GERMAN FASTENERS ASSOCIATION
MANUFACTURERS OF MECHANICAL FASTENERS

DSV - Information

DSV-round-robin test 2014

Objectives:

- suitability for daily use of testing according to VDA 235-101
- evaluation of possible crosstalk of the sensors
- investigation of the capability of test rigs for reliable determination of friction coefficients

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Table of contents

Nomenclature and abbreviations

Symbols

D_b	effective diameter for the friction torque at the bolt head or nut bearing area	mm
$D_{b,0.25°}$	effective diameter for the friction torque at the bolt head or nut bearing area of bolts with the concavity angle 0.25°	mm
$D_{b,1°}$	effective diameter for the friction torque at the bolt head or nut bearing area of bolts with the concavity angle 1°	mm
F	preload	N
F_{Sd}	clamping force	N
P	pitch of the thread	mm
T	tightening torque	Nm
T_b	friction torque in the head or nut bearing area	Nm
T_{th}	thread torque	Nm
$T_{th,0.25°}$	thread torque for bolts with the concavity angle 0.25°	Nm
$T_{th,1°}$	thread torque for bolts with the concavity angle 1°	Nm
d_2	pitch diameter	mm
d_h	hole diameter	mm
d_w	outside diameter	mm
l	clamping length	mm
n	rotation speed	min^{-1}
t	waiting time	s
$\bar{x}$	mean value	
σ	standard deviation	
μ_b	coefficient of friction in the head bearing area	-
μ_{th}	coefficient of friction in the thread	-
μ_{tot}	total coefficient of friction	-
$\mu_{VDA\,max}$	maximum coefficient of friction according to VDA 235-101 [1]	-
$\mu_{VDA\,min}$	minimum coefficient of friction according to VDA 235-101 [1]	-
$\mu_{VDA\,range}$	range of the coefficient of friction according to VDA 235-101 [1]	-

Abbreviations

C_0	test rig without any complaint
C_1	test rig with probable adverse effects on the calibrating condition of several measurement values and / or the sensor function
C_2	test rig shows distinct indications of failure
all	consideration of all test rigs independent of the test rig type
n	consideration of the test rigs which measure F and T
th	consideration of the test rigs which measure F, T and T_{th}
b	consideration of the test rigs which measure F, T and T_b
thb	consideration of the test rigs which measure F, T, T_{th} and T_b

1 Introduction

The precise knowledge of coefficients of friction is the basis for the calculation of fastener systems and for a reliable assembly process of bolted joints to ensure a sufficient preload for a given application. For the determination of friction coefficients, different types of test rigs are used which can measure the values of preload F, the tightening torque T as well as thread torque T_{th} and / or friction torque in the head bearing area T_b. ISO 16047 [2] only gives information about the test prcedure, the reference parts and the formulas for calculating the coefficients of friction. Specifications for required ranges of friction coefficients in practical applications including multiple tightening are made in other documents like VDA 235-101 [1].
Considering the construction and function of used test rigs ISO 16047 [2] gives only basic guidelines. Thus a variety of different testing machines are in use which makes it complicated to compare test results today. The round-robin tests performed in the past by the working group Surface Coating Systems of the German Fasteners Association as well as by the working group ISO/TC 2/SC 1/WG 8 show that for the time being there is no existing acceptable method for exact determination and comparison of coefficients of friction.
The round-robin test 2014 continues a series of round-robin tests to determine the capability of test rigs to evaluate the reliability in determining coefficients of friction. Additional objectives of the round-robin test 2014 were to evaluate and to compare a possible crosstalk of the sensors, to find out the suitability for daily use of testing according to VDA 235-101 [1] and to compare the different test benches of the participating laboratories with regard to their reliability.

The organizers thank KAMAX Automotive GmbH and Dörken MKS-Systeme GmbH & Co. KG for their providing the test parts and for shipping them to the participants.

2 Task

Flanged bolts of the dimension M10 x 70 - 10.9 with different angles of concavity under the bolt head were used for the tests in combination with a corresponding washer. It could be expected that the thread torques T_{th} will stay at the same level whereas the torques measured in the bearing area of the bolt head T_b should differ between the two bolts due to the different friction diameter in head bearing area. A global evaluation of all data should show if the different test benches are able to reproduce this effect.
The big data base of test results should allow to compare the results of the variety of test rigs with different measurement principles and to evaluate the statistic reliability of a single test rig in a population.

3 Test parts

The following test and reference parts have been used (**Figure 1**):

Test bolt:

designation:	flanged bolt M10 x 70 - 10.9 with the concavity angle 0.25° or 1°
surface coating:	zinc flake coating (GEOMET 321 + PLUS VLh)
lubrication:	integral, no additional lubrication

Reference nut:

designation:	hexagon nut M10 - 10 according to ISO 4032 [3], AF16
surface coating:	plain, degreased according to ISO 16047 [2]
lubrication:	none

Reference washer:

designation:	Type HL outside diameter 30 mm
hardness and surface state:	225 HV10; R_a 0.5
surface coating:	plain, degreased according to ISO 16047 [2]
lubrication:	none

The pre-degreasing procedure according to ISO 16047 [2] was uniformly performed as follows:

- 1. step: 5 min white spirit 180 / 210
- 2. step: 5 min Isopropanol in an ultrasonic cleaner

After pre-degreasing the nuts and the washers were put into airtight bags.

For the test parts it was required not to clean them again or to lubrify them. They had to be used in their delivery condition. The participants were recommended to wear gloves during the tests, to care for cleanliness around the test bench and to make sure that the test material is used directly out of the plastic bags and not stored or spilled out on a support plate before assembling.

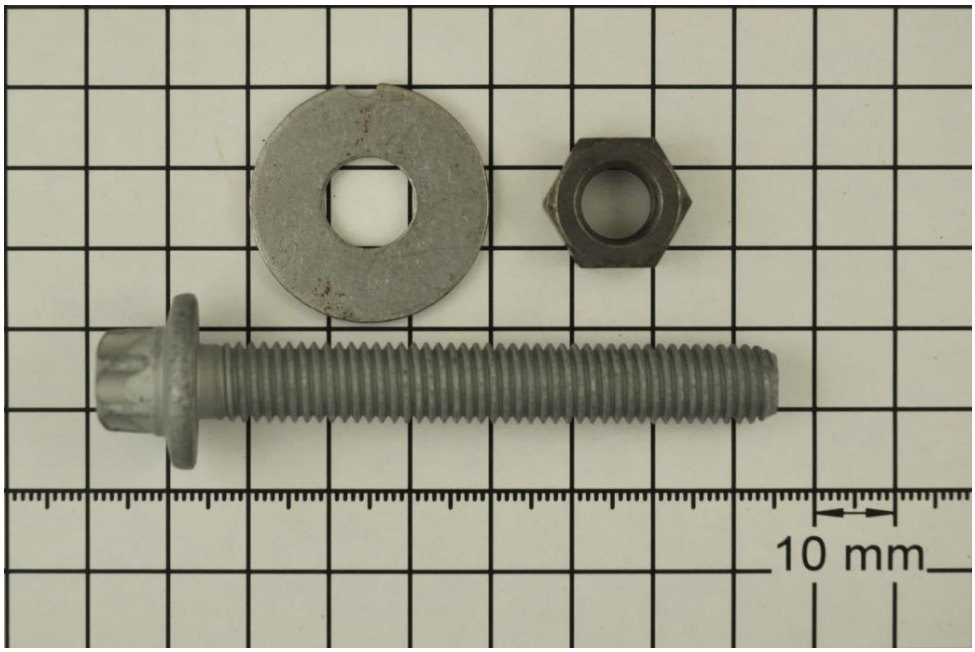


Figure 1: Test parts: bolt, nut and washer

4 Test procedure

With each test rig a series of 25 single tests for both concavity angles had to be carried out. The reference nuts and washers had to be prevented from turning during tightening. Therefore a groove was machined at the edge of each washer.
The test had to be carried out according to ISO 16047 [2]. In accordance with the specified property class of the bolt the shut off clamping force was specified to be $F_{Sd} = 38\,kN$ and the clamping force for calculating the coefficients of friction was $F = 36.1\,kN$. The tightening/rotation speed was specified with $n = 20\,min^{-1}$. The specified clamping length was between $l = 50\,mm$ and $55\,mm$. A triple tightening was required with a waiting period of $t = 1\,s$ after each tightening. After tightening, the bolts had to be untightened by turning the bolt back up to $360°$ with a rotation speed of $n = 20\,min^{-1}$. After waiting once again for $t = 1\,s$, the next tightening process had to be started.
It was recommended to program the software of the test rig such that the complete triple tightening and untightening process was run continuously (no stopping and restarting during the different steps) and to provide the complete data logging of tightening and untightening process.

A standardised analysing form was provided for all tests, which automatically converted the preload value F and the torque values into the coefficients of friction. For these calculations an effective diameter for the friction torque at the bolt head D_b was given. In addition all participants were also asked to measure D_b by themselves and enter it into the automated analysing form. For the bolts with the concavity angle 0.25° an effective diameter for the friction torque at the bolt head of $D_b = 17\,mm$ and for the bolts with the concavity angle 1° one of $D_b = 19.5\,mm$ was given .

The following correlations were used to calculate the coefficients of friction:

$$\mu_{tot} = \frac{\frac{T}{F} - \frac{P}{2 \cdot \pi}}{0.577 \cdot d_2 + 0.5 \cdot D_b} \qquad [2] \qquad 4\text{-}1$$

$$\mu_{th} = \frac{\frac{T_{th}}{F} - \frac{P}{2 \cdot \pi}}{0.577 \cdot d_2} \qquad [2] \qquad 4\text{-}2$$

$$\mu_b = \frac{2 \cdot T_b}{D_b \cdot F} \qquad [2] \qquad 4\text{-}3$$

For all test series the mean value and the standard deviation were calculated. In addition the minimum and the maximum values were determined.

5 Test results

In the following the test results of the participating companies which have been made anonymous are reported in **Annex 1**. The figures of the results as well as the mean values, the minima, the maxima and the standard deviations are presented in **Annex 2** to **Annex 9**. The numbering of the test rigs in **Annex 2** to **Annex 9** is arbitrary and does not correlate with the alphabetical order of the companies listed in **Annex 1**. Together with this evaluation each participating company gets the corresponding test number(s).
Concidering the different measurement principles as documented in the analysing form, the test rigs could be classified into different categories (**Table 1**). These categories were also used for the further evaluation.

Table 1: Differentiation of the participating test rigs and the reported test rig manufacturers depending on the measured characteristics

abbr.	values measured by the test rig: preload F	tightening torque T	thread torque T_{th}	friction torque in the head bearing area T_b	reported test rig manufacturer	number
n	X	X			Stellar Technologies unknown	3
th	X	X	X		self-construction REC® Engineering GmbH RS Technology Schatz AG unknown	52
b	X	X		X	Automatica TesT GmbH modification	37
thb	X	X	X	X	self-construction Automatica unknown	5
					sum:	97

By performing the round-robin test in the companies as well as during the evaluation of the reported results some inconsistencies have been detected (**Table 2**). Reasons for the inconsistencies were in the majority of the cases incorrect filling of the analysing form and the use of the test rig outside of its calibration range for this test. 18 inconsistencies from total 30 ones could be resolved. The 12 remaining inconsistencies concern either the results of the test rigs that have been used outside of their calibration range or a preload referring to the reported results deviating from the given preload of $F = 36.1\ kN$ by more than 5 %. The results of the test rigs where these inconsistencies appeared are always shown in the figures and tables in **Annex 3** to **Annex 9**, but the results are not included in a number of main values.

Table 2: Detected inconsistencies during performing and evaluation of the round-robin test

detected inconsistency	number of test rigs: occured	resolved	difference
incorrect input of the geometric parameters in the software of the test rig	2	2	0
mix-up between the columns of the torques in the analysing form	3	3	0
use of the test rig outside of its specified calibration range	10	-	10
in the analysing form torque values were not given for a preload of $F = 36.1\ kN$ (deviation > 5 %)	8	6	2
subsequent correction of the effective diameter for the friction torque under the bolt head D_b	4	4	0
misstatement of the measured or calculated values or of the calibration range	1	1	0
typing errors so that the torque balance was wrong $T - T_{th} - T_b \ll 0$	2	2	0
sum:	30	18	12

5.1. Effective diameter for the friction torque under the bolt head D_b

Both of the applied bolts were flanged bolts with different concavity angles of 0.25° or 1°. They are in accordance with DIN EN 1665 [4]. This standard allows a concavity angle in the range of 0.75° ± 0.5°.
In **Table 3** the contact surfaces under the head of the bolt and on the washer are shown for both variants. The bolts with a concavity angle of 1° produce a very narrow outer bearing contact area. In comparison the bolts with a concavity angle of 0.25° show a more planar contact area. Exclusively by optical examination of the contact surfaces it can be stated that the effective diameter for the friction torque at the bolt head, D_b, must be larger for the bolts with the concavity angle of 1° than those of the bolts with the concavity angle of 0.25°.

Table 3: Comparison of the contact surfaces under the bolt head and on the washer for the applied bolts with different concavity angles [5]

	concavity angle 0.25°	concavity angle 1°
bolt head		
washer		

The evaluation of the measured effective diameter for the friction torque at the bolt head D_b shows a large standard deviation (**Annex 2)**. For the mean values the results are:

- concavity angle of 0.25°: $\emptyset D_b = 16.8 \pm 1.3\ mm$ and
- concavity angle of 1°: $\emptyset D_b = 18.3 \pm 1.2\ mm$

In ~ 12 % of all 97 reported results the same effective diameter for the friction torque at the bolt head was given for both bolts ($D_{b,0.25°} = D_{b,1°}$). Reasons may be that the effective diameter for the friction torque at the bolt head D_b was calculated either with the outside diameter of the bolt head ($d_w \approx 20.1\ mm$) and the hole diameter ($d_h = 11\ mm$) according to formula 5-1 ($D_b = 16\ mm$) or formula 5-2 ($D_b = 15.6\ mm$) or the outside diameter was equated with the effective diameter for the friction torque at the bolt head ($D_b \approx d_w$).

$$\frac{D_b}{2} = \frac{d_w + d_h}{3} \cdot \left(1 - \frac{1}{\frac{d_w}{d_h} + 2 + \frac{d_h}{d_w}}\right) \qquad [6] \qquad 5\text{-}1$$

For narrow circular ring areas with $\frac{d_w}{d_h} \approx 1$ follows:

$$D_b = \frac{d_w + d_h}{2} \qquad [6] \qquad 5\text{-}2$$

Excluding these reported results with $D_{b,025°} = D_{b,1°}$ from the mean value determination, only slight changes of the effective diameter for the friction torque at the bolt head were found:

- concavity angle of 0.25°: $\emptyset D_b = 16.8 \pm 1.2\ mm$ and
- concavity angle of 1°: $\emptyset D_b = 18.5 \pm 0.9\ mm$

5.2. Practical suitability of the test according to VDA 235-101

With the test bolts the tightening processes should be performed three times to a clamp force of $F_{Sd} = 38\ kN$, and the torques at a preload of $F = 36.1\ kN$ should be reported. **Table 4** and **Table 5** show a summary of the mean values and standard deviations of the torques for *all* test rigs as well as grouped into the different measurement principles: *n*, *th*, *b* and *thb* (see also **Annex 3** and **Annex 4**). For the evaluation of the mean value deviation those test results were not included where preloads different from 36,1 kN were used for evaluation or where the test rigs were used outside their calibration range.

Table 4: concavity angle 0.25°: comparison of the mean values $\bar{x}$ and the standard deviations σ for a preload of $F = 36.1\ kN$

abbr.			1st tightening			2nd tightening			3rd tightening		
			T	T_{th}	T_b	T	T_{th}	T_b	T	T_{th}	T_b
all	$\bar{x}$	Nm	61.3	29.2	32.1	59.4	28.4	31.1	58.6	28.1	30.5
	σ	%	4.0	6.6	8.0	4.3	7.1	8.2	4.5	7.1	8.4
n	$\bar{x}$	Nm	59.8	-	-	58.8	-	-	58.1	-	-
	σ	%	13.0	-	-	14.7	-	-	14.6	-	-
th	$\bar{x}$	Nm	61.4	29.5	32.0	59.6	28.6	31.0	58.8	28.3	30.4
	σ	%	3.1	6.1	8.1	3.5	6.7	8.4	3.9	6.7	8.8
b	$\bar{x}$	Nm	61.4	29.1	32.3	59.4	28.2	31.2	58.5	27.8	30.7
	σ	%	3.8	6.7	8.3	3.8	7.2	8.5	3.8	7.0	8.2
thb	$\bar{x}$	Nm	59.4	27.5	31.9	57.9	26.9	30.9	56.6	26.4	30.3
	σ	%	4.7	11.0	3.2	6.0	11.3	5.0	5.3	11.1	4.3

Table 5: concavity angle 1°: comparison of the mean values $\bar{x}$ and the standard deviations σ for a preload of $F = 36.1\ kN$

abbr.			1st tightening			2nd tightening			3rd tightening		
			T	T_{th}	T_b	T	T_{th}	T_b	T	T_{th}	T_b
all	$\bar{x}$	Nm	64.3	29.3	35.0	62.5	28.4	34.0	61.8	28.1	33.7
	σ	%	3.2	7.1	6.6	3.8	7.5	6.8	4.0	7.5	6.8
n	$\bar{x}$	Nm	64.0	-	-	62.5	-	-	62.2	-	-
	σ	%	10.1	-	-	12.7	-	-	11.9	-	-
th	$\bar{x}$	Nm	64.2	29.4	34.8	62.6	28.6	33.9	62.0	28.4	33.5
	σ	%	2.4	6.6	7.4	3.1	7.0	7.6	3.6	7.2	7.7
b	$\bar{x}$	Nm	64.7	29.3	35.4	62.6	28.3	34.2	61.9	28.0	33.9
	σ	%	2.7	7.3	5.6	2.8	7.7	5.9	2.9	7.3	5.3
thb	$\bar{x}$	Nm	62.4	27.4	35.1	60.1	26.4	33.8	59.3	26.0	33.3
	σ	%	6.6	11.6	3.0	6.2	11.1	2.8	6.1	11.0	2.6

In general for both bolted joints it can be stated that with an increasing number of the tightening cycles the tightening torque T, the thread torque T_{th} and the friction torque in the head bearing area T_b decrease. This phenomenon is observed regardless of the measurement principle. Furthermore, it can be recognised that in most cases the percentage standard deviation in the tightening torque T is much lower than the percentage standard deviation of the partial torques T_{th} and T_b. The largest standard deviations from the tightening torque T of 10 % to 15 % result from the test rigs belonging to the measurement principle *n*. However, only three test rigs with this measurement principle took part in the round-robin test. For the test rigs with the measurement principle *th* and *b* the standard deviations of the partial torques are similar. The standard deviations of the partial torques are in a range of 6 % to 9 % and for the tightening torques T of 2 % to 4 %. Compared to the other measurement principles for the measurement principle *thb* (five test rigs) the smallest standard deviations in the friction torque in the head bearing area T_b and the largest in the thread torque T_{th} are observed.

5.3. Crosstalk behaviour of the test rigs

To investigate the crosstalk behaviour of the participating test rigs the mean value differences of thread torques of the two bolt variants were evaluated for the tightening processes and punctually at one preload (**Table 6** and **Annex 5**). For the mean values those test results were not included where the test rigs have been used outside of their calibration range.
The consideration of the mean value differences of *all* measurement principles shows that the mean values are 0 % and the percentage standard deviations ~ 3 %. For the test rigs with the measurement principle *thb* there is the largest percentage of mean value differences of -1 % to -2 % and test rigs with the measurement principle *b* have the largest percentage standard deviations of 4 % to 5 %.
From the test results it can be concluded that for the used test parts, in consideration of the tightening processes and the mean value differences of the thread torques for *all* measurement principles, even if grouped into the different measurement principles (*n*, *th*, *b*, *thb*) no crosstalk could be observed.

Table 6: concavity angle 0.25° and 1°: comparison of the thread torques $\frac{(\emptyset T_{th,1°} - \emptyset T_{th,0.25°}) \cdot 100}{\emptyset T_{th,1°}}$

abbr.			$\frac{(\emptyset T_{th,1°} - \emptyset T_{th,0.25°}) \cdot 100}{\emptyset T_{th,1°}}$		
			1st tightening	2nd tightening	3rd tightening
all	$\bar{x}$	%	0.0	-0.1	0.1
	σ	%	2.6	3.0	3.0
n	$\bar{x}$	%	-	-	-
	σ	%	-	-	-
th	$\bar{x}$	%	-0.1	0.0	0.2
	σ	%	1.4	1.8	1.9
b	$\bar{x}$	%	0.2	0.0	0.1
	σ	%	3.9	4.4	4.5
thb	$\bar{x}$	%	-0.5	-1.7	-1.1
	σ	%	0.9	2.0	1.2

5.4. Capability of test rigs for reliable determination of coefficients of friction

For calculating the coefficients of friction an effective diameter for the friction torque at the bolt head of $D_{b,0.25°} = 16.8\,mm$ was used for the bolts with a concavity angle of 0.25° and of $D_{b,1°} = 18.3\,mm$ for the bolts with a concavity angle of 1° (see **Paragraph 5.1**). In addition, the mean values of the preload and the torques were used for the calculation. **Table 7** and **Table 8** show the results of the coefficients of friction with mean values and standard deviations (**Annex 6** and **Annex 7**). For calculation of the mean value deviation those test results were not included where preloads different from 36,1 *kN* were used or where the test rigs have been used outside their calibration range.

