

Loss of preload in bolted connections due to typical coating systems for steel structures

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Abstract

Bolted connections can be preloaded either to ensure the structural safety or to improve the serviceability e.g. by minimizing the slip or by increasing the deformation stiffness. According to DAST-Guideline 024, target level I of preloading and target level II of preloading can be distinguished.

A design of bolted connections with target level II of preloading is carried out without consideration of the actual amount of preload. However, the preloading force is directly included in the design verification for connections of target level I, so that the nominal value of preloading force should not only be reliably achieved during the tightening of a connection, but a sufficient level of preloading force considering the resulting preload losses must be ensured over the service life of the structure. A special type of connections with target level I of preloading is represented by the slip-resistant connections, which performance mainly relies not only on the level of preload, but also on the associated slip factor. The determination of the latter can currently be carried out considering the test procedure acc. to EN 1090-2, Annex G.

A sufficient design and execution of low-maintenance connections depend on the knowledge of several influencing factors, such as the reliability of different tightening methods with the associated system reserves and/or the estimated loss of preload over the service life. Since an assessment of potential preload losses is only possible to a very limited extent according to the current state of the art in steel construction, a development of suitable verification methods is necessary. Furthermore, recommendations with regard to the execution of slip-resistant connections considering practical boundary conditions are desirable in order to assess their possible influence on the slip resistance.

A comprehensive investigation was carried out in order to address the gap in the knowledge that currently exists for preloaded bolted connections. Herein, practically applicable solutions for a sufficient design and execution of low-maintenance preloaded bolted connections in steel construction are provided based on the carried out estimation of the remaining preload level over the service life. Furthermore, an updated test procedure for the determination of preload losses is proposed. Finally, supplementary recommendations for the execution of slip-resistant connections regarding the practical boundary conditions are formulated.

Kurzfassung

Geschraubte Verbindungen werden entweder zur Sicherstellung der Tragfähigkeit oder zur Verbesserung der Gebrauchstauglichkeit vorgespannt. Bei Verbindungen der Zielebene I des Vorspannens nach DAST-Richtlinie 024 geht die Höhe der Vorspannkraft direkt in den rechnerischen Nachweis ein, so dass beim Vorspannen der Verbindung nicht nur der Nennwert der Vorspannkraft zuverlässig erreicht werden soll, sondern auch ein ausreichendes Vorspannkraftniveau hinsichtlich der potentiellen Vorspannkraftverluste über die komplette Lebensdauer sichergestellt werden muss. Zusätzlich zur Höhe der Vorspannung wird das Tragverhalten einer gleitfesten Verbindung (ebenfalls Zielebene I des Vorspannens) hauptsächlich durch die Haftreibungszahl beeinflusst, deren Bestimmung aktuell experimentell mittels eines Prüfverfahrens nach DIN EN 1090-2, Anhang G erfolgen kann. Die Bemessung von Schraubenverbindungen, welche rein aus Gebrauchstauglichkeitsgründen vorgespannt wurden (Zielebene II des Vorspannens nach DAST-Richtlinie 024), erfolgt vorspannungsfrei.

Die Kenntnis von verschiedenen Einflussfaktoren wie die Zuverlässigkeit des eingesetzten Anziehverfahrens mit den damit verbundenen Systemreserven und/oder das Ausmaß der potentiellen Vorspannkraftverluste sind zur Bemessung und Ausführung von wartungsarmen Verbindungen vorausgesetzt. Da eine Abschätzung potentieller Vorspannkraftverluste nach dem derzeitigen Stand der Technik im Stahlbau sehr eingeschränkt möglich ist, ist eine Entwicklung geeigneter Nachweisverfahren erforderlich. Darüber hinaus sind Empfehlungen zur Ausführung von gleitfesten Verbindungen unter Berücksichtigung von praktischen Randbedingungen wünschenswert, um deren möglichen Einfluss auf den Gleitwiderstand beurteilen zu können.

Um bestehende Wissenslücke zu schließen, wurden systematische Untersuchungen im Rahmen von drei IGF-Forschungsvorhaben Nr. 18711 BG, Nr. 19749 BG und Nr. 21196 BG durchgeführt. Basierend auf einer Abschätzung des verbleibenden Vorspannkraftniveaus unter Berücksichtigung verschiedener Anziehverfahren und Beschichtungssysteme wurden praktisch anwendbare Lösungen für Bemessung und Ausführung von wartungsarmen vorgespannten Schraubverbindungen im Stahlbau erarbeitet. Darüber hinaus wurde ein aktualisiertes Prüfverfahren zur Ermittlung der Vorspannkraftverluste vorgeschlagen. Abschließend wurden ergänzende Empfehlungen für die Ausführung von gleitfesten Verbindungen unter Berücksichtigung der praktischen Randbedingungen formuliert.

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Symbols and Abbreviations

Latin symbols

A_s	stress cross section of the bolt thread
$B_{p,Rd}$	design punching shear resistance of the bolt head and the nut
C_P	stiffness of the clamped parts
C_S	stiffness of the bolt
c_1	statistical coefficient for determination of the slip resistance according to SANS 10162-1 and CSA S16-09
DFT_{faying}	measured coating thickness of faying surfaces
DFT_{sbw}	measured coating thickness of surfaces beneath washers
DFT_{spec}	average measured coating thickness per test specimen
D_{Km}	effective diameter for the friction moment at the bolt head or nut surface bearing area
d or d_b	bolt diameter
d_2	pitch diameter of the bolt thread
$dM_A/d\theta$	difference quotient
D_u	multiplier for determination of the nominal slip resistance according to RCSC Specification
F_A	axial operating load
$F_{b,Rd}$	design bearing resistance per bolt
F_{ect}	load level of the passed extended creep test
F_{KR}	residual clamp load
F_M or F_P	assembly preload

$F_{M \min}$ or $F_{p,\min}$	required minimum assembly preload
$F_{M \max}$ or $F_{p,\max}$	maximum assembly preload
F_{PA}	additional load of clamped parts
$F_{p,act}$	actual measured bolt preload value
$F_{p,C}$	nominal minimum preloading force
$F_{p,C}^*$	reduced nominal minimum preloading force according to DAST-Guideline 024
$F_{p,ini}$	initial preload value
$F_{p,ini,0.05}$	5 % characteristic preload value
$F_{p,ini,0.05,eff}$	effective characteristic preload value
$F_{p,k=0.10}$	theoretical bolt preload for the modified torque method considering a k-factor of 0.1
$F_{p,k=0.16}$	theoretical bolt preload for the modified torque method considering a k-factor of 0.16
$F_{p,Ld}$	remaining preload level for the intended service life of a structure
$F_{p,mean}$	target/mean preload level for the determination of reliability
$F_{p,start}$	preload value at the beginning of a specific test
F_S	bolt load
F_{SA}	axial additional bolt load
F_{Sm}	mean slip load in a static slip load test
$F_{s,Rd}$	design value of the slip resistance at ultimate limit state
$F_{s,Rd,ser}$	design value of the slip resistance at serviceability limit state
$F_{t,Ed}$	design tensile force per bolt for ultimate limit state
$F_{t,Ed,ser}$	design tensile force per bolt for serviceability limit state
$F_{t,Rd}$	design tension resistance per bolt

F_V	other specified preloading force than $F_{p,C}$ or $F_{p,C}^*$ according to DAST-Guideline 024
$F_{v,Ed}$	design shear force per bolt
$F_{v,Ed,ser}$	design value of the acting shear force at serviceability limit state
$F_{v,Rd}$	design shear resistance per bolt
F_{yb}	preload value by the onset of the yielding of the bolt considering the nominal yield strength of the bolt material f_{yb}
F_Z	loss of preload as a result of embedding
$F(X)$	cumulative probability of parameter X
f	total deformation of a bolted connection
f_{PA}	deformation of the clamped parts due to additional load of clamped parts F_{PA}
f_{PM}	shrinkage of the clamped parts due to assembly preload F_M
f_{SA}	bolt elongation due to axial additional bolt load F_{SA}
f_{SM}	elongation of the bolt due to assembly preload F_M
f_{ub}	nominal ultimate strength of the bolt material
f_{yb}	nominal yield strength of the bolt material
f_Z	amount of embedding
$f_{Z,0.95}$	95 % fractile value of the amount of embedding
$f_{Z,i}$	amount of embedding for individual measurements
$f(X)$	probability density of parameter X
H_D	Shore hardness
k	k-factor (or k-value) determined according to EN 14399-2
k_i	individual k-factor
k_m	mean k-factor

k_n	coefficient for determination of characteristic values according to EN 1990, Annex D
k_s	reduction factor for different types of holes
L_f	coefficient for the loss of preload according to IEC 61400-6
M_A	tightening torque
$M_{A,pre}$	pre-tightening torque
M_G	tightening torque acting in the paired threads
M_{Gst}	pitch torque
M_{GR}	thread friction torque
M_K	friction moment in the head or nut bearing area, surface bearing friction moment
m	number of bolts in a slip-resistant connection
n	number of friction surfaces / number of bolts / number of tests
n_{spec}	number of valid measurements within a test specimen
P	thread pitch
p	obtained probability statistic for performing of the significance test
R	stress ratio
R^2	coefficients of determination of a linear regression
R_{y5}	mean maximum peak-to-valley height (roughness) of the steel surface
SE_X	standard error of a parameter X
s	guide value for scattering according to EN 13001-3-1
T_i	individual bolt pretension according to RCSC Specification
T_m	specified minimum bolt pretension according to RCSC Specification
t	plate thickness

$t_{\alpha/2}$	critical value considering the two-tailed Student's t-distribution and the respective degrees of freedom
V_{comb}	combined coefficient of variation used for the determination of reliability
V_k	coefficient of variation of the mean k-factor
V_s	slip resistance according to SANS 10162-1 and CSA S16-09
V_X	coefficient of variation for a specific variable X
Z_{crit}	critical external load at which an opening of the clamped parts (partly) occurs
Z_{max}	maximum applied cyclic load in a cyclic test

Greek symbols

α	significance level for statistical evaluation
α_A	tightening factor according to VDI 2230-1
β_2	reduction factor for slip-resistant connections due to lower clamping forces
γ_{M3}	partial factor for slip resistance at ultimate limit state
$\gamma_{M3,\text{ser}}$	partial factor for slip resistance at serviceability limit state
$\Delta F_{p,\text{cycl}}$	preload losses in a cyclic test
$\Delta F_{p,\text{cycl},2E9}$	extrapolated preload losses in a cyclic test to 2×10^9 load cycles
$\Delta F_{p,\text{ect},50a}$	extrapolated preload losses to the intended service life of 50 years for test specimens that passed the extended creep tests
$\Delta F_{p,\text{setting}}$	preload losses in a relaxation test
$\Delta F_{p,\text{setting},50a}$	extrapolated preload losses in a relaxation test to the intended service life of 50 years
$\Delta F_{p,\text{setting},50a,\text{reg}}$	extrapolated preload losses in a relaxation test to the intended service life of 50 years calculated based on a linear regression model

$\Delta F_{p, \text{setting}, 50a, 0.95}$	95 % fractile value of extrapolated preload losses in a relaxation test to the intended service life of 50 years
$\Delta F_{p, \text{setting}, 50a, 0.95, \text{reg}}$	95 % fractile value of extrapolated preload losses in a relaxation test to the intended service life of 50 years calculated based on a linear regression model
$\Delta F_{p, \text{setting}, Ld}$	extrapolated preload losses in a relaxation test to the intended service life of a structure
$\Delta \theta$	further angle of rotation
δ_P	elastic resilience of the clamped parts
δ_S	elastic resilience of the bolt
δ_{spec}	elastic resilience of a test specimen
θ	angle or rotation
μ	slip factor
μ_{act}	slip factor considering the actual preload value at slip
μ_{ect}	slip factor resulting from the passed extended creep tests
$\mu_{\text{ect}, \text{act}}$	actual slip factor during the extended creep test
μ_G	coefficient of friction in the thread
μ_{ini}	slip factor considering the initial preload value when the test starts
μ_{KR}	coefficient of friction in the surface bearing area
μ_{nom}	slip factor considering the nominal minimum preload value
Σt	clamping length of a bolted connection
$\Sigma t/d$	clamping length ratio of a bolted connection
σ	standard deviation
σ_X	standard deviation of parameter X
$\sigma_{\bar{X}}$	standard error of the mean of parameter X

Υ_{mean}	System reserve or system deficit based on the nominal minimum preloading force considering the mean initial preload value
$\Upsilon_{0.05}$	System reserve or system deficit based on the nominal minimum preloading force considering the 5 % characteristic initial preload value
Φ	load factor, quotient of the additional bolt load F_{SA} and the axial working load component F_A

Abbreviations

1K	one-pack
1K-ESI	one-pack ethyl-zinc silicate paint
2K	two-pack
2K-ESI	two-pack ethyl-zinc silicate paint
AiF	German Federation of Industrial Research Associations
AK	alkyd paint
AlSM	aluminium spray metallized
ASI	alkali-zinc silicate
ASTM	American Society for Testing and Materials
AY	acrylic paint
AY-PUR	acrylic polyurethane paint
CBG	center bolts group position
CSA	Canadian Standard for Design of Steel Structures
DAST	Deutscher Ausschuss für Stahlbau
DFT	dry film thickness
DIBt	Deutsches Institut für Bautechnik
DTI	Direct Tension Indicators

ECCS	European Convention for Constructional Steelwork
EG	micaceous iron oxide
EP	epoxy based paint
EPE	epoxy ester paint
EP-Zn	epoxy based zinc rich paint
EP-ZnPh	epoxy based zinc phosphate pigmented paint
ESI	ethyl zinc silicate primer
ETA	European Technical Assessment
EXC	execution class
GB	grit blasted
HDG	hot dip galvanizing
HDG-ASI	hot dip galvanizing surfaces with alkali-zinc silicate primer
HR	high-strength structural bolting assemblies for preloading; System HR
HRC	high-strength structural bolting assemblies for preloading; System HRC
HS	high solid
HV	high-strength structural bolting assemblies for preloading; System HV
IEC	International Electrotechnical Commission
IGF	Industrial Collective Research
ISO	International Organization for Standardization
JASS	Japanese Architectural Standard Specification
KV	Combined method
LVDT	Linear variable differential transformer
MDV	Modified torque method
MoS₂	molybdenum disulfide

NDFT	nominal dry film thickness
PE	plate edge position
PUR	polyurethane paint
PVC	polyvinyl chloride
RCSC	Research Council on Structural Connections
SANS	South African National Standard
SLS	Serviceability Limit State
SP	polyester resin
ULS	Ultimate Limit State
UDE/IML	Institute for Metal and Lightweight Structures of the University of Duisburg-Essen
VDI	Verein deutscher Ingenieure
VOC	volatile organic compounds
ZnSM	zinc spray metallized

1 Introduction

1.1 Problem definition

Joining technology describes constructive methods of assembling individual parts. The resulting connections differ, among other things, in their degree of detachability and can be classified as non-detachable (e.g. welded connections), conditionally detachable (e.g. riveted connections) or detachable (e.g. bolted connections). While the destruction of the complete component is necessary in the case of non-detachable connections or its auxiliary parts in the case of conditionally detachable connections, detachable connections usually do not show any damage to the components after they have been disassembled.

In steel structures, bolted connections offer desired flexibility where disassembly, maintenance or replacement of the parts are necessary and thus represent one of the most important joining techniques. Bolted connections can in principle be divided into preloaded and non-preloaded connections, whereby the design, calculation and dimensioning standard of connections made of steel EN 1993-1-8 [1] defines five categories - A to E - of bolted connections.

The preloading of bolted connections can be used either to ensure the structural safety or to improve the serviceability by minimizing slip and by increasing deformation stiffness. With regard to the intended use of preloading, DAST-Guideline 024 distinguishes between target level I of preloading (preloading for load-bearing capacity reasons - cat. B and C as well as cat. E according to EN 1993-1-8) and target level II of preloading (preloading for serviceability reasons - cat. A and D according to EN 1993-1-8). Connections of target level II are designed without consideration of the amount of preloading force, whereas the preloading force for the connections of target level I is directly included in the design verification format. Thus the nominal value of preloading force should not only be reliably achieved during the tightening of the connection, but a sufficient level of preloading force must be ensured over the service life of the structure.

The standard for execution of steel and aluminium structures EN 1090-2 [2] offers different tightening methods, among others the combined method, EN torque method, HRC tightening method and direct tension indicator (DTI) method, for preloading of bolting assemblies. At German national level, supplementary tightening methods such as the modified torque method are regulated in DAST-Guideline 024 [3]. Alternatively, the tractive method or lockbolts (both common in mechanical engineering) can also be used in accordance with an European Technical Assessment (ETA). The differences in the operating principles of the various tightening methods lead to different initial preloading forces after tightening, which, in relation to the nominal value of the preloading force, can either result in deficits or ideally in system reserves. Although prescribed by EN 1090-2, the required system reserves of 10 % are not necessarily met in practice.

Shortly after tightening of a bolted connection, setting effects resulting from the plastic flattening of the surfaces occur. Further time-dependent processes such as creep of the coating materials lead to a loss of preload, which contributes to the loosening of the bolted connection. External mechanical loads, such as shear loads in the case of slip-resistant connections, cause loss of preload due to reduction of the clamping package as a result of transverse contraction. Extreme cyclic loading can also cause the bolts to gradually turn loose. Here, a distinction is made between total and partial self-loosening.

The design and construction of low-maintenance connections, but also the production of economically efficient steel structures, thus depend on the knowledge of the so-called system reserves due to different tightening methods in combination with the estimated loss of preload (among other things for various coating systems). Since the implicit consideration of the loss of preload is only possible to a very limited extent according to the current state of the art in steel construction, a development of suitable verification methods based on the latest findings from systematic investigations is necessary.

1.2 Objective

Within the scope of this work, the suitability of typical coating systems for steel structures with common dry film thicknesses in practice is investigated with regard to the loss of preload in bolted connections. Special attention is paid

not only to systems that are usually used in preloaded bolted connections of target level I of preloading, but also in connections of target level II of preloading. In addition to the normative nominal dry film thicknesses, the influence of the highest permissible dry film thicknesses on the loss of preload is addressed, too. Further variations include the single-lap and double-lap design of the bolted connections as well as different clamping length ratios. Some of the most important tightening methods in German steel construction, the combined method and the modified torque method, will be contrasted with regard to their application in bolted connections. The possible procedure-related influence on the amount of the loss of preload as well as the system reserves resulting after tightening are determined and discussed.

With regard to bolted connections of target level I of preloading and their use in fatigue-loaded structures, the preloading force behaviour under cyclic loading is outlined. Furthermore, practical boundary conditions such as different tightening methods and their possible influence on the load-bearing behaviour are addressed with regard to slip-resistant connections.

The systematic experimental investigations and their evaluation were carried out at the Institute for Metal and Lightweight Structures of the University of Duisburg-Essen (UDE/IML). Herein, three IGF research projects: IGF No. 18711 BG "Development of a concept to assess the loss of preload in preloaded bolted connections under fatigue loading" [4], IGF No. 19749 BG "Influence of manufacturing- and assembly-related imperfections on the bearing behaviour of bolted slip-resistant connections in steel structures" [5] and IGF No. 21196 BG "Development of normative fundamentals for consideration of preload losses in preloaded bolted connections with coated faying surfaces in steel construction" [6] were taken as a basis. All three research projects were supported by the Federal Ministry for Economic Affairs and Climate Action through the German Federation of Industrial Research Associations (AiF) as part of the programme for promoting industrial cooperative research (IGF) on the basis of a decision by the German Bundestag. With regard to practical boundary conditions in slip-resistant connections, further investigations are based on two expert opinions entitled "Determination of slip factors for slip-resistant connections of the cross girder connections in the temporary bridges ZH 26" [7] and "Existing preload level in preloaded bolted connections with HV bolting assemblies M24 in the area of main girder - end cross beam and main girder - cross beam connections

of the temporary bridge ZH 26.105" [8] and are briefly presented in terms of this work.

The presented work aims at a sufficient design and execution of low-maintenance preloaded bolted connections in steel construction. Considering experimental test results, suitable verification methods are to be developed for the implicit consideration of the estimated loss of preload in combination with different tightening methods. Based on the current normative regulations and the experimental results, a test procedure for determination of preload losses shall be updated as well as supplementary recommendations for the execution of preloaded bolted connections shall be formulated.

1.3 Outline

A comprehensive investigation is carried out in order to address the gap in knowledge that currently exists by providing practically applicable solutions for a sufficient design and execution of low-maintenance preloaded bolted connections in steel construction.

Chapter 2 contains a brief introduction into design and execution of preloaded bolted connections in steel structures. Next to a presentation of the relevant tightening methods (here: modified torque method and combined method) and a short discussion regarding the execution of corrosion protection, the most important reliability-determining factors of a preloaded bolted connection such as the existing preload and a slip factor are introduced.

The described reliability-determining factors are focused on in Chapter 3. Herein, the current normative regulations and some of the fundamental experimental investigations are critically reviewed with regard to the reliability of different tightening methods and the necessary corrosion protection for preloaded bolted connections and slip-resistant connections as well as its influence on preload losses. With regard to maintaining of a sufficient preload level during the service life of steel structures, a gap of knowledge is identified for further development.

A comprehensive investigation into system reserves and preload losses under consideration of the modified torque method and the combined method as well as different coating systems is presented in Chapter 4. Herein, next to bolted connections that comply with the limitations for corrosion protection on contact

surfaces acc. to EN 1090-2, also connections coated with different paint and powder coating systems commonly used in steel construction were taken into account. The conducted investigations allow an estimation of the remaining preload level over the service life.

Chapter 5 focuses on the load-bearing behaviour of slip-resistant connections considering different practical boundary conditions that are not necessarily considered in the test procedure acc. to EN 1090-2, Annex G. Different influencing factors such as practical variations of the coating layer thickness, procedure-related tightening or a change in the bolt preload and the potential affect on the slip factor due to operational loads are addressed.

Based on the experimental investigations presented in Chapter 4 as well as the current normative regulations, a proposal for a normative consideration of preload losses in steel construction including an updated test procedure for their determination is given in Chapter 6. Furthermore, Chapter 6 involves some supplementary recommendations for the execution of slip-resistant connections based on the findings in Chapter 5.

Chapter 7 provides a conclusion based on all experimental investigations carried out in the frame of this study. Furthermore, an outlook on future studies regarding issues not investigated within the scope of this work is given.

2 Design and execution of preloaded bolted connections in steel structures

2.1 General

Due to their high flexibility, especially with regard to the assembling process, bolted connections represent one of the most important joining techniques in structural steel engineering. Depending on the type of loading, bolted connections are generally divided into shear and tension connections. The design, calculation and dimensioning standard of connections made of steel EN 1993-1-8 [1] defines five categories of bolted connections for this purpose. While the connections of category A are the so-called bearing type connections, the slip-resistant connections belong to categories B and C, depending on the limit state in the design. Category D connections are treated as non-preloaded tension connections, whereas the preloaded tension connections can be assigned to category E (more details follow in Chapter 2.2).

The load-bearing behaviour of a preloaded bolted connection differs significantly from that of a non-preloaded connection. While the positive load transmission through the contact of the connected components with the fastener can be assigned to non-preloaded connections, the preloading of a connection results either in the pure load transmission through the friction (cf. slip-resistant connections) or in a combined load transmission through the friction and through the contact of clamped components (cf. preloaded tension connections). The load-bearing behaviour of a preloaded connection can be described by an elastic spring model [9]-[10]. Here, the bolt including its subcomponents can be idealised as a spring subjected to tensile stress, whereby the clamped parts are simultaneously subjected to compressive stress and can be represented by a compressed spring. The representation of the load-deformation behaviour of a bolted connection can be summarised by the joint diagram, which is based on the spring stiffnesses C and the elastic resiliences δ of the individual parts depending on the material used and the geometric boundary conditions, see Figure 2.1. The mathematical approach considering various parameters such as corresponding lengths and

cross-sections for each of the individual structural elements is described in the German Guideline VDI 2230 - Part 1 [10] and is not explained in detail in the frame of this work.

