8 [10]) is possible and
- further investigations shall be done to analysis the relation torque-preload more detailed.

4.5.3 Test section III: Torque/clamp force test for stepwise tightening

To use the H360 system in steel and aluminium structures in accordance with the EN 1090-2 [13] the possibility of a stepwise tightening process is mandatory. To prove the suitability of the H360 system three torque/clamp force tests were performed. The installation procedure was divided into two steps:

- 1st step – tightening to 40 % of the designated torque T_{H360} (beginning of plastic deformation of the nut)
- 2nd step – tightening to 100 % of the designated torque T_{H360}

Table 11 shows resulting mean preloads of the steps.

Table 11: Results of the stepwise tightening procedure

No.	0.4 T_{H360} [Nm]	$F_{p,C,0.4TH360}$ [kN]	T_{H360} [Nm]	$F_{p,C,TH360}$ [kN]
01	244.06	61.17	610.13	162.52
02	244.11	59.43	610.23	174.38
03	244.01	63.70	610.18	174.15
mean	244.06	61.43	610.18	170.35
s_x	0.05	2.15	0.05	6.78
V_x [%]	0.02	3.50	0.01	3.98

In the first step the H360 systems were tightened with 0.4 T_{H360} = 244.06 Nm. Table 11 shows a resulting mean preload of $F_{p,C,0.4TH360}$ = 61.43 kN based on three tests with a coefficient of variation of 3.5 %. Before in the second step the fasteners were fully tightened with T_{H360}, a holding time of 10 mins was selected to subside the main setting effects. In Figure 24 a torque-angle-preload diagram is shown.

The achieved mean preload force with stepwise tightening to T_{H360} is $F_{p,C,TH360}$ = 170.35 kN with a slightly higher coefficient of variation of 3.98 %. A comparison of the resulting preload forces from section II ($F_{p,C,TH360}$ = 165.89 kN) shows that the preload after stepwise tightening is approx. 4.5 kN higher while the coefficient of variation lies well below the one determined in section II (8.87 %).

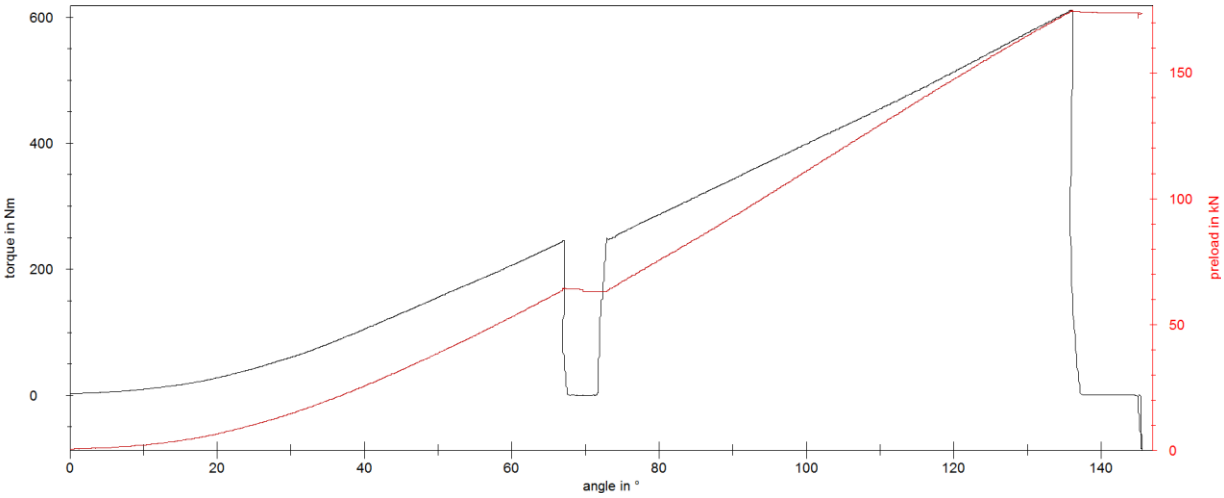

Figure 24: Torque-angle-preload diagram for stepwise tightening procedure

This leads to the assumption that the stepwise tightening procedure has a positive effect on the resulting preload, presupposed a sufficient waiting time after the first tightening step is maintained. However, to confirm this effect, a larger sample should be considered.

5 Summary

This report to the Deliverable D 3.1 (Task 3.1 of the project “SIRCOCO” (RFSR-CT-2014-00024)) compares alternative high-strength bolting systems for preloading - Lockbolts and H360 - and their use in slip-resistant connections. The measured and analysed initial preload levels of Lockbolts and H360 are in the same range as the well-known HV bolts. Both, HV bolts and H360, show nearly the same tightening factor α_A (relation of max to min preload) and the same relative deviation V_x (coefficient of variation). The tightening of these bolting assemblies was carried out by using torque method acc. to EN 1090-2 [13] by rotating the nut. For HV-M20x75-tzn-k1 bolts [11] the tightening factor α_A acc. to VDI 2230 [9] that is evaluated overall three coating systems is α_A = 1.52 (number of tests n = 47). For H360-M20-G40 J45 [1] the tightening factor α_A acc. to VDI 2230 [9] that is evaluated overall three coating systems is α_A = 1.58 (number of tests n = 71). The nominal preload for H360 $F_{p,C,H360}$ = 179.0 kN will not be reached in all tightening tests. The nominal preload values shall be reduced or the given tightening torque increased. Further investigations are necessary. Lockbolts showed less deviation of the preload due to the tension process of the installation procedure. For Bobtail Lockbolt-M20-G40 J45/46 [1] the tightening factor α_A acc. to VDI 2230 [9] that is evaluated overall three coating systems is α_A = 1.15 (number of tests n = 42).

Unlike in case of HV bolts, a re-tightening of Lockbolts is not possible, but in terms of compliant design and installation procedure also not necessary. Therefore the losses of preload due to setting effects, under external fatigue loading on the connection and under sustained load acting on the connection have to be taken into account. Lockbolts and H360 are preloadable and can be used in slip-resistant connections. For H360 it is necessary to keep in mind that the bolt head has to be held during the tightening and re-tightening processes.

For H360 re-tightening is in principle possible. In test the head of the bolts turns when turning the nut during the re-tightening process which leads to a drop of preload. In that case when tightening the bolt by turning the nut, the bolt head have to be held in place. A turning of the bolt head is not permitted.

The slip load-displacement behaviour in the slip load tests show the same characteristic curves. The results from the slip load test with slip-resistant connections with preloaded lockbolts and H360 show no deviations compared to those ones with HV bolts. All values of the slip load are in the same range. The designed slip-resistance $F_{S,Rk}$ acc. to EN 1993-1-8 [10] is reached with the use of lockbolts as well as H360 in slip-resistant connections.

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