Table 7: concavity angle 0.25°: comparison of the mean values $\bar{x}$ and the standard deviations σ for a preload of $F = 36.1\,kN$ and an effective diameter for the friction torque at the bolt head of $D_b = 16.8\,mm$

abbr.			1st tightening			2nd tightening			3rd tightening		
			μ_{tot}	μ_{th}	μ_b	μ_{tot}	μ_{th}	μ_b	μ_{tot}	μ_{th}	μ_b
all	$\bar{x}$	-	0.107	0.110	0.106	0.103	0.105	0.102	0.102	0.103	0.101
	σ	%	4.6	9.4	8.0	5.0	10.2	8.2	5.3	10.2	8.4
n	$\bar{x}$	-	0.104	-	-	0.101	-	-	0.100	-	-
	σ	%	15.2	-	-	16.8	-	-	16.7	-	-
th	$\bar{x}$	-	0.107	0.111	0.105	0.104	0.106	0.102	0.102	0.105	0.100
	σ	%	3.6	8.7	8.1	4.0	9.6	8.4	4.6	9.7	8.8
b	$\bar{x}$	-	0.107	0.109	0.107	0.103	0.104	0.103	0.101	0.102	0.101
	σ	%	4.4	9.4	8.3	4.5	10.3	8.5	4.5	10.0	8.3
thb	$\bar{x}$	-	0.103	0.101	0.105	0.100	0.097	0.102	0.098	0.094	0.100
	σ	%	5.5	16.0	3.2	7.0	16.7	5.0	6.3	16.5	4.3

Table 8: concavity angle 1°: comparison of the mean values $\bar{x}$ and the standard deviations σ for a preload of $F = 36.1\ kN$ and an effective diameter for the friction torque at the bolt head of $D_b = 18.3\ mm$

abbr.			1st tightening			2nd tightening			3rd tightening		
			μ_{tot}	μ_{th}	μ_b	μ_{tot}	μ_{th}	μ_b	μ_{tot}	μ_{th}	μ_b
all	$\bar{x}$		0.107	0.110	0.106	0.104	0.105	0.103	0.103	0.104	0.102
	σ	%	3.7	10.0	6.7	4.3	10.8	6.8	4.6	10.8	6.8
n	$\bar{x}$		0.107			0.103			0.103		
	σ	%	11.8			14.5			13.5		
th	$\bar{x}$		0.107	0.111	0.105	0.104	0.106	0.103	0.103	0.105	0.102
	σ	%	2.8	9.3	7.4	3.6	10.1	7.6	4.2	10.3	7.7
b	$\bar{x}$		0.108	0.110	0.107	0.104	0.105	0.104	0.103	0.103	0.103
	σ	%	3.1	10.2	5.7	3.2	11.0	5.9	3.3	10.5	5.3
thb	$\bar{x}$		0.104	0.100	0.106	0.099	0.095	0.102	0.098	0.093	0.101
	σ	%	7.6	16.9	3.0	7.3	16.4	2.8	7.1	16.4	2.6

Considering the mean values for the coefficients of friction, regardless of the bolt's concavity angle, the measurement principle of the test rig and the tightening processes the total coefficient of friction μ_{tot}, the coefficient of friction in the thread μ_{th} and the coefficient of friction in the head bearing area μ_b are between 0.09 to 0.11. Thereby the mean values are within the specified friction coefficient range VDA 235-101 [1] (**Table 9**). Similar to the standard deviations of the torques (see **Paragraph 5.2**) in most cases the standard deviations of the total coefficient of friction μ_{tot} are significantly smaller than those of the partial coefficients of friction.
To evaluate the capability of the different test rigs, they were assigned to three quality categories (**Table 10** and **Figure 2**) using the VDA 235-101 coefficient of friction range. For this, the mean values of the coefficients of friction were used.

Table 9: coefficient of friction range according to VDA 235-101 [1]

coefficient of friction	$\mu_{VDA\,max}$	$\mu_{VDA\,min}$	$\mu_{VDA\,range}$	$\frac{\mu_{VDA\,range}}{6}$	$\frac{\mu_{VDA\,range}}{3}$
total coefficient of friction μ_{tot}	0.14	0.09	0.050	0.008	0.017
coefficient of friction in the thread μ_{th}	0.16	0.08	0.080	0.013	0.027
coefficient of friction in the head bearing area μ_b	0.16	0.08	0.080	0.013	0.027

Table 10: quality categories of the test rigs

quality category	description
C_0	test rig with proper function $mean\ value\ of\ all\ test\ rigs - \frac{coefficient\ of\ friction\ range\ according\ to\ VDA\ 235-101}{6}$ $\leq mean\ value\ of\ a\ test\ rig$ $\leq mean\ value\ of\ all\ test\ rigs + \frac{coefficient\ of\ friction\ range\ according\ to\ VDA\ 235-101}{6}$
C_1	test rig with probable adverse effects on the calibrating condition of single measurement values and / or the sensor function $mean\ value\ of\ all\ test\ rigs - \frac{coefficient\ of\ friction\ range\ according\ to\ VDA\ 235-101}{3}$ $\leq mean\ value\ of\ a\ test\ rig$ $< mean\ value\ of\ all\ test\ rigs - \frac{coefficient\ of\ friction\ range\ according\ to\ VDA\ 235-101}{6}$ $mean\ value\ of\ all\ test\ rigs + \frac{coefficient\ of\ friction\ range\ according\ to\ VDA\ 235-101}{6}$ $< mean\ value\ of\ a\ test\ rig$ $\leq mean\ value\ of\ all\ test\ rigs + \frac{coefficient\ of\ friction\ range\ according\ to\ VDA\ 235-101}{3}$
C_2	test rig with distinct indications of malfunction $mean\ value\ of\ a\ test\ rig <$ $mean\ value\ of\ all\ test\ rigs - \frac{coefficient\ of\ friction\ range\ according\ to\ VDA\ 235-101}{3}$ $mean\ value\ of\ a\ test\ rig >$ $mean\ value\ of\ all\ test\ rigs + \frac{coefficient\ of\ friction\ range\ according\ to\ VDA\ 235-101}{3}$

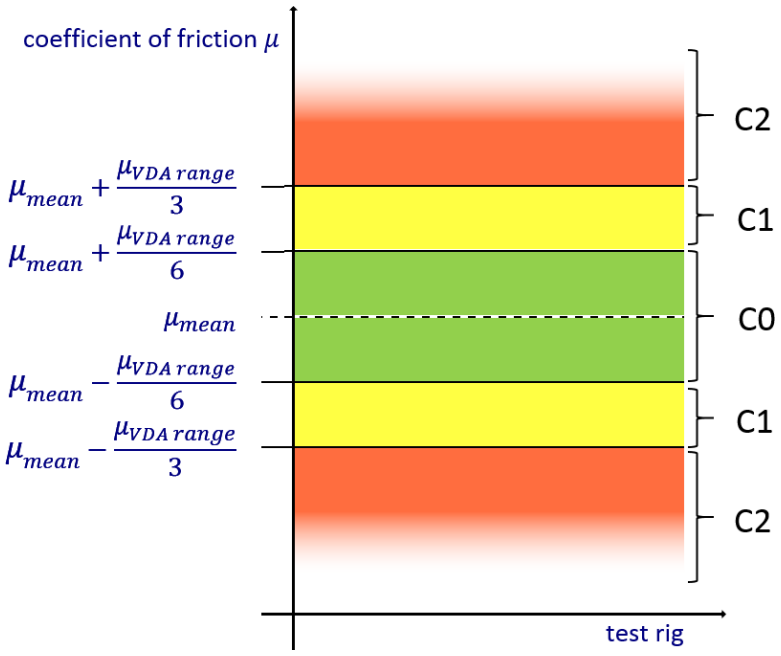


Figure 2: schematic diagram for the quality categories of the test rigs

The classification of all test rigs shows that 66 % of the participating test shows a proper function without complaint which is quality class C_0 (**Table 11**, **Annex 8** and **Annex 9**). 25 % of the test rigs can be assigned to the quality class C_1 and 9 % have distinct indications of malfunction (C_2). In many cases the classification of the test rigs does not meet the quality category C_0 because of the increased deviation of the partial coefficients of friction.
In comparison with the results of the round-robin test 2008 [7] with 81 participating test rigs there are 24 % more test rigs in the round-robin test 2014 which can be assigned to quality category C_0 whereas the number of the test rigs of category C_2 has decreased by 6 %. It is assumed that most participants of the round-robin test 2008 used the same test rig for the round-robin test 2014. The significant improvement of the results can be attributed to the following reasons:

- Other tests parts were used
  - In the round-robin test 2014 a flat washer of the hardness class HL was used which could be installed independently from its orientation in the test rig. In the round-robin test 2008 a non flat washer of the hardness class HH was used which was in a number of cases fixed incorrect despite of a relevant marking.
  - A coating was chosen which provided very reproducible results for each of the tested bolts for the first tightening as well as for the multiple tightening.
- The test parts were not only cleaned uniformly, as in 2008. In addition, they were put into airtight bags, and instructions for handling and cleanliness in the test environment were given.

The question whether today the test rigs are calibrated more often and the employees are better trained cannot be figured out from the present data. But this may also have a positive effect on the reliability of the test results.

Table 11: classification of the test rigs in three quality categories
[1)] Evaluation of the torques at a different preload
[2)] Use of the test rig/sensor outside of its calibration range

abbr.	quality category C_0	C_0 1)	C_0 2)	C_1	C_1 1)	C_1 2)	C_2	C_2 1)	C_2 2)	number
n	1	-	-	1	-	-	1	-	-	3
th	34	-	1	12	-	2	3	-	-	52
b	21	-	3	5	-	4	3	1	-	37
thb	3	1	-	-	-	-	1	-	-	5
sum:	59	1	4	18	-	6	8	1	-	97
	64 ≙ 66.0 %			24 ≙ 24.7 %			9 ≙ 9.3 %			
comparison with DSV-round-robin test 2008 (81 test rigs) [7]:										
	34 ≙ 42.0 %			35 ≙ 43.2 %			12 ≙ 14.8 %			

6 Summary

97 test rigs took part in the round-robin test 2014. As there was no decision criterion and the test parts were taken from one single batch, the total lot of measurement data was considered to be normally distributed:

- Practical suitability of the test according to VDA 235-101 [1]
  - For both bolted joints and for a preload of $F = 36.1\ kN$ the tightening torque and the partial torques decrease with an increasing number of the tightening cycles
  - In most cases the standard deviation of the tightening torque is much lower than the standard deviation of the partial torques
- Crosstalk behaviour of the test rigs
  - No crosstalk can be observed for the used test parts regarding the tightening processes, evaluated for one specified preload and the mean value differences of thread torques
  - The mean value differences of *all* measurement principles are ~ 0 %
  - Test rigs with the measurement principle *b* have the largest standard deviations
- Capability of test rigs for reliable determination of coefficients of friction
  - The test rigs were grouped into three quality categories C_0, C_1 and C_2 using the VDA 235-101 [1] coefficient of friction range
  - 66 % of the participating test rigs belong to the highest quality class C_0
  - In many cases test rigs do not meet the quality category C_0 because of the increased deviation of the partial coefficients of friction.
  - In comparison with the results of the round-robin test 2008 there is an improvement which however has to be also attributed to the tests parts, the mode of dispatch and the instructions for handling and cleanliness
- Similar to the round-robin test 2008 it was concluded for the 2014 round-robin test
  - a difference between the measurement principles *th* and *b* could not be observed during the conducted investigations
  - The manual determination of the effective diameter for the friction torque at the bolt head D_b results in a large standard deviation. There is still a big potential for improvement, because this diameter has a great influence on the calculation of the coefficient of friction.

Annex:

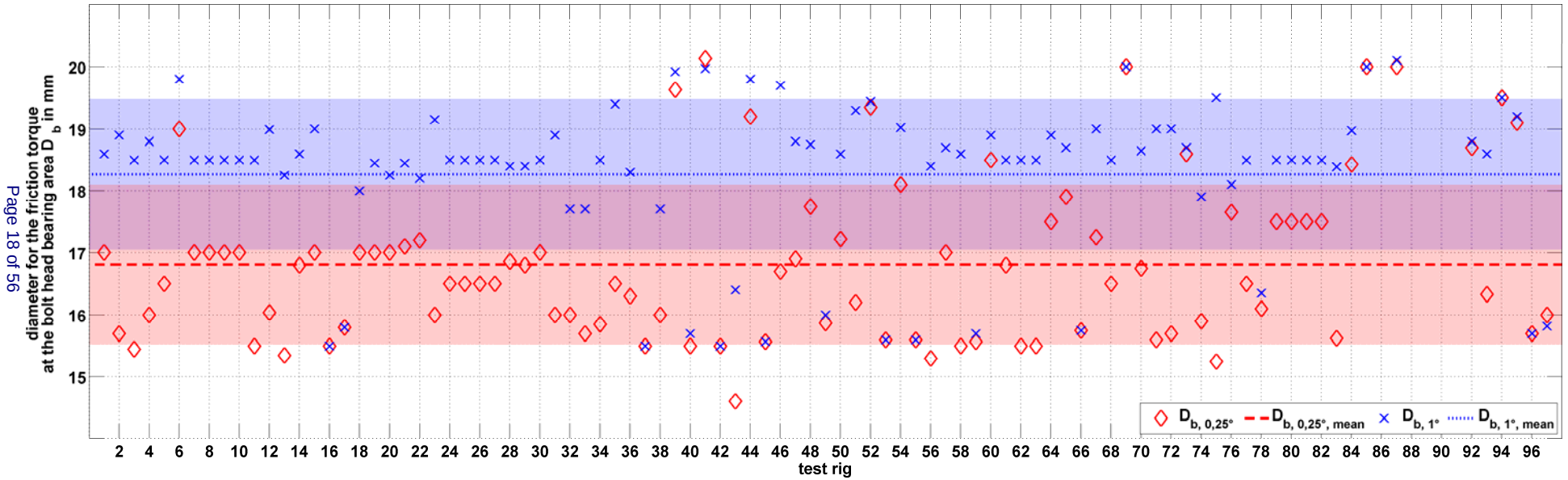
Annex 1 Participating companies in the DSV-round-robin test 2014

participant	location	country	number of test rigs
ABC Umformtechnik GmbH & Co. KG	Gevelsberg	DE	2
Acument Global Technologies	Fenton	US	1
AGRATI La Bridoire Sarl	La Bridoire	FR	1
AGRATI France	Créteil Cedex	FR	2
A. AGRATI S.p.A.	Veduggio con Colzano	IT	2
Aoyama Seisakusho Co., Ltd.	Niwa-gun	JP	1
Atotech Deutschland GmbH	Berlin	DE	10
Audi AG	Ingolstadt	DE	1
Automatica	Lure	FR	1
Formteil- und Schraubenwerk Finsterwalde GmbH	Finsterwalde	DE	1
Benseler Oberflächentechnik GmbH	Markgröningen	DE	1
Böllhoff Verbindungstechnik GmbH	Bielefeld	DE	1
Bossard AG	Zug	CH	1
Bulten GmbH	Bergkamen	DE	1
Bulten Hallstahammar AB	Hallstahammar	SE	1
Cétim	Saint Etienne Cedex 9	FR	2
COVENTYA S.A.S.	Villeneuve La Garenne	FR	1
Daimler AG	Stuttgart	DE	1
Dörken MKS GmbH	Herdecke	DE	6
Dr.-Ing. h.c. F. Porsche AG	Weissach	DE	1
DYTSA Holding S.A.	Banyoles	ES	1
Enthone GmbH	Langenfeld	DE	1
ESKA Automotive GmbH	Chemnitz	DE	1
Fuchs Schraubenwerk GmbH	Siegen	DE	1
Adam Opel AG	Rüsselsheim	DE	1
Hillebrand GmbH & Co. KG	Wickede	DE	1
IfW der TU Darmstadt	Darmstadt	DE	1
Industrial Fasteners Institute	Independence	US	8
KAMAX Holding GmbH & Co. KG	Homberg/Ohm	DE	6
Karl Berrang GmbH	Mannheim	DE	1
Klever Beschichtungstechnik GmbH & Co. KG	Bergneustadt	DE	1
Leist Oberflächentechnik e.K.	Bad Hersfeld	DE	3
LISI Automotive Knipping	Kierspe	DE	1
LISI Automotive BETEO GmbH & Co. KG	Gummersbach	DE	1
MacDermid Limited	Birmingham	GB	1
Magni Europe GmbH & Co. KG	Schorndorf	DE	2
MAN Truck & Bus AG	Nürnberg	DE	1
Meira Corporation	Nagoya City	JP	1
Nedschroef Helmond B.V.	Helmond	NL	3
Nedschroef Plettenberg GmbH	Plettenberg	DE	1
NOF METAL COATINGS EUROPE S.A.	Creil	FR	4
NOF METAL COATINGS NORTH AMERICA INC.	Chardon	FR	1
Nord-Lock France S.A.R.L.	Saint-Priest	FR	1
omniTECHNIK Mikroverkapselungs GmbH	München	DE	1
REC Fastening GmbH	Breidenbach	DE	1
RIBE Verbindungstechnik GmbH & Co. KG	Schwabach	DE	4
Saga Tekkohsho Co., Ltd.	*Fujisawa City*	JP	1
SBE-Varvit S.p.A.	Monfalcone - Gorizia	IT	1
Schatz AG	Remscheid	DE	1
TesT GmbH	Erkrath	DE	1
Volkswagen AG	Hannover	DE	1
Volkswagen AG	Wolfsburg	DE	1
Westsächsische Hochschule Zwickau	Zwickau	DE	1
Whitesell Germany GmbH & Co. KG	Neuwied	DE	1
Zeschky Beschichtungstechnik GmbH	Wetter	DE	1
ZF-Friedrichshafen AG	Friedrichshafen	DE	1
		sum	97

Annex 2 Measured effective diameter for the friction torque at the bolt head D_b

test rig Nr.	D_b in mm concavity angle 0.25°	concavity angle 1°	test rig Nr.	D_b in mm concavity angle 0.25°	concavity angle 1°
1	17.00	18.60	51	16.20	19.30
2	15.70	18.90	52	19.35	19.44
3	15.45	18.50	53	15.60	15.60
4	16.00	18.80	54	18.10	19.02
5	16.50	18.50	55	15.60	15.60
6	19.00	19.80	56	15.30	18.40
7	17.00	18.50	57	17.00	18.70
8	17.00	18.50	58	15.50	18.60
9	17.00	18.50	59	15.57	15.70
10	17.00	18.50	60	18.50	18.90
11	15.50	18.50	61	16.80	18.50
12	16.04	18.99	62	15.50	18.50
13	15.35	18.25	63	15.50	18.50
14	16.80	18.60	64	17.50	18.90
15	17.00	19.00	65	17.90	18.70
16	15.50	15.50	66	15.75	15.75
17	15.80	15.80	67	17.25	19.00
18	17.00	18.00	68	16.50	18.50
19	17.00	18.45	69	20.00	20.00
20	17.00	18.25	70	16.75	18.65
21	17.10	18.45	71	15.60	19.00
22	17.20	18.20	72	15.70	19.00
23	16.00	19.15	73	18.60	18.70
24	16.50	18.50	74	15.90	17.90
25	16.50	18.50	75	15.25	19.50
26	16.50	18.50	76	17.65	18.10
27	16.50	18.50	77	16.50	18.50
28	16.86	18.40	78	16.10	16.35
29	16.80	18.40	79	17.50	18.50
30	17.00	18.50	80	17.50	18.50
31	16.00	18.90	81	17.50	18.50
32	16.00	17.70	82	17.50	18.50
33	15.70	17.70	83	15.63	18.39
34	15.85	18.50	84	18.43	18.97
35	16.50	19.40	85	20.00	20.00
36	16.30	18.30	86	-	-
37	15.50	15.50	87	20.00	20.10
38	16.00	17.70	88	-	-
39	19.63	19.92	89	-	-
40	15.50	15.70	90	-	-
41	20.13	19.97	91	-	-
42	15.50	15.50	92	18.70	18.80
43	14.60	16.40	93	16.33	18.60
44	19.20	19.80	94	19.50	19.50
45	15.57	15.57	95	19.10	19.20
46	16.70	19.70	96	15.70	15.70
47	16.90	18.80	97	16.00	15.82
48	17.74	18.75			
49	15.87	16.00			
50	17.22	18.60			

	D_b in mm concavity angle 0.25°	concavity angle 1°
mean value $\bar{x}$	16.8	18.3
standard deviation σ	1.3	1.2
standard deviation σ_{rel} in %	7.7	6.6
minimum x_{min}	14.6	15.5
maximum x_{max}	20.1	20.1


diameter for the friction torque
at the bolt head bearing area D b in mm
test rig
D b, 0,25°
D b, 0,25°, mean
D b, 1°
D b, 1°, mean