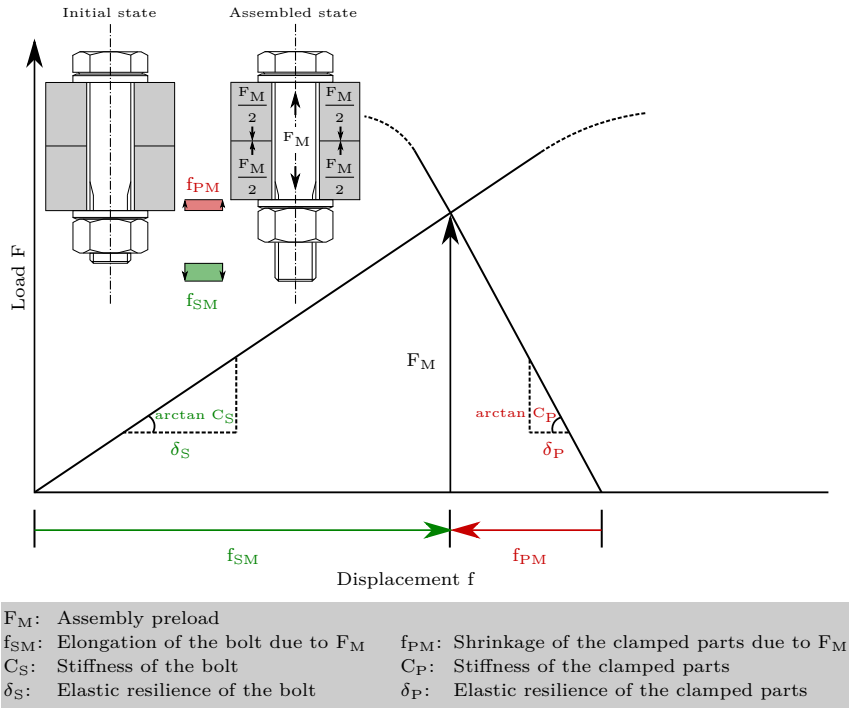
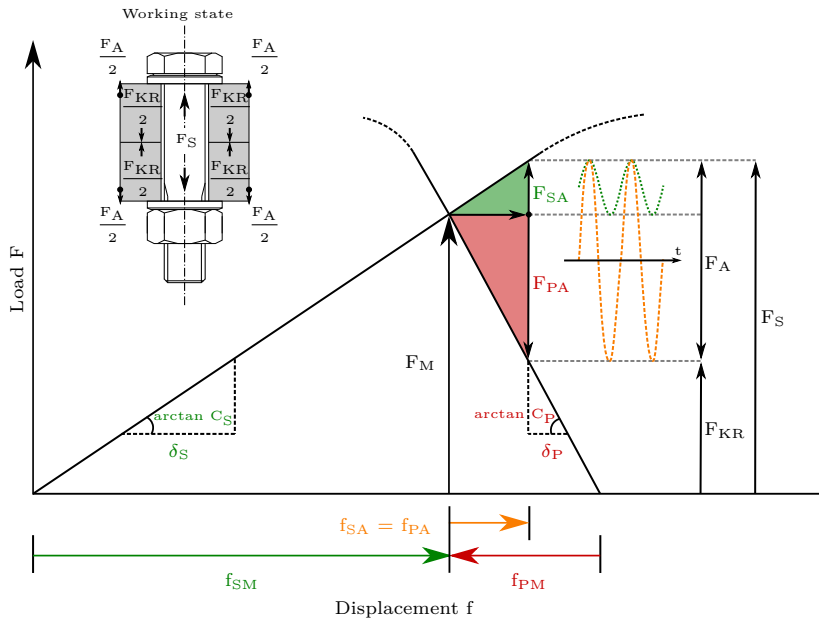


Figure 2.1 Schematic illustration of a joint diagram in the assembly state of a concentrically clamped bolted joint

In the assembly state, the bolting assembly is tightened up to an assembly preload F_M or preload level F_P (used in the further course of this work). Thus the bolt is stretched by a certain amount f_{SM} and the resulting clamped package is compressed by f_{PM} - a balance of forces is achieved between the bolt tensile force and the compressive force in the clamped package.

In the working state, on the other hand, an external operating load F_A is introduced (here: concentrically) into the connection via clamped parts, thus simultaneously changing the internal force equilibrium, see Figure 2.2. It must be mentioned that the displacement curves for the bolt and the clamped parts

usually deviate from the curves of the assembly state due to the location of the point of load introduction and the difference in stiffnesses between the assembly and the working states. Due to the tensile load F_A , the bolt is stretched by f_{SA} , while the clamped parts experience an easing of tension f_{PA} of the same amount. Thus, the initial assembly preload F_M increases by the additional bolt force F_{SA} (now F_S) and the clamping force F_{KR} (initially F_M) decreases by the amount F_{PA} .



F_S : Bolt load	F_{PA} : Additional load of clamped parts
F_{SA} : Axial additional bolt load	f_{PA} : Deformation of the clamped parts due to F_{PA}
f_{SA} : Bolt elongation due to F_{SA}	F_{KR} : Residual clamp load
F_A : Axial load	

Figure 2.2 Schematic illustration of a joint diagram in the working state of a concentrically clamped bolted joint

In Figure 2.2, the external tensile load F_A is shown as a cyclic loading with an exemplary amplitude curve. Since the stiffness of the bolt is significantly lower compared to the clamped parts, this simultaneously leads to an uneven distribution of the operating load F_A . Since the fatigue strength of a non-preloaded

bolted connection only corresponds to a fraction of its load-bearing capacity, the preloading is especially beneficial by generating a sufficient compression in the clamped package or by exploiting the stiffness ratios in order to reduce the additional bolt force F_{SA} and therefore to increase the fatigue life of the bolts. For this reason, exemplary preloaded bolted tension connections are usually applied in ring flange connections in tower-like, circular-cylindrical or conical steel structures such as towers of wind turbines, chimneys or masts [11]-[15].

In cases of preloaded bolted connections where the external load is applied orthogonally to the bolt axis, the load transmission occurs purely through the friction surfaces. Herein, the existing bolt preload plays an essential role by generating the necessary compression and therefore activating the frictional bond - the slip resistance. The other decisive variable is the so-called slip factor which, on one hand, is directly dependent on the bolt preload, but on the other hand can be improved by various types of surfaces treatments and special coatings on the faying surfaces of the friction areas. With regard to the fatigue strength, this state of the connection is characterised by an advantageous force distribution, low (elastic) deformations of the clamped components and especially by a relatively uniform stress distribution in the net cross-section. Figure 2.3 shows a comparison of the stress distribution in the net cross-section for bearing type and slip-resistant connections. Here, it can be clearly seen that the positive load transmission through the contact of the connected components result in high notch stresses, which can be avoided by a sufficient bolt preload and therefore by the resulting frictional effect. In contrast to the bearing type connections, the preload in the contact surfaces even leads to lower stresses in the bolt area than at the outer edges. This once again emphasizes the importance of preloading with regard to the fatigue strength of the bolted connection.

Therefore, slip-resistant connections offer a reasonable solution considering fatigue strength with minimized slip/deformation and an increased stiffness of the connections. The resulting areas of application in steel construction are mostly based on connections in lattice towers, bridges, radio masts and wind turbine towers.

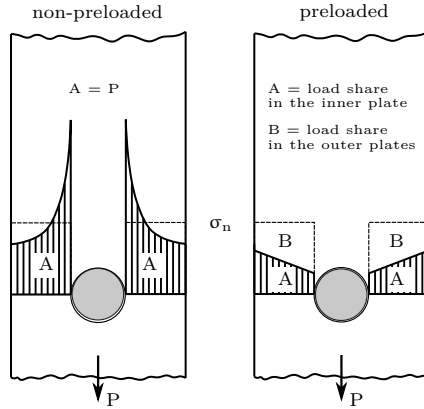


Figure 2.3 Stress distribution in non-preloaded and preloaded bolted connections according to Steinhardt/Möhler [16]

2.2 Design and target levels of preloading

EN 1993-1-8 as well as the execution standard for steel and aluminium structures EN 1090-2 [2] note that preloading can also be used as a quality measure. With regard to the aim of preloading in steel construction, DAST-Guideline 024 [3] consequently distinguishes between two target levels, see Figure 2.4, whereby the terminology was first introduced by Schmidt [17]-[20].

The introduction of the target levels is intended to emphasize the importance of the preloading force, but at the same time it also highlights different possibilities for the execution of a preloaded bolted connection including the necessary measures regarding the application and the handling of the preloading force. The distinction between the two target levels also enables to specify the requirements for inspection and testing with respect to the necessary degree of rigorousness. While preloading of connections of target level I serves to guarantee the structural safety quantitatively, bolted connections of target level II are preloaded to improve the serviceability qualitatively. A similar approach to the execution of preloaded bolted connections under consideration of the purpose and safety requirements can be found in normative regulations for applications in the automotive industry (VDI/VDE 2862-1 [21]) or in plant construction, mechanical engineering and equipment manufacturing (VDI/VDE 2862-2 [22]). The design guide for railway vehicles and their components DIN 25201-1 [23] also classifies the bolted connections with regard to hazard potential in the event of failure of

the bolted joint, where different requirements regarding design, execution and quality assurance are given. A few application examples of bolted connections with target levels I and II of preloading are shown in Figure 2.5.

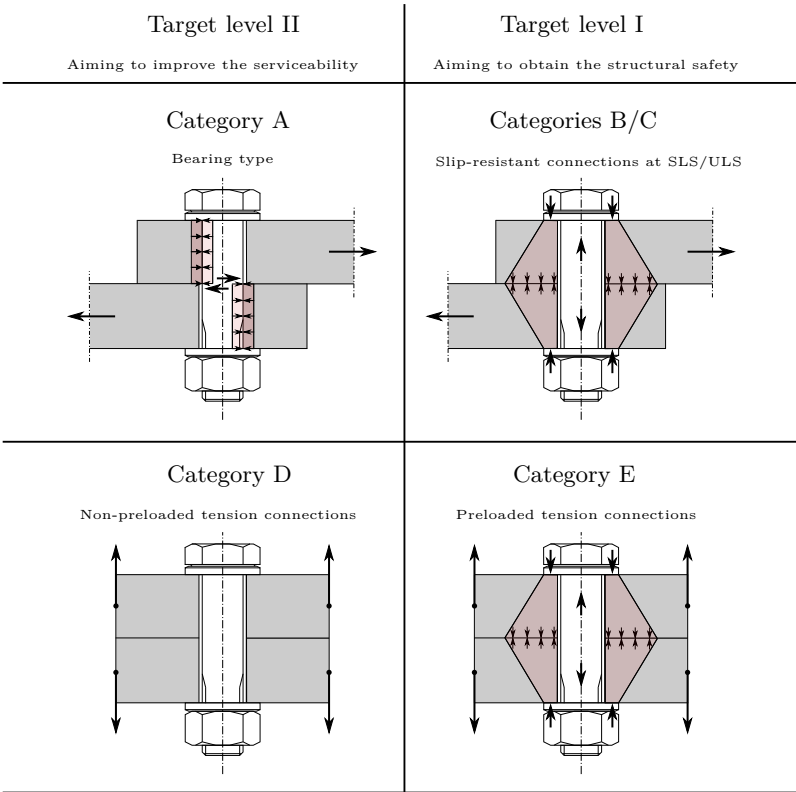


Figure 2.4 Categories of bolted connections according to EN 1993-1-8 [1] and target levels of preloading according to DAST-Guideline 024 [3]

Thus, connection categories B, C and E according to EN 1993-1-8 clearly belong to target level I including their design, execution and maintenance specifications, whereas preloaded connections of categories A and D can be assigned to target level II and are treated as non-preloaded connections during design and execution.

The two target levels of preloading are reflected in the design verification format of EN 1993-1-8 for bolted connections. Herein, no preloading force-related

resistances are included in the design of the connections of categories A and D. The design of preloaded tension connections of category E seems to be carried out analogically to that of the connections of category D. In this case though, EN 1993-1-8 prescribes a controlled tightening of the bolting assemblies with property classes of 8.8 or 10.9. The current final draft prEN 1993-1-8:2021-03 [24] supplements its' predecessor noting that *"the influence of preloading on the variation of the bolt force is not considered in the design of tension connections under static loading but may need to be accounted for in fatigue loading"*. It is also worth mentioning that the influence of the bolt preload on the stiffness of the equivalent T-stub in tension is considered in the stiffness coefficients of the relevant components. This, of course, requires bolting assemblies with controlled tightening according to EN 1090-2.



Figure 2.5 Examples of bolted connections with target level I and target level II of preloading in steel construction

The direct influence of the preloading force is clearly visible in the verification format according to EN 1993-1-8 for slip-resistant connections. Herein, the

design value of the acting shear force $F_{v,Ed,ser}$ at the serviceability limit state (category B) shall not exceed the design value of the slip resistance $F_{s,Rd,ser}$, see Equation (2.1). In addition, the shear and the bearing resistance of the bolted connection of this category must be checked.

$$F_{s,Rd,ser} = \frac{k_s \cdot n \cdot \mu}{\gamma_{M3,ser}} \cdot F_{p,C} \quad (2.1)$$

where k_s is a reduction factor for different types of holes, n is the number of the friction surfaces, μ is the slip factor, $\gamma_{M3,ser}$ is the partial factor for slip resistance at serviceability limit state (here: $\gamma_{M3,ser} = 1.1$) and $F_{p,C}$ is the nominal minimum preloading force.

The verification format for slip-resistant connections of category C (at ultimate limit state) does not differ much. Here, the design shear force per bolt $F_{v,Ed}$ must be less than the design value of the slip resistance $F_{s,Rd}$, see Equation (2.2). According to prEN 1993-1-8 a design check regarding the shear and the bearing resistances is not necessary.

$$F_{s,Rd} = \frac{k_s \cdot n \cdot \mu}{\gamma_{M3}} \cdot F_{p,C} \quad (2.2)$$

where γ_{M3} is the partial factor for slip resistance at ultimate limit state (here: $\gamma_{M3} = 1.25$).

In cases, where an additional external tensile force acts on the slip-resistant connection of categories B and C, the slip resistance from Equations (2.1) and (2.2) shall be reduced:

$$F_{s,Rd,ser} = \frac{k_s \cdot n \cdot \mu \cdot (F_{p,C} - 0.8 \cdot F_{t,Ed,ser})}{\gamma_{M3,ser}} \quad (2.3)$$

where $F_{t,Ed,ser}$ is the design tensile force per bolt for serviceability limit state and

$$F_{s,Rd} = \frac{k_s \cdot n \cdot \mu \cdot (F_{p,C} - 0.8 \cdot F_{t,Ed})}{\gamma_{M3}} \quad (2.4)$$

where $F_{t,Ed}$ is the design tensile force per bolt for ultimate limit state.

For this matter, the load-bearing behaviour of a preloaded tension connection as shown in Figure 2.2 is applied. Herein, the pressure on the friction surfaces experiences a reduction by the tensile force (analogous to the additional plate load F_{PA} in Figure 2.2), whereby the bolt force itself is slightly increased (see F_{SA} in Figure 2.2). As can be seen from Equations (2.3) and (2.4), the assigned

proportion of the design tensile force $F_{t,Ed,ser}$ or $F_{t,Ed}$ which leads to a reduction of the clamping force is assumed to 80 % (or 0.8) for the design verification format. This proportion is based on the assumption that the ratio of the bolt cross section to the pressure contact surface is equal to 1:4 [25].

With regard to the requirements given in EN 14399 series [26]-[35] and provided that a controlled tightening is carried out, EN 1090-2 and EN 1993-1-8 specify a nominal minimum preloading force $F_{p,C}$:

$$F_{p,C} = 0.7 \cdot f_{ub} \cdot A_s \quad (2.5)$$

where f_{ub} is the nominal ultimate strength of the bolt material and A_s is the stress cross section of the bolt thread.

According to EN 1090-2, "*Unless otherwise specified*", this level of preload shall be used for all preloaded bolted connections. However, other (lower) preload levels are not excluded and can be specified under consideration of suitable bolting assemblies, the tightening method, the tightening parameters and the inspection requirements. In Germany, according to DIN EN 1993-1-8/NA [36], lower preload levels (here: $F_V \leq F_{p,C}$) can be specified and applied considering regulations in DAST-Guideline 024. Herein, next to the preload level $F_{p,C}$, also the preload level $F_{p,C}^*$ is allowed, see Equation (2.6).

$$F_{p,C}^* = 0.7 \cdot f_{yb} \cdot A_s \quad (2.6)$$

where f_{yb} is the nominal yield strength of the bolt material. Furthermore, any desired preload level F_V , see Equations (2.7) and (2.8), can be applied:

$$F_{p,C}^* \leq F_V \leq F_{p,C} \quad (2.7)$$

or

$$F_V \leq F_{p,C}^* \quad (2.8)$$

In case of the preload level F_V according to Equation (2.7), a procedure testing is required in order to determine a suitable tightening method and parameters, where for lower preload levels than $F_{p,C}^*$, see Equation (2.8), the modified torque method shall be applied using a proportionally reduced tightening torque M_A .

2.3 Preloading of bolting assemblies

2.3.1 General

In steel construction, the harmonization of the bolting assemblies is based on two series of European standards:

- **EN 15048 series** [37]-[38] for non-preloaded bolting assemblies and
- **EN 14399 series** [26]-[35] for high-strength structural bolting assemblies for preloading including e.g.
 - bolting assemblies with system HR acc. EN 14399-3 or
 - bolting assemblies with system HV acc. EN 14399-4.

In the frame of this work, the main focus lies within high-strength structural bolting assemblies for preloading, where especially hexagon bolt and nut assemblies of system HV according to EN 14399-4 in combination with plain chamfered washers according to EN 14399-6 as one of the most traditional configurations in German steel construction are considered.

Preloading of bolting assemblies must be generally carried out in a certain way that guarantees the reproducibility of the applied preload to the connection. In practice, this can be achieved by using either rotatory or tractive methods [10], although in the frame of this work, the main focus lies within the traditional rotatory methods. Innovative mixed methods (e.g. turning the nut without introducing a torsional stress on the bolt [39]) play a rather subordinate role and are not explained in detail.

Assembly preload created in the bolt by the rotatory methods is usually not measured directly, but rather by taking into account indirect parameters such as:

- tightening torque M_A ,
- angle or rotation θ ,
- difference quotient $dM_A/d\theta$,
- deformation and
- hydraulic pressure.

Every tightening method given in EN 1090-2 is based on some of the above mentioned parameters - either as control or monitoring variables, which indicates the complexity of the tightening procedure itself. In the following chapters, the most important parameters for tightening (here: tightening torque M_A and angle or rotation θ) as well as the relevant rotatory methods considered in this work are presented and discussed.

2.3.2 Parameters for preloading

2.3.2.1 Tightening torque and k-class

The tightening torque M_A represents the most important control or monitoring variable. In case of constant friction ratios in the paired threads of the bolt and nut as well as in the bearing surface of the rotated element (nut or bolt head), a linear relationship between the tightening torque M_A and the assembly preload F_M in the elastic deformation region is built. The tightening torque is composed of two main components:

- proportion of the tightening torque acting in the paired threads M_G , also thread torque and
- friction moment in the head or nut bearing area M_K , also surface bearing friction moment.

At this point it must be mentioned that the thread torque M_G can be divided into the pitch torque M_{GSt} and the thread friction torque M_{GR} [9]. Herewith, the composition of the tightening torque can be described by Equation (2.9):

$$M_A = M_{GSt} + M_{GR} + M_K \quad (2.9)$$

During tightening, a larger part of the tightening torque M_A is used to overcome the friction of the connection between the nut and the washer and between the thread flanks of the bolt and nut. This process involves the components of the thread friction torque M_G and the surface bearing friction moment M_K . For this reason, the required assembly preload de facto results from the thread pitch torque. In this case, the wedge effect caused by thread pitch is decisive, where its efficiency is subject to a wide range of influencing factors such as lubrication condition, materials used in the connection, tolerances in the paired threads etc. [9]. Considering typical lubricated high-strength bolting assemblies,

approximately 80 % to 90 % of the applied tightening torque is generally used to overcome the friction. Conversely, this means that only the remaining 10 % to 20 % of the applied tightening torque is used to effectively generate the preloading force.

According to VDI 2230-1, in order to achieve the assembly preload F_M , the following tightening torque M_A (metric ISO threads with corresponding thread pitch P and flank angle of 60°) is required:

$$M_A = F_M \cdot \left(0.16 \cdot P + 0.58 \cdot d_2 \cdot \mu_G + \frac{D_{K_m}}{2} \cdot \mu_{KR} \right) \quad (2.10)$$

where d_2 is the pitch diameter of the bolt thread, μ_G is the coefficient of friction in the thread, D_{K_m} is the effective diameter for the friction moment at the bolt head or nut surface bearing area and μ_{KR} is the coefficient of friction in the surface bearing area.

In steel construction, the bracketed expression is usually replaced by the k-factor in combination with bolt diameter d , so that the Equation (2.10) can be simplified to:

$$M_A = F_M \cdot k \cdot d \quad (2.11)$$

or

$$k = \frac{M_A}{F_M \cdot d} \quad (2.12)$$

The k-factor (determination according to EN 14399-2 [27]) and the resulting k-class (classification according to EN 14399-1 [26]), see Table 2.1, describe the quality of lubrication in the delivered condition of the bolting assembly. It is also known as "calibrated lubrication" which shall guarantee a sufficient (desired) level of preload in the bolt, provided that the tightening is carried out properly.

Table 2.1 k-classes according to EN 14399-1 with corresponding k-values

k-class		Requirement
K0	No requirement on lubrication	-
K1	Individual values k_i	$0.10 \leq k_i \leq 0.16$
K2	Mean value k_m	$0.10 \leq k_m \leq 0.23$
	Coefficient of variation V_k	$V_k \leq 0.06$

For this reason, certain k-classes are normatively required for the use of different tightening methods by EN 1090-2, see Table 2.2. It is worth mentioning that the k-class does not give any information on the combined stresses resulting from normal and torsional shear stresses as it is the case during design and verification according to VDI 2230-1, see Equation (2.10). However, this is not necessary in steel construction, since the suitability for preloading according to EN 14399 must be verified under consideration of the preload levels from EN 1993-1-8 by the manufacturers themselves. At this point, the suitability test for preloading acc. to EN 14399-2 is not discussed in detail.

Table 2.2 Required k-classes for different tightening methods according to EN 1090-2 and DAST-Guideline 024

Tightening method		K0	K1	K2
Torque method (EN)				•
Combined method			•	•
Tension control bolts	using HR nuts			•
	using HRD nuts	•	•	•
Method with direct tension indicators (DTI)		•	•	•
Modified torque method			•	

2.3.2.2 Angle of rotation

In contrast to the tightening torque, the influence of the angle of rotation θ on a bolted connection is mainly characterized by its material properties and is based on the total deformation of the bolt and the clamped parts. Based on the notation given in Figure 2.1 and acc. to [9], the total deformation f of a bolted connection can be approximated to:

$$f_{SM} + f_{PM} = \frac{\theta \cdot P}{360^\circ} \quad (2.13)$$

The application of the preload force with the help of the angle of rotation is characterized by two important features. Firstly, the behaviour of the angle of rotation-preload force-curve at the beginning of the tightening is nonlinear because of the irregular interfaces of the joint. Therefore, it is reasonable to bring all interfaces of the joint to contact by applying a specific amount of torque during the first step of the tightening procedure. Secondly, the plastic range of

the angle of rotation-preload force-curve is characterized by a nearly horizontal curve. This means that a comparatively exact preload force can be achieved despite possible angle of rotation errors. Since a pure angle-controlled tightening is very complex and it is well known that the highest precision of this method is achieved when the bolt is tightened into the plastic range, the angle or rotation as a tightening parameter in steel construction is optimally used e.g. as a second tightening step for partially preloaded connections in form of a further angle of rotation $\Delta\theta$.

2.3.3 Tightening methods

The corresponding amount of preloading force considered in the design verification, see Chapter 2.2, must usually be reliably applied by tightening methods according to EN 1090-2 (at European level) and according to DAST-Guideline 024 (at German national level). The use of alternative tightening methods is also possible, e.g. in combination with an European Technical Assessment (ETA).

In the following chapters, a short summary of the common tightening methods in German steel construction in form of the modified torque method and combined method is given. Alternative tightening methods such as the method with direct tension indicators (DTI) according to EN 14399-9 [34], tension control bolts (HRC tightening method) according to EN 14399-10 [35] as well as lock bolts or the tractive method (used in accordance with an European Technical Assessment (ETA)) play a rather subordinate role in the frame of this work and are not further discussed.

2.3.3.1 Modified torque method acc. to DAST-Guideline 024

The modified torque method according to DAST-Guideline 024 is the most established tightening method in Germany. The specifications for the tightening torque that is necessary in order to achieve the preload level $F_{p,C}^*$ (formerly known as "Regelvorspannkraft" F_V) for hot dip galvanized bolting assemblies, lubricated with molybdenum disulfide (MoS_2) were already implemented in DAST-Guideline 010 (1976-06) [40], in DIN 18800-7 (1983-05) [41] as well as in TGL 13510/03 (1984-06) [42]. In order to avoid any unnecessary confusions with the EN torque method according to EN 1090-2, the former name "torque

method" ("Drehmoment-Verfahren") is currently replaced by "modified torque method".

Hereby, the desired preload level of the connection is achieved by applying a predefined tightening torque and taking into account the approximately linear relationship between tightening torque and preloading force. "Calibrated lubrication", as described in Chapter 2.3.2.1, is therefore a crucial part/requirement for the application. As can be seen from Table 2.2, a lubrication for bolting assemblies of k-class K1 is required. Most commonly in Germany, this is provided by using high-strength structural bolting assemblies of the HV system according to EN 14399-4 [29] or EN 14399-8 [33] in combination with washers according to EN 14399-6 [31].

The tightening procedure is carried out in two steps. For the first tightening step any desired pre-tightening torque $M_{A,pre}$ of up to $0.75 M_A$ may be chosen. In terms of the second step, the prescribed tightening torque M_A has to be fully applied in order to achieve the required preload level $F_{p,C}^*$. Depending on the diameter of the HV bolting assembly and the property class, DAST-Guideline 024 specifies the required tightening parameters for HV bolting assemblies M12 to M36. Table 2.3 exemplarily summarises the preload level $F_{p,C}^*$ and the corresponding pre- and tightening torques for the execution of the modified torque method (here: 10.9 HV bolting assemblies). Additionally, DAST-Guideline 021 [43] provides the necessary tightening parameters for HV bolting assemblies M39 to M72. These will not be further discussed in the frame of this work.