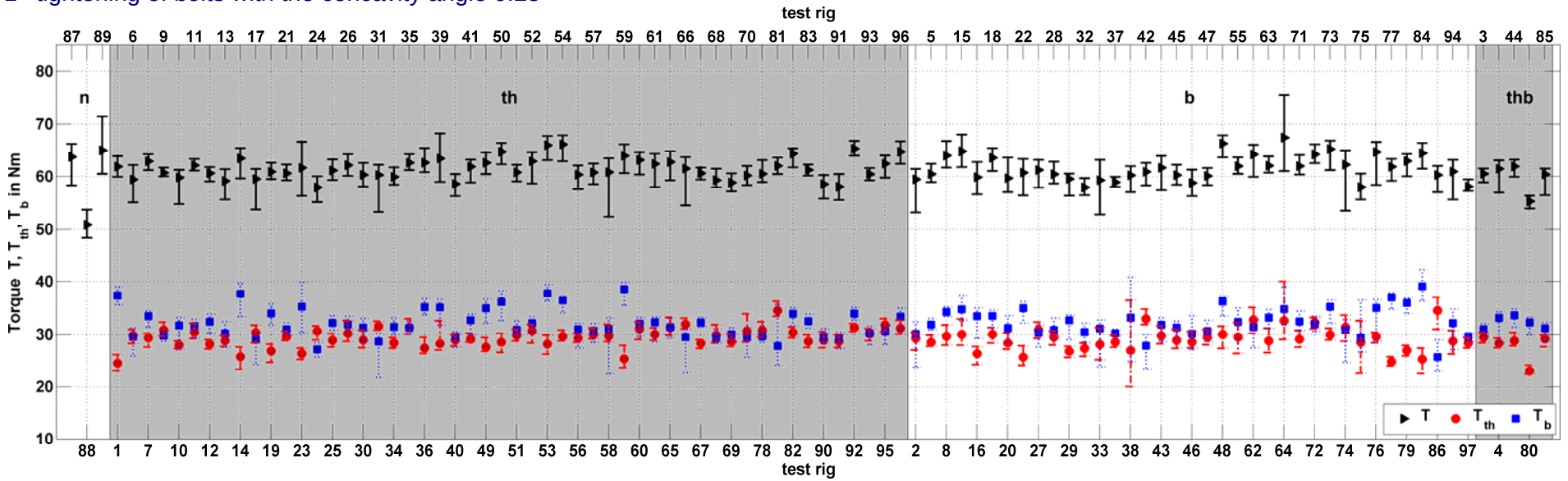
Annex 3 Documented torques for bolts with a concavity angle of 0.25°

test rig Nr.	test rig type	1st tightening				2nd tightening				3rd tightening			
		preload F kN	tightening torque T Nm	thread torque T_{th} Nm	friction torque in the head bearing area T_b Nm	preload F kN	tightening torque T Nm	thread torque T_{th} Nm	friction torque in the head bearing area T_b Nm	preload F kN	tightening torque T Nm	thread torque T_{th} Nm	friction torque in the head bearing area T_b Nm
1	th	36.12	61.86	24.54	37.31	36.12	59.49	23.40	36.09	36.12	58.88	23.20	35.69
2	b	36.10	59.42	29.28	30.14	36.10	57.23	28.24	28.98	36.10	56.22	27.92	28.29
3	thb	36.10	60.49	29.49	30.99	36.10	58.92	28.92	30.00	36.10	58.21	28.75	29.46
4	thb	36.10	61.43	28.36	33.16	36.10	61.43	28.36	33.16	36.10	59.15	27.16	32.08
5	b	36.10	60.43	28.54	31.89	36.10	57.92	27.59	30.33	36.10	56.77	27.23	29.55
6	th	36.11	59.38	29.83	29.55	36.11	57.04	28.82	28.22	36.11	55.94	28.51	27.43
7	th	36.10	62.88	29.38	33.44	36.10	60.86	29.01	32.20	36.10	59.73	28.40	31.32
8	b	36.10	63.96	29.70	34.26	36.10	61.37	28.44	32.92	36.10	60.16	27.90	32.26
9	th	36.10	60.67	30.89	29.79	36.10	58.15	29.66	28.51	36.10	57.05	29.24	27.81
10	th	36.10	59.75	28.01	31.74	36.10	58.12	27.36	30.77	36.10	57.55	27.28	30.26
11	th	36.10	62.10	30.45	31.64	36.10	60.07	29.76	30.31	36.11	59.12	29.48	29.64
12	th	36.21	60.59	28.19	32.41	36.20	58.62	27.27	31.35	36.16	58.02	27.00	31.02
13	th	36.12	59.10	28.85	30.25	36.12	57.56	28.22	29.34	36.12	56.48	27.79	28.70
14	th	36.12	63.42	25.78	37.64	36.12	61.16	24.24	36.92	36.12	60.14	24.13	36.01
15	b	36.09	64.76	30.04	34.73	36.08	62.47	28.91	33.56	36.11	61.77	28.51	33.26
16	b	36.10	59.82	26.37	33.45	36.10	57.74	25.31	32.43	36.10	56.79	24.94	31.86
17	th	36.11	59.48	30.38	29.10	36.12	57.22	28.92	28.29	36.12	56.48	28.64	27.84
18	b	36.10	63.54	30.06	33.51	36.10	62.58	29.58	33.03	36.10	60.83	28.96	31.87
19	th	36.10	60.87	26.88	33.98	36.10	58.46	25.61	32.85	36.10	58.12	25.66	32.47
20	b	36.10	59.63	28.41	31.22	36.10	57.42	27.20	30.23	36.10	56.60	26.83	29.77
21	th	36.08	60.58	29.57	31.02	36.10	59.20	28.60	30.60	36.09	58.64	28.30	30.35
22	b	36.10	60.69	25.71	34.98	36.10	58.27	24.63	33.64	36.10	57.06	24.20	32.86
23	th	36.12	61.62	26.39	35.23	36.12	59.29	25.72	33.57	36.12	58.51	25.51	33.00
24	th	36.06	57.86	30.64	27.22	36.10	55.64	29.83	25.81	36.10	54.64	29.54	25.10
25	th	36.12	61.12	28.92	32.21	36.13	58.68	28.03	30.65	36.12	57.44	27.73	29.71
26	th	36.10	62.12	30.21	31.91	36.10	60.05	29.29	30.76	36.10	59.25	28.92	30.33
27	b	36.10	61.20	30.88	30.33	36.10	59.34	30.09	29.25	36.10	58.31	29.71	28.60
28	b	36.10	60.40	29.54	30.86	36.13	58.76	28.57	30.17	36.10	57.65	28.26	29.42
29	b	36.11	59.49	26.82	32.67	36.12	57.36	25.98	31.37	36.07	56.39	25.75	30.64
30	th	36.10	60.28	28.96	31.32	36.10	57.88	28.01	29.87	36.10	56.92	27.69	29.23
31	th	36.12	60.25	31.57	28.68	36.12	58.63	31.14	27.50	36.12	57.62	30.99	26.63
32	b	36.10	57.86	27.37	30.48	36.10	55.34	26.10	29.24	36.10	54.44	25.85	28.58
33	b	36.10	59.25	28.13	31.12	36.10	56.98	27.16	29.82	36.10	56.24	26.72	29.52
34	th	36.06	59.88	28.44	31.44	36.07	58.21	27.96	30.25	36.04	57.60	27.97	29.63
35	th	36.10	62.59	31.34	31.26	36.10	60.59	30.81	29.78	36.10	59.41	30.52	28.89
36	th	36.11	62.62	27.45	35.16	36.10	60.72	26.70	34.02	36.10	59.73	26.54	33.18
37	b	36.10	58.85	28.61	30.23	36.10	57.00	27.46	29.53	36.10	56.06	27.16	28.89
38	b	36.10	60.18	26.99	33.19	36.10	58.96	26.08	32.89	36.10	57.68	25.19	32.49
39	th	36.10	63.41	28.29	35.12	36.10	61.41	26.94	34.48	36.10	60.78	26.62	34.17

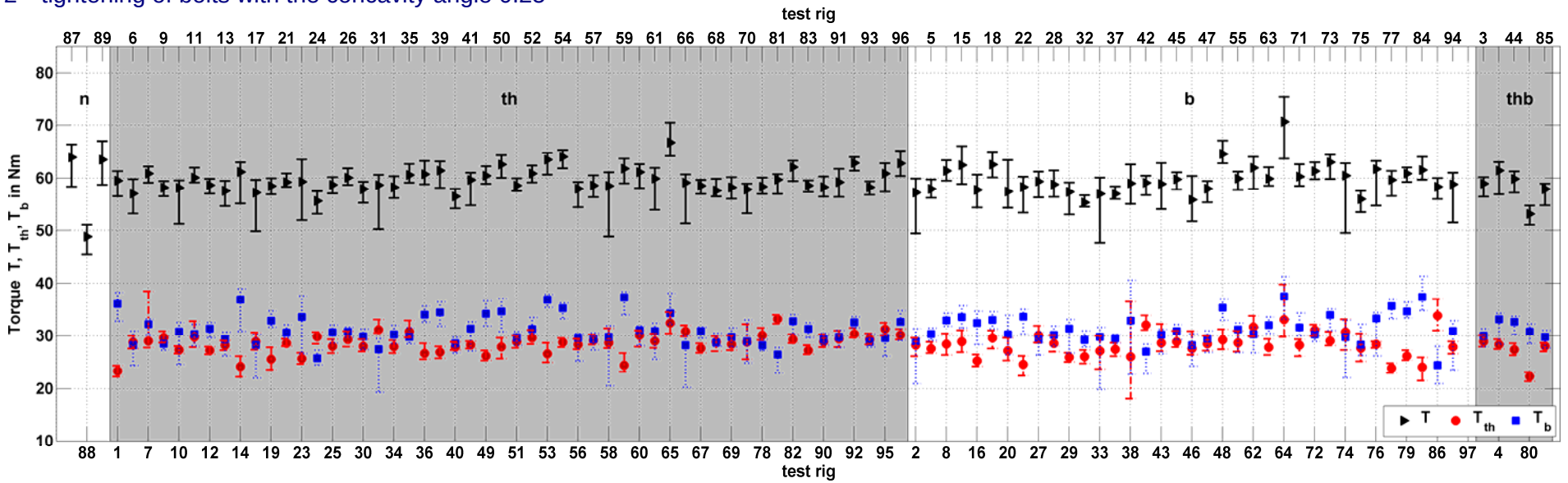
test rig Nr.	test rig type	1st tightening				2nd tightening				3rd tightening			
		preload F kN	tightening torque T Nm	thread torque T_{th} Nm	friction torque in the head bearing area T_b Nm	preload F kN	tightening torque T Nm	thread torque T_{th} Nm	friction torque in the head bearing area T_b Nm	preload F kN	tightening torque T Nm	thread torque T_{th} Nm	friction torque in the head bearing area T_b Nm
40	th	36.08	58.53	28.95	29.58	36.07	56.49	27.88	28.60	36.07	55.84	27.59	28.25
41	th	36.10	61.84	29.13	32.71	36.10	59.62	28.29	31.34	36.10	58.75	28.02	30.73
42	b	36.10	60.86	32.96	27.90	36.10	59.08	32.06	27.03	36.10	58.18	31.78	26.42
43	b	36.10	61.64	29.79	31.85	36.11	58.86	28.65	30.20	36.09	57.81	28.35	29.47
44	thb	38.00	61.88	28.83	33.62	38.00	59.83	27.40	32.66	38.00	58.98	27.16	32.15
45	b	36.10	60.21	28.92	31.33	36.10	59.75	28.89	30.87	36.10	59.04	28.42	30.60
46	b	36.10	58.73	28.59	30.15	36.10	55.86	27.61	28.25	36.10	55.36	27.48	27.84
47	b	36.10	60.06	29.46	30.63	36.10	57.95	28.49	29.48	36.10	57.02	28.15	28.88
48	b	36.10	66.26	30.03	36.23	36.10	64.60	29.23	35.37	36.10	64.01	28.90	35.11
49	th	36.10	62.59	27.64	34.96	36.10	60.43	26.24	34.20	36.10	59.61	26.07	33.54
50	th	36.13	64.68	28.57	36.12	36.13	62.60	27.93	34.67	36.13	61.62	27.60	34.02
51	th	36.12	60.76	29.86	30.90	36.11	58.55	28.87	29.68	36.12	57.47	28.46	29.01
52	th	36.11	62.87	30.71	32.17	36.11	60.86	29.60	31.26	36.11	60.21	29.34	30.87
53	th	36.12	65.93	28.21	37.73	36.12	63.51	26.63	36.88	36.12	62.71	26.20	36.52
54	th	36.12	66.09	29.64	36.45	36.12	64.06	28.78	35.28	36.12	63.18	28.52	34.66
55	b	36.10	61.95	29.54	32.40	36.10	59.88	28.70	31.18	36.10	58.96	28.39	30.57
56	th	36.12	60.31	29.31	31.00	36.12	57.95	28.34	29.61	36.12	56.88	28.06	28.82
57	th	36.12	60.74	30.00	30.74	36.12	58.55	29.15	29.40	36.12	57.66	29.05	28.61
58	th	36.11	60.79	29.73	31.06	36.12	58.48	28.68	29.80	36.12	57.62	28.43	29.19
59	th	36.12	63.92	25.40	38.52	36.12	61.79	24.47	37.33	36.12	61.12	24.33	36.79
60	th	36.10	63.12	31.07	32.04	36.10	61.13	30.10	31.03	36.10	60.31	29.75	30.56
61	th	36.10	62.38	30.04	32.34	36.10	59.88	29.00	30.88	36.10	58.95	28.76	30.20
62	b	36.11	64.18	32.78	31.41	36.11	61.96	31.67	30.28	36.09	61.32	31.60	29.72
63	b	36.12	62.03	28.81	33.20	36.10	59.87	27.82	32.04	36.10	58.84	27.41	31.43
64	b	38.51	67.38	32.60	34.78	38.51	70.58	33.08	37.50	38.51	73.52	33.58	39.93
65	th	36.10	62.74	31.33	31.41	36.10	66.73	32.43	34.30	36.10	68.71	32.71	36.00
66	th	36.10	61.47	31.94	29.53	36.11	59.09	30.84	28.25	36.11	58.27	30.59	27.68
67	th	36.12	60.60	28.34	32.25	36.12	58.52	27.65	30.86	36.11	57.53	27.34	30.18
68	th	36.12	59.25	29.93	29.32	36.12	57.61	28.87	28.74	36.12	57.23	28.61	28.61
69	th	36.11	58.78	28.69	30.08	36.12	58.19	28.41	29.78	36.08	57.87	28.34	29.53
70	th	36.10	60.14	30.63	29.50	36.10	57.80	28.83	28.97	36.10	56.60	28.65	27.96
71	b	36.16	61.95	29.13	32.46	36.17	60.27	28.25	31.60	36.16	59.52	27.94	31.07
72	b	36.10	64.18	32.27	31.92	36.10	61.33	31.08	30.24	36.10	60.20	30.70	29.50
73	b	36.10	65.19	29.97	35.22	36.10	63.03	29.04	33.99	36.10	62.18	28.66	33.52
74	b	36.09	62.22	31.39	30.83	36.11	60.46	30.72	29.74	36.10	59.42	30.31	29.11
75	b	35.60	57.91	28.52	29.39	36.10	55.98	27.66	28.32	36.12	55.17	27.50	27.68
76	b	36.10	64.64	29.62	35.02	36.10	61.71	28.40	33.31	36.10	60.57	28.03	32.54
77	b	36.12	61.83	24.84	36.99	36.13	59.63	23.94	35.70	36.14	58.58	23.66	34.91
78	th	36.10	60.47	30.80	29.67	36.10	58.34	30.10	28.24	36.10	57.35	29.86	27.49
79	b	36.10	62.93	26.98	35.94	36.10	60.85	26.21	34.64	36.10	59.74	25.74	33.99
80	thb	36.10	55.27	23.06	32.26	36.10	53.17	22.39	30.78	36.10	52.36	22.09	30.26
81	th	36.13	62.00	34.51	27.84	36.01	59.68	33.19	26.49	36.08	59.37	33.06	26.31

test rig Nr.	test rig type	1st tightening preload F kN	1st tightening tightening torque T Nm	1st tightening thread torque T_{th} Nm	1st tightening friction torque in the head bearing area T_b Nm	2nd tightening preload F kN	2nd tightening tightening torque T Nm	2nd tightening thread torque T_{th} Nm	2nd tightening friction torque in the head bearing area T_b Nm	3rd tightening preload F kN	3rd tightening tightening torque T Nm	3rd tightening thread torque T_{th} Nm	3rd tightening friction torque in the head bearing area T_b Nm
82	th	36.10	64.31	30.40	33.91	36.10	62.09	29.30	32.79	36.10	61.36	28.97	32.39
83	th	36.10	61.22	28.71	32.51	36.10	58.55	27.25	31.30	36.10	57.69	26.92	30.76
84	b	36.10	64.41	25.32	39.07	36.10	61.54	24.12	37.42	36.10	60.50	23.83	36.66
85	thb	36.10	60.37	29.20	31.17	36.10	57.89	28.07	29.82	36.10	56.76	27.52	29.23
86	b	36.32	60.24	34.52	25.72	36.31	58.32	33.84	24.48	36.54	57.96	32.60	25.36
87	n	36.10	63.72			36.10	63.97			36.10	63.06		
88	n	36.10	50.87			36.10	48.82			36.10	48.31		
89	n	36.14	64.94			36.69	63.53			36.60	62.82		
90	th	36.10	58.49	28.93	29.56	36.10	58.25	28.88	29.37	36.10	57.52	28.47	29.05
91	th	36.10	57.99	28.68	29.31	36.10	59.20	29.42	29.78	36.10	57.87	28.64	29.23
92	th	36.10	65.27	31.33	33.95	36.10	62.88	30.33	32.56	36.10	61.93	29.94	31.98
93	th	36.12	60.41	30.17	30.23	36.12	58.22	29.35	28.88	36.12	57.43	29.12	28.31
94	b	36.10	60.91	28.76	32.15	36.10	58.79	27.90	30.89	36.10	57.93	27.46	30.47
95	th	36.12	62.42	31.82	30.60	36.12	60.84	31.25	29.59	36.12	59.96	31.07	28.89
96	th	36.1	64.67	31.19	33.36	36.10	62.81	30.15	32.66	36.10	62.39	29.97	32.42
97	b	36.1	58.025	28.41	29.61								
mean value $\bar{x}$		36.1	61.3	29.2	32.1	36.1	59.4	28.4	31.1	36.1	58.6	28.1	30.5
standard deviation σ		0.1	2.4	1.9	2.6	0.1	2.5	2.0	2.6	0.1	2.6	2.0	2.6
standard deviation σ_{rel} in %		0.3	3.9	6.5	8.1	0.3	4.2	7.0	8.4	0.3	4.4	7.1	8.5
minimum x_{min}		35.6	50.9	23.1	25.7	36.0	48.8	22.4	24.5	36.0	48.3	22.1	25.1
maximum x_{max}		36.3	66.3	34.5	39.1	36.7	66.7	33.8	37.4	36.6	68.7	33.1	36.8

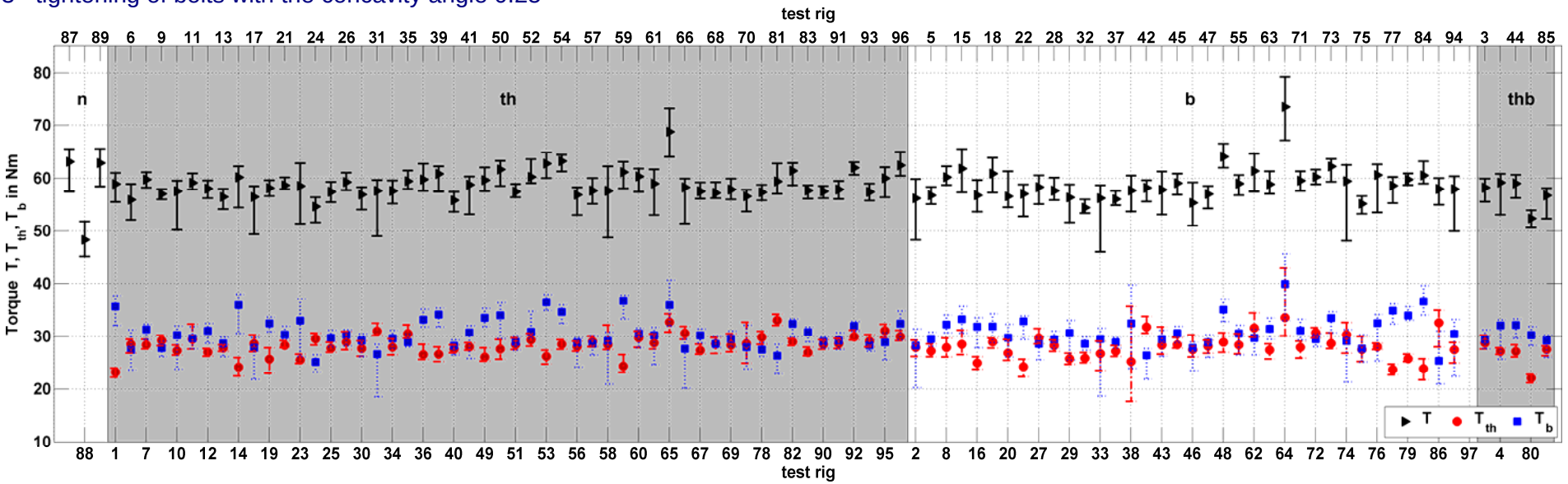
1st tightening of bolts with the concavity angle 0.25°



2nd tightening of bolts with the concavity angle 0.25°



3rd tightening of bolts with the concavity angle 0.25°



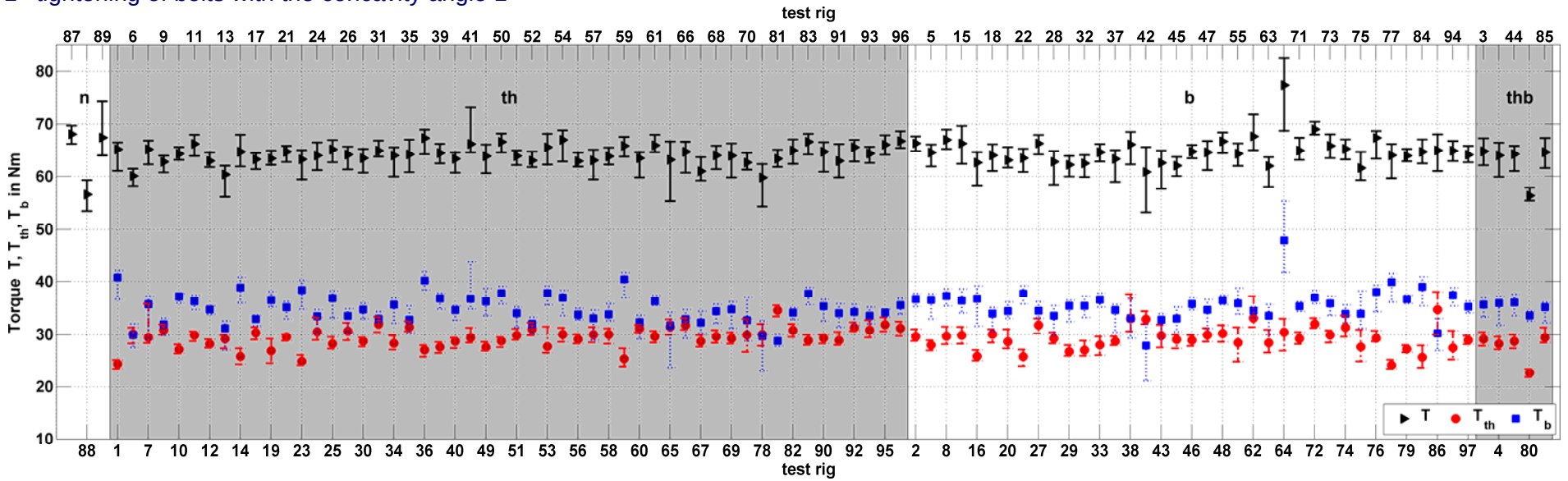
Annex 4 Documented torques for bolts with a concavity angle of 1°

test rig Nr.	test rig type	1st tightening				2nd tightening				3rd tightening			
		preload F kN	tightening torque T Nm	thread torque T_{th} Nm	friction torque in the head bearing area T_b Nm	preload F kN	tightening torque T Nm	thread torque T_{th} Nm	friction torque in the head bearing area T_b Nm	preload F kN	tightening torque T Nm	thread torque T_{th} Nm	friction torque in the head bearing area T_b Nm
1	th	36.12	65.15	24.40	40.75	36.12	63.07	23.34	39.72	36.12	62.64	23.28	39.36
2	b	36.10	66.28	29.65	36.66	36.10	64.19	28.49	35.69	36.10	63.40	28.06	35.33
3	thb	36.10	64.77	29.15	35.62	36.10	62.77	28.29	34.48	36.10	61.96	28.07	33.89
4	thb	36.10	63.99	28.26	35.94	36.10	61.31	27.03	34.52	36.10	60.42	26.63	34.00
5	b	36.10	64.53	28.01	36.52	36.10	62.52	27.29	35.23	36.10	61.78	27.03	34.75
6	th	36.11	60.07	30.13	29.94	36.11	57.64	29.49	28.15	36.11	56.70	29.24	27.45
7	th	36.10	65.14	29.47	35.71	36.10	63.68	28.50	35.18	36.10	63.03	28.28	34.76
8	b	36.10	66.95	29.70	37.26	36.10	64.84	28.42	35.98	36.10	63.38	28.02	35.34
9	th	36.10	62.78	30.85	31.94	36.10	60.03	29.48	30.56	36.10	59.15	29.26	29.89
10	th	36.09	64.29	27.16	37.14	36.10	62.96	26.56	36.40	36.08	62.38	26.49	35.89
11	th	36.10	66.18	29.89	36.29	36.10	64.35	29.17	35.18	36.10	63.51	28.95	34.55
12	th	36.18	62.95	28.23	34.72	36.18	60.78	27.15	33.63	36.16	60.00	26.72	33.28
13	th	36.11	60.35	29.18	31.17	36.12	58.88	28.61	30.27	36.12	58.15	28.31	29.84
14	th	36.12	64.67	25.83	38.84	36.11	62.51	24.16	38.34	36.12	61.72	24.14	37.58
15	b	36.11	66.26	29.86	36.40	36.10	64.47	28.85	35.63	36.06	64.09	28.55	35.53
16	b	36.10	62.63	25.88	36.74	36.10	60.33	25.09	35.24	36.10	59.58	24.77	34.81
17	th	36.12	63.26	30.33	32.94	36.12	60.94	28.81	32.12	36.12	59.97	28.52	31.44
18	b	36.10	64.01	30.04	33.96	36.10	62.40	29.28	33.14	36.10	61.75	29.15	32.58
19	th	36.10	63.41	26.92	36.50	36.10	61.60	27.02	34.58	36.10	60.73	26.70	34.04
20	b	36.10	63.08	28.66	34.42	36.10	60.69	27.07	33.62	36.10	59.16	26.33	32.83
21	th	36.07	64.69	29.55	35.13	36.10	62.98	28.69	34.29	36.09	62.23	28.41	33.83
22	b	36.10	63.49	25.80	37.69	36.10	61.31	24.92	36.39	36.10	60.07	24.52	35.56
23	th	36.13	63.26	24.92	38.34	36.12	61.14	24.26	36.88	36.12	60.32	23.93	36.39
24	th	36.06	63.98	30.52	33.46	36.10	62.24	29.79	32.45	36.08	61.51	29.64	31.87
25	th	36.12	65.12	28.26	36.86	36.12	62.62	27.23	35.39	36.12	61.49	26.87	34.62
26	th	36.10	64.15	30.63	33.51	36.10	62.17	29.74	32.42	36.10	61.72	29.48	32.24
27	b	36.10	66.26	31.77	34.49	36.10	64.96	31.40	33.56	36.10	64.19	31.22	32.98
28	b	36.12	62.79	29.26	33.54	36.10	61.13	28.07	33.06	36.12	60.52	27.87	32.66
29	b	36.11	62.21	26.77	35.43	36.10	60.30	25.90	34.39	36.09	59.44	25.84	33.59
30	th	36.10	63.48	28.77	34.72	36.10	60.84	27.79	33.05	36.10	60.11	27.53	32.57
31	th	36.12	64.89	31.93	32.96	36.12	63.53	31.37	32.16	36.12	62.86	31.23	31.64
32	b	36.10	62.48	27.07	35.42	36.10	59.89	25.67	34.22	36.10	58.96	25.52	33.44
33	b	36.10	64.60	28.04	36.56	36.10	62.52	27.29	35.23	36.10	61.62	26.92	34.70
34	th	36.05	63.98	28.35	35.63	36.03	62.62	27.90	34.72	36.04	62.40	27.85	34.55
35	th	36.10	64.19	31.40	32.79	36.10	61.88	30.67	31.20	36.10	60.94	30.42	30.52
36	th	36.11	67.28	27.08	40.20	36.11	65.61	26.51	39.10	36.10	64.94	26.38	38.56
37	b	36.10	63.33	28.72	34.60	36.10	61.02	27.76	33.24	36.10	60.07	27.58	32.50
38	b	36.10	66.07	32.99	33.08	36.10	62.83	32.10	30.74	36.10	62.34	31.08	31.26
39	th	36.10	64.44	27.64	36.81	36.10	62.51	26.35	36.16	36.10	61.80	26.06	35.74

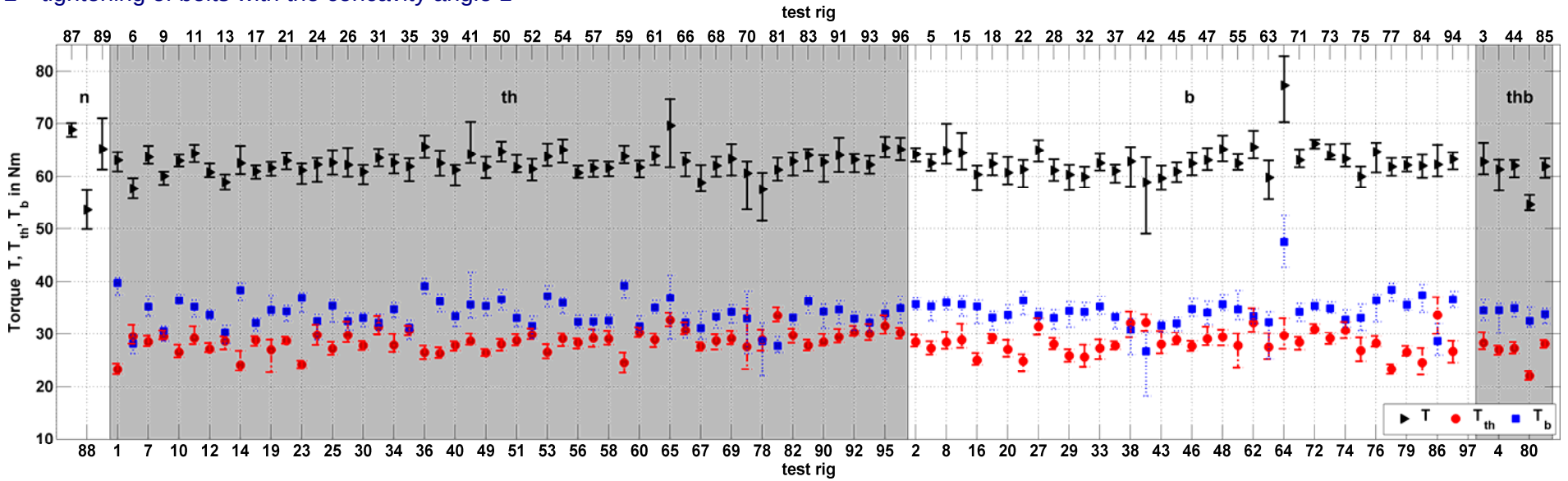
test rig Nr.	test rig type	1st tightening				2nd tightening				3rd tightening			
		preload F kN	tightening torque T Nm	thread torque T_{th} Nm	friction torque in the head bearing area T_b Nm	preload F kN	tightening torque T Nm	thread torque T_{th} Nm	friction torque in the head bearing area T_b Nm	preload F kN	tightening torque T Nm	thread torque T_{th} Nm	friction torque in the head bearing area T_b Nm
40	th	36.07	63.35	28.73	34.62	36.07	61.22	27.86	33.36	36.04	60.64	27.62	33.02
41	th	36.10	66.17	29.43	36.75	36.10	64.22	28.62	35.60	36.10	63.64	28.42	35.22
42	b	36.10	60.82	32.90	27.92	36.10	58.87	32.19	26.73	36.10	58.02	31.80	26.20
43	b	36.09	62.58	29.81	32.77	36.11	59.63	28.04	31.59	36.10	58.84	27.63	31.21
44	thb	38.00	64.24	28.74	36.06	38.00	62.02	27.28	34.93	38.00	61.10	27.13	34.32
45	b	36.10	62.04	29.06	33.00	36.10	60.90	28.90	32.02	36.10	60.06	28.35	31.68
46	b	36.10	64.71	28.92	35.79	36.10	62.47	27.70	34.77	36.10	62.36	27.79	34.44
47	b	36.10	64.58	29.94	34.64	36.11	63.10	29.04	34.06	36.09	63.10	28.77	34.32
48	b	36.10	66.66	30.20	36.46	36.10	65.15	29.40	35.65	36.10	64.20	28.97	35.23
49	th	36.10	63.85	27.62	36.24	36.10	61.79	26.47	35.33	36.10	61.36	26.33	35.03
50	th	36.12	66.57	28.80	37.77	36.13	64.70	28.06	36.64	36.12	63.88	27.90	35.99
51	th	36.12	63.89	29.86	34.03	36.12	61.80	28.73	33.07	36.12	61.24	28.39	32.85
52	th	36.11	63.03	31.01	32.03	36.11	61.41	29.86	31.55	36.12	61.74	29.48	32.27
53	th	36.12	65.53	27.74	37.79	36.12	63.77	26.57	37.20	36.12	62.88	26.21	36.67
54	th	36.12	66.95	30.03	36.92	36.12	65.05	29.10	35.95	36.12	64.14	28.88	35.26
55	b	36.10	64.31	28.47	35.85	36.10	62.48	27.80	34.68	36.10	61.67	27.55	34.11
56	th	36.11	62.91	29.12	33.78	36.11	60.69	28.36	32.33	36.12	59.63	28.04	31.59
57	th	36.12	63.06	30.01	33.05	36.11	61.57	29.18	32.40	36.12	61.11	29.04	32.07
58	th	36.12	63.82	30.01	33.81	36.12	61.60	29.05	32.56	36.12	60.81	28.78	32.03
59	th	36.12	65.80	25.40	40.40	36.12	63.81	24.62	39.19	36.12	63.06	24.58	38.48
60	th	36.10	63.47	31.14	32.33	36.10	61.70	30.23	31.48	36.10	61.21	29.88	31.33
61	th	36.10	65.90	29.64	36.26	36.10	63.90	28.89	35.01	36.10	63.37	28.71	34.65
62	b	36.10	67.61	33.09	34.50	36.10	65.56	32.14	33.42	36.10	65.01	31.90	33.11
63	b	36.08	61.98	28.44	33.53	36.10	59.77	27.52	32.25	36.09	58.63	27.15	31.50
64	b	38.51	77.27	30.45	47.90	38.51	77.20	29.69	47.51	38.51	79.44	30.11	49.33
65	th	36.10	63.17	31.43	31.74	36.10	69.55	32.65	36.90	36.10	71.21	33.15	38.06
66	th	36.10	64.69	31.75	32.94	36.10	62.89	30.68	32.20	36.10	62.60	30.49	32.11
67	th	36.11	60.98	28.72	32.26	36.11	58.79	27.66	31.13	36.12	57.88	27.41	30.46
68	th	36.12	64.01	29.62	34.38	36.12	62.02	28.68	33.34	36.12	61.41	28.52	32.89
69	th	36.10	63.94	29.25	34.73	36.10	63.32	29.09	34.23	36.09	63.28	29.21	33.99
70	th	36.11	62.65	29.95	32.69	36.14	60.56	27.58	32.96	36.10	59.83	27.20	32.65
71	b	36.11	64.89	29.25	35.32	36.16	63.10	28.41	34.20	36.17	62.68	28.08	34.03
72	b	36.10	68.97	31.99	36.97	36.10	66.20	30.89	35.31	36.10	65.29	30.50	34.79
73	b	36.10	65.80	29.92	35.88	36.10	64.01	29.14	34.87	36.10	63.23	28.83	34.40
74	b	36.11	65.24	31.33	33.90	36.11	63.36	30.63	32.73	36.06	62.65	30.17	32.48
75	b	36.09	61.59	27.66	33.92	36.09	59.96	26.86	33.10	36.10	59.36	26.42	32.96
76	b	36.10	67.34	29.33	38.01	36.10	64.66	28.23	36.44	36.10	63.83	27.90	35.93
77	b	36.11	64.02	24.17	39.85	36.13	61.82	23.37	38.45	36.11	60.82	23.16	37.66
78	th	36.10	59.76	30.05	29.71	36.10	57.50	28.89	28.60	36.10	56.65	28.62	28.04
79	b	36.10	63.93	27.26	36.66	36.10	62.14	26.57	35.57	36.10	61.09	26.08	35.01
80	thb	36.10	56.31	22.70	33.61	36.10	54.61	22.09	32.52	36.10	53.95	21.84	32.10
81	th	36.13	63.36	34.55	28.81	36.04	61.24	33.51	27.73	36.08	60.78	33.39	27.38

test rig Nr.	test rig type	1st tightening preload F kN	1st tightening tightening torque T Nm	1st tightening thread torque T_{th} Nm	1st tightening friction torque in the head bearing area T_b Nm	2nd tightening preload F kN	2nd tightening tightening torque T Nm	2nd tightening thread torque T_{th} Nm	2nd tightening friction torque in the head bearing area T_b Nm	3rd tightening preload F kN	3rd tightening tightening torque T Nm	3rd tightening thread torque T_{th} Nm	3rd tightening friction torque in the head bearing area T_b Nm
82	th	36.10	64.92	30.80	34.12	36.10	62.86	29.73	33.13	36.10	62.28	29.38	32.90
83	th	36.10	66.58	28.88	37.70	36.10	64.02	27.82	36.21	36.10	63.09	27.54	35.55
84	b	36.10	64.67	25.69	38.98	36.10	62.01	24.62	37.40	36.10	61.42	24.24	37.19
85	thb	36.10	64.62	29.45	35.17	36.10	61.90	28.14	33.76	36.10	60.71	27.60	33.11
86	b	36.57	64.92	34.68	30.24	36.20	62.24	33.60	28.64	36.29	61.92	32.08	29.84
87	n	36.10	68.04			36.10	68.80			36.10	67.71		
88	n	36.11	56.54			36.10	53.62			36.10	53.83		
89	n	36.00	67.38			36.71	65.20			36.80	65.15		
90	th	36.10	64.70	29.36	35.34	36.10	62.74	28.47	34.27	36.10	62.18	28.47	33.72
91	th	36.10	62.94	28.91	34.04	36.10	64.04	29.38	34.66	36.10	62.60	28.74	33.86
92	th	36.10	65.54	31.29	34.25	36.10	63.18	30.25	32.93	36.10	62.41	29.92	32.49
93	th	36.12	64.36	30.83	33.53	36.12	62.20	30.03	32.16	36.12	61.58	29.94	31.62
94	b	36.10	64.86	27.49	37.38	36.10	63.28	26.70	36.58	36.10	62.50	26.28	36.22
95	th	36.12	66.02	31.85	34.18	36.12	65.44	31.53	33.91	36.11	65.54	31.49	34.06
96	th	36.10	66.72	31.18	35.53	36.10	65.12	30.20	34.93	36.10	64.84	30.06	34.78
97	b	36.1	64.12	28.94	35.22								
mean value $\bar{x}$		36.1	64.3	29.3	35.0	36.1	62.5	28.4	34.0	36.1	61.8	28.1	33.7
standard deviation σ		0.1	2.1	2.1	2.3	0.1	2.3	2.1	2.3	0.1	2.4	2.1	2.3
standard deviation σ_{rel} in %		0.3	3.3	7.2	6.6	0.3	3.7	7.4	6.8	0.3	3.9	7.5	6.8
minimum x_{min}		36.0	56.3	22.7	28.8	36.0	53.6	22.1	27.7	36.0	53.8	21.8	27.4
maximum x_{max}		36.6	69.0	34.7	40.7	36.7	69.5	33.6	39.7	36.8	71.2	33.4	39.4

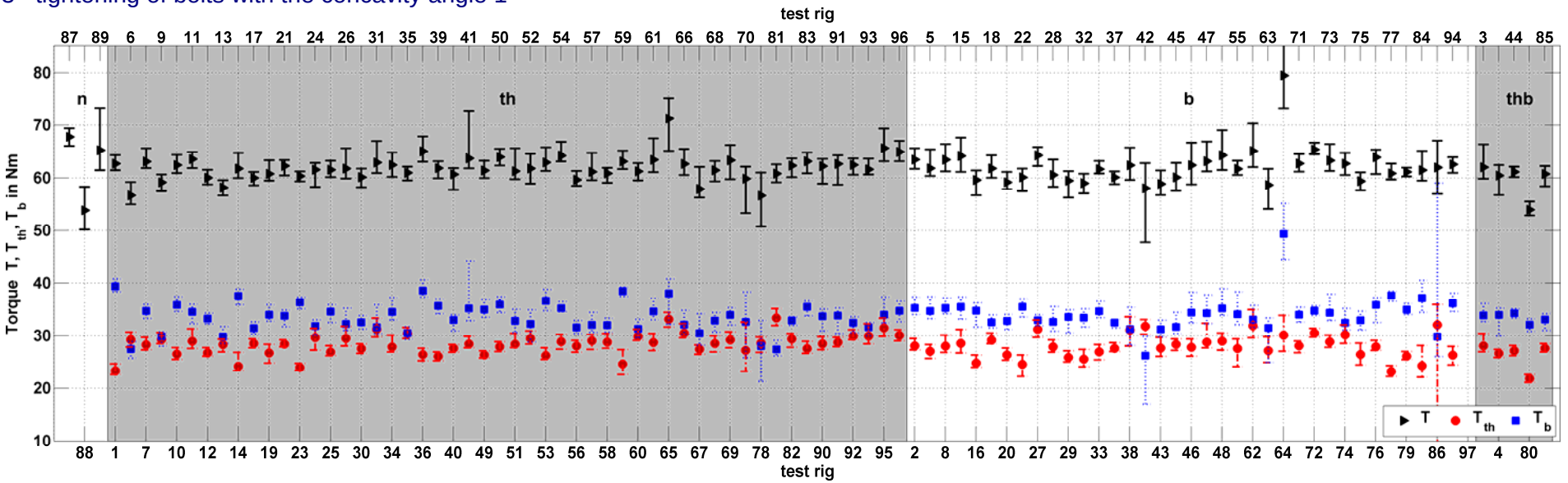
1st tightening of bolts with the concavity angle 1°



2nd tightening of bolts with the concavity angle 1°



3rd tightening of bolts with the concavity angle 1°



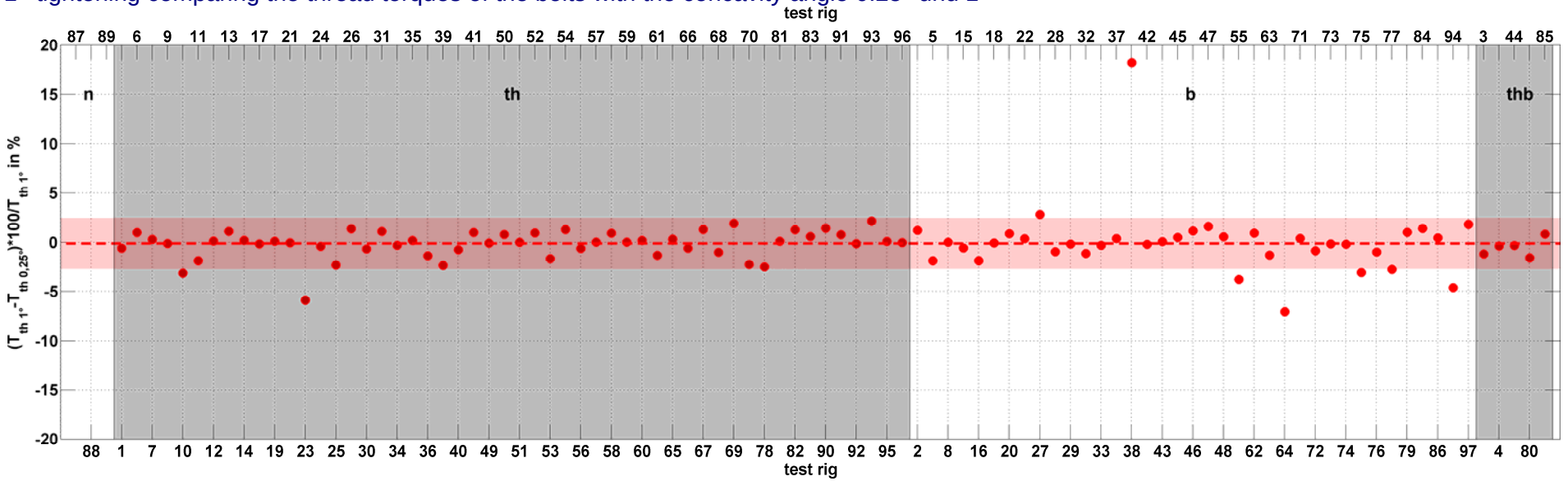
Annex 5 Difference of the documented thread torques of the bolts with the concavity angle 0.25° and 1°

test rig Nr.	test rig type	difference of the thread torques $\frac{(\emptyset T_{th.1°} - \emptyset T_{th.0.25°}) \cdot 100}{\emptyset T_{th.1°}}$ 1st tightening in %	2nd tightening in %	3rd tightening in %
1	th	-0.6	-0.2	0.4
2	b	1.2	0.9	0.5
3	thb	-1.2	-2.2	-2.4
4	thb	-0.4	-4.9	-2.0
5	b	-1.9	-1.1	-0.7
6	th	1.0	2.3	2.5
7	th	0.3	-1.8	-0.4
8	b	0.0	-0.1	0.4
9	th	-0.1	-0.6	0.1
10	th	-3.1	-3.0	-3.0
11	th	-1.9	-2.0	-1.8
12	th	0.1	-0.4	-1.1
13	th	1.1	1.4	1.9
14	th	0.2	-0.3	0.0
15	b	-0.6	-0.2	0.1
16	b	-1.9	-0.9	-0.7
17	th	-0.2	-0.4	-0.4
18	b	-0.1	-1.1	0.6
19	th	0.1	5.2	3.9
20	b	0.9	-0.5	-1.9
21	th	0.0	0.3	0.4
22	b	0.4	1.1	1.3
23	th	-5.9	-6.0	-6.6
24	th	-0.4	-0.1	0.3
25	th	-2.3	-2.9	-3.2
26	th	1.4	1.5	1.9
27	b	2.8	4.2	4.8
28	b	-1.0	-1.8	-1.4
29	b	-0.2	-0.3	0.4
30	th	-0.7	-0.8	-0.6
31	th	1.1	0.7	0.7
32	b	-1.1	-1.7	-1.3
33	b	-0.3	0.5	0.7
34	th	-0.3	-0.2	-0.4
35	th	0.2	-0.5	-0.3
36	th	-1.4	-0.7	-0.6
37	b	0.4	1.1	1.5
38	b	18.2	18.8	18.9
39	th	-2.4	-2.2	-2.1