Table 2.3 Preload level $F_{p,C}^*$ and the corresponding pre- and tightening torques for 10.9 HV bolting assemblies using the modified torque method according to DAST-Guideline 024

Bolt diameter	M12	M16	M20	M22	M24	M27	M30	M36
Preload level $F_{p,C}^*$ [kN]	50	100	160	190	220	290	350	510
Pre-tightening torque $M_{A,pre}$ [Nm]	75	190	340	490	600	940	1240	2100
Tightening torque M_A [Nm]	100	250	450	650	800	1250	1650	2800

As the slightly lower preload level $F_{p,C}^*$ (in general around 10 % compared to $F_{p,C}$) indicates, the modified torque method aims to avoid tightening into the plastic range of the bolting assemblies - the main problem regarding the torque

method according to EN 1090-2, as described in [20]. As can be seen from Table 2.3, the nominal tightening torque values M_A ensure easy handling and, more importantly, do not depend on the combination of manufacturer/delivery lot, as the suitable lubrication must be provided by the bolt manufacturer itself in accordance with the suitability tests for preloading according to EN 14399-2. However, this positive aspect regarding the easy handling has its downside, since the actual bolt preload in the connection mostly depends on the individual lubrication for each and every assembly. As seen in Table 2.1, the individual values k_i may lie within $0.10 \leq k_i \leq 0.16$ which means that high scattering of the actual preload in the connection is inevitable, see Figure 2.6. Furthermore, given the limit k -values of 0.10 and 0.16, neither preloading into the overelastic range nor below the preload level $F_{p,C}^*$ can be arithmetically ruled out, as the dashed red lines for $F_{p,k=0.1}$ and $F_{p,k=0.16}$ in Figure 2.6 indicate.

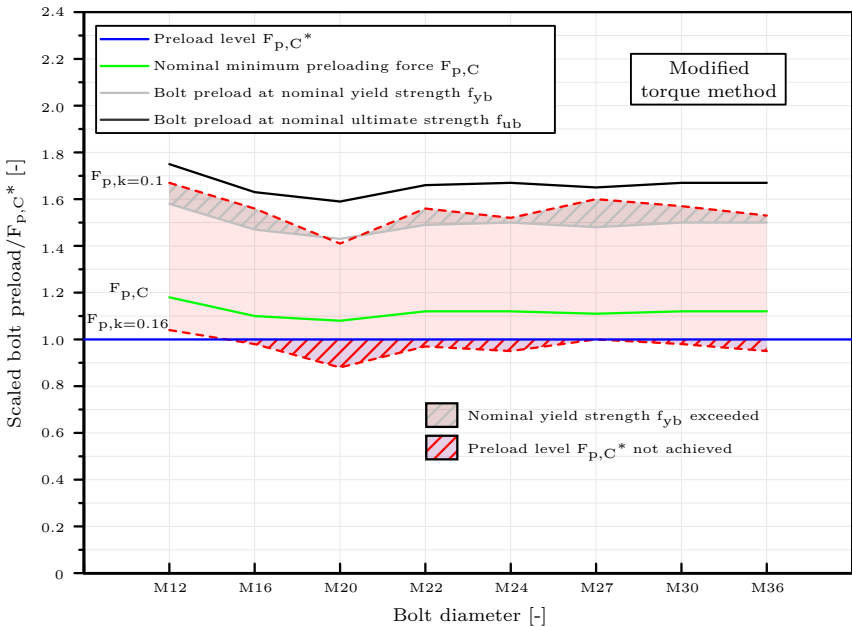


Figure 2.6 Arithmetical scattering of the actual bolt preload for bolting assemblies of k -class K1 for the prescribed tightening torques according to DAST-Guideline 024 (here: HV 10.9 bolting assemblies)

As mentioned in Chapter 2.2, further advantages of the modified torque method include the possibility of a proportional reduction of the tightening torque M_A in

cases, where lower preload level is needed and, most importantly, the possibility of a re-tightening as a control measure or to compensate possible preload losses using the same tightening torque M_A after several days. Unluckily, the latter regulation, which was an established part in DIN 18800-7 (beginning with the 2002-09 [44] version) as well as later in the German National Annex DIN EN 1993-1-8/NA (2010-12) [45], disappeared from the current standards through their conversion. The current German National Annex DIN EN 1993-1-8/NA (2020-11) [36] notes that supplementary tightening methods to EN 1090-2 are dealt with in the DAST-Guideline 024. Unfortunately, DAST-Guideline 024 does not directly mention the possibility of a re-tightening for the compensation of preload losses after several days. Obviously, it does not disregard this huge advantage of the modified torque method, as this feature should by all means still be used today. It is intended to implement this regulation into the new revision of DAST-Guideline 024.

2.3.3.2 Combined method acc. to EN 1090-2 and DAST-Guideline 024

A controlled tightening into the plastic range using the tightening torque as a control variable is only possible with reliable tightening parameters in combination with a suitable lubrication. Given many influencing factors that can affect this precondition on the construction site, tightening torque as a control variable is not necessarily the most practical and reliable option for common steel construction. Although the EN torque method according to EN 1090-2 is normatively approved in Europe, major justified concerns about the reliability of this method led to its elimination from the regulations for execution of the steel structures in Germany. Instead of this, DAST-Guideline 024 prescribes tightening by means of the combined method in order to achieve the nominal minimum preloading force $F_{p,C}$ as already given in EN 1090-2. Herein, torque-controlled and angle-controlled tightening are combined to ensure optimal utilisation of the bolt - the tightening itself is therefore carried out in two steps.

The roots of this tightening *approach* can be traced back to the 1950s, where it was introduced (based on the "*one full turn method*") by *Frincke* [46] and later by *Ball* and *Higgins* [47]. Backed by the knowledge gained from experimental investigations, the turn-of-nut method was incorporated in the Specifications for Structural Joints using ASTM A325 Bolts (1962-03) [48] approved by the Research Council on Riveted and Bolted Structural Joints of the Engineering

Foundation in the USA. In Germany, the so-called "*angle of rotation method*" ("*Drehwinkelverfahren*") was firstly introduced for its application in steel construction by the former DAST-Guideline 010 [40] only in 1976 and showed a similar overall approach - a snug tightening (or pre-tightening) by applying relatively low torque values is complemented by comparatively high angles of rotation. As a result, from today's point of view, the difference between the American turn-of-nut method and the European combined method lies in discrepancies in the torque values for pre-tightening and the subsequent angles of rotation. As mentioned in RCSC Specification [49], the angle of rotation for the combined method is likely less because of a usually higher initial tension condition after the first tightening step.

For the combined method, just like in case of the modified torque method, a pre-tightening torque $M_{A,pre}$ of $0.75 M_A$ is used for the first tightening step. Here, the values between EN 1090-2 and DAST-Guideline 024 differ slightly, whereby the latter represents the more practical approach (originating from the former German modified combined method according to DIN EN 1993-1-8/NA (2010-12) [45]) by rounding up the values given in EN 1090-2, see Table 2.4. In this case, the k-class of the bolting assemblies might correspond either to K1 or to K2 in the state of delivery, although the latter, given the cost effectiveness, has no significance in Germany. The considerable variation of the resulting bolt preload is acceptable, since the total deformations of the bolt and the clamped parts are intended to remain within the elastic range during the first tightening step, see Figure 2.7. In this case, it is rather of a greater importance to guarantee that the clamped parts are fully in contact, which the specified tightening torques surely provide.

Table 2.4 Preload level $F_{p,C}$ and the corresponding pre-tightening torques as well as further angle of rotation for the 10.9 HV bolting assemblies (K1) using combined method according to EN 1090-2 and DAST-Guideline 024

Bolt diameter		M12	M16	M20	M22	M24	M27	M30	M36
Preload level $F_{p,C}$ [kN]		59	110	172	212	247	321	393	572
Torque $M_{A,pre}$ [Nm]	DAST-Guideline 024	75	190	340	490	600	940	1240	2100
	EN 1090-2	67	165	322	439	557	815	1107	1935
Further angle of rotation $\Delta\theta$	60°	$\Sigma t < 2d$							
	90°	$2d \leq \Sigma t \leq 6d$							
	120°	$6d \leq \Sigma t \leq 10d$							

Angle-controlled tightening is provided by the second tightening step of the combined method. Herein, a specific angle of rotation (here: relative angle between nut and bolt) as a tightening parameter (see Chapter 2.3.2.2) is used in order to utilize the overelastic range of the bolt and therefore to make the optimum use of it. The possibility of overstressing is almost excluded due to a sensible limitation of further angle of rotation, as Table 2.4 indicates. Herein, sufficient toughness and ductility criteria of the bolting assemblies (among other things the values for $\Delta\theta_1$ (informative) and $\Delta\theta_2$ in accordance with EN 14399-4 and EN 14399-8 for HV bolting assemblies) shall be ensured by the manufacturers in a suitability test according to EN 14399-2 [27]. Technically, the angle-controlled tightening is an indirect method of length measurement [10], see also Equation (2.13). For this reason, more resilient connections with an increasing clamping length ratio are assigned with higher further rotation angles in order to provide the optimum utilisation of the bolts and therefore comparable bolt preloads.

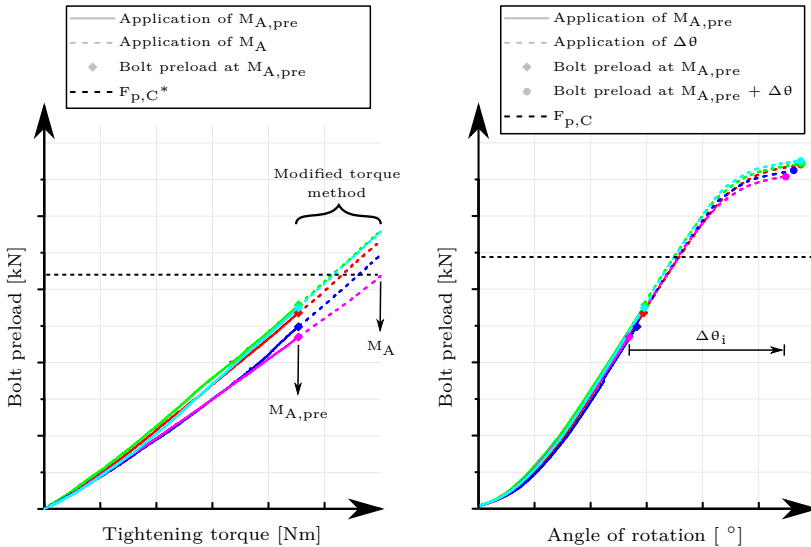


Figure 2.7 Preloading of bolting assemblies using combined method according to DAST-Guideline 024 (left: first tightening step - bolt preload/tightening torque curves, right: second tightening step - bolt preload/angle of rotation curves)

Given a controlled tightening into the overelastic range, significantly higher initial preload values $F_{p,ini,KV}$ than the nominal minimum preloading force $F_{p,C}$

in the range of $\geq 25\%$ (here: 10.9 HV bolting assemblies) can be expected, see Equation (2.14).

$$F_{p,ini,KV} \geq \frac{F_{yb}}{F_{p,C}} = \frac{0.9 \cdot f_{ub} \cdot A_s}{0.7 \cdot f_{ub} \cdot A_s} \approx 1.285 F_{p,C} \quad (2.14)$$

where F_{yb} is the preload by the onset of yielding in the bolt.

This offers clear advantages with regard to the possible preload losses, but at the same time does not pose a risk of overstressing, since elastic recovery directly after the tightening and therefore a partial release of torsional stresses prevent further plasticising of the bolt under operational forces.

2.4 Execution of corrosion protection on steel components

2.4.1 General

According to EN ISO 8044 [50] and EN ISO 12944-1 [51], corrosion can be defined as the "*physicochemical interaction between a metallic material and its environment that results in changes in the properties of the metal, and that may often lead to significant impairment of the function of the metal, the environment or the technical system, of which these form a part*". As a rule, steel surfaces are subjected to corrosion and should therefore be protected in order to avoid damage during the intended service life of the structure. According to EN 1090-2 only structures with a short service life of up to one year and/or which are exposed to an environment with negligible corrosivity are excluded from corrosion protection. In general, it is distinguished between active and passive corrosion protection. In contrast to the active corrosion protection, no control of the corrosive agent and the reaction itself is given for the passive corrosion protection. Here, the prevention of possible damage to the metallic material merely relies on the mechanical isolation from the aggressive corrosive agents by using protective layers, films or other coatings. EN 1090-2 refers to three different passive corrosion protection methods which are of outstanding importance in steel construction:

- painting in accordance with EN ISO 12944 series [51]-[59] and Annex F of EN 1090-2,
- metal coating by thermal spraying in accordance with EN ISO 2063 (parts 1 [60] and 2 [61]), EN ISO 12679 [62], EN ISO 12670 [63] and Annex F of EN 1090-2 and

- metal coating by galvanizing in accordance with EN ISO 1461 [64], EN ISO 14713-1 [65], EN ISO 14713-2 [66] and Annex F of EN 1090-2.

In addition to the protective paint systems (liquid coatings consisting of additives, carriers, pigments and resins) considered in the EN ISO 12944 series, also the powder coating systems (additives, pigments and resins formulated in a powder form) according to DIN 55633-1 [67] should be noted. Although the use of powder coatings in common steel construction is currently not predominant, it is becoming increasingly important in architectural steel construction and especially in the area of lightweight steel structures [20].

High corrosion protection can also be achieved by using a combination of metal coating by galvanizing and painting, the so-called duplex systems. This also applies for the above mentioned powder organic coatings in accordance with EN 13438 [68] and EN 15773 [69].

Generally, the required performance of the corrosion protection shall be specified considering two main input parameters:

- the expected life of the corrosion protection (varying between "*Very Low*" (VL) and "*Very High*" (VH) depending on EN ISO 12944-1 or EN ISO 14713-1) and
- the corrosivity category (from C1 "*Very Low*" (or insignificant) to CX "*Extreme*" according to EN 12944-2 and EN ISO 14713-1).

The way in which the specified performance is achieved can be very different. Besides the selection of the suitable corrosion protection method, the technical requirements and instructions for the execution and inspection of the corrosion protection including a suitable preparation of the steel surfaces are vital, whereby necessary guidance is given in the normative Annex F of EN 1090-2, see Figure 2.8.

In the following chapters, a brief introduction into normative regulations regarding the surface preparation of steel substrates (i.e. surfaces, welds and edges of steel components according to EN 1090-2) is given. Furthermore, different coating methods are considered. Specific supplementary regulations for bolted connections (here: concept of inaccessible surfaces) with regard to their corrosion protection and the risk of preload losses including currently regulated coatings and coating systems are discussed in Chapter 3.3.

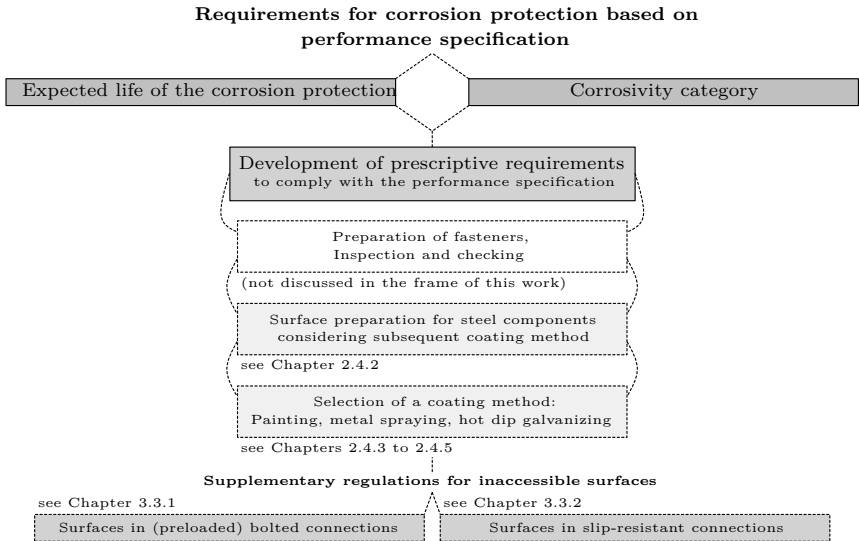


Figure 2.8 Schematic illustration of the main points with regard to specification of corrosion protection on steel components according to EN 1090-2, Annex F

Although the following chapters explicitly deal with different corrosion protection methods and the preparation of the steel substrates, it must be mentioned, that one of the most important active contributions regarding the effective corrosion protection should be made in terms of the corrosion preventive design. Different literatures and even EN ISO 12944-3 provide guidance on how to minimize the risk of corrosion damage by an appropriate design of steel structures prior to corrosion protection through coating systems and should in all cases be taken into consideration.

2.4.2 Preparation of steel substrates

In order to achieve the desired effectiveness of a corrosion protection, an appropriate surface preparation has to be carried out prior to the application of the coating system, thermal spraying or galvanizing of the steel surfaces. Here, substances and materials that impair corrosion protection are removed and a specific surface roughness matched to the subsequent corrosion protection is established that allows satisfactory adhesion of the coating to the surface.

In general, the surface preparation for subsequent painting, hot dip galvanizing or thermal spray metallizing has to be carried out in accordance with the specifications given in EN ISO 12944-4 [54]. Additional requirements are made in EN ISO 14713 for hot dip galvanizing and in EN ISO 2063 for metal coatings by thermal spraying.

For the behaviour of protective coatings by painting, the fundamental influencing factors such as rust and mill scale, surface contaminants or roughness can be assessed using procedures in the international standards EN ISO 8501, EN ISO 8502 and EN ISO 8503. At this point especially EN ISO 8501-3 [70] must be highlighted, as it sets requirements for the preparation grades P1 (light preparation) to P3 (very thorough preparation) regarding properties of the suitable steel surfaces for the application of coating materials. Specific preparation grades are prescribed by EN 1090-2 and are dependent on the expected life of the corrosion protection and the corrosivity category. EN 12944-3 even prescribes the highest preparation grade P3 for applications with high or very high expected life of the corrosion protection and the corrosivity categories C4 and above. On the other hand, EN ISO 8504 provides guidance regarding surface preparation methods, whereby particularly EN ISO 8504-2 "Abrasive blast-cleaning" [71] shows a great relevance and deals with different blasting media (including criteria for their selection) as well as different blasting methods. Steel surfaces obtained by abrasive blasting are usually visually inspected for surface cleanliness. Here, EN ISO 8501-1 defines four blast-cleaning grades (no normative requirements for specific applications though), whereby particularly

- Sa 2^{1/2} *very thorough blast-cleaning* and
- Sa 3 *blast-cleaning to visually clean steel*

are commonly required by the manufacturers in the technical data sheets of coating materials. The DSTV-Guideline "Korrosionsschutz von Stahlbauten in atmosphärischen Umgebungsbedingungen durch Beschichtungssysteme" [72] substantiates the requirements in EN ISO 12944 and generally prescribes blast-cleaning grade Sa 2^{1/2}, see exemplarily Figure 2.9, unless otherwise specified. In general, this surface condition can be reached by blasting with grit (G) or shot (S) blasting media, whereby the roughness of the steel surface shall correspond to the profile grade "medium" (G or S) according to EN ISO 8503-1 [73] with a mean maximum peak-to-valley height R_{y5} (also known as R_z) of 60 μm to 100 μm and 40 μm to 70 μm respectively. For the optimal requirements regarding the

surface roughness, DSTV-Guideline [72] refers to the technical data sheets of the coating material manufacturers.

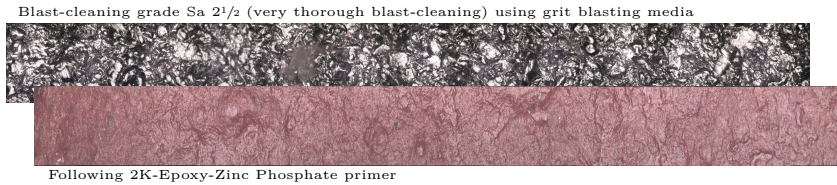


Figure 2.9 Example of a grit blasted surface and the subsequent priming coat

Steel surfaces for thermal spray metallizing have to be prepared up to blast-cleaning grade Sa 2¹/₂ for zinc and zinc-aluminium alloys as well as up to Sa 3 for aluminium and aluminium-magnesium alloys. Hereby, suitable grit abrasives (G) must be used in order to enlarge the substrate surface and to increase the adhesion by mechanical anchoring. Typically, the desirable roughness of the steel surface shall correspond to R_{y5} of 50 μm to 100 μm .

The common preparation of steel surfaces prior to hot dip galvanizing of steel components to be used in steel structures consist of procedures such as degreasing, rinsing and pickling with subsequential fluxing. Here, impurities such as rust and mill scales have to be removed, which is vital in order to ensure an adherent and durable coating on the steel surface. Abrasive blast-cleaning, as in cases of painting or thermal spray metallizing, is generally not required prior to hot dip galvanizing. In cases, where an overpainting of the zinc coating is intended, an additional cleaning of the surfaces (and at the same time a preparation for subsequent coating) must be carried out in a way that the zinc layer does not suffer from any damage regarding high layer removals or the impairment of the adhesion to the steel surface. The most common procedure for this purpose is the so-called sweep blasting according to EN ISO 12944-4. By means of sweep blasting, a clean and reasonably rough surface (profile grade "fine" according to EN ISO 8503-1) is achieved by a low blast pressure, an impact angle of around 30 to 45 degrees and fine, non-metallic abrasives.

2.4.3 Paint and powder systems

Protective coating materials are based on different components, which can be generally divided into five groups [74]:

- binders,
- pigments,
- fillers,
- additives and
- organic solvents and/or water.

Whereas binders predominantly include synthetically produced polymers (resins) such as alkyd resin, epoxy resin, polyurethane etc. and significantly determine the properties of the coating material, the pigments in the first place contribute to the aesthetical properties (color, appearance etc.) of a coating material. Functional properties such as scratch resistance, mechanical strength, but also the essential corrosion protection can also be imparted by pigments in form of a zinc dust, zinc phosphate or zinc oxide, which are common in practical applications. Incorporated fillers, on the other hand, are solid particles that impart desired mechanical properties to the coating such as toughness, texture etc., where micaceous iron oxide represents one of the most common functional fillers. These three main component categories form the solid part of a coating, where miscellaneous additives can also be supplied in order to improve e.g. the flow properties, forming of a film or to prevent unwanted properties.

Solvents, on the other hand, dissolve the binder and provide a suitable consistency, so that pigments and fillers can be incorporated into the material. Among other things, solvents have an influence on the flow characteristics of the coating and on the film formation. The latter plays an important role, as during the formation process and curing a specific amount of solvents evaporate into the environment as volatile organic compounds (VOC). This is also known as VOC emissions and it contributes to the air and water pollution as noted in the European Council Directive 1999/13/EC [75]. For this reason, the VOC emissions are limited by the threshold values for solvent consumption in certain installations. In Germany, the rules on the permissible solvent emissions were tightened in the recent years by the so-called "VOC-Verordnung" [76], which led to considerable changes in the range of coating materials. One of the possibilities for reducing

the VOC emissions is the use of high-solid coating materials as well as water-soluble coating materials. Powder coatings offer a very environmentally friendly approach as mostly solvent-free solutions. In contrast to conventional liquid coatings, where film formation occurs at normal temperatures mostly through evaporation of the solvent (physical curing) or through evaporation of the solvent and a reaction between the base paint and a hardener (chemical curing), powder coatings (consisting of binders, pigments, fillers and additives formulated in a powder form) build a solid film at higher temperatures between 80 °C and 250 °C (thermal curing). Here, powder coatings are electrostatically charged and conveyed to the steel substrate via compressed air. Finally, a melting of the individual powder particles, wetting of the surface and a subsequent cross-linking take place during the process of burn-in in the oven [77]. Due to the necessary application conditions, the powder coatings can only be processed using special equipment, in any case only in the shop and not on construction site.

In general, coating systems consist of several layers with different coating thicknesses:

- a priming coat (primer),
- an intermediate coat or coats and
- a top coat.

Each of the layers in the coating system must be matched to each other and should be capable of performing specific functions.

According to EN ISO 12944-5, the *priming coat* shall provide adhesion to sufficiently roughened, cleaned metal, but also to the subsequent (intermediate) coats. This layer can also take over the essential protective function due to its functional pigmentation. For this reason, EN ISO 12944-5 distinguishes between zinc-rich primers, Zn (R), with zinc dust pigment content of the paint of a ≥ 80 % by mass in dry film and other (misc.) primers such as zinc phosphate.

Intermediate coats are used as barriers for corrosive media. In general, one or two intermediate coats are necessary depending on the required corrosion protection. The coat itself must be adapted to the primer and the top coat regarding its binder base and must provide a good adhesion to both layers.

The coating system is completed by the *top coat*. Next to the aesthetical and optical properties, this coat must possess a great resistance to the weathering

influences (among other things ultraviolet radiation and water), chemicals and mechanical stresses. For specific applications one-layer coating systems are normatively permitted, too. Generally, such a coat combines the above mentioned functions of a primer and a top coat.

The performance of corrosion protection of a paint system mainly depends on the type of coating material and the coating layer thicknesses. Given the expected life of a corrosion protection and the corrosivity category, EN ISO 12944-5, Annex B specifies the minimum requirements for protective (paint) systems consisting of surface preparation, minimum number of coatings and the (minimum) nominal dry film thickness (NDFT) of the paint system. In accordance with the requirements in Annex B of EN ISO 12944-5 and based on practical experience as well as laboratory testing according to EN ISO 12944-6, Annexes C to E of EN ISO 12944-5 provide specific formulations of paint systems for carbon steel surfaces, hot dip galvanized steel surfaces and thermal-sprayed metallic coatings. The regulations in EN ISO 12944-5 therefore describe the way how the objective (here: expected life of the corrosion protection and the corrosivity category) is to be achieved - although usually, more than one option regarding the paint systems exist. This, crucially offers a favourable flexibility in finding a cost-effective and technically reasonable solution in order to meet the normative requirements by choosing the suitable corrosion protection depending on the available equipment and personnel, but also on the seasonal conditions etc.

2.4.4 Thermal spraying

Thermal-sprayed metallic coatings result from a process of spraying molten zinc, zinc-aluminium alloys as well as aluminium and aluminium-magnesium alloys (powder or wire form) onto grit blasted steel surface, which provides the necessary adhesion. Since the metallized surfaces are porous, a special treatment in form of a sealing, as mentioned in Annex F of EN 1090-2, must be carried out immediately after the cooling and before overcoating with paint (if necessary) in order to fill the metal pores. In practice, according to [20], this is often achieved by heavily diluting the priming coat of the paint coating system (usually 2-component primer, based on epoxy resin (2K-EP)). In this case, the subsequent layers should be applied in accordance with the specifications in the technical data sheets of the coating material manufacturers. Several paint systems on thermal-sprayed metallic coatings are prescribed by Annex E of EN ISO 12944-5 for applications,

where very high duration of corrosion protection by at the same time very high atmospheric corrosivity of up to C5 is required.

2.4.5 Hot dip galvanizing

Hot dip galvanized surfaces result from immersing steel into a molten zinc bath. During a metallurgical reaction an alloy between steel and zinc with a sufficient adhesion is created. The thickness and the structure of the coating can vary and are dependent on various parameters such as the chemical composition of the steel (especially the phosphorus and silicon content), immersion time, material thickness etc. [78]. The usual range of the zinc thickness varies between 50 μm and 150 μm , but zinc layers of 200 μm and above are common especially for massive steel components. Although hot dip galvanizing is known as a reasonably priced procedure and recent studies show that hot-dip galvanized components can be successfully applied for steel composite bridges with a long-lasting corrosion protection of up to 100 years, see practical report on the German pilot project in [79], accelerated zinc erosion might not be excluded under corrosive media such as acidic and alkaline conditions, in the case of permanent humidity etc. [74]. For this reason, a duplex system consisting of zinc coating and subsequent organic coating (under consideration of e.g. sweep blasting as described in Chapter 2.4.2) represents a reasonable alternative. The favourable synergistic effect of duplex systems is noted by EN ISO 14713-1, stating that the durability of such systems is significantly higher than the durabilities of the individual zinc and paint coatings combined. Here, the layer of paint or powder coating reduces the rate of zinc abrasion, where zinc itself provides cathodic protection and prevents the underfilm corrosion in case of damage of the exterior layer. In addition to that, duplex systems provide preferable aesthetical appearance due to the possibility of colouring.

Depending on the expected life of the corrosion protection and the corrosivity category, a selection of duplex systems is provided by Annex D of EN ISO 12944-5. Here, it can be clearly seen that a combination of an organic coating on a hot dip galvanized steel surface represents an effective corrosion protection system with a very long protection period.

2.5 Other reliability-determining factors with regard to design and execution of preloaded bolted connections

2.5.1 General

Based on explanations in *Merkblatt 302* [80], the reliability of a preloaded bolted connection, from a perspective of design and execution, essentially depends on the following factors:

- the determination of a connection category as well as the target level of preloading including correct assumptions during design,
- the choice of a suitable corrosion protection as well as tightening method,
- the preservation of a sufficient preload level over the service life of the structure and
- sufficient resistance to the acting forces and other influences.

Here, it can be seen that every aspect relates to determination, generation and preservation of the bolt preload and its accompanying factors. Herewith, by implication, the reliability of a preloaded bolted connection relies on the existing preload, which, on one hand, generates the necessary compression in the clamped package and therefore reduces the additional bolt force F_{SA} , but, on the other hand, activates the frictional bond in cases where a slip resistance is needed. As can be seen from Equations (2.1) to (2.4), the slip factor as the other decisive variable in this matter, also determines the load-bearing capacity of a bolted connection and depends on the actual preload level as well as the surface condition in the friction areas.

Since the determination and generation of the required bolt preload as well as the possibilities with regard to corrosion protection on steel components were discussed in Chapters 2.2 to 2.4, the challenging factor for the preservation of the bolt preload in form of preload losses as well as the slip factor as another decisive variable are briefly introduced in the following chapters.

2.5.2 Preload losses

Next to the prevention of possible errors during design or assembly process, especially the preservation of the achieved preload level requires a special attention and in particular an extensive knowledge about the possible preload losses. Some

of the fundamental experiences with preload losses were already made in the 1930s by Würges [81] and respectively Thum/Würges [82]. The investigations showed that the permanent elongation of the bolt and the deformation of the surface roughness of all paired surfaces are, among other things, responsible for the loss of preload under operational loads. Since then this topic has been investigated and expanded by many researchers, but it still remains as relevant today. Preload losses in bolted connections are unavoidable and therefore have to be appropriately dealt with. In general, the drop in preload force in bolted connections subjected to cyclic loading may occur due to self-loosening and/or loosening, see Figure 2.10.

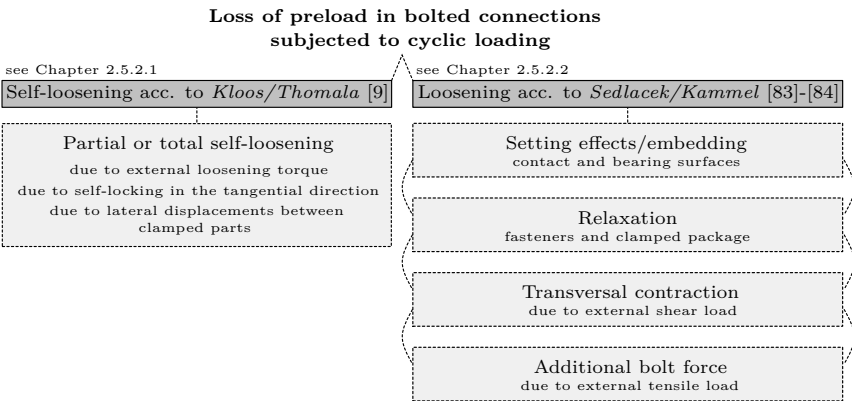


Figure 2.10 Causes for the loss of preload in bolted connections subjected to cyclic loading according to Kloos/Thomala [9] and Sedlacek/Kammel [83]-[84]

2.5.2.1 Self-loosening

Self-loosening describes a reduction or a loss of the self-locking of a preloaded connection. The investigations of Goodier/Sweeney [85] and Sauer [86] have shown that bolted connections subjected to cyclic tensile loading experience partial self-loosening. Paland [87] later confirmed this in his work and found out that cyclic loading reduces the coefficients of friction in the thread and nut bearing surface by up to 85 %. However, a total self-loosening could not be determined. From today’s point of view, a self-loosening under axial cyclic loading plays a rather subordinate role in steel construction due to a sufficiently small helix angle of the metric ISO threads. In the presence of an appropriate

preloading force, the self-locking in the tangential direction cannot be overcome under typical loads.

In the comprehensive study of *Junker/Strelow* [88]-[90], self-loosening under the consideration of shear cyclic loading was investigated. It was found that lateral displacements between the clamped parts can lead to self-loosening even at "full preload". Such transverse force - transverse displacement characteristics are firmly established in the design guide for railway vehicles and their components DIN 25201-4 [91]. However, according to this standard, a slip-resistant design of bolted connections with its associated limitation of lateral displacements is sufficient in order to effectively secure bolted connections against self-loosening. Furthermore, an increase of the preloading force represents an effective action to counteract self-loosening.

2.5.2.2 Loosening

A special attention has to be paid to *loosening* (sometimes described as slackening), as it is inevitable and occurs directly after the tightening of bolted connections. Different literatures use deviating definitions in order to describe the causes of loosening. A distinction made by *Sedlacek/Kammel* [83]-[84] represents a more practical approach with regard to applications in steel construction. Herein, preload losses in bolted connections due to loosening are further distinguished in preload losses due to:

- setting effects/embedding in the contact and bearing surfaces,
- relaxation of the fasteners and the clamped package,
- transversal contraction due to external (tensile or compression) shear load and
- external tensile load.

The term *setting effects/embedding* primarily refers to the plastic flattening of the surface roughness (local plastic deformations) under compression, e.g. at the loaded flanks of the paired threads, at faying surfaces and other interfaces. Setting effects occur already at low stresses and during tightening. At latter, a larger amount of embedding is to expect, so that the resulting preload losses after reaching the assembly state are lower than the actual roughness of the surfaces would indicate. The extent of setting effects and the associated amounts

of embedding are mostly dependent on the elapsed time, the working load, the number of interfaces and the roughness of the paired surfaces. However, the amount of the loss of preload due to embedding is significantly increased by paint systems and metal coatings, whereby especially the coating thickness and properties such as elasticity/hardness play a decisive role for the resulting loss of preload. Furthermore, coated surfaces show an increased sensitivity to creep and therefore lead to further time-dependent plastic deformations which subsequently reflect in the preload losses of bolted connections.

Relaxation (also known as stress-relaxation) describes the time-dependent viscoplastic deformation behaviour of the fasteners and/or the clamped package under tension. Here, the conversion of elastic deformations into plastic deformations take place. The extent of relaxation is mainly dependent on the elapsed time, the materials used including their thermal stability and the strength properties, the operating temperatures as well as the loads. Since this behaviour is very complex and consists of many influencing factors, a universal estimation of preload losses due to relaxation turns out to be very difficult and in most cases requires at least the creep curves of a specific material. According to [83], stress-relaxation is of subordinate significance for the loss of preload for typical operating temperatures in steel construction.

Shear loaded connections (e.g. slip-resistant connection) are subjected to preload losses due to *transversal contraction*. Here, the clamped package under tensile shear loads is elastically compressed, which leads to a reduction of the clamping length and therefore of the axial displacement of the bolt. In case of an external compression load, this behaviour would be reversed, as the axial displacement of the bolt and therefore the bolt preload would be slightly increased. As long as the occurring stresses in the gross cross-section area under external load remain within the elastic range, the resulting preload losses due to transversal contraction itself can be assumed as uncritical. In this regard, what mainly causes permanent preload losses is the embedding after unloading of the connection. *Steinhardt/Möhler* [16] reported a remaining loss of preload of around 8 % after the first tensile static loading of shear loaded preloaded bolted connections, whereby practically no further decrease of the bolt preload could be determined during subsequent repeated loading. A similar behaviour was observed under cyclic loading. Here, a noticeable permanent drop of the bolt preload was experienced after the first load cycle, whereby subsequent preload changes resulted from the elastic transversal contraction and did not affect the fatigue

strength of the connection. As mentioned before, this behaviour only applies to stresses within the elastic range of the materials used. Overloads would lead to plastic deformation of the clamped components and/or the fasteners and must therefore be avoided at all costs.

External tensile load might concern both, preloaded shear connections and preloaded tension connections. The resulting load-bearing behaviour was already described in the joint diagram for the working state (Figure 2.2). For slip-resistant connections, the additional tensile bolt force reduces the pressure on the friction surfaces and therefore influences the slip resistance of the connection. This reduction is currently considered in the design as shown in Equations (2.3) and (2.4). Next to the reduction of the clamp load, the additional bolt force leads to higher stresses under the washers and connected surfaces, which, following the example of transversal contraction, might result in permanent preload losses due to embedding after unloading of the connection. As mentioned before, plastic deformation due to overloads would lead to increased preload losses. This must be avoided through sensible limitation of external stresses.

As can be seen from the explanations above, permanent preload losses in common steel structures mainly occur due to local plastic deformations. Depending on the material in question and the working loads, those deformations can either be mostly completed after several hours (flattening of the roughness of metallic surface) or show a strong time-dependent behaviour (compression of the surface coatings). Since the time-dependent preload losses in bolted connection cannot be entirely allocated to pure creep or to pure relaxation, it can be therefore seen as a complex combination of setting effects and relaxation processes.

2.5.3 Slip factor

The design of slip-resistant connections relies on the sufficient load transmission through the friction surfaces. The slip factor, as an experimental value for the design of slip-resistant connections, covers the most essential influencing parameters for the actual performance of the connection such as condition of the faying surfaces including the composition of the coating material and the coating thickness. Various guidelines and standards classify some surface treatments and provide slip factors for the sensible application in design. EN 1090-2 distinguishes between seven different surfaces treatments, as can be seen in Table 2.5.

Table 2.5 Classifications for friction surfaces according to EN 1090-2

Surface treatment	Class	Slip factor μ
Surfaces blasted with shot or grit with loose rust removed, not pitted	A	0.50
Hot dip galvanized surfaces according to EN ISO 1461, subsequently flash (sweep) blasted and with alkali-zinc silicate paint with a nominal thickness of 60 μm	B	0.40
Surfaces blasted with shot or grit:		
a) coated with alkali-zinc silicate paint with a nominal thickness of 60 μm ;	B	0.40
b) thermally sprayed with aluminium or zinc or a combination of both to a nominal thickness not exceeding 80 μm		
Hot dip galvanized surfaces according to EN ISO 1461, subsequently flash (sweep) blasted (or equivalent abrasion method)	C	0.35
Surfaces cleaned by wire-brushing or flame cleaning, with loose rust removed	C	0.30
Surfaces as rolled	D	0.20

Herein, four different types of surface treatments can be distinguished:

- faying surfaces without any coating,
- alkali-zinc silicate (ASI) as inorganic zinc-rich coating,
- thermal-sprayed metallic coatings and
- hot dip galvanized surfaces.

As can be seen from Table 2.5, the slip factor for uncoated surfaces mainly depends on the selected post-treatment. While a slip factor $\mu = 0.2$ can be assumed for as rolled surfaces without any post-treatment, grit or shot blasting may improve the slip-resistant behaviour significantly ($\mu = 0.5$), however, unprotected surfaces of connections made of carbon steel are susceptible to corrosion. On the other hand, inorganic zinc-rich coatings, thermal spray metallizing or hot dip galvanizing as well as duplex systems (hot dip galvanizing + inorganic zinc-rich coating) may provide a necessary corrosion protection of a slip-resistant connection, however, their influence on the slip factor has to be sensibly taken into account. Although a slip factor μ of 0.4 is prescribed for ASI coating, recent

investigations [5], [92] carried out at the Institute for Metal and Lightweight Structures showed that $\mu > 0.5$ can comfortably be achieved. On the other hand, especially a slip factor μ of 0.35 for hot dip galvanized surfaces should be critically questioned. A comprehensive investigation into slip-resistant connections carried out by *Afzali* [92] shows a clear influence of different galvanizing processes and post-treatments on the achieved slip factor. Furthermore, a carried out literature review considering post-treated (here: sweep blasted or equivalent) hot dip galvanized surfaces show large variations of the determined slip factor between 0.20 to 0.44 [92]. Finally, based on the investigations in [93], *Ungermann et al.* even proposed a reduction of the slip factor for hot dip galvanized and subsequently sweep blasted surfaces. Instead of the currently permitted slip factor μ of 0.35 according to EN 1090-2, a slip factor μ of 0.25 is recommended due to increased creep effects of the zinc layer thicknesses of $\leq 250 \mu\text{m}$. At this point, it should be mentioned that a slightly lower slip factor (compared to EN 1090-2) for hot dip galvanized surfaces of $\mu = 0.3$ is assumed by RCSC Specification [49]. Herein, a different testing method and the evaluation criterion compared to specifications in EN 1090-2, Annex G apply. However, according to *Afzali* [92], more conservative results (especially for coated faying surfaces) are usually achieved by determining the slip factor in the creep tests according to EN 1090-2 compared to RCSC. A brief overview of specifications in other international standards is given in Chapter 3.3.4.

In cases where the classification of the friction surfaces of slip-resistant connections is not possible, a generalized procedure according to EN 1090-2, Annex G shall be applied in order to experimentally determine the slip factor, see Figure 2.11. Since the test procedure has been discussed extensively in numerous publications (e.g. *Afzali* [92] etc.), no detailed explanation will be provided. However, with regard to focus areas within the scope of this work, creep tests and extended creep tests, see Figure 2.11, shall be highlighted, as the final slip factor according to EN 1090-2, Annex G is calculated either considering the characteristic 5 % fractile value in case of a passed creep test or after three passed extended creep tests under consideration of a specific, constant load level applied during the test. In general, the determination of the final slip factor is based on the following equation:

$$\mu = \frac{X \% \cdot F_{Sm}}{m \cdot n \cdot F_{p,C}} \quad (2.15)$$

where $X \% \cdot F_{Sm}$ is the test load of the passed creep or extended creep test, m is the number of bolts in slip-resistant connection, n is the number of friction surfaces and $F_{p,C}$ is the nominal minimum preloading force.

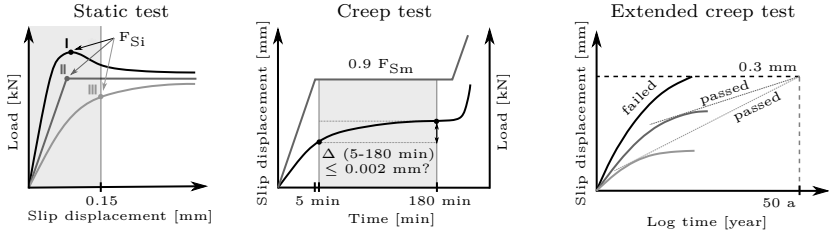


Figure 2.11 Slip factor tests according to EN 1090-2, Annex G

In addition to the pure surface treatment, the slip factor is influenced by various system properties of a connection that have to be considered. The complexity of the test procedure and the need for transferability of all boundary conditions to real structures might lead to major limitations during design and execution, since every deviation from the experimental procedure must be taken into account in a meaningful way. For example, the already addressed potential of preload losses, especially due to coating systems between washers and connected surfaces, leads to the necessity of surface masking under the washers, which can result in additional costs. As described in Chapter 2.3.3, some tightening methods might lead to a high scattering of the actual preload in the connection, which is not necessarily considered in the test procedure, as the bolts shall be tightened to within $\pm 5 \%$ of the specified preload $F_{p,C}$ at the beginning of each test according to EN 1090-2, Annex G.

2.6 Summary and conclusions

In steel construction, bolted connections are preloaded either for load-bearing capacity reasons (target level I of preloading) or for serviceability reasons (target level II of preloading). Connections of target level I rely on a specified preload level, which has to be ensured over the whole service life of the structure. Connections of target level II, on the other hand, are preloaded to avoid slippage and deformation - a certain amount of preload is desired, but not mandatory with regard to safety aspects.

After tightening of bolted connections, preload losses occur due to setting effects/embedding in the contact and bearing surfaces, which contributes to loosening of the connection. Further possible reasons for preload losses involve time-dependant processes such as relaxation, but also operational loads including cyclic loading. In order to ensure the operational safety of preloaded bolted connections, those influencing factors have to be estimated and considered reasonably.

In general, steel surfaces are subjected to corrosion and should receive a sufficient protection in order to avoid any damage during the intended service life of the structure. Passive corrosion protection is the most common way of protecting steel surfaces by using protective layers, films or other coatings and offers mechanical isolation from the aggressive corrosive agents. However, because of their chemical composition, typical coating systems might also lead to higher preload losses due to creep effects. For this reason, an extensive knowledge about possible preload losses for specific coatings/coating systems is necessary in order to consider this influence during design and to guarantee a sufficient preload level during the service life of steel structures.

It becomes clear that the choice of a suitable corrosion protection in order to minimize the possible preload losses as well as the generation of high system reserves by suitable tightening methods play an essential role for the durability of a preloaded bolted connection.

3 Influencing factors for preloaded bolted connections during design and execution of steel structures

3.1 General

Bolted connections represent one of the most important joining techniques in structural steel engineering. Depending on the type of loading (here: generally distinguished between shear and tension), EN 1993-1-8 [1] defines five categories of bolted connections. Regardless of the category of bolted connections, these can/must be preloaded (given the required property class of bolting assemblies of at least 8.8) in order to ensure the structural safety (target level I) or to improve the serviceability (target level II). As discussed in Chapter 2.2, the latter describes a solution, where bolted connections are preloaded, but handled as non-preloaded connections during design. Apart from that, target levels of preloading can particularly be distinguished by considering different requirements for inspection and testing with respect to the necessary degree of rigorousness, as a summarizing overview in Table 3.1 emphasizes.

As explanations in Chapter 2 suggest, some of the most important factors for a preloaded bolted connections from design point of view are:

- **preloading force** e.g. $F_{p,C}$, $F_{p,C}^*$ or no preload (all categories) and
- assumption of a **suitable slip factor** (categories B/C of bolted connections).

On the other hand, the following influencing factors must be considered in the frame of the execution:

- **tightening method:**
 - preloading force used for design exceeded/not achieved,
 - actual slip factor/slip resistance affected,
 - possible influence on the extent of preload losses (e.g. due to tightening into overelastic range).

- **corrosion protection:**

- influence on the achieved preloading force e.g. due to high coating thickness,
- main influencing variable for preload losses,
- influence on the slip factor through the friction surfaces.

Figure 3.1 gives an overview of the complexity of dependencies with regard to design values and some of the necessary steps that have to be considered during the execution. As can be seen, especially system reserves due to the tightening method and its reliability with regard to the nominal preloading force as well as preload losses mostly resulting from the selected corrosion protection have to be considered reasonably. This, however, requires a solid normative foundation.

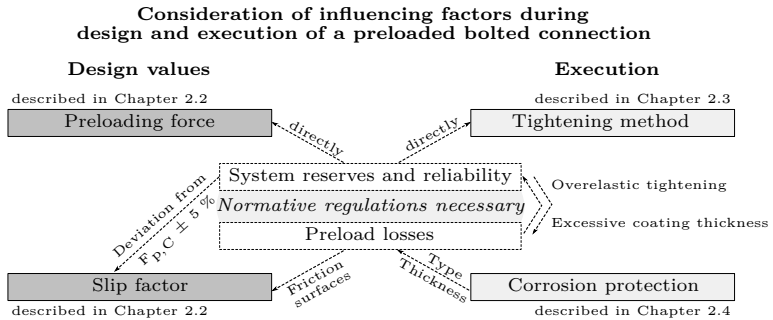


Figure 3.1 Some of the main influencing factors to be considered during design and execution of a preloaded bolted connection

In the following chapters, the normative regulations and some of the fundamental experimental investigations regarding the design and execution of preloaded bolted connections are presented and discussed. Herein, the main focus lies on the preloading of bolting assemblies and its reliability with regard to the required preload levels as well as the necessary corrosion protection for preloaded bolted connections and its influence on preload losses.

Table 3.1 Categories of bolted connections and the corresponding normative requirements for their design and execution

Category	B/C	E	A	D
Target level	I	I	II	II
Verification format acc. to EN 1993-1-8	shear res. ¹⁾ : $F_{v,Ed} \leq F_{v,Rd}$			
	bearing res. ¹⁾ : $F_{v,Ed} \leq F_{b,Rd}$	tension res.: $F_{t,Ed} \leq F_{t,Rd}$	shear res.: $F_{v,Ed} \leq F_{v,Rd}$	tension res.: $F_{t,Ed} \leq F_{t,Rd}$
	slip res. at SLS ¹⁾ : $F_{v,Ed,ser} \leq F_{s,Rd,ser}$	punching shear res.: $F_{t,Ed} \leq B_{p,Rd}$	bearing res.: $F_{v,Ed} \leq F_{b,Rd}$	punching shear res.: $F_{t,Ed} \leq B_{p,Rd}$
	slip res. at ULS ²⁾ : $F_{v,Ed} \leq F_{s,Rd}$			
Documentation acc. to EN 1090-2	Execution specification incl. executive drawings and constructor's documentation (quality-assuring and evidential)			
Inspection	coated (friction) surfaces visually before tightening during and after tightening ³⁾		visually	visually
Generally in accordance with:				
Corrosion protection acc. to EN 1090-2	<u>expected life of the corrosion protection</u> acc. to EN ISO 12944-1 [51] and EN ISO 14713-1 [65] <u>corrosivity category</u> acc. to EN ISO 12944-2 [52] and EN ISO 14713-1 [65]			
Additional requirements regarding coated surfaces acc. to EN 1090-2	<u>friction surfaces</u> acc. to Table 17		<u>average DFT</u> ⁵⁾ \geq NDFT	
	or verified in accordance with Annex G	<u>contact surfaces</u> with max. 100 μ m NDFT ⁴⁾	<u>minimum DFT</u> \geq 80% NDFT	
	<u>other</u> <u>contact surfaces</u> with max. 100 μ m NDFT ⁴⁾		<u>maximum DFT</u> \leq 2 \times NDFT generally \leq 3 \times NDFT for edges etc.	

¹⁾ only for connections of category B²⁾ only for connections of category C³⁾ dependent on execution class (EXC) and tightening method⁴⁾ NDFT: nominal dry film thickness⁵⁾ DFT: measured dry film thicknessAbbreviations:

res.: resistance

3.2 System reserves and reliability due to tightening method

3.2.1 Normative regulations in EN 1090-2 and DAST-Guideline 024

As prescribed by EN 1993-1-8, a controlled tightening of bolting assemblies according to EN 1090-2 is carried out in order to achieve a specific preloading force that is included in the design. Depending on the applied standard or guideline (here: EN 1090-2 or DAST-Guideline 024), a nominal minimum preloading force $F_{p,C}$ or the slightly lower preload level $F_{p,C}^*$ (also known as the "standard preload level" ("*Regelvorspannkraft*") in Germany) are assumed for the design. Initial preload levels of $F_V \leq F_{p,C}^*$ or $F_{p,C}^* \leq F_V \leq F_{p,C}$ are also possible according to DAST-Guideline 024, although considering the current bolting technology and the equipment on the construction site, this seems not to be as beneficial in terms of the cost effectiveness or the necessary effort as it was in the past, when the tightening was still carried out by hand on many construction sites.

In all cases, the required preload level should be reliably achieved using specified tightening methods. Since considerable scattering of the actual preloading forces after tightening is unavoidable, preload levels $F_{p,C}$, $F_{p,C}^*$ or lower should be seen as characteristic lower fractile values, so that higher preloading forces are not only desirable, but also targeted regardless of the tightening method. The resulting exceedance of the nominal preloading force by the initial preloading force $F_{p,ini}$ can be defined as the *system reserve*, as introduced by *Stranghöner et al.* [94]-[95] and *Makevičius* [96].