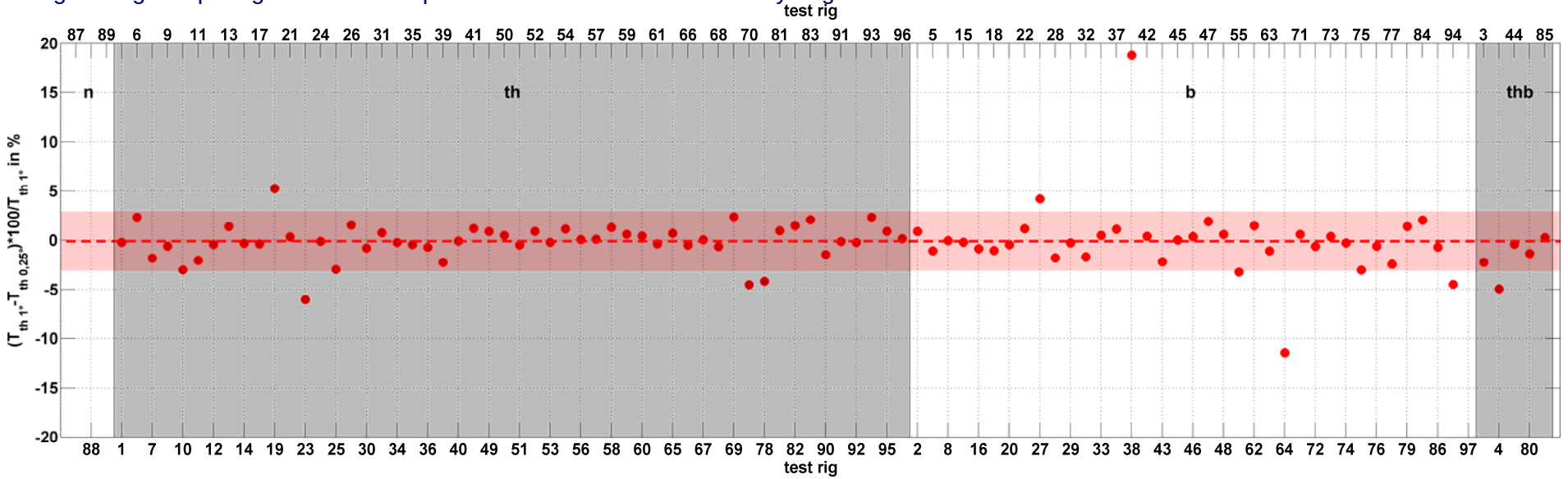
test rig Nr.	test rig type	difference of the thread torques $\frac{(\emptyset T_{th.1°} - \emptyset T_{th.0.25°}) \cdot 100}{\emptyset T_{th.1°}}$ 1st tightening in %	2nd tightening in %	3rd tightening in %
40	th	-0.8	-0.1	0.1
41	th	1.0	1.2	1.4
42	b	-0.2	0.4	0.1
43	b	0.1	-2.2	-2.6
44	thb	-0.3	-0.4	-0.1
45	b	0.5	0.0	-0.3
46	b	1.2	0.3	1.1
47	b	1.6	1.9	2.2
48	b	0.6	0.6	0.3
49	th	-0.1	0.9	1.0
50	th	0.8	0.5	1.1
51	th	0.0	-0.5	-0.2
52	th	1.0	0.9	0.5
53	th	-1.7	-0.2	0.0
54	th	1.3	1.1	1.2
55	b	-3.8	-3.2	-3.0
56	th	-0.6	0.1	-0.1
57	th	0.0	0.1	0.0
58	th	0.9	1.3	1.2
59	th	0.0	0.6	1.0
60	th	0.2	0.4	0.4
61	th	-1.3	-0.4	-0.1
62	b	0.9	1.4	1.0
63	b	-1.3	-1.1	-1.0
64	b	-7.1	-11.4	-11.5
65	th	0.3	0.7	1.3
66	th	-0.6	-0.5	-0.3
67	th	1.3	0.0	0.2
68	th	-1.0	-0.7	-0.3
69	th	1.9	2.3	3.0
70	th	-2.3	-4.5	-5.3
71	b	0.4	0.6	0.5
72	b	-0.9	-0.6	-0.7
73	b	-0.2	0.4	0.6
74	b	-0.2	-0.3	-0.5
75	b	-3.1	-3.0	-4.1
76	b	-1.0	-0.6	-0.5
77	b	-2.8	-2.4	-2.2
78	th	-2.5	-4.2	-4.4
79	b	1.0	1.4	1.3
80	thb	-1.6	-1.4	-1.1
81	th	0.1	0.9	1.0

test rig Nr.	test rig type	difference of the thread torques $\frac{(\emptyset T_{th.1°} - \emptyset T_{th.0.25°}) \cdot 100}{\emptyset T_{th.1°}}$ 1st tightening in %	2nd tightening in %	3rd tightening in %
82	th	1.3	1.4	1.4
83	th	0.6	2.0	2.2
84	b	1.4	2.0	1.7
85	thb	0.8	0.3	0.3
86	b	0.5	-0.7	-1.6
87	n			
88	n			
89	n			
90	th	1.4	-1.5	0.0
91	th	0.8	-0.1	0.3
92	th	-0.1	-0.2	-0.1
93	th	2.2	2.3	2.8
94	b	-4.6	-4.5	-4.5
95	th	0.1	0.9	1.3
96	th	0.0	0.1	0.3
97	b	1.8		
mean value $\bar{x}$		0.0	-0.1	0.1
standard deviation σ		2.6	3.0	3.0
minimum x_{min}		-7.1	-11.4	-11.5
maximum x_{max}		18.2	18.8	18.9

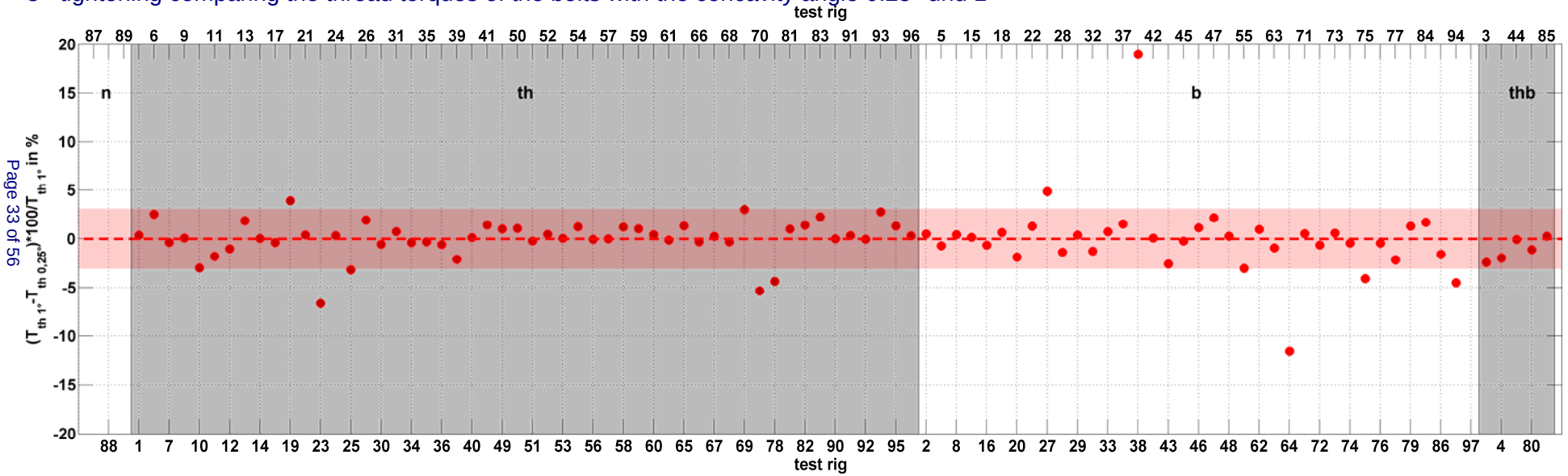
1st tightening comparing the thread torques of the bolts with the concavity angle 0.25° und 1°



2nd tightening comparing the thread torques of the bolts with the concavity angle 0.25° und 1°



3rd tightening comparing the thread torques of the bolts with the concavity angle 0.25° und 1°



Annex 6 Calculated coefficients of friction with the effective diameter for the friction torque at the bolt head $D_b = 16.8\,mm$ for bolts with a concavity angle 0.25°

test rig Nr.	test rig type	1st tightening				2nd tightening				3rd tightening			
		preload F kN	total coefficient of friction μ_{tot}	coefficient of friction in the thread μ_{th}	coefficient of friction in the head bearing area μ_b	preload F kN	total coefficient of friction μ_{tot}	coefficient of friction in the thread μ_{th}	coefficient of friction in the head bearing area μ_b	preload F kN	total coefficient of friction μ_{tot}	coefficient of friction in the thread μ_{th}	coefficient of friction in the head bearing area μ_b
1	th	36.12	0.108	0.085	0.123	36.12	0.104	0.079	0.119	36.12	0.102	0.077	0.118
2	b	36.10	0.103	0.110	0.099	36.10	0.099	0.104	0.096	36.10	0.097	0.103	0.093
3	thb	36.10	0.106	0.111	0.102	36.10	0.102	0.108	0.099	36.10	0.101	0.107	0.097
4	thb	36.10	0.108	0.105	0.109	36.10	0.108	0.105	0.109	36.10	0.103	0.099	0.106
5	b	36.10	0.105	0.106	0.105	36.10	0.100	0.101	0.100	36.10	0.098	0.099	0.097
6	th	36.11	0.103	0.113	0.097	36.11	0.099	0.107	0.093	36.11	0.096	0.106	0.090
7	th	36.10	0.110	0.110	0.110	36.10	0.106	0.108	0.106	36.10	0.104	0.105	0.103
8	b	36.10	0.113	0.112	0.113	36.10	0.107	0.105	0.109	36.10	0.105	0.103	0.106
9	th	36.10	0.106	0.118	0.098	36.10	0.101	0.112	0.094	36.10	0.099	0.110	0.092
10	th	36.10	0.104	0.103	0.105	36.10	0.101	0.100	0.101	36.10	0.100	0.099	0.100
11	th	36.10	0.109	0.116	0.104	36.10	0.105	0.112	0.100	36.11	0.103	0.111	0.098
12	th	36.21	0.105	0.104	0.107	36.20	0.101	0.099	0.103	36.16	0.100	0.098	0.102
13	th	36.12	0.103	0.108	0.100	36.12	0.100	0.104	0.097	36.12	0.097	0.102	0.095
14	th	36.12	0.112	0.091	0.124	36.12	0.107	0.083	0.122	36.12	0.105	0.082	0.119
15	b	36.09	0.114	0.114	0.115	36.08	0.110	0.108	0.111	36.11	0.108	0.106	0.110
16	b	36.10	0.104	0.094	0.110	36.10	0.100	0.089	0.107	36.10	0.098	0.087	0.105
17	th	36.11	0.104	0.116	0.096	36.12	0.099	0.108	0.093	36.12	0.097	0.106	0.092
18	b	36.10	0.112	0.114	0.110	36.10	0.110	0.112	0.109	36.10	0.106	0.108	0.105
19	th	36.10	0.106	0.097	0.112	36.10	0.101	0.090	0.108	36.10	0.101	0.091	0.107
20	b	36.10	0.104	0.105	0.103	36.10	0.099	0.099	0.100	36.10	0.098	0.097	0.098
21	th	36.08	0.106	0.111	0.102	36.10	0.103	0.106	0.101	36.09	0.102	0.105	0.100
22	b	36.10	0.106	0.091	0.115	36.10	0.101	0.085	0.111	36.10	0.099	0.083	0.108
23	th	36.12	0.108	0.094	0.116	36.12	0.103	0.091	0.111	36.12	0.101	0.090	0.109
24	th	36.06	0.100	0.117	0.090	36.10	0.096	0.113	0.085	36.10	0.094	0.111	0.083
25	th	36.12	0.107	0.108	0.106	36.13	0.102	0.103	0.101	36.12	0.099	0.102	0.098
26	th	36.10	0.109	0.115	0.105	36.10	0.105	0.110	0.101	36.10	0.103	0.108	0.100
27	b	36.10	0.107	0.118	0.100	36.10	0.103	0.114	0.096	36.10	0.101	0.112	0.094
28	b	36.10	0.105	0.111	0.102	36.13	0.102	0.106	0.099	36.10	0.100	0.104	0.097
29	b	36.11	0.104	0.097	0.108	36.12	0.099	0.092	0.103	36.07	0.097	0.091	0.101
30	th	36.10	0.105	0.108	0.103	36.10	0.100	0.103	0.098	36.10	0.098	0.101	0.096
31	th	36.12	0.105	0.122	0.095	36.12	0.102	0.120	0.091	36.12	0.100	0.119	0.088
32	b	36.10	0.100	0.100	0.101	36.10	0.095	0.093	0.096	36.10	0.093	0.092	0.094
33	b	36.10	0.103	0.104	0.103	36.10	0.098	0.099	0.098	36.10	0.097	0.096	0.097
34	th	36.06	0.104	0.106	0.104	36.07	0.101	0.103	0.100	36.04	0.100	0.103	0.098
35	th	36.10	0.110	0.121	0.103	36.10	0.106	0.118	0.098	36.10	0.103	0.117	0.095
36	th	36.11	0.110	0.100	0.116	36.10	0.106	0.096	0.112	36.10	0.104	0.095	0.109

test rig Nr.	test rig type	1st tightening				2nd tightening				3rd tightening			
		preload F kN	total coefficient of friction μ_{tot}	coefficient of friction in the thread μ_{th}	coefficient of friction in the head bearing area μ_b	preload F kN	total coefficient of friction μ_{tot}	coefficient of friction in the thread μ_{th}	coefficient of friction in the head bearing area μ_b	preload F kN	total coefficient of friction μ_{tot}	coefficient of friction in the thread μ_{th}	coefficient of friction in the head bearing area μ_b
37	b	36.10	0.102	0.106	0.100	36.10	0.098	0.100	0.097	36.10	0.097	0.099	0.095
38	b	36.10	0.105	0.098	0.109	36.10	0.102	0.093	0.108	36.10	0.100	0.088	0.107
39	th	36.10	0.112	0.105	0.116	36.10	0.107	0.097	0.114	36.10	0.106	0.096	0.113
40	th	36.08	0.102	0.108	0.098	36.07	0.098	0.103	0.094	36.07	0.096	0.101	0.093
41	th	36.10	0.108	0.109	0.108	36.10	0.104	0.105	0.103	36.10	0.102	0.103	0.101
42	b	36.10	0.106	0.129	0.092	36.10	0.103	0.125	0.089	36.10	0.101	0.123	0.087
43	b	36.10	0.108	0.113	0.105	36.11	0.102	0.107	0.100	36.09	0.100	0.105	0.097
44	thb	38.00	0.102	0.100	0.105	38.00	0.098	0.093	0.102	38.00	0.097	0.091	0.101
45	b	36.10	0.105	0.108	0.103	36.10	0.104	0.108	0.102	36.10	0.103	0.105	0.101
46	b	36.10	0.102	0.106	0.099	36.10	0.096	0.101	0.093	36.10	0.095	0.100	0.092
47	b	36.10	0.105	0.111	0.101	36.10	0.100	0.106	0.097	36.10	0.099	0.104	0.095
48	b	36.10	0.117	0.114	0.119	36.10	0.114	0.110	0.117	36.10	0.113	0.108	0.116
49	th	36.10	0.110	0.101	0.115	36.10	0.105	0.094	0.113	36.10	0.104	0.093	0.111
50	th	36.13	0.114	0.106	0.119	36.13	0.110	0.103	0.114	36.13	0.108	0.101	0.112
51	th	36.12	0.106	0.113	0.102	36.11	0.102	0.108	0.098	36.12	0.099	0.105	0.096
52	th	36.11	0.110	0.117	0.106	36.11	0.106	0.112	0.103	36.11	0.105	0.110	0.102
53	th	36.12	0.117	0.104	0.124	36.12	0.112	0.096	0.122	36.12	0.110	0.093	0.120
54	th	36.12	0.117	0.112	0.120	36.12	0.113	0.107	0.116	36.12	0.111	0.106	0.114
55	b	36.10	0.109	0.111	0.107	36.10	0.104	0.107	0.103	36.10	0.102	0.105	0.101
56	th	36.12	0.105	0.110	0.102	36.12	0.100	0.105	0.098	36.12	0.098	0.103	0.095
57	th	36.12	0.106	0.114	0.101	36.12	0.102	0.109	0.097	36.12	0.100	0.109	0.094
58	th	36.11	0.106	0.112	0.102	36.12	0.101	0.107	0.098	36.12	0.100	0.105	0.096
59	th	36.12	0.113	0.089	0.127	36.12	0.108	0.084	0.123	36.12	0.107	0.083	0.121
60	th	36.10	0.111	0.119	0.106	36.10	0.107	0.114	0.102	36.10	0.105	0.112	0.101
61	th	36.10	0.109	0.114	0.107	36.10	0.104	0.108	0.102	36.10	0.102	0.107	0.100
62	b	36.11	0.113	0.128	0.104	36.11	0.109	0.123	0.100	36.09	0.107	0.122	0.098
63	b	36.12	0.109	0.107	0.109	36.10	0.104	0.102	0.106	36.10	0.102	0.100	0.104
64	b	38.51	0.111	0.117	0.108	38.51	0.117	0.119	0.116	38.51	0.123	0.122	0.123
65	th	36.10	0.110	0.121	0.104	36.10	0.118	0.127	0.113	36.10	0.122	0.128	0.119
66	th	36.10	0.108	0.124	0.097	36.11	0.103	0.118	0.093	36.11	0.101	0.117	0.091
67	th	36.12	0.106	0.105	0.106	36.12	0.102	0.101	0.102	36.11	0.100	0.100	0.100
68	th	36.12	0.103	0.113	0.097	36.12	0.100	0.108	0.095	36.12	0.099	0.106	0.094
69	th	36.11	0.102	0.107	0.099	36.12	0.101	0.105	0.098	36.08	0.100	0.105	0.097
70	th	36.10	0.105	0.117	0.097	36.10	0.100	0.108	0.096	36.10	0.098	0.107	0.092
71	b	36.16	0.108	0.109	0.107	36.17	0.105	0.104	0.104	36.16	0.103	0.103	0.102
72	b	36.10	0.113	0.126	0.105	36.10	0.107	0.119	0.100	36.10	0.105	0.117	0.097
73	b	36.10	0.115	0.114	0.116	36.10	0.111	0.109	0.112	36.10	0.109	0.107	0.111
74	b	36.09	0.109	0.121	0.102	36.11	0.105	0.117	0.098	36.10	0.103	0.115	0.096
75	b	35.60	0.102	0.108	0.098	36.10	0.096	0.101	0.093	36.12	0.095	0.100	0.091
76	b	36.10	0.114	0.112	0.115	36.10	0.108	0.105	0.110	36.10	0.106	0.103	0.107
77	b	36.12	0.108	0.086	0.122	36.13	0.104	0.081	0.118	36.14	0.102	0.080	0.115

test rig Nr.	test rig type	1st tightening preload F kN	1st tightening total coefficient of friction μ_{tot}	1st tightening coefficient of friction in the thread μ_{th}	1st tightening coefficient of friction in the head bearing area μ_b	2nd tightening preload F kN	2nd tightening total coefficient of friction μ_{tot}	2nd tightening coefficient of friction in the thread μ_{th}	2nd tightening coefficient of friction in the head bearing area μ_b	3rd tightening preload F kN	3rd tightening total coefficient of friction μ_{tot}	3rd tightening coefficient of friction in the thread μ_{th}	3rd tightening coefficient of friction in the head bearing area μ_b
78	th	36.10	0.106	0.118	0.098	36.10	0.101	0.114	0.093	36.10	0.099	0.113	0.091
79	b	36.10	0.111	0.098	0.119	36.10	0.106	0.094	0.114	36.10	0.104	0.091	0.112
80	thb	36.10	0.095	0.077	0.106	36.10	0.091	0.073	0.102	36.10	0.089	0.072	0.100
81	th	36.13	0.109	0.138	0.092	36.01	0.104	0.131	0.088	36.08	0.103	0.130	0.087
82	th	36.10	0.113	0.116	0.112	36.10	0.109	0.110	0.108	36.10	0.107	0.108	0.107
83	th	36.10	0.107	0.107	0.107	36.10	0.102	0.099	0.103	36.10	0.100	0.097	0.101
84	b	36.10	0.114	0.089	0.129	36.10	0.108	0.082	0.123	36.10	0.106	0.081	0.121
85	thb	36.10	0.105	0.109	0.103	36.10	0.100	0.103	0.098	36.10	0.098	0.101	0.096
86	b	36.32	0.104	0.137	0.084	36.31	0.100	0.133	0.080	36.54	0.099	0.125	0.083
87	n	36.10	0.112			36.10	0.113			36.10	0.111		
88	n	36.10	0.086			36.10	0.082			36.10	0.081		
89	n	36.14	0.115			36.69	0.110			36.60	0.109		
90	th	36.10	0.102	0.108	0.097	36.10	0.101	0.108	0.097	36.10	0.100	0.106	0.096
91	th	36.10	0.100	0.107	0.097	36.10	0.103	0.111	0.098	36.10	0.100	0.107	0.096
92	th	36.10	0.115	0.121	0.112	36.10	0.110	0.115	0.107	36.10	0.109	0.113	0.105
93	th	36.12	0.105	0.115	0.100	36.12	0.101	0.110	0.095	36.12	0.099	0.109	0.093
94	b	36.10	0.106	0.107	0.106	36.10	0.102	0.103	0.102	36.10	0.100	0.100	0.100
95	th	36.12	0.109	0.123	0.101	36.12	0.106	0.120	0.098	36.12	0.104	0.119	0.095
96	th	36.10	0.114	0.120	0.110	36.10	0.110	0.115	0.108	36.10	0.109	0.114	0.107
97	b	36.10	0.101	0.105	0.098								
mean value $\bar{x}$		36.1	0.107	0.110	0.106	36.1	0.103	0.105	0.102	36.1	0.102	0.103	0.101
standard deviation σ		0.1	0.005	0.010	0.008	0.1	0.005	0.011	0.008	0.1	0.005	0.011	0.008
standard deviation σ_{rel} in %		0.3	4.6	9.4	8.0	0.3	5.0	10.2	8.2	0.3	5.3	10.2	8.4
minimum x_{min}		35.6	0.086	0.077	0.084	36.0	0.082	0.073	0.080	36.0	0.081	0.072	0.083
maximum x_{max}		36.3	0.117	0.138	0.129	36.7	0.118	0.133	0.123	36.6	0.122	0.130	0.121