According to Annex I of EN 1090-2, a system reserve of 10 % is considered in the specified tightening procedures of EN 1090-2. This means that these 10 % can be taken for compensation of possible preload losses. In the following chapters, some background information considering this regulation of EN 1090-2 is given. Furthermore, normative considerations of system reserves in other international guidelines as well as some of the most important experimental findings are presented.

3.2.2 Reliability of different tightening methods

All normative regulations in EN 1090-2 and DAST-Guideline 024 regarding tightening of bolting assemblies require a standard compliant lubrication in the delivery condition at the time of their use. Once this requirement is fulfilled, any of the specified tightening methods can be applied without any restrictions.

The possibility of a calibration test for preloaded bolting assemblies under site conditions according to EN 1090-2, Annex H or procedure qualification for the determination of tightening parameters for preloaded bolted connections according to DAST-Guideline 024 should also be pointed out, but will not be further discussed in terms of this work.

As pointed out before, preload level $F_{p,C}$ should be seen as the characteristic 5 % fractile value in accordance with clause 4.2 of EN 1990 [97]. This, of course, transfers to every other preload level, such as $F_{p,C}^*$ according to DAST-Guideline 024. The reliability of the tightening methods given in EN 1090-2 with regard to their ability to fulfil the demand of EN 1990 by the second tightening step was evaluated by *Berenbak* [98] in 2012 and accepted by CEN/TC 135 WG2 to use for the next revision of the EN 1090-2. The evaluation was carried out under consideration of the EN 1090-2 torque method, combined method, HRC tightening method as well as the direct tension indicator (DTI) method, where the assumption has been made that the connections are fully in contact after the first tightening step. Furthermore, no human inaccuracies were taken into account.

The determined reliability values are summarized in Table 3.2.

Table 3.2 Reliability of tightening methods in EN 1090-2 as determined by *Berenbak* [98]

Tightening method	Reliability
EN torque method	79.4 %
Combined method	100 %
HRC method	81 %
Direct tension indicator (DTI) method	> 95 %

Instead of a required reliability of 95 %, comparatively poor values of 79.4 % for the torque method and 81 % for the HRC method were determined, see exemplarily Figure 3.2 (left). This was mainly caused by contradictory rules regarding the coefficient of variation V_k (here: notation analogous to *Berenbak* [98]). Even though the design for these tightening methods was mainly based on a k-class K2 with $V_k \leq 0.06$ (HRC method also allows k-classes K0 or K1 by using HRD nuts) in accordance with the 2011 edition of EN 1090-2 [99], a slightly lower requirement of $V_k \leq 0.10$ for K2 was demanded by the EN 14399-3 [100]-[101],

EN 14399-4 [102]-[103] or EN 14399-10 [104] at that time - this non-conformity has consequently been aggravated in the revised versions of EN 14399-3 [28], EN 14399-4 [29] and EN 14399-10 [35], leading to an increased reliability of around 95 % for the above mentioned tightening methods in the current version of EN 1090-2. *The current normative regulation states that the potential loss of preloading force of no more than 10 % is implicitly considered in the specified tightening methods.* This is based on the fact that $\approx 10\%$ higher target preload value than $F_{p,C}$ was taken into account in terms of the evaluation by *Berenbak*.

As can be drawn from the observations in Chapter 2.3.3.2, the combined method according to EN 1090-2 and DAST-Guideline 024 offers a 100 % reliability with regard to its ability to achieve the preload level $F_{p,C}$ due to the angle-controlled tightening during the second step, see Figure 3.2 (right). Furthermore, due to the tightening into the overelastic range, significantly higher initial preload values $F_{p,ini,KV}$ and herewith system reserves of $> 25\%$ can be expected, as shown in Figure 2.7.

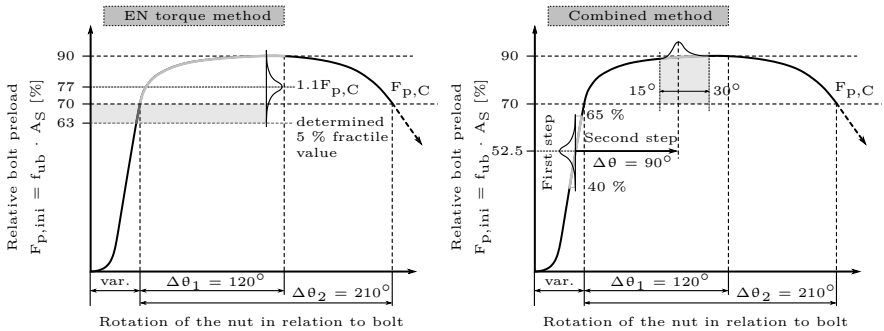


Figure 3.2 Distribution of bolt preloads by means of rotation-relative bolt preload curves for EN torque method (left) considering coefficient of variation $V_k = 0.10$ for bolting assemblies and a mean value of $\approx 1.1F_{p,C}$ as well as for combined method (right) according to *Berenbak* [98]

Given the example of *Berenbak*, a similar evaluation can be carried out for the modified torque method according to DAST-Guideline 024. The reliability regarding characteristic lower fractile values should be based on the preload level $F_{p,C}^* = 0.7 \cdot f_{yb} \cdot A_s$. Considering a mean k -value of 0.13 (k -class K1 with $0.10 \leq k_i \leq 0.16$), the target preload value for different bolt diameters (here: M12 to M36) is mostly around $0.8 \cdot f_{yb} \cdot A_s$. Other than for k -class K2, the coefficient of variation is formally not limited to a specific value - herewith, a generalized

statement regarding the coefficient of variation is not possible. However, given a long-term tradition of using k-class K1 in Germany and a large number of suitability tests for preloading carried out at UDE/IML, but also considering experiences from other literatures (e.g. *Scheer et al.* [105] or *Valtinat et al.* [106]), empirical values with a range of around 0.06 (lower value) $\leq V_k \leq 0.12$ (higher value) are selected for a rough calculation, see Table 3.3.

Table 3.3 Determination of the combined coefficient of variation V_{comb} for modified torque method acc. to DAST-Guideline 024 considering the selected empirical values for k-class K1

Subject	Coefficient of variation [-]
Testing tools (EN 14399-2)	
A: Bolt force measuring device, $\pm 2 \%$	0.02
B: Bolt force measuring device, repeatability error, $\pm 1 \%$	0.01
C: Torque measuring device, $\pm 1 \%$	0.01
D: Torque measuring device, repeatability error, $\pm 1 \%$	0.01
E: Installation tools (DAST-Guideline 024)	0.04
F: k-class K1 (empirical values)	0.06 (low) 0.12 (high)
Combined coeff. of variation V_{comb}¹⁾	$V_{\text{comb,low}}$ $V_{\text{comb,high}}$ 0.077 0.129

¹⁾ V_{comb} is calculated considering individual coeff. of variation of subjects A to F:

$$V_{\text{comb}} = \sqrt{A^2 + B^2 + C^2 + D^2 + E^2 + F^2}.$$

The determination of reliability for the modified torque method is carried out in Table 3.4 and is based on the approach presented by *Berenbak* in [98]. Herein, the combined coefficients of variation of $V_{\text{comb,low}} = 0.077$ and $V_{\text{comb,high}} = 0.129$ are assumed following the considerations in Table 3.3. Firstly, the determination of reliabilities emphasizes that the modified torque method is strongly dependent not only on the lubrication conditions, but also on the accuracy of the applied testing and tightening tools. Provided that the coefficient of variation of a specific batch of bolting assemblies with k-class K1 is $V_k \leq 0.06$, the required preload level $F_{p,C}^*$ seems to be reliably achieved in nearly 95 % of cases, so that the requirement for the characteristic lower fractile value is fulfilled. On the other hand, this means that a V_k of equal or less than 0.06 (corresponds to 6 %) is preconditioned for k-class K1 in order for the modified torque method to deliver preloading forces that are assumed for design. Theoretically, a general non-fulfilment of this requirement leads to significant shortfalls in terms of reliability. As can be seen in Table 3.4, a significantly higher assumed coefficient of variation

V_k of 0.12 for k-class K1 even results in an achievement of the nominal preload level in only 83.3 % instead of 95 % of all cases.

A predestined scattering of the k-values and especially a marginal reliability of the modified torque method makes it difficult to assume any well founded system reserves for their consideration during design and execution. Considering this and taking into account the objectives of target level I of preloading, a flawless function of this tightening method under operating conditions seems to rely on the competence of the bolt manufacturers and assemblers on construction site. However, at this point, it is very important to mention a counterargument to the possible reliability issues of the modified torque method, especially with regard to potential preload losses: the possibility of re-tightening after several days.

Table 3.4 Determination of reliability of the modified torque method based on the approach of *Berenbak* [98] using empirical coefficients of variation $V_{comb,low}$ and $V_{comb,high}$ for k-class K1 from Table 3.3

Subject	Formula	Result for	
		$V_{comb,low}$	$V_{comb,high}$
Nominal preload value $F_{p,C}^*$ where $X = 0.7$	$F_{p,C}^* = 0.7 \cdot f_{yb} \cdot A_S$		
Target/mean preload value where $\mu_X = 0.8$	$F_{p,mean} \approx 0.8 \cdot f_{yb} \cdot A_S$		
Characteristic 5 % value $F_{p,0.05}$	$F_{p,0.05} = (1 - k_n \cdot V_{comb}) \cdot \mu_X$	0.699	0.630
Reliability index β	$\beta = \frac{\mu_X - X}{\mu_X \cdot V_{comb}}$	1.627	0.967
Reliability regarding $F_{p,0.05}$	Cumulative distribution function (CDF)	94.8 %	83.3 %

$X = 0.7$ corresponds to 70 % of the bolt yield strength for the nominal preload $F_{p,C}^*$.
 $\mu_X = 0.8$ corresponds to the target preload $F_{p,mean}$ based on the mean k-value of 0.13.
 $k_n = 1.64$ for characteristic values according to EN 1990, Annex D.

3.2.3 Considerable influencing factors on the construction site

The considerations in Chapter 3.2.2 emphasize that the quality of the lubrication and the associated features play a dominant role for every torque-controlled tightening method, including the modified torque method. However, next to the possible errors regarding an estimation of the coefficient of friction (here: k-class) or the fact that k-values are subjected to high scattering, also an inaccuracy of the

tightening tools including operating and reading errors should be considered. As listed by *Junker* [107], factors such as deviation of the actual torque (tightening and re-tightening) delivered by the tightening tool and an error by setting the target initial tightening or re-tightening torque directly affect the achieved preload.

For this reason, VDI 2230-1 introduces the tightening factor α_A for design in mechanical engineering, see Equation (3.1), and provides guide values suitable for defined assemblies. Also known as "assembly uncertainty factor", α_A is intended to consider all of the above mentioned errors that might lead to considerable scatter of the bolt preload after the tightening.

$$\alpha_A = \frac{F_{M \max}}{F_{M \min}} \quad (3.1)$$

Here, α_A is used as the ratio between the maximum assembly preload $F_{M \max}$ and the required minimum assembly preload $F_{M \min}$ - a sensible procedure for the individual design of the components.

Similarly to the approach in VDI 2230-1, a variation of the bolt preload due to scattering can be taken into account according to the standard for general design of cranes EN 13001-3-1 [108] by calculating the maximum and minimum values (here: $F_{p,\max}$ and $F_{p,\min}$) using guide values for the scattering s . In fact, the provided guide values for scatter of 0.09 (controlled tightening with bolt force or bolt elongation measurement), 0.18 (controlled tightening with measurement of the angle of rotation) and 0.23 (controlled tightening with measurement of the tightening torque) can be converted to the "assembly uncertainty factor" α_A for comparability reasons using the relationship in Equation (3.2).

$$s = \frac{\alpha_A - 1}{\alpha_A + 1} \quad (3.2)$$

In cases where several identical and uniformly loaded bolts (here: n) are used in a connection, the guide values for scatter can be reduced for their consideration in $F_{p,\min}$ considering s/\sqrt{n} . Herein, the minimum guide values for a scatter of ≥ 0.10 (controlled tightening with measurement of the angle of rotation and tightening torque) and ≥ 0.05 (controlled tightening with bolt force or bolt elongation measurement) shall be considered.

The general rules for design, calculation and mounting in the French standard NF E 25-030-1 [109] prescribe that the torque values for the calibration of the

tightening tools should be given under consideration of operating parameters such as:

- variation in energy characteristics,
- variation due to the operator,
- incorrect positioning of the wrench and
- tightening speed.

The device accuracy of 4 % (here: permissible deviation of the torque value), as prescribed by EN 1090-2 (and consequently by DAST-Guideline 024), is based on a calibration of assembly tools in accordance with EN ISO 6789-1 [110] and EN ISO 6789-2 [111]. Although EN ISO 6789-1/-2 de facto deals with hand torque tools, the requirements can be adopted to automatic torque tools (pneumatically operated, electric and hydraulic tools) as well. Impact wrenches, as a rule, fail to provide the required accuracy of 4 %. In any case, the intended use of the tightening tool must be accompanied by either a declaration of conformity or a calibration certificate.

A classification of the tightening tools provided by NF E 25-030-1 (2007-12) [112] suggests that the accuracy for the electric torque wrenches with reaction arms (± 10 %) or pneumatic torque wrenches (± 15 % to ± 20 %) *under consideration of operating parameters* may fall below the requirement for the device accuracy of 4 %, as prescribed by EN 1090-2. These rules again emphasize the possible sources of error that are currently not taken into account in German steel construction with regard to the torque-controlled tightening.

The Specification for Structural Joints using High-Strength Bolts [49] approved by the Research Council on Structural Connections (RCSC) in the United States of America prescribes a pre-installation verification for the suitability of the bolting assembly. The trigger for such a procedure are the tolerances of the bolting assemblies and bolting components that are manufactured under separate American Society for Testing and Materials (ASTM) standards, which in the cumulative way may lead to a significant variation in the installation characteristics. The pre-installation verification intends to consider these tolerances *together with other operating parameters such as the equipment and the steelwork*. This kind of testing must be carried out on a daily basis prior to the installation using the torque-controlled tightening (here: *calibrated wrench method*).

A similar practical approach can also be found in the Japanese Architectural Standard Specification JASS 6 [113], where a procedure is proposed for tightening using the torque control method in order to determine the proper torque value prior to commencement of tightening. Here, a tightening of five bolts using a tension meter and a calibrated tightening tool must be carried out. The aim is to confirm that the calculated required tightening torque value enables to achieve the average bolt tension $\pm 15\%$ of high strength hexagon bolts. The corresponding torque value can later be used for inspection purposes as well.

3.2.4 Normative consideration of system reserves and other experimental findings

As mentioned before, EN 1090-2 states that a system reserve of 10 % is implicitly considered in the specified tightening procedures. Some background information considering this regulation was briefly introduced in Chapter 3.2.2. Furthermore, based on different international regulations, some of the other possible influencing factors on construction site that are not necessarily considered in the current regulation in EN 1090-2 were pointed out in Chapter 3.2.3.

In this chapter, a brief overview of the current normative regulations regarding system reserves/influence of different tightening methods in selected standards/guidelines are given and some of the most important experimental findings to this regard are summarized.

American Approach

RCSC Specification for Structural Joints using High-Strength Bolts [49] uses a multiplier D_u during the determination of the nominal slip resistance. Here, D_u reflects the statistical relationship between the average historical bolt pretension and the specified minimum bolt pretension T_m (based on 70 % of the tensile strength). According to this standard, a generalized value of $D_u = 1.13$ can be assumed for building structures. In case of design for bridge structures, a reduced value of $D_u = 1.00$ shall be used. The value of 1.13 is based on an analysis carried out by *Kulak et al.* [114] and refers to the calibrated wrench method. According to RCSC Specification, this value can also be used for all installation methods, in cases, where field test data is not given. On the other hand, an increase of the multiplier D_u is also possible. Here, an approval by

the Engineer of Record or by a Specification body is necessary, as mentioned in ANSI/AISC 360-16 [115].

The American turn-of-nut method represents a simple and reliable tightening procedure, which relies upon application of a designated amount of relative rotation between bolt and nut - a similar approach to the combined method, as already described in Chapter 2.3.3.2. Herein, the nut rotation from a snug-tight condition (here: snug-tightening procedure is used bring the clamped parts into firm contact and typically can be achieved *"with a few impacts of an impact wrench, application of an electric torque wrench until the wrench begins to slow, or the full effort of a worker on an ordinary spud wrench"* according to RCSC Specification) mainly varies from $\frac{1}{3}$ to $\frac{1}{2}$ of a turn (nut rotation of even one full turn is possible) and depends on the bolt length as well as disposition of outer faces of bolted parts. As can be expected, due to the characteristics of angle-controlled tightening, the turn-of-nut method intends to tighten the bolt into the overelastic range in order to achieve the highest precision. *Kulak et al.* [114] state that the turn-of-nut method may lead to a substantially higher actual bolt tension in comparison to the required minimum tension, see exemplarily Figure 3.3. An analysis of the experimental data shows, that the average actual bolt tension is likely to exceed the required minimum bolt tension by approximately 20 % (as reported by *Frank/Yura* [116]) up to 35 %, see A325 bolts tightened by $\frac{1}{2}$ turn in Figure 3.4. For this reason, RCSC Specification refers to the possibility of D_u of about 1.35 for A325 bolts and of about 1.26 for A490 bolts, both according to ASTM F3125 [117], for the turn-of-nut method.

Furthermore, design recommendations by *Fisher/Struik* in 1974 [118] already considered different tightening procedures and their influence on the design shear stresses for slip-resistant connections by introduction of the reduction factor β_2 . A value β_2 of 1.0 was recommended for turn-of-nut method, where lower clamping forces resulting from calibrated wrench method led to β_2 of 0.85. Herewith, an expectedly higher reliability of the turn-of-nut method compared to the calibrated wrench method can be emphasized.

Investigations carried out by *Roemaker et al.* [119] show that tightening of TnA 144 bolts (ASTM F3148 [120]) using combined method provided by RCSC Specification under different temperature conditions (here: $0^\circ\text{F}/72^\circ\text{F}/170^\circ\text{F}$, which is equivalent to $-17.8^\circ\text{C}/22.2^\circ\text{C}/76.7^\circ\text{C}$) leads to an average ratio of

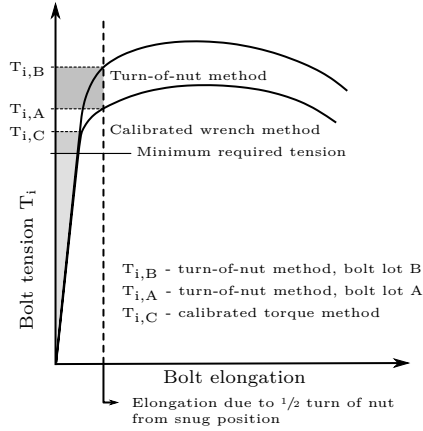


Figure 3.3 Influences of tightening using calibrated wrench method and turn-of-nut method on the bolt for different bolt lots according to *Kulak et al.* [114]

achieved preload/minimum preload value of 1.37. This value is also noted as possible D_u value for the combined method by RCSC Specification.

The positive influence of the turn-of-nut method on the slip resistance is also considered in South African National Standard SANS 10162-1 [121] and Canadian Standard for Design of steel structures CSA S16-09 [122]. Herein, a higher statistical coefficient c_1 is used for the turn-of-nut method than for the calibrated wrench method for the determination of the slip resistance V_s , by multiplying c_1 with other determining factors such as the mean slip coefficient, the number of faying surfaces or shear planes in a bolted joint, the number of bolts etc. The coefficient c_1 considers the difference between the initial clamping force after tightening and the nominal value and reflects the distribution of the actual slip factor values about the mean value and includes a 5 % probability of slip, where the values for coefficient c_1 correspond to the statistical parameter D (also named as "slip factor") provided by *Kulak et al.* [114]. The design check for slip resistance including the above mentioned parameters D_u in the current RCSC Specification as well as c_1 in the SANS 10162-1/CSA S16-09 are based upon different design principles (slip resistance at the factored-load level or at the service-load level), but are developed by using the same statistical basis from *Kulak et al.* [114]. For this reason, both approaches result in a similar probability of slip and more importantly, provide a possibility to take into account

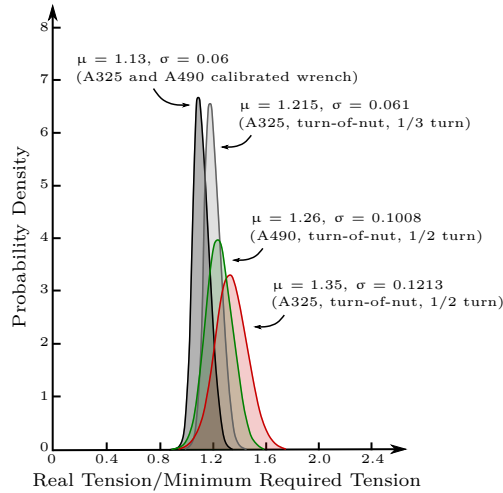


Figure 3.4 Frequency distribution curve of the achieved/minimum required bolt tension for different tightening procedures according to *Kulak et al.* [114]

the beneficial influence of higher preload levels achieved by using turn-of-nut method.

Fundamental investigations in Europe

Valtinat et al.

In Germany, some of the fundamental investigations with regard to the tightening behaviour of hot dip galvanized bolting assemblies and the transition from DAST-Guideline 010 [40]/DIN 18800-7 [41]/TGL 13510/03 [42] to the Eurocode regulations were carried out by *Valtinat et al.* [123]-[125]. High temperature galvanized HV bolting assemblies lubricated with molybdenum disulfide (MoS_2) of property classes 10.9 and 12.9 and different diameters were examined and the necessary characteristic data for torque-controlled and angle-controlled tightening were determined.

Next to the analysis of the tightening instructions of the former DIN 18800-7 and the resulting preload values for the torque method, also an assessment of the tightening behaviour with regard to the recommendations of the ECCS-Technical Committee [126] for the combined method was carried out. According to the test results in [123]-[125], the preload levels resulting from this tightening correspond

to the beginning of the plastic range of the bolt preload-angle of rotation curves and therefore emphasize high plastic reserves during tightening. Furthermore, an optimum utilisation of the bolt is offered. As can be seen from Figure 3.5, the achieved relative bolt preloads $F_{p,6}$ at the beginning of bolt plastification (point 6 in the bolt preload-angle of rotation diagram) correspond to approx. 50 % higher preloads compared to the nominal preload force $F_{p,C}^*$.

With regard to the torque method acc. to DIN 18800-7, preload values in the expected range from a partial undercut of the nominal preload force ($< F_{p,C}^*$) up to the end of the linear elastic area (about $1.2 F_{p,C}^*$) were observed. This behaviour was later confirmed by further tightening tests carried out by laboratories in Germany, Belgium and France [106] and presented in ECCS Committee TC10. Hot dip galvanized M20 HV bolting assemblies showed a variation of individual k-values between 0.134 and even 0.212.

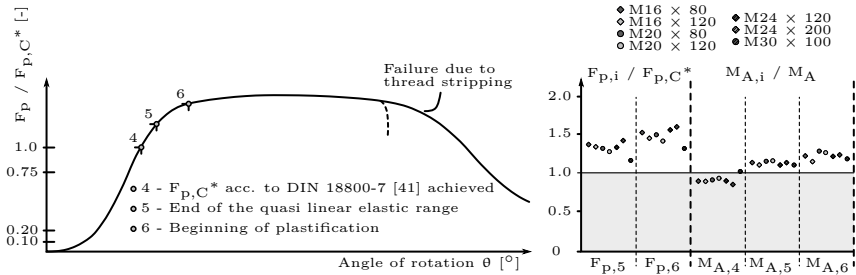


Figure 3.5 Typical bolt preload-angle of rotation diagram as well as a representation of the achieved relative bolt preloads $F_{p,i} / F_{p,C}^*$ and tightening torques $M_{A,i} / M_A$ for the selected points acc. to Valtinat *et al.* [124]

Scheer et al.

Investigations into preloading of M24 HV 10.9 bolting assemblies by using the torque method carried out by Scheer *et al.* [105] showed a broad distribution of the achieved preload levels and even some shortfalls with regard to the minimum preload level $F_{p,C}^*$ according to DIN 18800-7 [41] of up to 20 % (report 6312/A). This was confirmed by extended systematic investigations reported in [105] (report 6312/B). Herein, considering all M24 HV bolting assemblies (three different bolt manufacturers), an average deficit of 14 % with regard to the preload level $F_{p,C}^*$ was determined. In the same study, M16 HV bolting assemblies from three different bolt manufacturers showed better performance with an average achieved system reserve of around 10 %, but an unsurprisingly

high scattering of the test results with $F_{p,min} = 90 \text{ kN}$ and $F_{p,max} = 128.5 \text{ kN}$ (the coefficient of variation considering all test results for M16 test series equals to $\approx 8 \%$). This corresponds very well with the arithmetical scattering of the actual bolt preload showed in Figure 2.6 and the fact, that M20 and M24 HV bolting assemblies represent critical bolt diameters with regard to the possible k-values and the required minimum preload level $F_{p,C}^*$.

The tightening tests carried out by *Scheer et al.* [105] were also evaluated in accordance with the "*angle of rotation method*" (here: DIN 18800-7 (1983-05)). In compliance with considerations made by *Valtinat et al.* [123]-[125], average system reserves of around 47 % and 54 % considering preload value $F_{p,C}^*$ were determined for M16 and M24 HV bolting assemblies respectively.