Annex 7 Calculated coefficients of friction with the effective diameter for the friction torque at the bolt head $D_b = 18.3\ mm$ for bolts with a concavity angle 1°

test rig Nr.	test rig type	1st tightening				2nd tightening				3rd tightening			
		preload F kN	total coefficient of friction μ_{tot}	coefficient of friction in the thread μ_{th}	coefficient of friction in the head bearing area μ_b	preload F kN	total coefficient of friction μ_{tot}	coefficient of friction in the thread μ_{th}	coefficient of friction in the head bearing area μ_b	preload F kN	total coefficient of friction μ_{tot}	coefficient of friction in the thread μ_{th}	coefficient of friction in the head bearing area μ_b
1	th	36.12	0.109	0.084	0.123	36.12	0.105	0.078	0.120	36.12	0.104	0.078	0.119
2	b	36.10	0.111	0.112	0.111	36.10	0.107	0.106	0.108	36.10	0.106	0.103	0.107
3	thb	36.10	0.108	0.109	0.108	36.10	0.104	0.105	0.104	36.10	0.103	0.103	0.103
4	thb	36.10	0.107	0.104	0.109	36.10	0.102	0.098	0.104	36.10	0.100	0.096	0.103
5	b	36.10	0.108	0.103	0.111	36.10	0.104	0.099	0.107	36.10	0.103	0.098	0.105
6	th	36.11	0.099	0.114	0.091	36.11	0.095	0.111	0.085	36.11	0.093	0.110	0.083
7	th	36.10	0.109	0.111	0.108	36.10	0.106	0.106	0.106	36.10	0.105	0.105	0.105
8	b	36.10	0.113	0.112	0.113	36.10	0.108	0.105	0.109	36.10	0.106	0.103	0.107
9	th	36.10	0.104	0.118	0.097	36.10	0.099	0.111	0.093	36.10	0.097	0.110	0.090
10	th	36.09	0.107	0.099	0.112	36.10	0.105	0.095	0.110	36.08	0.104	0.095	0.109
11	th	36.10	0.111	0.113	0.110	36.10	0.108	0.109	0.106	36.10	0.106	0.108	0.105
12	th	36.18	0.105	0.104	0.105	36.18	0.100	0.098	0.102	36.16	0.099	0.096	0.101
13	th	36.11	0.100	0.109	0.094	36.12	0.097	0.106	0.092	36.12	0.095	0.105	0.090
14	th	36.12	0.108	0.092	0.118	36.11	0.104	0.083	0.116	36.12	0.102	0.082	0.114
15	b	36.11	0.111	0.113	0.110	36.10	0.108	0.108	0.108	36.06	0.107	0.106	0.108
16	b	36.10	0.104	0.092	0.111	36.10	0.100	0.088	0.107	36.10	0.098	0.086	0.105
17	th	36.12	0.105	0.115	0.100	36.12	0.101	0.107	0.097	36.12	0.099	0.106	0.095
18	b	36.10	0.107	0.114	0.103	36.10	0.104	0.110	0.100	36.10	0.103	0.109	0.099
19	th	36.10	0.106	0.097	0.110	36.10	0.102	0.098	0.105	36.10	0.101	0.096	0.103
20	b	36.10	0.105	0.107	0.104	36.10	0.100	0.098	0.102	36.10	0.098	0.094	0.099
21	th	36.07	0.108	0.111	0.106	36.10	0.105	0.107	0.104	36.09	0.103	0.105	0.102
22	b	36.10	0.106	0.091	0.114	36.10	0.102	0.087	0.110	36.10	0.099	0.085	0.108
23	th	36.13	0.105	0.087	0.116	36.12	0.101	0.083	0.112	36.12	0.100	0.081	0.110
24	th	36.06	0.107	0.117	0.101	36.10	0.103	0.113	0.098	36.08	0.102	0.112	0.097
25	th	36.12	0.109	0.104	0.112	36.12	0.104	0.099	0.107	36.12	0.102	0.097	0.105
26	th	36.10	0.107	0.117	0.101	36.10	0.103	0.112	0.098	36.10	0.102	0.111	0.098
27	b	36.10	0.111	0.123	0.104	36.10	0.109	0.121	0.102	36.10	0.107	0.120	0.100
28	b	36.12	0.104	0.110	0.101	36.10	0.101	0.103	0.100	36.12	0.100	0.102	0.099
29	b	36.11	0.103	0.097	0.107	36.10	0.100	0.092	0.104	36.09	0.098	0.092	0.102
30	th	36.10	0.106	0.107	0.105	36.10	0.101	0.102	0.100	36.10	0.099	0.101	0.099
31	th	36.12	0.108	0.124	0.100	36.12	0.106	0.121	0.097	36.12	0.105	0.120	0.096
32	b	36.10	0.104	0.098	0.107	36.10	0.099	0.091	0.104	36.10	0.097	0.090	0.101
33	b	36.10	0.108	0.103	0.111	36.10	0.104	0.099	0.107	36.10	0.102	0.097	0.105
34	th	36.05	0.107	0.105	0.108	36.03	0.104	0.103	0.105	36.04	0.104	0.103	0.105

test rig Nr.	test rig type	1st tightening preload F kN	1st tightening total coefficient of friction μ_{tot}	1st tightening coefficient of friction in the thread μ_{th}	1st tightening coefficient of friction in the head bearing area μ_b	2nd tightening preload F kN	2nd tightening total coefficient of friction μ_{tot}	2nd tightening coefficient of friction in the thread μ_{th}	2nd tightening coefficient of friction in the head bearing area μ_b	3rd tightening preload F kN	3rd tightening total coefficient of friction μ_{tot}	3rd tightening coefficient of friction in the thread μ_{th}	3rd tightening coefficient of friction in the head bearing area μ_b
35	th	36.10	0.107	0.121	0.099	36.10	0.103	0.117	0.094	36.10	0.101	0.116	0.092
36	th	36.11	0.113	0.098	0.122	36.11	0.110	0.095	0.118	36.10	0.109	0.094	0.117
37	b	36.10	0.106	0.107	0.105	36.10	0.101	0.102	0.101	36.10	0.099	0.101	0.098
38	b	36.10	0.111	0.130	0.100	36.10	0.105	0.125	0.093	36.10	0.104	0.119	0.095
39	th	36.10	0.108	0.101	0.111	36.10	0.104	0.094	0.109	36.10	0.103	0.093	0.108
40	th	36.07	0.106	0.107	0.105	36.07	0.102	0.102	0.101	36.04	0.101	0.101	0.100
41	th	36.10	0.111	0.111	0.111	36.10	0.107	0.106	0.108	36.10	0.106	0.105	0.107
42	b	36.10	0.101	0.129	0.085	36.10	0.097	0.125	0.081	36.10	0.095	0.123	0.079
43	b	36.09	0.104	0.113	0.099	36.11	0.098	0.103	0.096	36.10	0.097	0.101	0.094
44	thb	38.00	0.101	0.099	0.104	38.00	0.097	0.092	0.100	38.00	0.095	0.091	0.099
45	b	36.10	0.103	0.109	0.100	36.10	0.101	0.108	0.097	36.10	0.099	0.105	0.096
46	b	36.10	0.108	0.108	0.108	36.10	0.104	0.101	0.105	36.10	0.104	0.102	0.104
47	b	36.10	0.108	0.113	0.105	36.11	0.105	0.109	0.103	36.09	0.105	0.107	0.104
48	b	36.10	0.112	0.115	0.110	36.10	0.109	0.111	0.108	36.10	0.107	0.108	0.107
49	th	36.10	0.107	0.101	0.110	36.10	0.103	0.095	0.107	36.10	0.102	0.094	0.106
50	th	36.12	0.112	0.107	0.114	36.13	0.108	0.103	0.111	36.12	0.107	0.102	0.109
51	th	36.12	0.107	0.113	0.103	36.12	0.103	0.107	0.100	36.12	0.101	0.105	0.099
52	th	36.11	0.105	0.119	0.097	36.11	0.102	0.113	0.095	36.12	0.102	0.111	0.098
53	th	36.12	0.110	0.102	0.114	36.12	0.106	0.095	0.113	36.12	0.105	0.093	0.111
54	th	36.12	0.112	0.114	0.112	36.12	0.109	0.109	0.109	36.12	0.107	0.108	0.107
55	b	36.10	0.107	0.106	0.109	36.10	0.104	0.102	0.105	36.10	0.102	0.101	0.103
56	th	36.11	0.105	0.109	0.102	36.11	0.100	0.105	0.098	36.12	0.098	0.103	0.096
57	th	36.12	0.105	0.114	0.100	36.11	0.102	0.109	0.098	36.12	0.101	0.109	0.097
58	th	36.12	0.106	0.114	0.102	36.12	0.102	0.109	0.099	36.12	0.101	0.107	0.097
59	th	36.12	0.110	0.089	0.122	36.12	0.106	0.085	0.119	36.12	0.105	0.085	0.116
60	th	36.10	0.106	0.120	0.098	36.10	0.102	0.115	0.095	36.10	0.101	0.113	0.095
61	th	36.10	0.111	0.112	0.110	36.10	0.107	0.108	0.106	36.10	0.106	0.107	0.105
62	b	36.10	0.114	0.130	0.104	36.10	0.110	0.125	0.101	36.10	0.109	0.124	0.100
63	b	36.08	0.103	0.105	0.102	36.10	0.099	0.101	0.098	36.09	0.097	0.099	0.095
64	b	38.51	0.123	0.106	0.136	38.51	0.123	0.102	0.135	38.51	0.127	0.104	0.140
65	th	36.10	0.105	0.121	0.096	36.10	0.118	0.128	0.112	36.10	0.121	0.131	0.115
66	th	36.10	0.108	0.123	0.100	36.10	0.105	0.117	0.097	36.10	0.104	0.116	0.097
67	th	36.11	0.101	0.107	0.098	36.11	0.097	0.101	0.094	36.12	0.095	0.100	0.092
68	th	36.12	0.107	0.112	0.104	36.12	0.103	0.107	0.101	36.12	0.102	0.106	0.100
69	th	36.10	0.107	0.110	0.105	36.10	0.106	0.109	0.104	36.09	0.105	0.110	0.103
70	th	36.11	0.104	0.113	0.099	36.14	0.100	0.101	0.100	36.10	0.099	0.099	0.099
71	b	36.11	0.109	0.110	0.107	36.16	0.105	0.105	0.103	36.17	0.104	0.103	0.103
72	b	36.10	0.116	0.124	0.112	36.10	0.111	0.118	0.107	36.10	0.109	0.116	0.105
73	b	36.10	0.110	0.113	0.109	36.10	0.107	0.109	0.106	36.10	0.105	0.107	0.104

test rig Nr.	test rig type	1st tightening preload F kN	1st tightening total coefficient of friction μ_{tot}	1st tightening coefficient of friction in the thread μ_{th}	1st tightening coefficient of friction in the head bearing area μ_b	2nd tightening preload F kN	2nd tightening total coefficient of friction μ_{tot}	2nd tightening coefficient of friction in the thread μ_{th}	2nd tightening coefficient of friction in the head bearing area μ_b	3rd tightening preload F kN	3rd tightening total coefficient of friction μ_{tot}	3rd tightening coefficient of friction in the thread μ_{th}	3rd tightening coefficient of friction in the head bearing area μ_b
74	b	36.11	0.109	0.121	0.103	36.11	0.106	0.117	0.099	36.06	0.104	0.115	0.098
75	b	36.09	0.102	0.101	0.103	36.09	0.099	0.097	0.100	36.10	0.098	0.095	0.100
76	b	36.10	0.113	0.110	0.115	36.10	0.108	0.104	0.110	36.10	0.107	0.103	0.109
77	b	36.11	0.107	0.083	0.121	36.13	0.103	0.078	0.116	36.11	0.101	0.077	0.114
78	th	36.10	0.099	0.114	0.090	36.10	0.094	0.108	0.087	36.10	0.093	0.106	0.085
79	b	36.10	0.107	0.099	0.111	36.10	0.103	0.095	0.108	36.10	0.101	0.093	0.106
80	thb	36.10	0.092	0.075	0.102	36.10	0.089	0.072	0.098	36.10	0.087	0.070	0.097
81	th	36.13	0.106	0.138	0.087	36.04	0.102	0.133	0.084	36.08	0.101	0.132	0.083
82	th	36.10	0.109	0.118	0.103	36.10	0.105	0.112	0.100	36.10	0.104	0.110	0.100
83	th	36.10	0.112	0.108	0.114	36.10	0.107	0.102	0.110	36.10	0.105	0.101	0.108
84	b	36.10	0.108	0.091	0.118	36.10	0.103	0.085	0.113	36.10	0.102	0.083	0.113
85	thb	36.10	0.108	0.111	0.106	36.10	0.103	0.104	0.102	36.10	0.100	0.101	0.100
86	b	36.57	0.107	0.136	0.090	36.20	0.103	0.132	0.086	36.29	0.102	0.124	0.090
87	n	36.10	0.115			36.10	0.116			36.10	0.114		
88	n	36.11	0.092			36.10	0.087			36.10	0.087		
89	n	36.00	0.114			36.71	0.107			36.80	0.107		
90	th	36.10	0.108	0.110	0.107	36.10	0.104	0.106	0.104	36.10	0.103	0.106	0.102
91	th	36.10	0.105	0.108	0.103	36.10	0.107	0.110	0.105	36.10	0.104	0.107	0.103
92	th	36.10	0.110	0.121	0.104	36.10	0.105	0.115	0.100	36.10	0.104	0.113	0.098
93	th	36.12	0.107	0.118	0.101	36.12	0.103	0.114	0.097	36.12	0.102	0.113	0.096
94	b	36.10	0.109	0.100	0.113	36.10	0.105	0.096	0.111	36.10	0.104	0.094	0.110
95	th	36.12	0.111	0.123	0.103	36.12	0.110	0.122	0.103	36.11	0.110	0.122	0.103
96	th	36.10	0.112	0.120	0.108	36.10	0.109	0.115	0.106	36.10	0.108	0.114	0.105
97	b	36.10	0.107	0.108	0.107								
mean value $\bar{x}$		36.1	0.107	0.110	0.106	36.1	0.104	0.105	0.103	36.1	0.103	0.104	0.102
standard deviation σ		0.1	0.004	0.011	0.007	0.1	0.005	0.011	0.007	0.1	0.005	0.011	0.007
standard deviation σ_{rel} in %		0.3	3.7	10.0	6.6	0.3	4.8	10.8	6.8	0.3	4.9	10.6	6.9
minimum x_{min}		36.0	0.092	0.075	0.087	36.0	0.087	0.072	0.084	36.0	0.087	0.070	0.083
maximum x_{max}		36.6	0.116	0.138	0.123	36.7	0.118	0.133	0.120	36.8	0.121	0.132	0.119

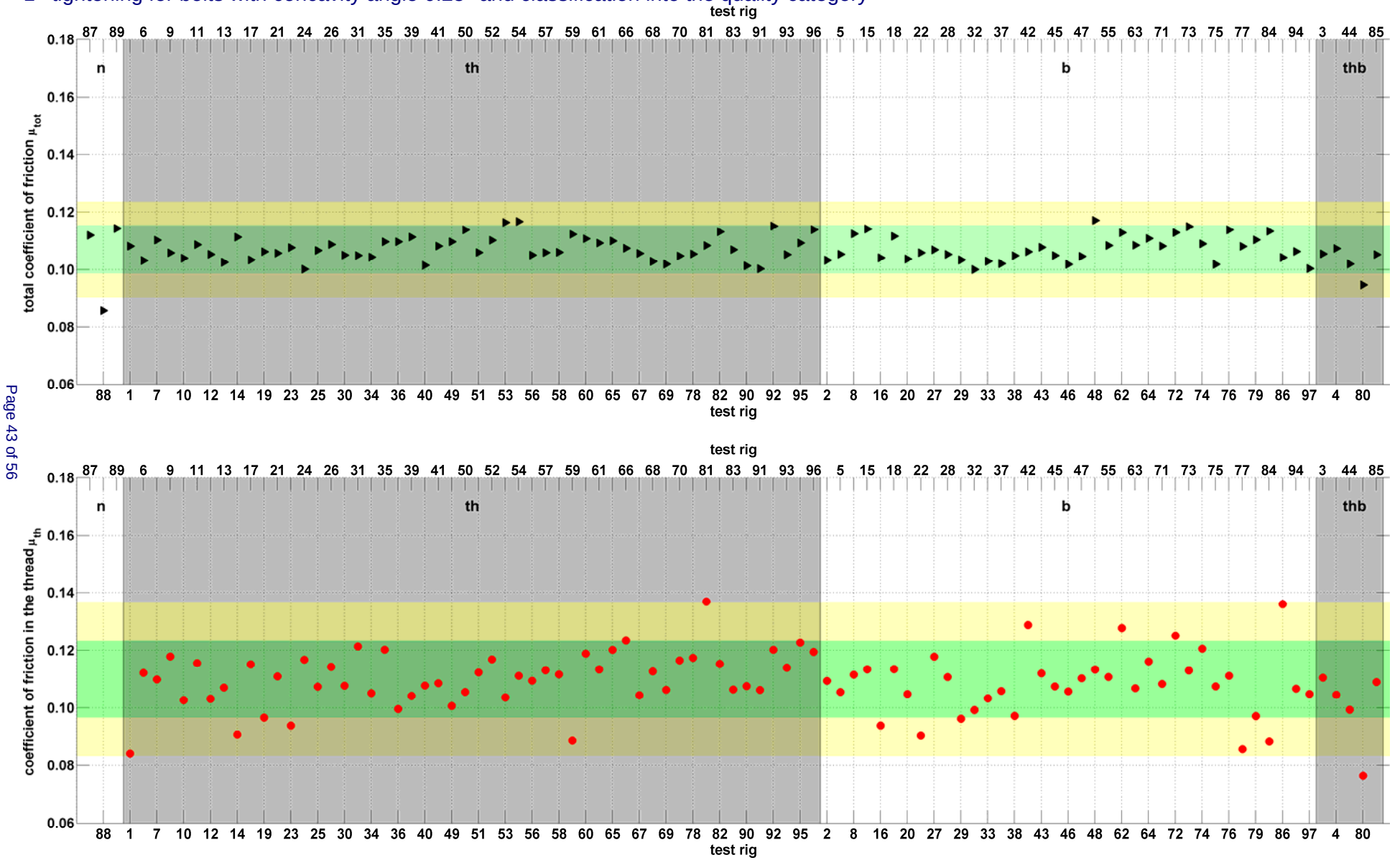
Annex 8 Classification of the test rigs into quality categories for bolts with the concavity angle 0.25°

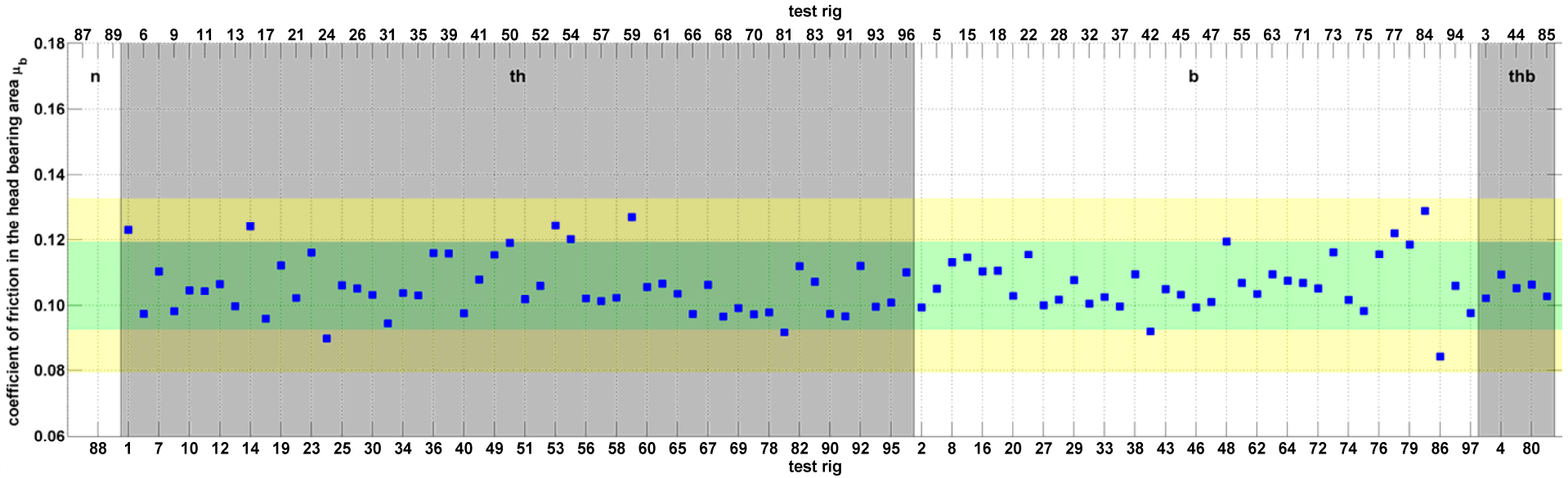
test rig Nr.	test rig type	1st tightening			2nd tightening			3rd tightening			total evaluation
		total coefficient of friction μ_{tot}	coefficient of friction in the thread μ_{th}	coefficient of friction in the head bearing area μ_b	total coefficient of friction μ_{tot}	coefficient of friction in the thread μ_{th}	coefficient of friction in the head bearing area μ_b	total coefficient of friction μ_{tot}	coefficient of friction in the thread μ_{th}	coefficient of friction in the head bearing area μ_b	
1	th	C0	C1	C1	C0	C1	C1	C0	C1	C1	C1
2	b	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
3	thb	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
4	thb	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
5	b	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
6	th	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
7	th	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
8	b	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
9	th	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
10	th	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
11	th	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
12	th	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
13	th	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
14	th	C0	C1	C1	C0	C1	C1	C0	C1	C1	C1
15	b	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
16	b	C0	C1	C0	C0	C1	C0	C0	C1	C0	C1
17	th	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
18	b	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
19	th	C0	C0	C0	C0	C1	C0	C0	C0	C0	C0
20	b	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
21	th	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
22	b	C0	C1	C0	C0	C1	C0	C0	C1	C0	C1
23	th	C0	C1	C0	C0	C1	C0	C0	C1	C0	C1
24	th	C0	C0	C1	C0	C0	C1	C0	C0	C1	C1
25	th	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
26	th	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
27	b	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
28	b	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
29	b	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
30	th	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
31	th	C0	C0	C0	C0	C1	C0	C0	C1	C0	C1
32	b	C0	C0	C0	C1	C0	C0	C1	C0	C0	C1
33	b	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
34	th	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
35	th	C0	C0	C0	C0	C0	C0	C0	C1	C0	C1
36	th	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
37	b	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
38	b	C0	C0	C0	C0	C0	C0	C0	C1	C0	C1
39	th	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0

test rig Nr.	test rig type	1st tightening			2nd tightening			3rd tightening			total evaluation
		total coefficient of friction μ_{tot}	coefficient of friction in the thread μ_{th}	coefficient of friction in the head bearing area μ_b	total coefficient of friction μ_{tot}	coefficient of friction in the thread μ_{th}	coefficient of friction in the head bearing area μ_b	total coefficient of friction μ_{tot}	coefficient of friction in the thread μ_{th}	coefficient of friction in the head bearing area μ_b	
40	th	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
41	th	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
42	b	C0	C1	C1	C0	C1	C1	C0	C1	C1	C1
43	b	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
44	thb	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
45	b	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
46	b	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
47	b	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
48	b	C1	C0	C0	C1	C0	C1	C1	C0	C1	C1
49	th	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
50	th	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
51	th	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
52	th	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
53	th	C1	C0	C1	C1	C0	C1	C1	C0	C1	C1
54	th	C1	C0	C1	C1	C0	C1	C1	C0	C1	C1
55	b	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
56	th	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
57	th	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
58	th	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
59	th	C0	C1	C1	C0	C1	C1	C0	C1	C1	C1
60	th	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
61	th	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
62	b	C0	C1	C0	C0	C1	C0	C0	C1	C0	C1
63	b	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
64	b	C0	C0	C0	C1	C1	C1	C2	C1	C1	C2
65	th	C0	C0	C0	C1	C1	C0	C2	C1	C1	C2
66	th	C0	C1	C0	C0	C0	C0	C0	C1	C0	C1
67	th	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
68	th	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
69	th	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
70	th	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
71	b	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
72	b	C0	C1	C0	C0	C1	C0	C0	C1	C0	C1
73	b	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
74	b	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
75	b	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
76	b	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
77	b	C0	C1	C1	C0	C1	C1	C0	C1	C1	C1
78	th	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
79	b	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
80	thb	C1	C2	C0	C1	C2	C0	C1	C2	C0	C2
81	th	C0	C2	C1	C0	C1	C1	C0	C1	C1	C2

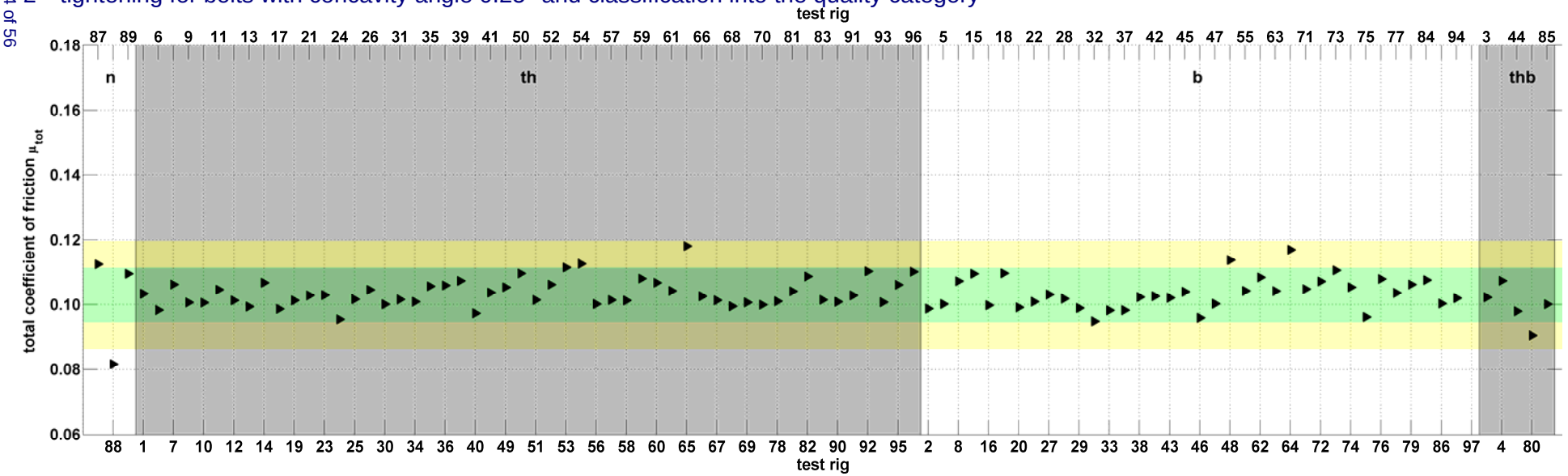
test rig Nr.	test rig type	1st tightening			2nd tightening			3rd tightening			total evaluation
		total coefficient of friction μ_{tot}	coefficient of friction in the thread μ_{th}	coefficient of friction in the head bearing area μ_b	total coefficient of friction μ_{tot}	coefficient of friction in the thread μ_{th}	coefficient of friction in the head bearing area μ_b	total coefficient of friction μ_{tot}	coefficient of friction in the thread μ_{th}	coefficient of friction in the head bearing area μ_b	
82	th	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
83	th	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
84	b	C0	C1	C1	C0	C1	C1	C0	C1	C1	C1
85	thb	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
86	b	C0	C2	C1	C0	C2	C1	C0	C1	C1	C2
87	n	C0			C1			C1			C1
88	n	C2			C2			C2			C2
89	n	C0			C0			C0			C0
90	th	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
91	th	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
92	th	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
93	th	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
94	b	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
95	th	C0	C1	C0	C0	C1	C0	C0	C1	C0	C1
96	th	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
97	b	C0	C0	C0							C0

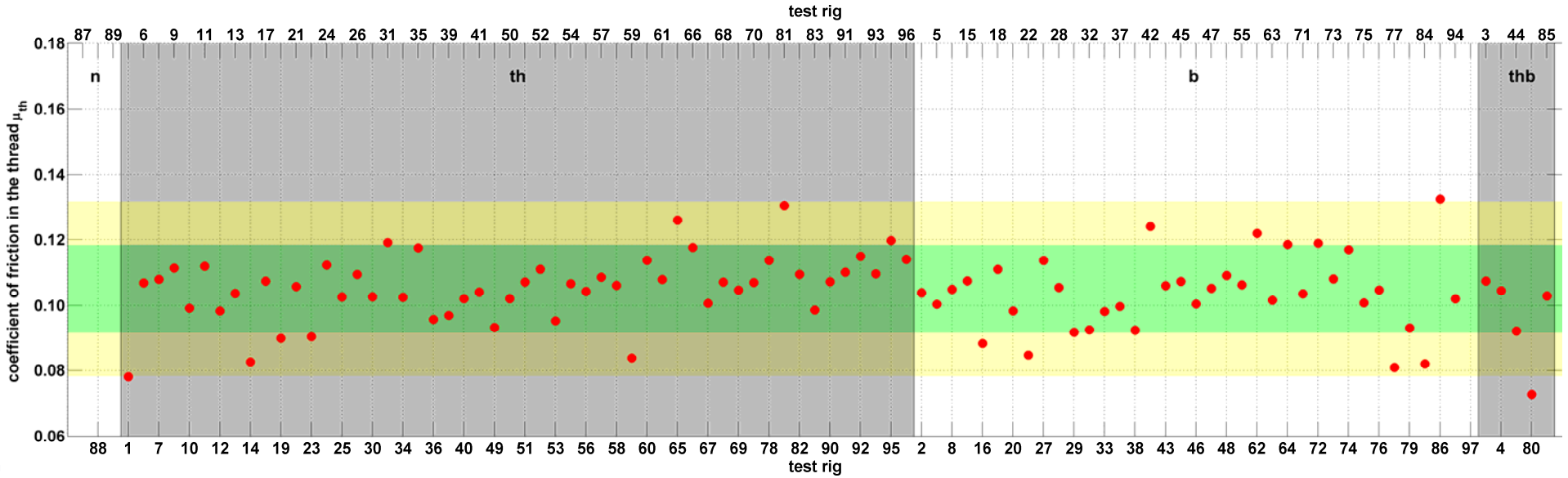
1st tightening for bolts with concavity angle 0.25° and classification into the quality category

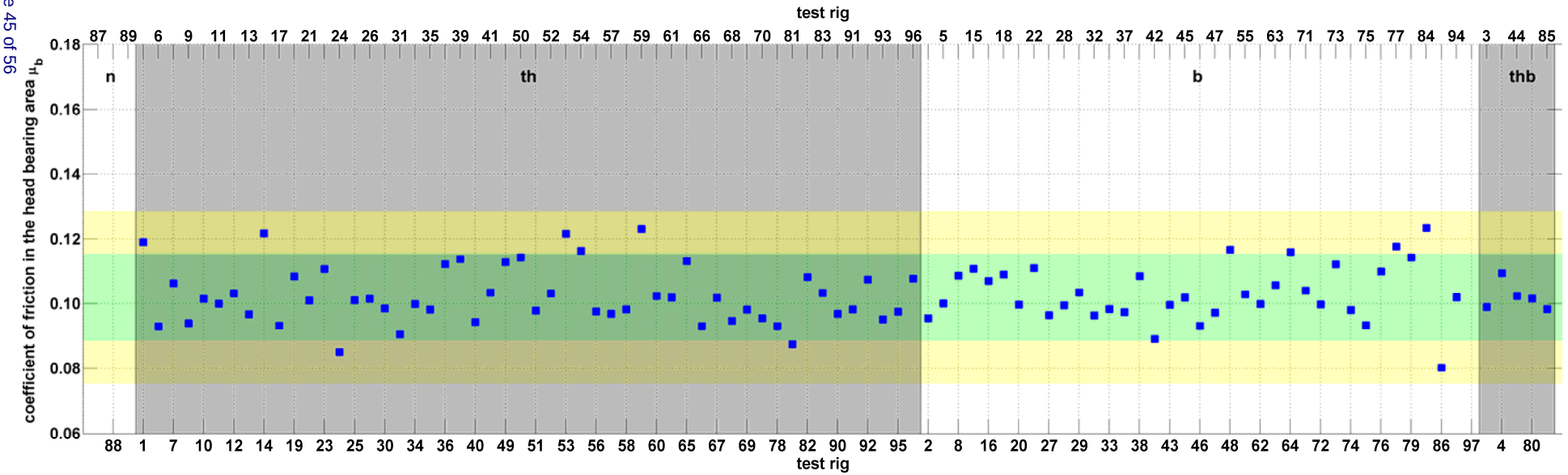




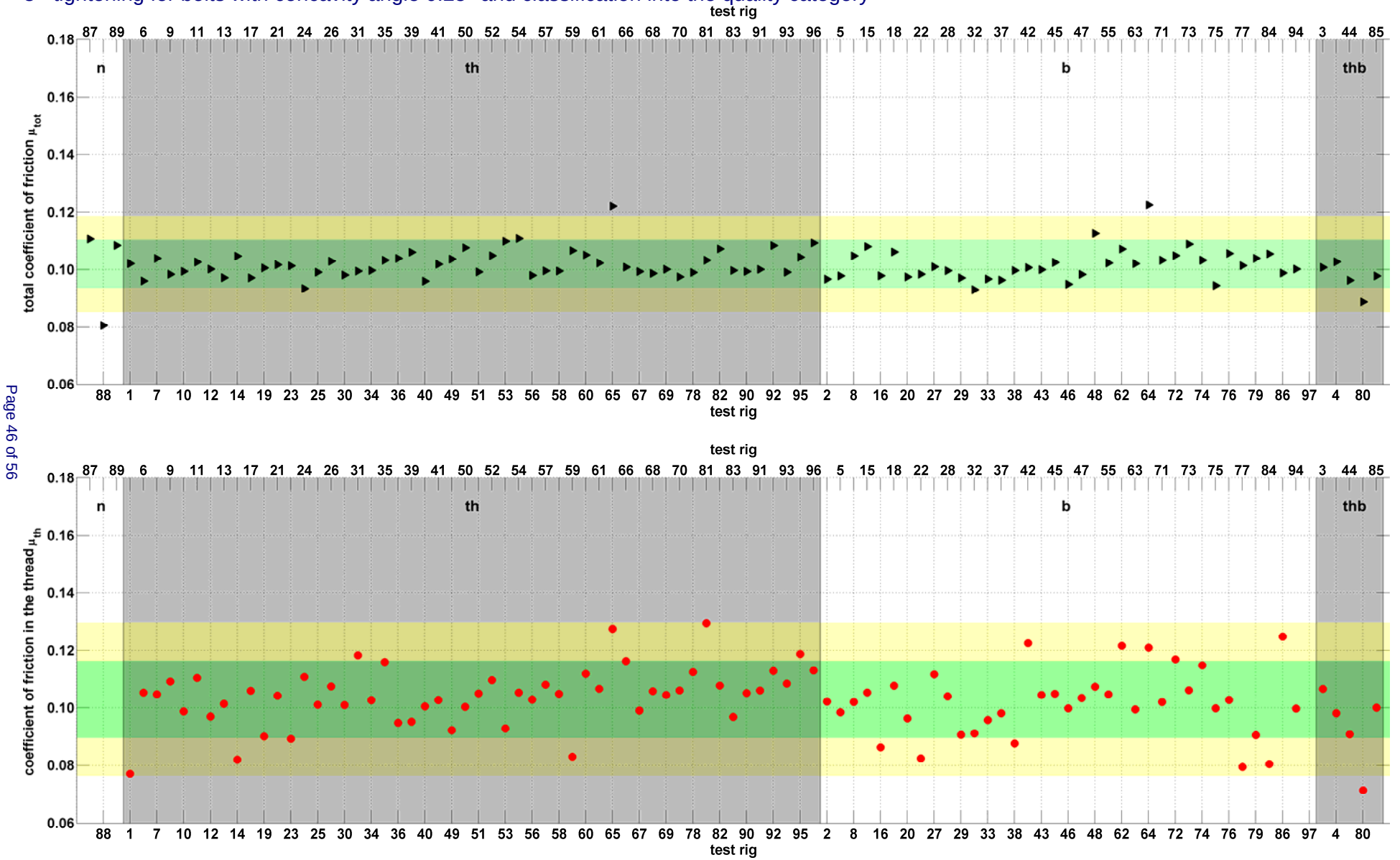
2nd tightening for bolts with concavity angle 0.25° and classification into the quality category

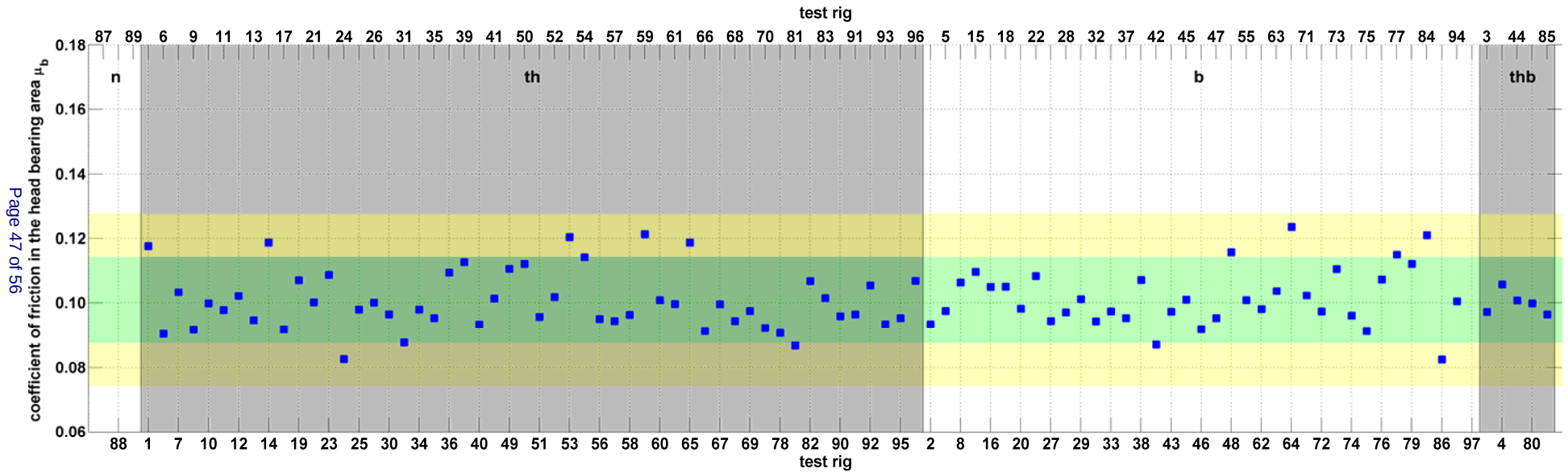



test rig
87 89 6 9 11 13 17 21 24 26 31 35 39 41 50 52 54 57 59 61 66 68 70 81 83 91 93 96 5 15 18 22 28 32 37 42 45 47 55 63 71 73 75 77 84 94 3 44 85
n
th
b
thb
coefficient of friction in the thread μ_{th}
0.18
0.16
0.14
0.12
0.10
0.08
0.06
88 1 7 10 12 14 19 23 25 30 34 36 40 49 51 53 56 58 60 65 67 69 78 82 90 92 95 2 8 16 20 27 29 33 38 43 46 48 62 64 72 74 76 79 86 97 4 80
test rig


test rig
87 89 6 9 11 13 17 21 24 26 31 35 39 41 50 52 54 57 59 61 66 68 70 81 83 91 93 96 5 15 18 22 28 32 37 42 45 47 55 63 71 73 75 77 84 94 3 44 85
n
th
b
thb
coefficient of friction in the head bearing area μ_b
0.18
0.16
0.14
0.12
0.10
0.08
0.06
88 1 7 10 12 14 19 23 25 30 34 36 40 49 51 53 56 58 60 65 67 69 78 82 90 92 95 2 8 16 20 27 29 33 38 43 46 48 62 64 72 74 76 79 86 97 4 80
test rig

3rd tightening for bolts with concavity angle 0.25° and classification into the quality category




test rig
87 89 6 9 11 13 17 21 24 26 31 35 39 41 50 52 54 57 59 61 66 68 70 81 83 91 93 96 5 15 18 22 28 32 37 42 45 47 55 63 71 73 75 77 84 94 3 44 85
n
th
b
thb
0.18
0.16
0.14
0.12
0.10
0.08
0.06
coefficient of friction in the head bearing area μ_b
88 1 7 10 12 14 19 23 25 30 34 36 40 49 51 53 56 58 60 65 67 69 78 82 90 92 95 2 8 16 20 27 29 33 38 43 46 48 62 64 72 74 76 79 86 97 4 80
test rig

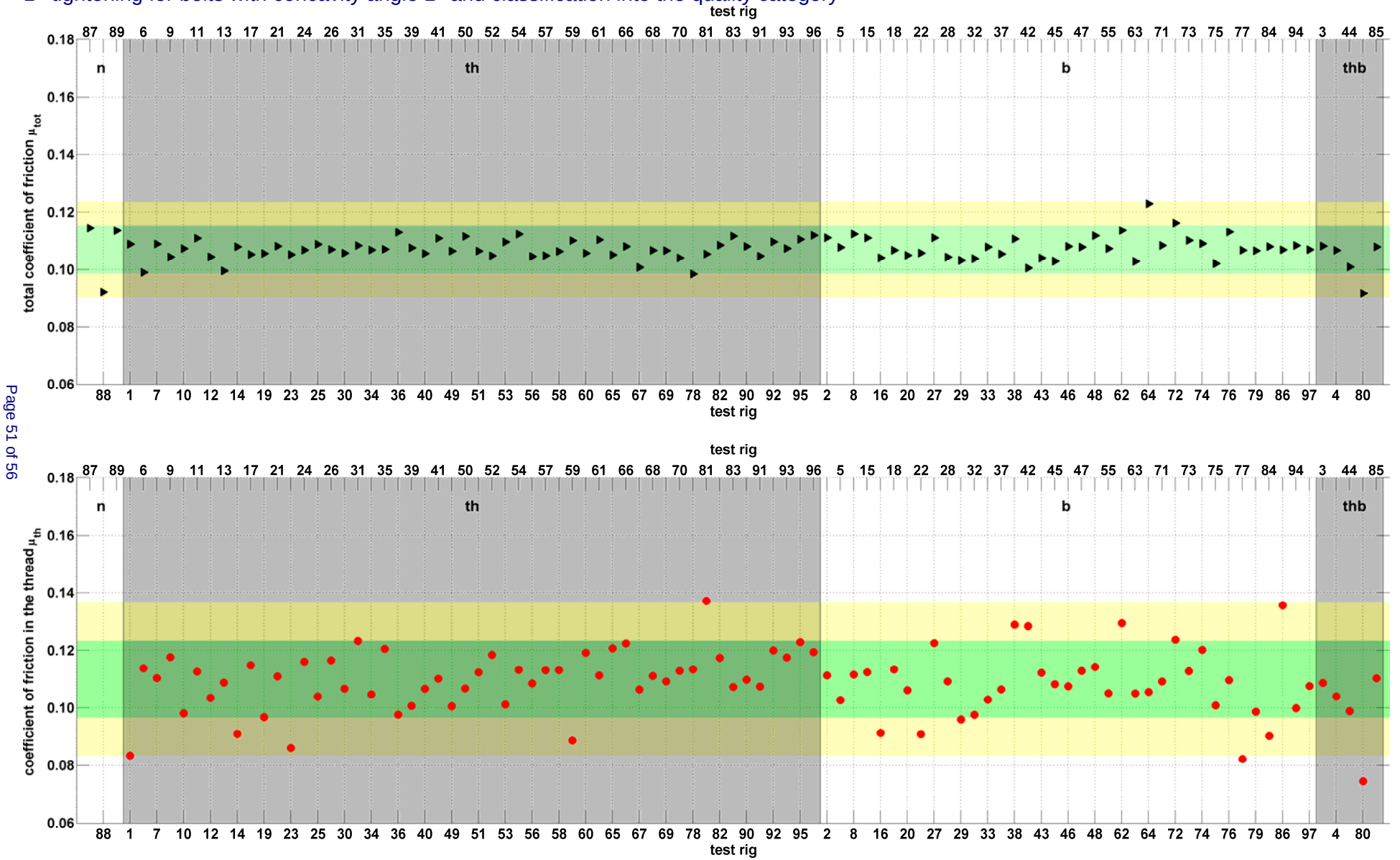
Annex 9 Classification of the test rigs into quality categories for bolts with the concavity angle 1°