Dubois/Piraprez

In 1991, *Piraprez* [127] analyzed bolt preloads achieved by using the torque method and the combined method under laboratory conditions and on site. With regard to the torque method, comparatively high deviations between k-values in laboratory and on site were determined. An alteration of the lubricant as well as the positioning of the tightening tool were reported as possible influencing factors for such discrepancies. Considering every investigated connection, torque control led to an undercutting of the required preload level (here: approx. $F_{p,C}^*$) in 50 % of all cases, where the minimum average preload level showed deficits of up to 28 % compared to $F_{p,C}^*$. In case of the combined method, the required preload level (here: approx. $F_{p,C}$) was obtained in every connection, leading to system reserves of around 10 % to 33 %.

Investigations into optimal parameters for the combined method carried out by *Dubois/Piraprez* [128] show, that a high level of preload corresponding to the onset of yielding in the bolt with very low dispersion is assured. Furthermore, the risk of an overloading of the bolt is excluded by a fixed value of the angle of rotation.

Lange/Friede

The torque method as well as combined method acc. to DIN 18800-7 (2008-11) [129] were also applied during investigations of *Lange/Friede* [130]-[131]. For the torque method, average deficits of 2 % to 13 % regarding the required preload level $F_{p,C}^*$ were determined for M16 and M20 10.9 HV bolting assemblies. M24 HV bolting assemblies, however, led to an average system reserve of around 16 % by

applying the necessary tightening torque. As expected, bolting assemblies, which were tightened by using the combined method, achieved the required preload in all cases and even possessed an average system reserve of $> 40\%$ (in relation to $F_{p,C}^*$) despite the lower angle of rotation of 60° (for comparison: 90° according to EN 1090-2 and DASt-Guideline 024 today). This, once again, complies very well with considerations made by *Valtinat et al.* [123]-[125] regardless of minor deviations in tightening parameters.

Schaumann/Rutkowski

Extensive experimental investigations into preloading of bolted connections under site conditions were carried out by *Schaumann/Rutkowski* [132]-[133]. Here, nearly 600 HV 10.9 bolting assemblies (M36 \times 205) were tightened using the torque method according to DIN 18800-7 (2002-09). Two different tightening tools were used: electric torque wrench (measurement campaign 1) and hydraulic wrench (measurement campaign 2). In case of the test series with the electric torque wrench, the bolting assemblies were re-tightened after 103 days by using 110 % of the initial tightening torque M_A . A re-tightening after 42 days by using 1.0 M_A was also carried out for selected bolts during measurement campaign 2. Table 3.5 summarizes the experimental results.

Table 3.5 Results of the measuring campaigns 1 and 2 according to *Schaumann/Rutkowski* [132], [133]

	Electric wrench		Hydraulic wrench	
	Tightening	Re-tightening	Tightening	Re-tightening
No. [-]	268	259	304	293
$F_{p,ini,mean}$ [kN]	510	482	698	625
Coeff. of variation V_X [%]	12	12	8	9
$F_{p,ini,min}$ [kN]	182	241	447	438
$F_{p,ini,max}$ [kN]	669	805	874	834
Required preload $F_{p,C}^* = 510$ kN				

Tightening torque $M_A = 2800$ Nm for M36 10.9 HV bolting assemblies.

Initial preload values $F_{p,ini}$ are related to 20 seconds after (re-)tightening.

The required preload level $F_{p,C}^*$ of 510 kN was achieved only in 53 % of all cases by using an electric wrench and nearly in all cases after the tightening when using a hydraulic wrench ($F_{p,ini} < F_{p,C}^*$ in one case after the tightening and

in five cases after the re-tightening). Compared to the tightening, around 5 % lower initial preload values were observed by means of re-tightening with 1.1 M_A (electric wrench). A re-tightening by using 1.0 M_A (hydraulic wrench) led to about 10 % lower initial preload values. According to *Schaumann/Rutkowski* [132]-[133], the discrepancies of the test results between the two wrenches can be traced back to the speed at which the torque is applied and especially to the duration of the maximum acting torque in case of hydraulic wrench.

3.3 Regulations with regard to contact surfaces and handling of preload losses

3.3.1 (Preloaded) bolted connections

Contact surfaces in preloaded bolted connections fall under the concept of inaccessible surfaces according to EN 1090-2. The German National Guideline RI-ERH-KOR [134] for the preservation of civil engineering structures even assigns bolted connections to the "areas with special character" ("*Bereiche mit Sondercharakter*") and points out that these are often exposed to local corrosion. For this reason, surfaces of bolted connections require (independent of the degree of preloading) at least a minimum corrosion protection to counteract the risk of cavity corrosion and should be treated before assembly.

With regard to possible preload losses, EN 1090-2 regulates contact surfaces of preloaded bolted connections as follows:

- no excess paint is allowed (EN 1090-2, Clause 10.8),
- the treatment should consist of a priming coat and an intermediate coat as a maximum (EN 1090-2, Clause 10.8),
- the treatment should consist of a priming coat with a maximum dry coating thickness of 100 µm (EN 1090-2, Annex F.4).

Here, the limitation of the dry coating thickness de facto leaves the contact surfaces with the only option of a priming coat (alternatively also a one-layer coating system as mentioned in Chapter 2.4.3, a pre-fabrication primer or a metal coating), as compliance with the required coating layer thickness proves to be difficult considering an additional intermediate coat. More importantly, this leads to the necessity of surface masking in cases, where the components are brought to the construction site with a finalized coating system. Furthermore,

as masking is usually carried out manually, this also results in high efforts in terms of time, emerging costs, but also poses a risk to errors. As mentioned in EN ISO 12944-5, the majority of the coats in a coating system or the complete coating system should preferably be applied in the shop - the approach of masking therefore represents a standard case today.

In case of preloaded bolted connections of target level II, it must be considered whether these strict rules and especially the inevitable masking of the contact surfaces are necessary. From a formal point of view, compliance with these rules are not preconditioned, since connections of target level II are preloaded for serviceability reasons and the preload level is not considered in their design. On the other hand, a certain amount of preloading force is needed in order to achieve the maximum improvement in serviceability, see explanatory notes in Chapter 3.3.3.2, so that a suitable coating system should be selected wisely. As noted in Chapter 2.4, the selection of the corrosion protection system for non-preloaded connections and preloaded connections of target level II can usually be based on the expected life of the corrosion protection and the corrosivity category e.g. by using EN ISO 12944-5. In this case, several requirements regarding the achieved coating layer thicknesses acc. to EN 1090-2, Annex F shall be fulfilled. Firstly, the average measured dry film thickness (DFT) should exceed the nominal dry film thickness (NDFT). Furthermore, the minimum measured coating thickness shall not be less than 80 % of the NDFT. Finally, the maximum coating layer thickness shall not exceed $2 \times \text{NDFT}$ in general or $3 \times \text{NDFT}$ for edges, welds and other areas that receive stripe coating.

A similar approach regarding permissible coatings and/or coating systems can be found in ZTV-ING [135] by Federal Ministry for Digital and Transport. According to this guideline, every contact surface in bolted connections should be coated in general. Furthermore, surfaces of non-preloaded bolted connections (including preloaded bolted connections with target level II of preloading) must be protected with the coating system that is used for other surfaces of the structure, where similar requirements for the achieved layer thicknesses to those given in EN 1090-2, Annex F apply. Finally, a list of six verified coating systems is provided for their use in preloaded bolted connections. These are presented and discussed in Chapter 3.3.3, see also Table 3.6.

ZTV-ING generally follows a different approach than e.g. EN ISO 12944-5. Instead of describing the way in which the aim (here: protection duration, corrosiv-

ity category) can be achieved without prescribing exact coatings or coating system for a suitable corrosion protection, ZTV-ING refers to TL/TP-ING [136] and its Part 4, Section 3 consisting of TL KOR - Stahlbauten and TP KOR - Stahlbauten. Herein, TL KOR - Stahlbauten provides regulations on the requirements and the quality assurance of coating materials and systems for the corrosion protection of steel structures. TP KOR - Stahlbauten contains information on the performance of the tests required by TL KOR-Stahlbauten. Finally and most importantly, the Federal Highway Research Institute (BAST) provides a compilation of the tested coating materials according to TL KOR - Stahlbauten [137] that fulfil the requirements for *frame formulations* for their use in steel structures. The selection of corrosion protection systems for various applications according to ZTV-ING in combination with the certified materials according to TL KOR - Stahlbauten represents a system that has been established in Germany for many years. Herewith, the required reliability on the performance of the protected steel structures is assured.

The regulations in EN 1090-2, EN ISO 12944-5 and ZTV-ING clearly prescribe that bolted connections shall be protected only with paint systems, which do not lead to an unacceptable decrease in the preloading force. The selected paint systems and precautions that need to be taken into account, of course, depend on the type of structure and on subsequent handling, assembly and transportation. Given the preloaded bolted connections of target level I and their high sensitivity to preload losses, the only possibility to avoid surface masking and the associated significant costs is a realistic estimation of preload losses and their consideration during design and execution.

3.3.2 Slip-resistant connections and critical remarks regarding the consideration of preload losses

With regard to an unacceptable loss of preload, EN 1090-2 restricts the coating thickness on contact surfaces of preloaded bolted connections, as explained in Chapter 3.3.1. Meaningfully, those regulations regarding contact surfaces shall be applied to slip-resistant connections as well. EN 1090-2, Clause 8.4 justifiably excludes thick surface coatings between washers and connected surfaces and thus emphasizes the necessity of surface masking.

For the friction surfaces of slip-resistant connections, a classification of the slip factor can either be assumed in accordance with EN 1090-2, Table 17 or

experimentally determined according to EN 1090-2, Annex G, see explanatory notes in Chapter 2.5.3. In any case, footnote (b) of Table 17 of EN 1090-2 has an outstanding significance for the handling of preload losses:

"The potential loss of preloading force from its initial value is considered in these slip factor values."

The test procedure in Annex G of EN 1090-2, or more specifically the required creep and extended creep test, indeed ensure that the possibility of creep deformation of the connection is taken into account. Due to the boundary conditions of the experiment (here: test duration, high tensile shear load, linear extrapolation of the "slip displacement - log time curve"), a crucial amount of preload losses is implicitly considered in the slip factor. This is clearly visible by complementing the slip resistance $F_{s,Rd}$ from Equation (2.2) with Equation (2.15) for the determination of the slip factor:

$$F_{s,Rd} = \frac{k_s \cdot n \cdot \mu}{\gamma_{M3}} \cdot F_{p,C} = \frac{k_s \cdot n \cdot \frac{X \% \cdot F_{Sm}}{m \cdot n \cdot F_{p,C}}}{\gamma_{M3}} \cdot F_{p,C} = \frac{k_s \cdot \frac{X \% \cdot F_{Sm}}{m}}{\gamma_{M3}} \quad (3.3)$$

The preload level $F_{p,C}$ de facto disappears from the verification format, showing that:

- the design assumes a sufficient preloading force (here: $\geq F_{p,C} \pm 5 \%$) at the time of commissioning of a structure and
- lower preloading force over the service life of the structures is largely secured through the experimental procedure (withstanding the constant corresponding test load $X \% \cdot F_{Sm}$).

The relation between preload losses and the corresponding slip factor in a passed extended creep test is exemplarily illustrated in Figure 3.6.

Fatigue loads are unavoidable over the service life of a structure considering the application areas of slip-resistant connections. For this reason, it has to be questioned, whether fatigue loads affect the preload in a connection and consequently the assumed slip factor. Based on the investigations conducted by *Steinhardt/Möhler* [16], [138], special remarks regarding the load-bearing characteristics of slip-resistant connections under fatigue loading were included in the "Preliminary guidelines for slip-resistant connections" (*"Vorläufige Richtlinien für HV-Verbindungen"*) [139]. Herein, no significant slip deformation was observed for fatigue loads of up to 90 % of the static slip load. Furthermore, a subsequent

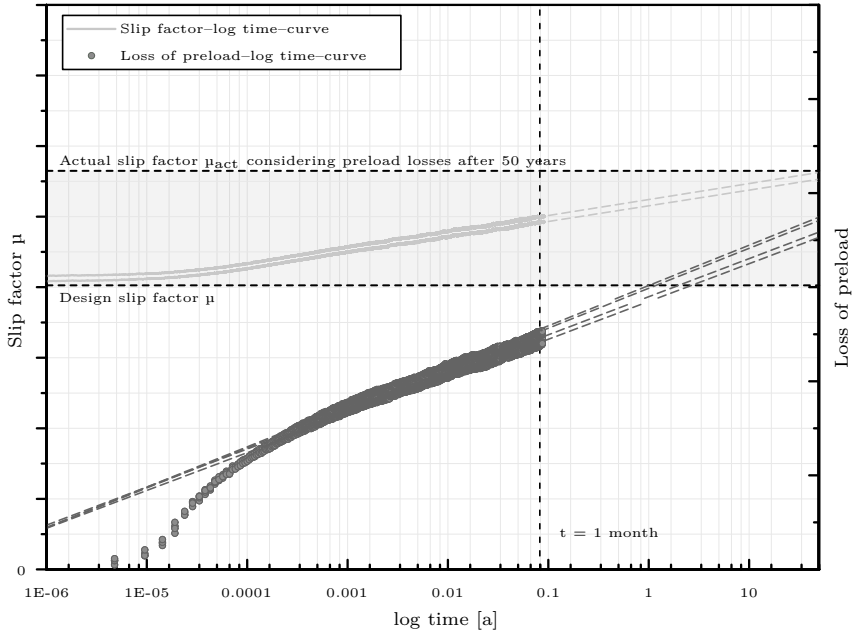


Figure 3.6 Schematic illustration of preload losses and the corresponding slip factor over the intended service life

static slip test carried out on test specimens, which did not show any cracking during 2 million load cycles, led to higher static slip coefficients compared to test specimens that were not subjected to cyclic loading.

Similar tendencies were observed in the comprehensive studies ORE - D 90 [140] in the late 1960's. One of the test programmes considered fatigue loading and its influence on aluminium spray metalized and alkali-zinc silicate coated specimens. It was found that fatigue loads with a stress ratio R of 0.075 do not influence the slip resistance of a connection negatively. Furthermore, aluminium spray metalized specimens even showed higher static slip factors after fatigue loading. For connections with alkali-zinc silicate coating, a constant sustained load (analogous to the extended creep test) was found out to represent the more critical load constellation with regard to the slip factor. Furthermore, the carried out tests with fatigue loads with $R = -1$ showed, that the fatigue strength (and not the slip resistance) of slip-resistant connections represents a decisive parameter for their design.

A very important study regarding the fatigue strength of coated slip-resistant connections was conducted by *Frank/Yura* [116] in 1981. Herein, a correlation between the creep and fatigue behaviour of specimens coated with organic zinc, organic zinc with an epoxy topcoat as well as the inorganic zinc was observed. The tests indicated that the slippage due to fatigue loading can be eliminated by incorporating a creep preformance criterion into the requirements for the execution of slip-resistant connections and by limiting the maximum design load to that observed in long-term creep tests.

Investigations into slip factors for slip-resistant connections with various surface conditions (here: hot dip galvanized or blasted surfaces painted with alkali-zinc-silicate coating) and tested under sustained and/or cyclic loads have been carried out by *Gruintjes/Bouwman* [141]. In these studies, it was determined that the constant load with a specific maximum load level (reference case A, see Figure 3.7) is a much more unfavourable constellation than a combination of a constant load and cyclic load (cases B and C) regarding the behaviour of a slip-resistant connection. Furthermore, a combination of constant load and cyclic load (cases D and E) might even far exceed the slip resistance resulting from the investigations under sustained constant load (reference case A).

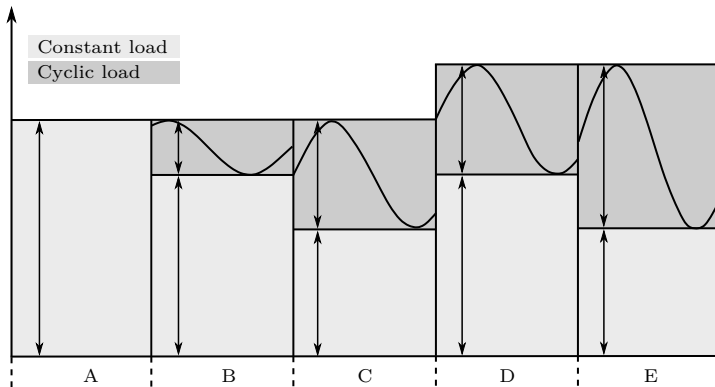


Figure 3.7 Load combinations as investigated by *Gruintjes/Bouwman* according to [141]

The influence of cyclic loading on the load bearing capacity of slip-resistant connections was also investigated by *Valtinat et al.* [142]-[143]. Tests carried out on hot dip galvanized and swept surfaces as well as on hot dip galvanized surfaces painted with alkali-zinc-silicate coating showed higher static slip co-

efficients after cyclic loading and, herewith, confirmed the behaviour reported by *Steinhardt/Möhler*. This behaviour was addressed to the so-called "lock-up effect" of the contact surfaces during cyclic loading. Additionally, a change in the failure behaviour from a "soft" *nonlinear slip deformation* to a "hard" *impact-like slip* was observed. The above mentioned "lock-up effect" and its favourable influence on the slip resistance was also reported in following studies carried out by *Sedlacek/Kammel* [83], *Schaumann/Rutkowski* [144], *Stranghöner et al.* [4] as well as *Ungermann et al.* [145].

As can be seen from the summarized experimental investigations above, the slip-resistant behaviour under cyclic loading and its influence on the assumed slip factor was one of the research objectives since the introduction of slip-resistant connections. On the basis of these investigations, it can be stated, that the current test procedure according to EN 1090-2, Annex G and especially the extended creep test reflect the most critical load constellation in a steel structure. Therefore, experimentally determined slip factors represent the most critical values with regard to potential preload losses as well as the inevitable fatigue loads.

3.3.3 Specifications for consideration of preload losses in bolted connections acc. to EN 1090-2, Annex I and ZTV-ING

The issue concerning preload losses in preloaded bolted connections at the normative level in Germany was first introduced in 1990 in TGL 13510/08 [146] and in MLK-Guideline C1, Annex 1 [147]. In both regulations, it was pointed out that, if more than a primer coat is applied on a bolted connection, the coating system should be checked for its suitability with regard to preload losses. The first guidance (e.g. in MLK-Guideline C1, Annex 1) considering the handling of preloaded bolted connections with coated surfaces originated from initial research activities conducted at the Institute for Steel Construction Leipzig GmbH. Additionally, the test results of systematic investigations into preload losses in preloaded bolted connections with different coating systems carried out by *Katzung et al.* [148]-[150] were implemented in the DSTV-Guideline "Korrosionsschutz von Stahlbauten in atmosphärischen Umgebungsbedingungen durch Beschichtungssysteme" (1999) [72] and subsequently forwarded to the normative regulations in the old German standard for execution of steel structures DIN 18800-7 (since 2002) [44], [129]. Herein, a list of coating systems was provided

with regard to their suitability on contact surfaces of bearing type connections that are preloaded for serviceability reasons ("*planmäßig vorgespannte Scher-/Lochleibungsverbindungen (SLV/ SLVP)*"). The investigations of *Katzung et al.* [148]-[150] and the resulting list of coating systems for their use on contact surfaces of preloaded bolted connections represent a background for the current normative regulations given in EN 1090-2 and ZTV-ING.

EN 1090-2, Clause 8.5 refers to the possibility of preload losses due to relaxation and creep of surface coatings and indicates that these are implicitly considered in the specified tightening methods. EN 1090-2, Annex I supplements this statement by limiting the implicitly covered loss of preload to no more than 10 %. *Thick coatings* or *coatings with particularly creep-prone material* are an exception to this rule. In this case, the possible preload losses shall be assessed and, if necessary, additional measures for their compensation shall be taken. At this point, the above mentioned rules based on the investigations carried out by *Katzung et al.* [148]-[150] and implemented in DSTV-Guideline [72] as well as in DIN 18800-7 [44], [129] are considered. A new informative Annex I of EN 1090-2 (not part of the standard until 2018) provides a list of different coatings/coating systems with associated possible preload losses that may be used as a reference basis to check their suitability in preloaded bolted connections. A similar list of six verified coating systems is also provided by ZTV-ING. A summary of these coatings and coating systems considered in Annex I of EN 1090-2 and ZTV-ING is given in Table 3.6. Furthermore, a test procedure to determine the loss of preload is proposed in cases, when an estimation of preload losses is not possible based on the values in Table 3.6.

The following chapters deal with the historical development of the current normative regulations for consideration of preload losses acc. to EN 1090-2 and ZTV-ING. In addition to a brief introduction into the background investigations carried out by *Katzung et al.* [148]-[150], critical points with regard to the current state of the art are highlighted.

Table 3.6 Potential loss of preload from coatings/coating systems in combination with preloaded contact surfaces according to EN 1090-2 and ZTV-ING

System	Reference		Preload loss	Suitable for			Note
	[55]	[136]		A/D	B/C	E	
Hot dip galvanizing (HDG)	n/a	n/a	≤ 10 %	•	•	•	1), 2)
Alkali metallic zinc silicate primer (ASI)	n/a	685.03	≤ 10 %	•	•	•	1)
One layer 2 pack-EP or -PUR coating with Zn(R)	C3.08	-	≤ 10 %	•	•	•	1)
One layer 2 pack-EP coating with Zn(R) 2K-EP-Zn	C2.07 C3.08 C4.08	687.03 687.04 697.03	≤ 10 %	•		•	1)
Ethyl zinc silicate primer (ESI)	C2.07 C3.08 C4.08	686.03	≤ 10 %	•	•	•	1)
Multilayer 1 pack-PUR coating systems with Zn(R)	C3.09 C4.09 C4.10 C4.11	-	≤ 30 %	•			1)
1K-PUR-system 1K-PUR-Zn GB 1K-PUR-EG ZB 1K-PUR-EG DB	C4.11 C5.07	689.04 689.12... 689.30...	≤ 30 %	•			1)
EP-/PUR-system 2K-EP GB 2K-EP-EG ZB 2K-EP-EG ZB 2K-PUR DB	C5.08	687.03... 687.12... 687.12... 687.30...	≤ 30 %	•			1)
PVC/PVC-combined coatings with any thickness AK- or AY Hydro-coatings with > 120 µm	n/a	-	> 30 %				1)

Systems listed in:

both standards	EN 1090-2, Annex I	ZTV-ING
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1) valid for: six coated surfaces (EN 1090-2, Annex I) / two clamped coated contact surfaces (ZTV-ING)

2) certificate of compliance acc. to EN ISO 1461 required

3.3.3.1 General remarks considering background investigations carried out by *Katzung et al.* [148]-[150]

The aim of the investigations carried out by *Katzung et al.* [148]-[150] was to determine preload losses in bolted connections under consideration of the following variables:

- different coatings/coating systems,
- variation of coating thickness,
- variation of curing time,
- different bolt diameters and various number of bolts in a connection and
- number of contact surfaces.

In [148]-[150], a verification of the suitability of typical coatings with the usual coating layer thicknesses was intended for their application on contact surfaces of the *bearing type connections of category A that are preloaded for serviceability reasons* in steel construction. The main boundary conditions included a constant clamping length ratio of $\Sigma t/d = 2.5$ and tightening of the bolting assemblies by the torque method acc. to DIN 18800-7 (today: modified torque method). The measurement of the preload losses was conducted by length measurement of the calibrated bolts by using an outside micrometer with an accuracy of around $\pm 6 \%$. Figure 3.8 exemplarily shows a two-bolt test specimen used for the investigations by *Katzung et al.* [148]-[150] as well as a several time-loss of preload curves for selected coatings/coating systems.

The investigated variables of the curing time, the size of the connection and the number of bolts showed no significant influence on the loss of preload.

3.3.3.2 Definition of a suitable amount of preload losses in EN 1090-2, Annex I and ZTV-ING

As can be seen from the current regulations in EN 1090-2, Annex I, different coatings and coating systems are generally assigned to one of the following three groups with regard to potential preload losses:

- Loss of preload $\leq 10 \%$: suitable in all preloaded bolted connections,

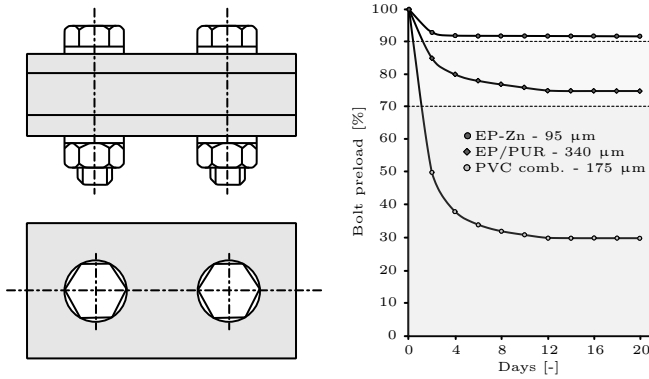


Figure 3.8 Exemplary illustration of a two-bolt test specimen used for investigations carried out by *Katzung et al.* [148]-[149] as well as exemplary time-loss of preload curves for different coatings/coating systems [150]

- loss of preload ≤ 30 %: suitable in preloaded bolted connections of categories A and D (here: target level II of preloading) and
- loss of preload > 30 %: not suitable for components in preloaded bolted connections.

This represents a slight modification of the distinction originally made by *Katzung et al.* [148]-[150] considering the fact that the verification of the suitability of typical coatings was intended for their application on contact surfaces of the bearing type connections that are preloaded for serviceability reasons ("*planmäßig vorgespannte Scher-/Lochleibungsverbindungen (SLV/ SLVP)*") in steel construction:

- Loss of preload ≤ 10 %: suitable in preloaded bearing type connections ("*SLV/ SLVP*") subjected to tension, shear and bearing,
- loss of preload ≤ 30 %: suitable in preloaded bearing type connections ("*SLV/ SLVP*") subjected to shear and bearing and
- loss of preload > 30 %: not suitable in preloaded bearing type connections ("*SLV/ SLVP*").