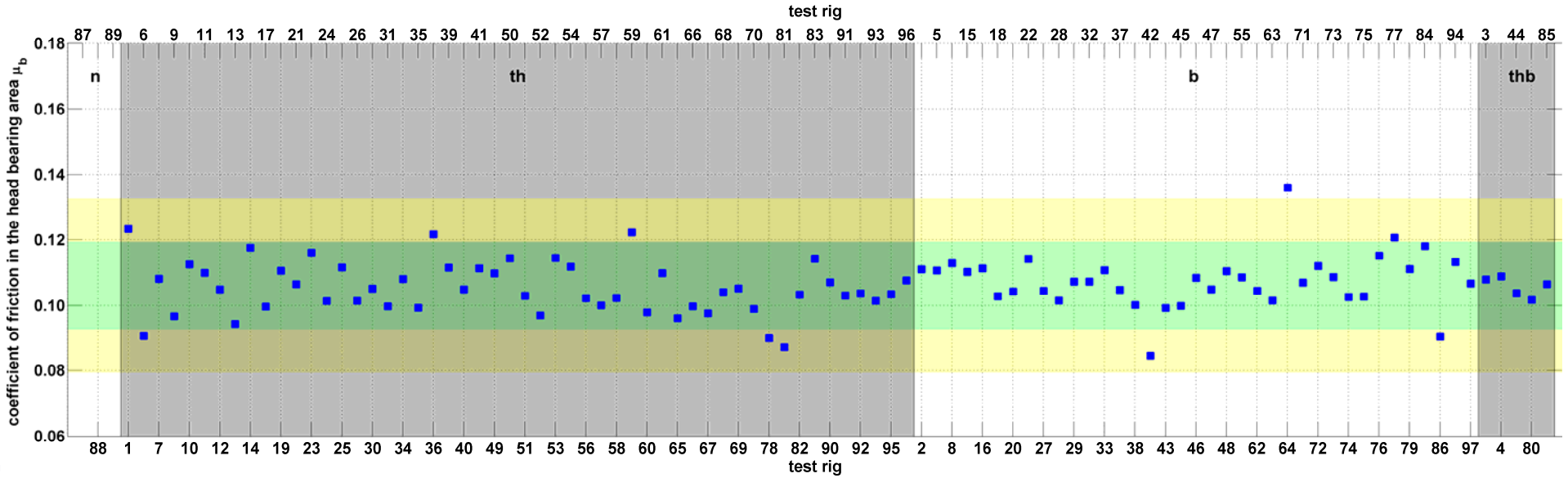
test rig Nr.	test rig type	1st tightening			2nd tightening			3rd tightening			total evaluation
		total coefficient of friction μ_{tot}	coefficient of friction in the thread μ_{th}	coefficient of friction in the head bearing area μ_b	total coefficient of friction μ_{tot}	coefficient of friction in the thread μ_{th}	coefficient of friction in the head bearing area μ_b	total coefficient of friction μ_{tot}	coefficient of friction in the thread μ_{th}	coefficient of friction in the head bearing area μ_b	
1	th	C0	C1	C1	C0	C2	C1	C0	C1	C1	C2
2	b	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
3	thb	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
4	thb	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
5	b	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
6	th	C1	C0	C1	C1	C0	C1	C1	C0	C1	C1
7	th	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
8	b	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
9	th	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
10	th	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
11	th	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
12	th	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
13	th	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
14	th	C0	C1	C0	C0	C1	C0	C0	C1	C0	C1
15	b	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
16	b	C0	C1	C0	C0	C1	C0	C0	C1	C0	C1
17	th	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
18	b	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
19	th	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
20	b	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
21	th	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
22	b	C0	C1	C0	C0	C1	C0	C0	C1	C0	C1
23	th	C0	C1	C0	C0	C1	C0	C0	C1	C0	C1
24	th	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
25	th	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
26	th	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
27	b	C0	C0	C0	C0	C1	C0	C0	C1	C0	C1
28	b	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
29	b	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
30	th	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
31	th	C0	C1	C0	C0	C1	C0	C0	C1	C0	C1
32	b	C0	C0	C0	C0	C1	C0	C0	C1	C0	C1
33	b	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
34	th	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
35	th	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
36	th	C0	C0	C1	C0	C0	C1	C0	C0	C1	C1
37	b	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
38	b	C0	C1	C0	C0	C1	C0	C0	C1	C0	C1
39	th	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0

test rig Nr.	test rig type	1st tightening			2nd tightening			3rd tightening			total evaluation
		total coefficient of friction μ_{tot}	coefficient of friction in the thread μ_{th}	coefficient of friction in the head bearing area μ_b	total coefficient of friction μ_{tot}	coefficient of friction in the thread μ_{th}	coefficient of friction in the head bearing area μ_b	total coefficient of friction μ_{tot}	coefficient of friction in the thread μ_{th}	coefficient of friction in the head bearing area μ_b	
40	th	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
41	th	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
42	b	C0	C1	C1	C0	C1	C1	C0	C1	C1	C1
43	b	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
44	thb	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
45	b	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
46	b	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
47	b	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
48	b	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
49	th	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
50	th	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
51	th	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
52	th	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
53	th	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
54	th	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
55	b	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
56	th	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
57	th	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
58	th	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
59	th	C0	C1	C1	C0	C1	C1	C0	C1	C1	C1
60	th	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
61	th	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
62	b	C0	C1	C0	C0	C1	C0	C0	C1	C0	C1
63	b	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
64	b	C1	C0	C2	C2	C0	C2	C2	C0	C2	C2
65	th	C0	C0	C0	C1	C1	C0	C2	C2	C0	C2
66	th	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
67	th	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
68	th	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
69	th	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
70	th	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
71	b	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
72	b	C1	C1	C0	C0	C0	C0	C0	C0	C0	C1
73	b	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
74	b	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
75	b	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
76	b	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
77	b	C0	C2	C1	C0	C2	C0	C0	C2	C0	C2
78	th	C1	C0	C1	C1	C0	C1	C1	C0	C1	C1
79	b	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
80	thb	C1	C2	C0	C1	C2	C0	C1	C2	C0	C2
81	th	C0	C2	C1	C0	C2	C1	C0	C2	C1	C2

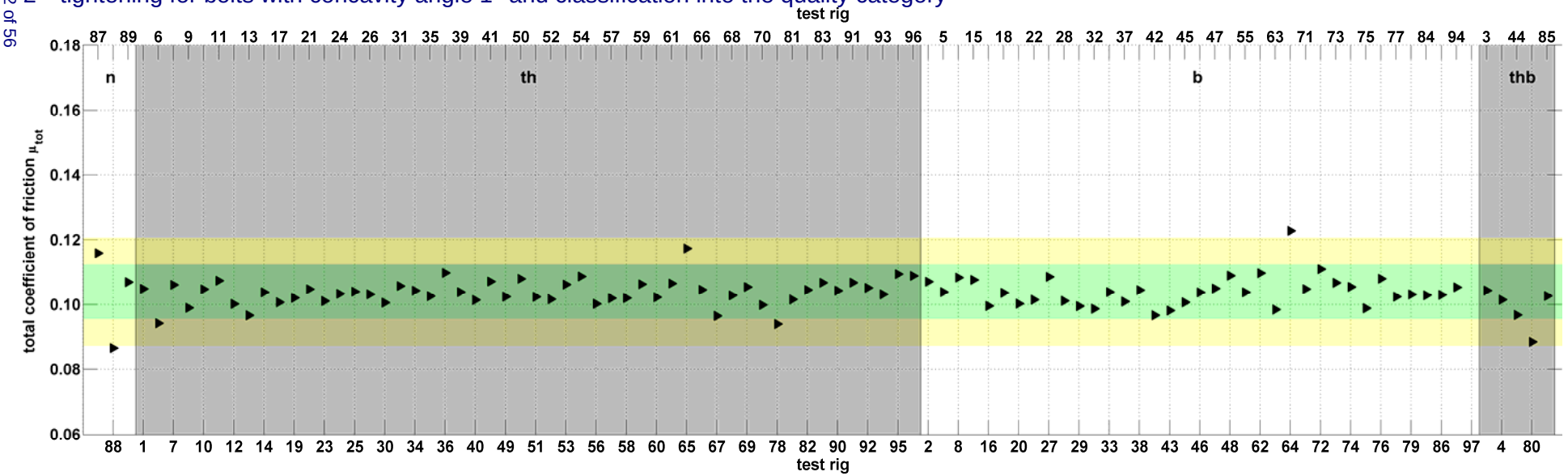
test rig Nr.	test rig type	1st tightening			2nd tightening			3rd tightening			total evaluation
		total coefficient of friction μ_{tot}	coefficient of friction in the thread μ_{th}	coefficient of friction in the head bearing area μ_b	total coefficient of friction μ_{tot}	coefficient of friction in the thread μ_{th}	coefficient of friction in the head bearing area μ_b	total coefficient of friction μ_{tot}	coefficient of friction in the thread μ_{th}	coefficient of friction in the head bearing area μ_b	
82	th	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
83	th	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
84	b	C0	C1	C0	C0	C1	C0	C0	C1	C0	C1
85	thb	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
86	b	C0	C1	C1	C0	C2	C1	C0	C1	C0	C2
87	n	C0			C1			C1			C1
88	n	C1			C2			C1			C2
89	n	C0			C0			C0			C0
90	th	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
91	th	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
92	th	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
93	th	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
94	b	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
95	th	C0	C0	C0	C0	C1	C0	C0	C1	C0	C1
96	th	C0	C0	C0	C0	C0	C0	C0	C0	C0	C0
97	b	C0	C0	C0							C0

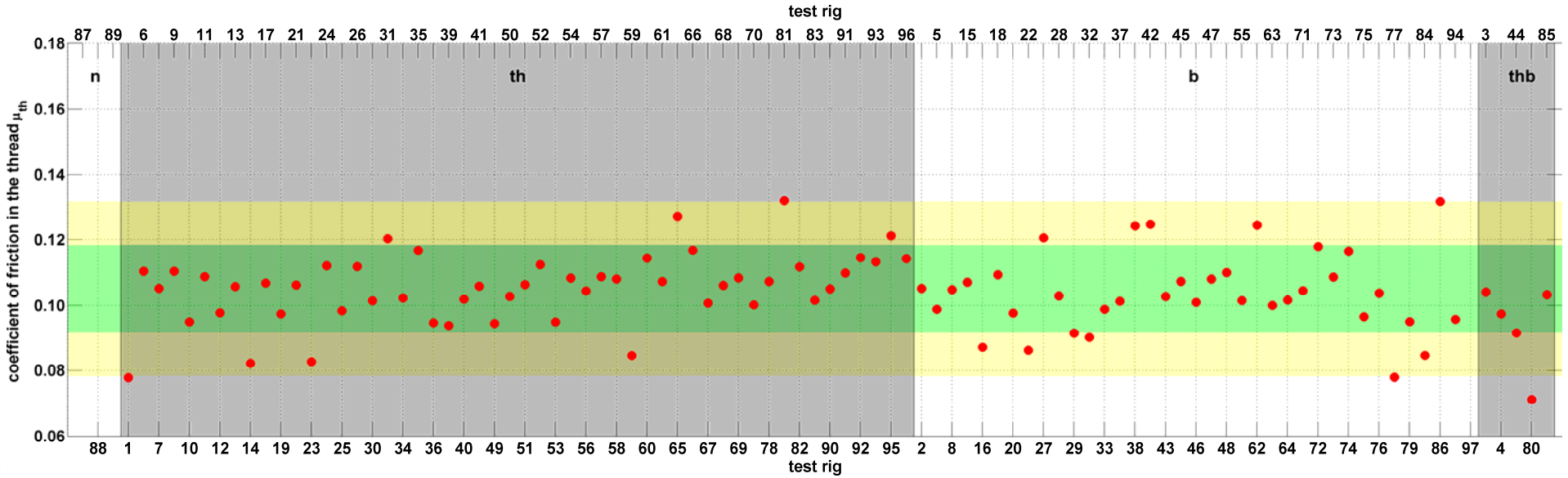
1st tightening for bolts with concavity angle 1° and classification into the quality category

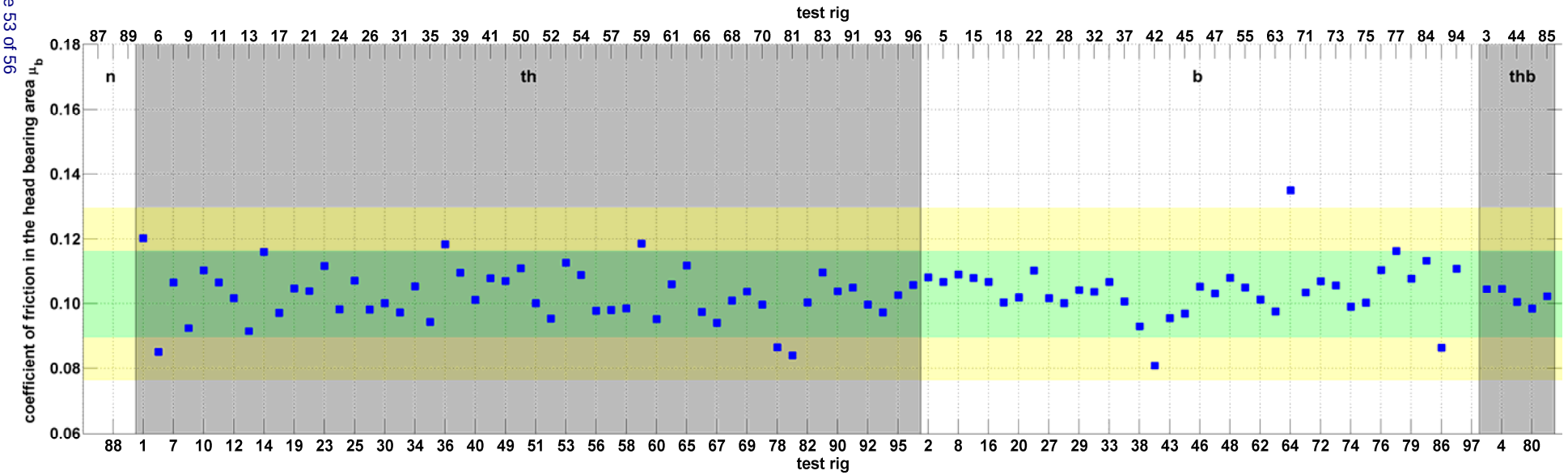




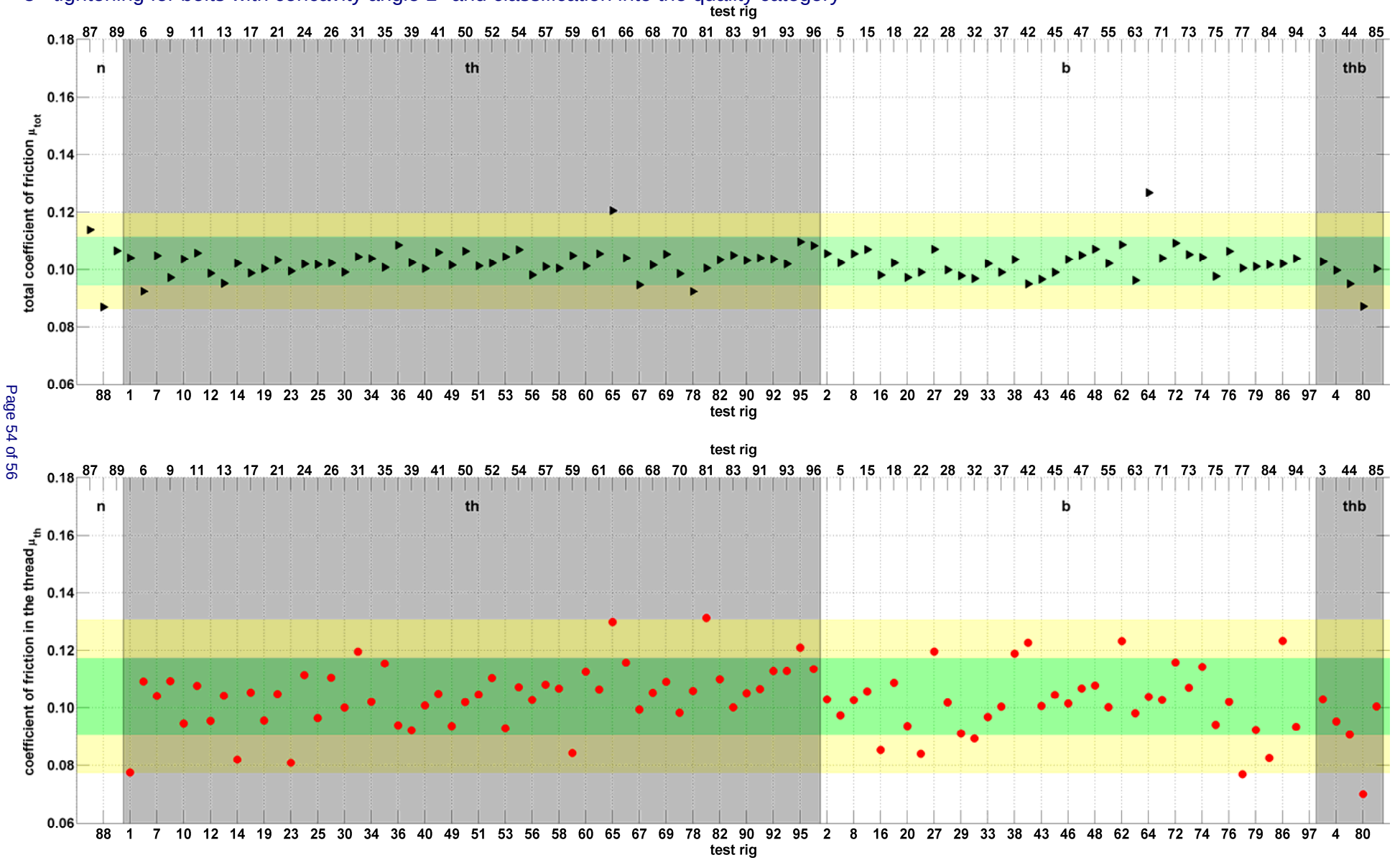
2nd tightening for bolts with concavity angle 1° and classification into the quality category

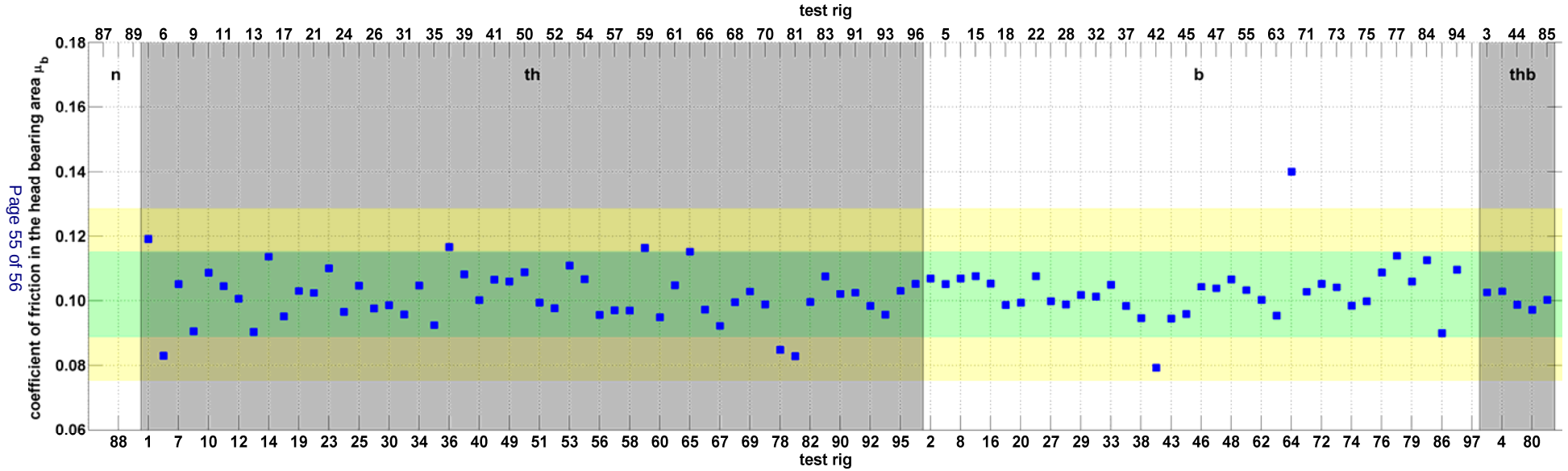



test rig
87 89 6 9 11 13 17 21 24 26 31 35 39 41 50 52 54 57 59 61 66 68 70 81 83 91 93 96 5 15 18 22 28 32 37 42 45 47 55 63 71 73 75 77 84 94 3 44 85
n
th
b
thb
coefficient of friction in the thread μ_{th}
0.18
0.16
0.14
0.12
0.10
0.08
0.06
88 1 7 10 12 14 19 23 25 30 34 36 40 49 51 53 56 58 60 65 67 69 78 82 90 92 95 2 8 16 20 27 29 33 38 43 46 48 62 64 72 74 76 79 86 97 4 80
test rig


test rig
87 89 6 9 11 13 17 21 24 26 31 35 39 41 50 52 54 57 59 61 66 68 70 81 83 91 93 96 5 15 18 22 28 32 37 42 45 47 55 63 71 73 75 77 84 94 3 44 85
n
th
b
thb
coefficient of friction in the head bearing area μ_b
0.18
0.16
0.14
0.12
0.10
0.08
0.06
88 1 7 10 12 14 19 23 25 30 34 36 40 49 51 53 56 58 60 65 67 69 78 82 90 92 95 2 8 16 20 27 29 33 38 43 46 48 62 64 72 74 76 79 86 97 4 80
test rig

3rd tightening for bolts with concavity angle 1° and classification into the quality category




test rig
87 89 6 9 11 13 17 21 24 26 31 35 39 41 50 52 54 57 59 61 66 68 70 81 83 91 93 96 5 15 18 22 28 32 37 42 45 47 55 63 71 73 75 77 84 94 3 44 85
n
th
b
thb
coefficient of friction in the head bearing area μ_b
0.18
0.16
0.14
0.12
0.10
0.08
0.06
88 1 7 10 12 14 19 23 25 30 34 36 40 49 51 53 56 58 60 65 67 69 78 82 90 92 95 2 8 16 20 27 29 33 38 43 46 48 62 64 72 74 76 79 86 97 4 80
test rig

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