The idea behind the initial distinction made by *Katzung et al.* [148]-[150] is mainly based on the design format according to DIN 18800-1 (1981-03) [151], in which the design proof was conducted considering the concept of permissible stresses. Other than today, the design verification format for bearing type connections

used to refer to the yield strength and not to the ultimate strength. Considering actual load-displacement diagrams of preloaded and non-preloaded bearing type connections, see Figure 3.9, it was noticed that preloading and the corresponding multiaxial stress state can lead to an increase of the bearing resistance pressure up to the point of the yield strength. This favourable influence was therefore taken into account for bearing type connections (through the bearing resistance pressure) from a preload level of $\geq 0.5 F_V$ (today: $50 \% F_{p,C}^*$). Furthermore, a distinction between non-preloaded and *partly preloaded* bearing type connections was made, where in the latter case a preload level of at least $0.5 F_V$ (or $50 \% F_{p,C}^*$ today) was considered to be necessary for the full effectiveness of the connection. DIN 18800-1 (1990-11) [152] did not contain a preload level of $0.5 F_V$ any more. According to *Katzung et al.* [150] this was due to the state-of-the-art bolting technology, which was no longer associated with more effort in terms of achieving a "full" preload. Furthermore, as noted by *Katzung et al.* [150], a definitive, linear increase of the bearing resistance pressure was observed up to the preload level of $0.5 F_V$ - from there on an increase was rather marginal. From a strictly formal point of view, DIN 18800-1 (1990-11) did not allow any normative advantages for preloaded bearing type connections compared to the non-preloaded bearing type connections anymore.

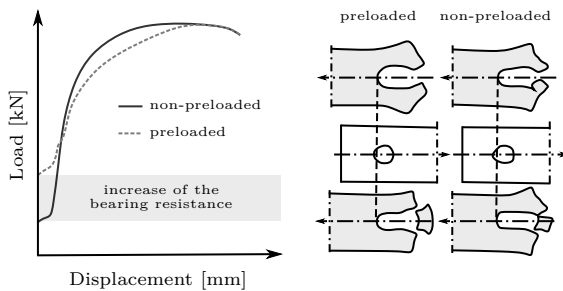


Figure 3.9 Load-displacement diagram of preloaded and non-preloaded bearing type connections with regard to their bearing resistance according to [153]

Based on the explanations above considering the design verification format of DIN 18800-1 (1981-03) [151] with regard to the bearing resistance pressure, *Katzung et al.* [148]-[150] assumed for the carried out distinction that a loss of preload limit of 30% (or a drop to 70% of the initial "full" preload $F_{p,C}^*$) is acceptable for preloaded bearing type connections ("*SLV/ SLVP*") subjected to shear and bearing. It was assumed by *Katzung et al.* [148]-[150] that a loss

of preload of 30 % should not affect the connection in such a way that the effectiveness regarding the increased bearing resistance pressure from a preload level of $\geq 0.5 F_V$ following the regulations in DIN 18800-1 (1981-03) [151] is not fully given. According to *Katzung et al.* [148]-[150], a loss of preload of 30 % was chosen considering the fact that not all influencing variables were investigated in [148]-[149] and, therefore, a higher loss of preload is possible. Furthermore, the test results in [148]-[149] showed high scattering.

In [150], *Katzung et al.* pointed out that preloading prevents the opening of the interfaces of the clamped parts under axial operational loads and considerably reduces the additional bolt force, see also Chapter 2.1. This results in an increase of the fatigue strength of the connection, which can also be assumed for preloaded bearing type connections with an additional external tensile force (here: category A-D according to EN 1993-1-8). The proportion of the additional bolt force is directly dependent on the actual preload level in the connection. For the distinction of permissible preload losses, *Katzung et al.* [148]-[150] assumed that a loss of preload limit of 10 % (or a drop to 90 % of the initial "full" preload $F_{p,C}^*$) is not unusual even for slip-resistant connections and can be assumed as acceptable for the full effectiveness of preloaded bearing type connections subjected to tension, shear and bearing. Therefore, the definition of a loss of preload of max. 10 % was used in order to classify different coating systems with regard to their suitability in preloaded bearing type connections with an additional tensile load.

From today's point of view, it is very important to (once again) distinguish between the two target levels of preloading and to place the requirements that come along with that correctly in order to sensibly characterize an acceptable amount of preload losses.

Connections that are preloaded in order to ensure the structural safety (target level I) rely on the preload level that has been considered during design. Given a formal requirement of a system reserve of 10 % for the specified tightening procedures (EN 1090-2, Annex I), it is sensible to assume that a loss of preload of ≤ 10 % should not pose a risk for the structural safety of preloaded bolted connections of categories B/C and E. A compliance with this regulation shall be mainly ensured by limiting the coating thickness between washers and connected surfaces in slip-resistant connections and a generalized limitation of the coating thickness for preloaded tension connections. The need for a re-tightening after

several days is justifiably pointed out for EN torque method in Annex I of EN 1090-2.

Connections that are preloaded in order to improve the serviceability (target level II) do not rely on a specific preload level, so that from design's point of view, any preload losses can be handled in a much more flexible manner. It is indeed a decision that has to be made between the parties involved in the construction, to which extent the preload losses can be allowed and whether a specific limitation justifies the considerable additional costs that have to be taken into account.

The current design format for the bearing resistance given in EN 1993-1-8 does not match the "yield strength" approach given in the old German standard DIN 18800-1 [151]-[152] and [154]. However, this does not disregard the favourable influence of a certain degree of preloading on the load-displacement behaviour of a bearing type connections as shown in Figure 3.9. Therefore, assuming that design verification formats in EN 1993-1-8 and DIN 18800-1 lead to a comparable degree of utilization of the bearing type connection, a loss of preload of 30 % can still be assumed to represent a suitable limit for the classification of the coating systems in preloaded bolted connections, as Table I.1 of EN 1090-2, Annex I suggests. It has to be made clear, that this limit aims for a *full effectiveness* considering serviceability reasons, but as discussed before, a linear increase of the bearing resistance pressure was observed up to the preload level of $0.5 F_V$ [150] - this is de facto an improvement of the serviceability at any degree of preloading. For this reason, a sharpening of the statements made by EN 1090-2, Annex I should be considered. Current indication stating that coating systems, which lead to a loss of preload of $> 30 \%$, are not suitable for their application in preloaded bolted connections of categories A and D is incorrect and reflects on the regulations in DIN 18800-1 (an increase of the *effectiveness and safety* of the connection through preloading) than in EN 1993-1-8 (an increase of the *effectiveness* of the connection through preloading, safety aspects are already guaranteed by design proofs). As indicated before, a note/comment on the individual assessment of the suitability of preload losses $> 30 \%$ would be helpful in order to avoid any misunderstandings between the parties involved in the construction.

3.3.3.3 General remarks on potential loss of preload acc. to EN 1090-2, Annex I and ZTV-ING

As can be seen from a summary in Table 3.6, indications in EN 1090-2, Annex I together with ZTV-ING can be used for a qualitative assessment of the potential loss of preload for specific coatings/coating systems. In this chapter, the most important points with regard to the assumed potential preload losses in the current normative regulations are discussed.

According to *Schmidt et al.* [20], EN 1090-2, Table I.1 covers only around one third of the coatings that are commonly used in steel construction today. This, of course, can be attributed to the age of the studies on which this table is based and more importantly, to considerable changes in the range of coating materials due to the tightening of permissible solvent emissions by the "VOC regulation" in Germany [76].

The values given in EN 1090-2, Annex I and ZTV-ING were mostly adopted from DIN 18800-7 [129] and are based on relaxation tests carried out by *Katzung et al.* [148]-[150] which do not consider the possibility of external loading. The mere adoption of the values (e.g. for alkali metallic zinc silicate primer) from investigations of *Katzung et al.* [148]-[150] to connections that are intended to be used in fatigue-loaded structures currently has no scientific background. In particular, the compliance with preload losses below 10 % for the given metal coatings and paints should be critically questioned with regard to unavoidable fatigue loads, especially in preloaded tension connections of category E. This should be one of the reasons, why the footnote (b) in Table I.1 points out the *possible necessity* to conduct the structural design with a reduced nominal preload level of $0.9 F_{p,C}$. At this point, it should be mentioned that a maximum of 90 % of the preload value $F_{p,C}^*$ is prescribed for the verification of fatigue resistance of ring flange connections for steel towers according to DIBt-Guideline for wind turbines [155] and a similar approach is integrated in the IEC 61400-6 [156], see Chapter 3.3.4.10, where a verification of fatigue resistance shall be carried out with maximum 90 % of the nominal preload value in cases where the initial preload losses are compensated by a re-tightening step.

Furthermore, the given loss of preload values are based on a preload level of around $F_{p,C}^*$ due to the application of the torque method (now: modified torque method) for the investigations carried out by *Katzung et al.* [148]-[150]. Since EN 1090-2 also deals with other tightening methods such as the combined method,

the HRC method or direct tension indicator (DTI) method, in purely formal terms, the assumed loss of preload values in Table I.1 also apply to them. This should be handled in a particularly critical manner, as the transferability of the preload losses, especially with regard to high initial preload levels in case of the combined method or high surface pressures on the DTI protrusions, is yet to be systematically investigated, among other things for the listed coatings and coating systems. Recent systematic investigations into connections with direct tension indicators carried out at UDE/IML [157]-[159], [94]-[95] showed, that direct tension indicators seem to be particularly unfavorable with regard to preload losses, see exemplary Figure 3.10, so that the transferability at least for this method is to be questioned.

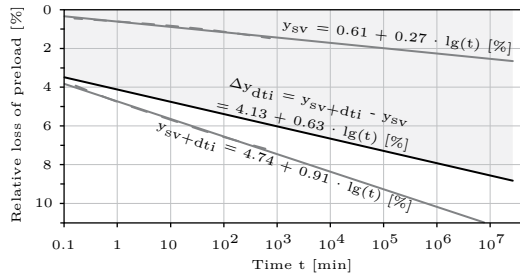


Figure 3.10 Mean relative loss of preload due to direct tension indicator Δy_{dti} , estimated by extrapolation of the regression function according to *Schiborr* [157]

It should also be noted that regulations in EN 1090-2, Annex I and ZTV-ING seem to differ from each other with regard to the number of coated surfaces that may be accepted for the estimation of potential loss of preload. Table I.1 of EN 1090-2 assumes that the given loss of preload values are valid for a total of six coated surfaces including those under the washers. This represents the specimen configuration in the fundamental studies carried out by *Katzung et al.* [148]-[150], see also Figure 3.8. DIN 18800-7 and now ZTV-ING restricted the validity of the given preload losses to cases with *two clamped coated contact surfaces* ("zwei zusammengespannte beschichtete Kontaktflächen").

3.3.3.4 Potential loss of preload for metal coatings and zinc rich primers acc. to EN 1090-2, Annex I and ZTV-ING

Hot dip galvanized (HDG) connections were not part of the investigations carried out by *Katzung et al.* [148]-[150]. In fact, the possible loss of preload for this kind

of metal coating was included for the first time in DIN 18800-7:2008-11 [129] and is currently listed in EN 1090-2, Annex I as a reference value of $\leq 10\%$. In the explanations on DIN 18800-7:2002-09, *Schmidt et al.* [17] assume, that the expected loss of preload in case of typical coating thicknesses (not significantly above $100\text{ }\mu\text{m}$) should not exceed 10% based on the rheological differences of metallic materials and polymers and considering the fact that creep effects shall subside more quickly with zinc coatings than with polymer coatings. Therefore, according to *Schmidt et al.* [17], a similar classification as for ASI or 2 pack-EP (2K-EP) coating with Zn(R) should be given. It seems that the current classification of unpainted hot dip galvanizing strictly relies on this assumption. Interestingly, a guide value considering a loss of preload $\leq 10\%$ for unpainted hot dip galvanized surfaces has been included in the normative regulations neglecting the test results from experimental investigations into preload losses on hot dip galvanized bolted connections preloaded by torque method acc. to DIN 18800-7 (field and laboratory testing) carried out by *Sedlacek and Kammel* [83]-[84] in 2001. Herein, it was shown that unpainted hot dip galvanized connections can lead to preload losses of up to 18% for zinc layer thicknesses of around $200\text{ }\mu\text{m}$ to $250\text{ }\mu\text{m}$. Considering test results reported by *Sedlacek and Kammel* [83]-[84], it is quite obvious that lower preload losses (possibly in a range of $\leq 10\%$ as given in EN 1090-2, Annex I) can only be achieved for zinc layer thicknesses not significantly above the required minimum values according to EN ISO 1461 (usually $\geq 85\text{ }\mu\text{m}$ for steel components with thickness of $> 6\text{ mm}$). This assumption is backed by experimental investigations carried out by *Stranghöner et al.* [159], where preload losses in a range of 7.7% to 11.2% were determined for hot dip galvanized connections with a zinc layer thickness of approx. $70\text{ }\mu\text{m}$. Herewith, an explicit mention of the unpainted HDG surfaces and contact surfaces with ASI primer without specification of the maximum permissible coating thicknesses in Table I.1 of EN 1090-2 may incorrectly suggest that these coatings are suitable in all preloaded bolted connections independent of the actual coating layer thicknesses.

Next to the above mentioned coatings, ZTV-ING also lists ethyl zinc silicate primer (ESI), see Table 3.6, as suitable for application in slip-resistant connections or preloaded tension connections. During experimental investigations carried out by *Katzung et al.* [148]-[150], ESI coating slightly exceeded the 10% loss of preload limit and showed comparable results to those for ASI coating (preload losses of 6% to 10%) with measured preload losses of 12% to 13% [150]

and therefore was recommended for the application in preloaded bearing type connections subjected to shear and bearing according to DIN 18800-7 [129] with a loss of preload $\leq 30\%$. A loss of preload of $\leq 30\%$ was even assumed in the 2019 version of ZTV-ING [160]. Interestingly, the current version of ZTV-ING [135] transferred ESI coating to applications with $\leq 10\%$ loss of preload.

3.3.3.5 Potential loss of preload for multilayer coating systems acc. to EN 1090-2, Annex I and ZTV-ING

The regulations for a multilayer 1 pack-PUR coating systems with Zn(R) reflect on the main purpose of Table I.1 of EN 1090-2; the table does not provide quantitative values for determination of preload losses, but rather serves as a reference basis to check the suitability of the surface coatings. The corresponding coating thicknesses between $160\text{ }\mu\text{m}$ and $260\text{ }\mu\text{m}$ (systems C3.09 and C4.11 according to EN ISO 12944-5 respectively) suggest that higher coating thicknesses may expectedly lead to an increased loss of preload (here: of up to $\leq 30\%$). However, a sensible assessment of possible preload losses with regard to the individual coating thicknesses is not possible.

3.3.3.6 Test procedure to determine loss of preload acc. to EN 1090-2, Annex I

According to Annex I (informative) of EN 1090-2, in cases, where an assessment of preload losses is not possible (e.g. by using Table I.1 of EN 1090-2), an experimental investigation may be undertaken. In this chapter, critical points with regard to the test procedure to determine preload losses of EN 1090-2, Annex I are discussed.

Unlike in the test procedure for determination of the slip factor according to EN 1090-2, Annex G, no significant variables are mentioned in Annex I of EN 1090-2 that may influence the test results and their validity. The following variables could be taken as significant on the test results with regard to preload losses:

- the composition of the coating,
- the surface treatment and treatment of primary layers in case of multi-layer systems,

- the maximum thickness of the coating,
- the curing procedure and the minimum time interval between application of the coating and tightening of the connection,
- the preload level in the connection and
- number and configuration of washers.

It is also important to document not only the test results, as EN 1090-2, Chapter I.2 suggests, but also to make sure that the test specimens are treated in a manner consistent with the intended structural application. Therefore, the actual surface roughness and the dry coating thickness as well as the curing procedure should be documented.

Furthermore, next to the example of the test specimen in EN 1090-2, Annex I, see Figure 3.11, a note should be added which suggests, that the test specimen geometries/configuration and the corresponding surface condition may differ with regard to the intended use in the structure. This should also include the possibility of using other than hot dip galvanized bolting assemblies. More importantly, a tightening of bolting assemblies according to the relevant method (combined method, HRC tightening method etc.) should be prescribed in order to determine the actual system reserves of the connections and the corresponding preload losses. Furthermore, with regard to a high sensitivity of the measurement for the corresponding test results (here: initial preload levels and the subsequent preload losses), it is advisable to prescribe at least the accuracy of the measuring equipment for the bolt preload, as it is the case for slip factor tests acc. to EN 1090-2, Annex G.

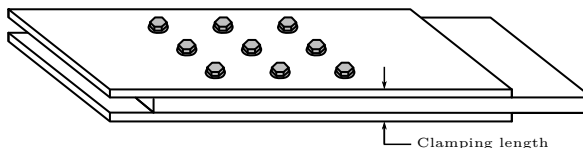


Figure 3.11 Example of a test specimen for determination of preload losses according to EN 1090-2, Annex I [2]

3.3.3.7 Evaluation of test results considering the test procedure to determine preload losses

The evaluation of preload losses based on the test procedure in EN 1090-2, Annex I is currently not adequately defined. In this chapter, the definition of the initial preload value as well as the test duration with subsequent analysis are discussed.

After tightening of the bolts, a considerable drop in the measured preload can be observed. This instant drop is not entirely related to the relaxation behaviour of the preloaded bolted connection as this phenomenon can be mainly explained by turning back of the nut and the elastic recovery of the bolt threads when the wrench is removed, see also *Chesson/Munse* [161]. Furthermore, in a study carried out by *Kloos/Schneider* [162], an instant reduction of the equivalent stress in the bolt of up to 10 % after tightening was detected, where an instant drop of around 50 % of the torsional stress could be determined in several cases. Today, the term "overshoot effect" [163] can be used in order to describe this phenomenon better. Despite the fact that the drop in the preload itself is system-dependent, a significant influence on the evaluation of the loss of preload can be assumed between the maximum peak and the first seconds after tightening, as experimental investigations in [94] and [163] show. Consequently, these recovery losses should not be considered during the evaluation in order to determine the actual initial preload values $F_{p,ini}$ and the corresponding preload losses.

The test procedure according to EN 1090-2, Annex I prescribes an assessment of preload losses based on the measurement carried out "*over a period of at least 30 days*". Experimental investigations into uncoated preloaded bolted connections carried out by *Ba-Saleem* [164] showed that the major preload losses due to setting effects can be attributed to the first 24 hours to 72 hours. According to *Ba-Saleem* [164], preload losses after 72 hours can be assumed to be negligible. According to *Katzung et al.* [148]-[149], the main loss of preload in coated connections occurs within the first few hours after tightening, where a stationary condition of the preload is achieved after six to nine weeks. *Yang/DeWolf* [165]-[166] reported that 90 % of the preload losses in galvanized bolted connections occurred during the first week after the tightening and a nearly stable condition of the clamping force was achieved after around 12 days after the tightening. Furthermore, an *exponential manner* of the loss of preload rate was observed - behaviour that has been reported in numerous

publications e.g. by *Chesson and Munse* [161], *Friede/Lange* [130]-[131], [167], *Sedlacek/Kammel* [83]-[84] and others. Based on the exponential manner of the loss of preload rate, mathematical models have been developed in order to estimate preload losses in bolted connections with coated surfaces (here: galvanizing, inorganic zinc and red lead paint) by *Yang/DeWolf* [168] and later by *Nah et al.* [169]-[170]. However, due to the variety of influencing factors, the developed mathematical models do not guarantee a universal validity for other than investigated specimen configurations. As *Bickford* [171] points out, with regard to many influencing factors that cause and contribute to preload losses as well as a natural distribution of the resulting values, the estimation in most cases must be done by carrying out experimental investigations. For the evaluation of test results and the consideration of the time-dependent behaviour, extrapolation of the test data to the intended service life of the structures has been established by simplifying the behaviour as a logarithmic function, see exemplary Figure 3.12. This approach has been implemented in experimental investigations carried out by *Valtinat/Hadrych* [172] and *Nah et al.* [169]-[170]. Furthermore, an extrapolation to 20 years or more has been conducted in recent studies of *Heistermann and Heistermann/Veljkovic* [173]-[174], *Ebert et al.* [175] and *Fric* [176] as well as in the comprehensive studies in the European research project "SIROCO" [159], [163], [177]-[178].

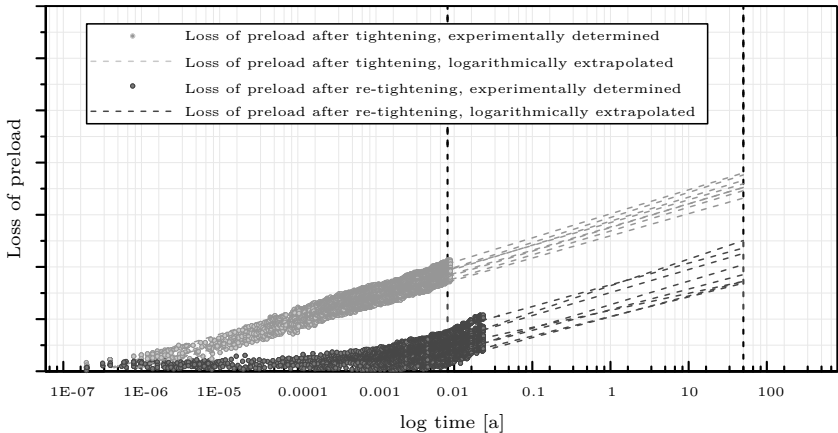


Figure 3.12 Example of a logarithmic extrapolation of experimentally determined preload losses

From the literature review considering investigations carried out by *Katzung et al.* [148]-[149], *Yang/DeWolf* [165]-[166] and others, it becomes clear, that a prescribed test duration of 30 days by EN 1090-2, Annex I is sufficient for determination of the loss of preload even for thick surface coatings. However, shorter test durations are conceivable. Furthermore, the latest systematic investigations indicate that the evaluation of the test results shall be carried out by considering the time-dependent behaviour in form of a logarithmic function and by extrapolating the experimentally determined preload losses to the intended service life of the structure.

3.3.4 Specifications in other international standards

3.3.4.1 General

In the following chapters, a brief overview of the current normative regulations in selected international standards with regard to contact and faying surfaces of preloaded bolted connections during design and execution is given. It is intended to highlight that analogous to regulations given in EN 1090-2, the friction surfaces of slip-resistant connections are sufficiently addressed in different international standards. However, the regulations for corrosion protection on contact surfaces (under the bolt head, nut or washers) as well as the handling of inevitable preload losses are very limited and represent a knowledge gap.

3.3.4.2 RCSC Specification for Structural Joints using High-Strength Bolts

RCSC Specification for Structural Joints using High-Strength Bolts [49] notes that faying surfaces of snug-tightened and preloaded bolted connections are permitted to be uncoated, coated with coatings of any formulation or galvanized. Just like in EN 1090-2, RCSC [49] notes that attention should be paid to specification and application of thick coatings within the faying surface, and on ply surfaces under the bolt head and under the nut or washer, as a significant loss of preload due to compressive creep may be unavoidable. It is also pointed out that galvanized faying surfaces with a thickness of around 100 μm (4 mils) might even consist half of compressible soft pure zinc surface layer, which has a particularly high susceptibility to creep. As expected, additional reduction in preload losses may result from higher coating thicknesses (here: 15 mils) and especially from coatings between washers and connected surfaces.

For slip-resistant connections either uncoated, clean surfaces or coated faying surfaces after blast cleaning shall be used. Here, class A coatings with a slip factor μ of at least 0.3 (also applies to unpainted clean mill scale or hot dip galvanizing) or surfaces of class B with $\mu = 0.5$, but not greater (applies to blast-cleaned steel surfaces or class B coatings) can be assumed. In several parts of the specification, reference is also made to the prevention of an overspray. Based on the investigations of *Polyzois/Frank* [179], special areas of faying surfaces around bolts were defined that have to remain uncoated with unqualified coatings, see Figure 3.13, but also free of an overspray, as this would expectedly lead to a reduction of the slip resistance. Importantly, RCSC Specification notes that in case of galvanized connections with many plies of thick metal coating, preload losses may be significant and "*re-pretensioning*" of the bolting assemblies may be required.

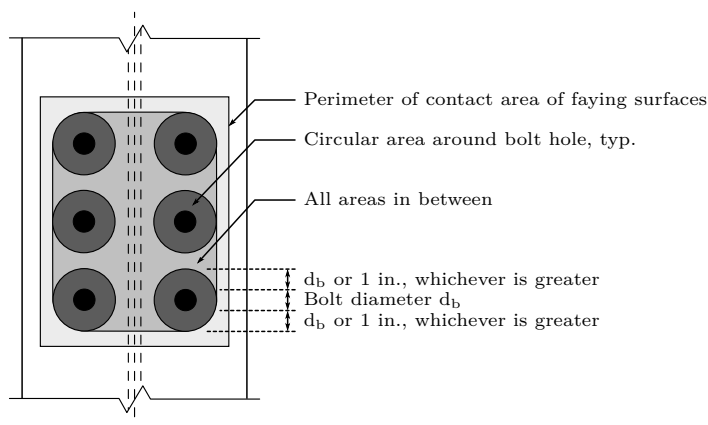


Figure 3.13 Areas of faying surfaces of slip-resistant connections to remain uncoated with unqualified coatings according to RCSC Specification [49]

If no class of the intended surface treatment for slip-resistant connections can be assumed, the mean slip factor can be established by testing according to Annex A. Developed by *Yura/Frank* in 1985 [180], this test procedure consists of two steps. Next to five static short-term tests (carried out either under compression or tension loading) also three creep tests shall be performed on tension-type specimens. Since the latter must be carried out under constant load for 1000 hours and the relative slip displacement measured on either side of the

specimens of less than 0.381 mm (0.015 in.) must be achieved, a sufficient design with regard to preload losses (relaxation in the bolting assembly, but also the effect of the coating itself) is guaranteed.

3.3.4.3 AS/NZS 5131 and AS 4100

Australian/New Zealand Standard AS/NZS 5131 [181] notes that the preparation of contact surfaces of a preloaded bolted connection shall generally avoid any interferences (such as oil, dirt etc.) that could prevent solid seating of the parts in snug-tight condition. Any applied finish for corrosion protection is permissible, except for slip-resistant connections. Here, masking of the bearing surfaces under bolt heads and nuts is generally required. A primer of no more than 125 μm of inorganic zinc silicates, zinc rich epoxy or zinc phosphate can be used around bolted connections. In these cases, masking should be applied for subsequent coats.

According to AS 4100 [182], a slip factor μ of 0.35 can be assumed for clean "as-rolled" surfaces. In case of any other surface finish (paint, galvanizing etc.), a slip factor test must be performed in accordance with the procedure specified in Annex J of AS 4100 (same as in Annex G of AS/NZS 5131). Here, the long-term creep behaviour of the connection is taken into account by applying the external load in increments and by ensuring that the creep at constant load due to the preceding load increment has effectively been ceased. This has to be performed up to the sudden slip or a load corresponding to a slip of 0.13 mm. AS/NZS 5131 even provides three different methods in order to determine the slip factor. In addition to the same procedure as given in AS 4100, also the Specification for Structural Joints using High-Strength Bolts [49] by RCSC or EN 1090-2, Annex G can be used. This flexible regulation corresponds to the reference made by AS 4100, which notes that slip factors for common surface conditions are included in EN 1090-2. Additionally, regulation in AS/NZS 2312 [183] shall be mentioned, which include a list of possible surface treatments for faying surfaces that may have a "*satisfactory coefficient of friction for mating*". This includes the common surface treatments of EN 1090-2 such as inorganic zinc silicate, thermal spraying with zinc or aluminium and finally, grit blasting.

3.3.4.4 IS 800 and IS 4000

The Indian Standard for General Construction in Steel IS 800 [184] provides twelve typical average slip factors for different surface conditions. Next to the uncoated surfaces or surfaces treated with abrasives, also zinc ($\mu = 0.25$) or aluminium ($\mu = 0.50$) spray metallized surfaces and alkali-zinc silicate ($\mu = 0.30$) as well as ethyl-zinc silicate ($\mu = 0.30$) paints on grit or shot blasted surfaces are considered. Here, the required coating thicknesses lie in the range between $30 \mu\text{m}$ - $60 \mu\text{m}$ and $60 \mu\text{m}$ - $80 \mu\text{m}$. Other treatments or especially paints are excluded from their use in slip-resistant connections, as contact surfaces in friction type connection shall not be painted in advance.

Analogous to regulations in other international standards, a coat of primer after cleaning of the surfaces is mandatory in order to protect the connections against corrosion. IS 800 gives guidance for protection of the steelwork for different desired service lives and, interestingly, divides the specified coating systems into "shop applied treatments" and "site applied treatments". Here, it becomes clear, that the selection of coating systems for site application is very limited. This once again emphasizes the importance of shop application for bolted connections, as IS 800 also prescribes that inaccessible surfaces after shop assembly *"shall receive the full specified protective treatment before assembly"*. If painting is considered to be carried out after erection, IS 800 very importantly notes that contact surfaces shall receive a coat of paint and then shall be brought together while the paint is still wet. This, of course, represents a counteractive measure in order to minimize the possible preload losses in bolted connections after preloading.

Another Indian Standard IS 4000 [185] mirrors the normative regulations from AS 4100 and AS/NZS 5131 and provides a slip factor μ of 0.35 for "as-rolled" clean surfaces. The specifications for standard test for evaluation of slip factor for cases, where it cannot be assumed, are exactly the same.

3.3.4.5 SANS 10162-1

South African National Standard SANS 10162-1 [121] points to an adequate protection against corrosion, where the thickness of material used, the severity of the conditions to which the structure will be exposed and the ease of subsequent inspection and maintenance shall be considered. However, SANS 10094 [186] refers to an application of a priming paint only after installation of bolts and

the corresponding inspection. The application of a primer refers to the edges of the joint, lines of contact between the joined components as well as the nuts, bolt heads etc. Additional sealing in cases of severely corrosive conditions might be necessary after the final tightening.

For design and execution of slip-resistant connections, certain preparation of faying surfaces with corresponding mean slip factors are provided by SANS 10162-1. Following the 1985 edition of RCSC Specification [187], class A (clean mill scale or blast-cleaned with class A coatings) and class B (blast-cleaned or blast-cleaned with class B coatings) and class C (hot dip galvanized wire brushed or blast cleaned) surfaces with mean slip factors of at least 0.33, 0.50 and 0.40 respectively are given. Here, the slip factors for class A and class C surfaces remained the same, despite the changes made in the 1994 edition of the RCSC Specification [188] (reduction of the value to 0.35 for class C for better agreement with the research carried out by *Kulak et al.* [114]) or the later reduction to 0.30 (current value in the RCSC Specification for the former classes A and C combined).

If the slip factor cannot be assumed, a determination can be carried out by the test procedure defined in SANS 10094, Annex A, which mirrors the test procedure developed by *Yura/Frank* [180] and currently given in the RCSC Specification for Structural Joints using High-Strength Bolts [49].

3.3.4.6 CSA S16-09

The Canadian Standard for Design of Steel Structures S16-09 [122] provides slip factors for surfaces of classes A, B and C - the same values as listed in SANS 10162-1 and originally anchored in the RCSC Specification. In case of all other coatings/surface preparation, tests to determine the mean slip coefficient are necessary. The test procedure corresponds to the approach in the current RCSC Specification [49].

According to this standard, steelwork shall generally have sufficient corrosion protection. If bearing type connections are preloaded, surfaces of Class A (clean mill scale or blast-cleaned with class A coatings) or better are generally required.

3.3.4.7 JASS 6

The Japanese Architectural Standard Specification JASS 6 [113] highlights the treatment of friction surfaces, which shall be made by removing mill scale, but keeping the surfaces open to the air so that red rust is spontaneously generated or by shot or grit blasting in order to achieve roughness values of not less than 50 μm . Floating mill scale shall be removed in all cases. This shall ensure a slip coefficient of ≥ 0.45 . Friction surfaces can also be galvanized and subsequently lightly blasted. For this, a surface roughness of not less than 50 μm shall be ensured.

According to the Standard Specifications for Steel and Composite Structures by Japan Society of Civil Engineers [189], different slip coefficients for various conditions such as inorganic zinc-rich paint ($\mu = 0.4$ to 0.5 depending on the coating thickness), rough surfaces $\mu = 0.25$ to 0.45 depending on the actual roughness of the surface) etc. can be assumed without testing. If one of the above mentioned treatments is not intended for an application, the determination of the slip coefficient or slip force must be carried out experimentally.

A special section in JASS 6 [113] dealing with anticorrosive paint provides a selection of possible anticorrosive paint on steel surfaces or galvanized steel surfaces. Very importantly, this section underlines that friction surfaces of high strength bolted connections and surfaces in contact after assembly shall generally not be painted. In cases, where paint is necessary, Special Notes provided by JASS 6 shall be taken into account.

3.3.4.8 GB 50017

The Chinese Code for Design of Steel Structures GB 50017 [190] provides slip factors mainly for uncoated, cleaned surfaces and for surfaces, coated with inorganic zinc paint after blast-cleaning. Interestingly, the slip factors are given dependent on the steel grade of connected parts. GB 50017 also addresses the possibility of preloading of a high-strength bolt in bearing-type joint connections.

For other surfaces of slip-resistant connections, a test procedure in GB/T 34478 [191] must be conducted in order to determine the corresponding slip factor.

3.3.4.9 VDI 2230-1

Based on the investigations of *Wiegand et al.* [192], the DDR-Standard for fatigue strength of bolted connections TGL 38512 [193] at first and currently VDI-Guideline 2230-1 provide guide values for amounts of embedding for contact surfaces in the threads, bearing areas and inner interfaces made of steel, but without coatings.

This allows an accurate consideration of the preload losses for design in mechanical engineering. The values for amounts of embedding f_Z correspond to the plastic deformation of the surface and are primarily dependent on the type of loading, the number and the corresponding roughness of the faying surfaces. The calculation of the loss of preload F_Z resulting from embedment f_Z is carried out by Equation (3.4):

$$F_Z = \frac{f_Z}{(\delta_S + \delta_P)} \quad (3.4)$$

where δ_S and δ_P are the elastic resiliences of the bolt and the clamped parts respectively. These parameters have been described in Figure 2.1. This calculation represents an approach that has been established in mechanical engineering for many years and, above all, can be used for individualized design. However, as mentioned above, this only applies to clamped parts without coatings. Currently, no generalized guide values for amounts of embedding for coated surfaces can be assumed.

3.3.4.10 IEC 61400-6

Some requirements considering preloaded bolted connections for towers and their foundation are incorporated in the first edition of International Standard IEC 61400-6 [156]. Herein, a verification of fatigue resistance of ring flange connections includes a generalized consideration of preload losses by limiting the maximum applicable design preload value to 90 % $F_{p,C}$ (here: $F_{p,C}$ represents a bolt preload given in the relevant design code or technical approval) provided that the initial preload losses are compensated by a re-tightening step after 240 hours, but not later than after six months. If this is not the case, the design must be carried out considering even a lower design preload of 70 % $F_{p,C}$.

For bolted connections resisting shear by friction, it is noted that the actual bolt preload shall exceed the preload force assumptions made during design

considering the intended service life. The minimum requirements for slip-resistant connections designed without test involve an inspection of the remaining preload force and a possible compensation of preload losses by re-tightening within the first six months after installation.

A more flexible design is offered by Clause 6.8.2 "*Test-assisted design*" of IEC 61400-6. According to this chapter, a "maintenance-free connection" can be achieved by ensuring that (1) the friction utilization at maximum fatigue loads does not exceed the friction utilization at maximum applied loads in the test and (2) the design value of the slip-resistant connection is calculated according to the Equation (3.5):

$$F_{s,Rd} = \frac{n \cdot \mu}{\gamma_M} \cdot F_{p,C} \cdot L_f \quad (3.5)$$

As can be seen from Equation (3.5), the number of the friction surfaces n , the slip factor μ , a partial factor for materials γ_M (recommended value is 1.25) and the nominal preloading force $F_{p,C}$ de facto do not differ from the current regulations in EN 1993-1-8. However, the introduction of the coefficient for the loss of preload L_f represents an interesting approach from a normative point of view, where the factor itself has to be either determined by testing of representative samples or an appropriate measurement campaign on the friction connections shall be conducted in order to validate the assumed value of L_f in the design phase. Some investigations considering laboratory and field measurements on slip-resistant connections were performed by Dörre *et al.* and are presented in [194].

Although this procedure/approach shows promising potential, especially with regard to a flexible design, the exact determination of the slip factor in combination with the coefficient for the loss of preload L_f during evaluation of the test results are unclear, since the corresponding slip factor changes continuously during the test, as described in Chapter 3.3.2 and and illustrated in Figure 3.6 for the extended creep tests. Similar behaviour can be expected for connections subjected to fatigue loading.

3.3.5 Literature review with regard to preload losses

3.3.5.1 General

As already mentioned in Chapter 2.5.2, an extensive knowledge on the possible preload losses during the service life of a structure is vital in order to preserve the necessary preload level. Since normative regulations on the estimation and handling of preload losses are very limited, as Chapters 3.3.3 and 3.3.4 show, experimental investigations into preload losses are inevitable. Especially the relaxation tests (no consideration of external loads) under consideration of different surface treatments have been established for the estimation of preload losses. In the following chapters, a brief literature review with regard to experimentally determined preload losses for the most common surface treatments is given. This overview intends to show a rough scale of potential preload losses that can be expected for unpainted, metallized and painted connections. Furthermore, a high variation of preload losses depending on influencing factors such as the type of surface treatment or the coating thickness is highlighted. Analogous to the current normative regulations in Table I.1 of EN 1090-2, Annex I, see explanations in Chapter 3.3.3.3, the potential preload losses are given without consideration of the actual preload level at the beginning of the respective test and the applied tightening method.

3.3.5.2 Uncoated

In general, steel surfaces are subjected to corrosion and should therefore be protected in order to avoid the damage during the intended service life of the structure. An exception to this rule applies only to structures with a short service life of up to one year and/or structures exposed to environment with negligible corrosivity. However, with regard to preloaded bolted connections, uncoated surfaces might be necessary in order to comply with the normative regulations in EN 1090-2 and simultaneously to avoid an increased amount of preload losses, see explanations in Chapter 3.3.1. A summary of potential preload losses found in literature for uncoated connections, as a possible result of e.g. surface masking, is given in Table 3.7.

As can be seen from test results reported by *Nah et al.* [169], *Katzung et al.* [150], *Isele et al.* [196], *Ebert et al.* [178], *Friede* [131] or *Stranghöner et al.* [159], the potential loss of preload of no more than 10 % that is supposed to be

Table 3.7 Summary of potential preload losses for uncoated surfaces based on selected experimental investigations

Reference	Surface condition	Bolt	Clamping length ratio [-]	Loss of preload [%]
<i>Duchardt</i> [195]	tempered steel 42CrMo4	23MnB4 8.8	≈ 3.1	6 - 8
<i>Yang/DeWolf</i> [165]	clean mill scale	ASTM A325 M22	≈ 3.8	5.6
<i>Nah et al.</i> [169]	clean mill scale	TCB M20 10.9	≈ 2.5	2.03
	rust			2.91
	shot blast			1.70
<i>Nah et al.</i> [169]	clean mill scale	ASTM A490 M20	≈ 2.5	13.6
	rust			7.90
	shot blast			10.5
<i>Chesson/Munse</i> ¹⁾ [161]	rust, wire brushed	ASTM A325	≈ 2.0	1.6 - 5.1
<i>Katzung et al.</i> [150]	blasted to Sa 2 ^{1/2}	HV M16 10.9	≈ 2.5	10.0
		HV M24 10.9		3.0
<i>Isele et al.</i> [196]	blasted to Sa 2 ^{1/2}	ISO 4017 M16 12.9	≈ 3.0	3.2
<i>Heistermann</i> [173]	grit blasted to Sa 2 ^{1/2}	TCB M30 10.9	≈ 1.9	4.8
<i>Ebert et al.</i> [178]	grit blasted to Sa 2 ^{1/2}	HV M20 10.9	≈ 2.5	8.6 - 10.8
		Lockbolt M20 10.9		6.2 - 7.6
<i>Friede</i> [131]	blasted to Sa 2 ^{1/2}	HV M20 10.9	≈ 2.5	3 - 10
		HV M20 10.9	2.6	6.2 - 7.7
			4.6	6.1 - 7.3
<i>Stranghöner et al.</i> [159]	as received	HV M16 10.9	2.8	6.7 - 9.4
			4.7	6.7 - 8.4

Given results of preload losses refer to the room temperature. Furthermore, potential preload losses are given without consideration of the actual preload level at the beginning of the respective test and the applied tightening method.

1) Preload losses refer to the "one minute load" and do not consider the drop from the maximum load of around 5 % on average.

implicitly considered in the tightening methods according to EN 1090-2, seems to be already used up for most of the uncoated surfaces.

3.3.5.3 Metal coating

As mentioned in Chapters 2.4.4 and 2.4.5, metal coatings by thermal spraying or galvanizing can be used in order to protect metal surfaces against corrosion and to achieve a specific slip factor at the same time. Furthermore, even higher corrosion protection due to the favourable synergistic effect can be achieved by application of duplex systems - a combination of metal coating with subsequent layer of paint. A summary of potential preload losses for metallized surfaces is given in Table 3.8.

As already noted in Chapter 3.3.3.4, the potential preload losses for hot dip galvanized surfaces are very dependent on the actual zinc layer thickness. The

Table 3.8 Summary of potential preload losses for metallized surfaces based on selected experimental investigations

Reference	Surface condition	Coating thickness [μm]	Bolt	Clamping length ratio [-]	Loss of preload [%]
<i>Yang/DeWolf</i> [165]	HDG	132	ASTM A325 M22	≈ 3.8	12.4
		323			15.3
		409			19.6
		500			19.9
<i>Sedlacek/Kammel</i> [83]	HDG	200 - 250	HV M30 10.9	≈ 3.3	14.3 - 18.4
	+ swept + ASI	190 - 290			13.8 - 15.7
	+ ASI	210 - 260			9.0 - 15.5
<i>Stranghöner et al.</i> [159]	HDG	70	HV M20 10.9	2.4	7.7 - 11.2
	+ swept	50			9.3 - 10.8
	+ ASI	170			20.0 - 21.2
	+ ESI	140			13.4 - 17.4

Given results of preload losses refer to the room temperature. Furthermore, potential preload losses are given without consideration of the actual preload level at the beginning of the respective test and the applied tightening method.

Abbreviations:

HDG: hot dip galvanized | ASI: alkali-zinc-silicate | ESI: ethyl-zinc-silicate

investigations carried out by *Sedlacek/Kammel* [83] and *Yang/DeWolf* [165] show that preload losses of up to $\approx 20\%$ can be determined even for unpainted hot dip galvanized surfaces. Herewith, a potential loss of preload of $\leq 10\%$, as given in EN 1090-2, Annex I for unpainted hot dip galvanized surfaces, is clearly exceeded. Investigations into preload losses carried out by *Stranghöner et al.* [159] show that lower preload losses in a range of $\approx 10\%$ can be achieved only by limiting the maximum zinc layer thicknesses in a connection.

3.3.5.4 Painted

As described in Chapter 2.4.1, next to the metal coatings by thermal spraying or galvanizing, also protective paint systems in accordance with EN ISO 12944 series can be applied for corrosion protection of bolted connections. The selection of the actual coating system is dependent on the required performance of the corrosion protection, however, usually multiple protective paint systems can be suitable in order to fulfil the corrosion protection requirements. This leads to a wide range of coatings and coating systems that are currently available in the market, for which the estimation of potential preload losses is very limited. Tables 3.9 and 3.10 intend to give a brief overview of potential preload losses found in literature for connections with different protective paint systems.

Table 3.9 Summary of potential preload losses for painted surfaces based on selected experimental investigations

Reference	Surface condition	Coating thickness [µm]	Bolt	Clamping length ratio [-]	Loss of preload [%]
<i>Nah et al.</i> [169]	red lead paint inorganic zinc	65 128	TCB M20 10.9	≈ 2.5	4.71 8.37
<i>Nah et al.</i> [169]	red lead paint inorganic zinc	125 96	ASTM A490 M20	≈ 2.5	18.7 15.0
<i>Sedlacek/Kammel</i> [83]	ASI	20 - 50	HV M30 10.9	≈ 3.3	12.7 - 14.2
<i>Katzung et al.</i> [150]	ASI	99 102	HV M16 10.9 HV M24 10.9	≈ 2.5	10.0 6.0
<i>Fric</i> [176]	ESI	60 - 80 51 - 76 53 - 95	HV M20 10.9	≈ 1.3 ≈ 2.2 ≈ 3.2	13.0 - 17.0 10.4 - 12.3 11.5 - 14.3
<i>Katzung et al.</i> [150]	ESI (1K)	122 135	HV M16 10.9 HV M24 10.9	≈ 2.5	17.0 9.0
<i>Katzung et al.</i> [150]	ESI (2K)	120 148	HV M16 10.9 HV M24 10.9	≈ 2.5	13.0 12.0
<i>Heistermann</i> [173]	ESI	50 - 80	TCB M30 10.9	≈ 1.9	8.8 10.5
<i>Isele et al.</i> [196]	EP	120	ISO 4017 M16 12.9	≈ 3.0	3.7
<i>Katzung et al.</i> [150]	2K-EP-Zn	95 97	HV M16 10.9 HV M24 10.9	≈ 2.5	8.0 10.0
<i>Friede</i> [131]	2K-EP-Zn 2K-EP-EG	150	HV M20 10.9	≈ 2.5	8 - 10
<i>Isele et al.</i> [196]	EP EP	240	ISO 4017 M16 12.9	≈ 3.0	6.1
<i>Isele et al.</i> [196]	EP PUR	240	ISO 4017 M16 12.9	≈ 3.0	6.2
<i>Friede</i> [131]	2K-EP-Zn 2K-EP-EG 2K-AY-PUR	230	HV M20 10.9	≈ 2.5	9 - 12
<i>Isele et al.</i> [196]	EP EP PUR	320	ISO 4017 M16 12.9	≈ 3.0	9.0
<i>Katzung et al.</i> ¹⁾ [148], [150]	2K-EP-Zn 2 × 2K-EP-EG 1K-AY-PUR	337 346	HV M16 10.9 HV M24 10.9	≈ 2.5	2.0 1.0 22.0 12.0
<i>Katzung et al.</i> [150]	2K-EP-ZnPh	83 84	HV M16 10.9 HV M24 10.9	≈ 2.5	18.0 4.0
<i>Katzung et al.</i> [150]	2K-EP-ZnPh 2 × 2K-EP-EG 1K-AY-PUR	347 334	HV M16 10.9 HV M24 10.9	≈ 2.5	14.0 20.0

Given results of preload losses refer to the room temperature. Furthermore, potential preload losses are given without consideration of the actual preload level at the beginning of the respective test and the applied tightening method.

¹⁾ Values in black correspond to preload losses after tightening as given in [148]. Values in grey are given in [150] and correspond to combined mean values after tightening and re-tightening based on results in [148].

Abbreviations:

1K: one-pack | 2K: two-pack | ASI: alkali-zinc-silicate | ESI: ethyl-zinc-silicate
EP: epoxy based paint | EP-Zn: epoxy based zinc rich paint
EP-ZnPh: epoxy based zinc phosphate pigmented paint
EG: micaceous iron oxide | PUR: polyurethane paint | AY-PUR: acrylic polyurethane paint
AK: alkyd paint | HS: high solid (low solvent)

Table 3.10 Summary of potential preload losses for painted surfaces based on selected experimental investigations (continued from Table 3.9)

Reference	Surface condition	Coating thickness [μm]	Bolt	Clamping length ratio [-]	Loss of preload [%]
<i>Katzung et al.</i> [150]	2K-EP-HS	181 173	HV M16 10.9 HV M24 10.9	≈ 2.5	16.0 8.0
<i>Katzung et al.</i> [150]	2K-EP-Hydro-ZnPh 2 × 2K-EP-Hydro-EG 2K-PUR-Hydro	384 367	HV M16 10.9 HV M24 10.9	≈ 2.5	28.0 17.0
<i>Katzung et al.</i> [150]	1K-PUR-Zn	113 121	HV M16 10.9 HV M24 10.9	≈ 2.5	11.0 13.0
<i>Katzung et al.</i> [150]	1K-PUR-Zn 1K-PUR 2 × 1K-PUR-EG	323 326	HV M16 10.9 HV M24 10.9	≈ 2.5	25.0 16.0
<i>Friede</i> [131]	1K-AK	80 160	HV M20 10.9	≈ 2.5	10 - 29 74 - 91
<i>Katzung et al.</i> ¹⁾ [148], [150]	AK-ZnPh	87 92	HV M16 10.9 HV M24 10.9	≈ 2.5	14.0 12.0 24.0 17.0
<i>Katzung et al.</i> ¹⁾ [148], [150]	AK-ZnPh AK-EG	184 205	HV M16 10.9 HV M24 10.9	≈ 2.5	31.0 21.0 52.0 34.0
<i>Katzung et al.</i> ¹⁾ [148], [150]	AY-Hydro-ZnPh	88 98	HV M16 10.9 HV M24 10.9	≈ 2.5	15.0 14.0 27.0 17.0
<i>Katzung et al.</i> ¹⁾ [148], [150]	AY-Hydro-ZnPh AY-Hydro-EG	199 172	HV M16 10.9 HV M24 10.9	≈ 2.5	69.0 45.0 38.0 25.0
<i>Katzung et al.</i> ¹⁾ [148], [150]	EPE-Zn	130 232	HV M16 10.9 HV M24 10.9	≈ 2.5	6.0 4.0 19.0 13.0
<i>Katzung et al.</i> ¹⁾ [148], [150]	EPE-Zn 2 × PVC-AY-EG	289 284	HV M16 10.9 HV M24 10.9	≈ 2.5	71.0 49.0 69.0 48.0
<i>Katzung et al.</i> ¹⁾ [148], [150]	PVC-AK-ZnPh	90 92	HV M16 10.9 HV M24 10.9	≈ 2.5	33.0 24.0 30.0 21.0
<i>Katzung et al.</i> ¹⁾ [148], [150]	PVC-AK-ZnPh 2 × PVC-AY	289 284	HV M16 10.9 HV M24 10.9	≈ 2.5	79.0 59.0 91.0 71.0

Given results of preload losses refer to the room temperature. Furthermore, potential preload losses are given without consideration of the actual preload level at the beginning of the respective test and the applied tightening method.

¹⁾ Values in black correspond to preload losses after tightening as given in [148]. Values in grey are given in [150] and correspond to combined mean values after tightening and re-tightening based on results in [148].

Abbreviations:

1K: one-pack | 2K: two-pack | ASI: alkali-zinc-silicate | ESI: ethyl-zinc-silicate
 EP: epoxy based paint | EP-Zn: epoxy based zinc rich paint | EPE: epoxy ester primer
 EP-ZnPh: epoxy based zinc phosphate pigmented paint | EG: micaceous iron oxide
 PUR: polyurethane paint | AY: acrylic paint | AY-PUR: acrylic polyurethane paint
 AK: alkyd paint | PVC: polyvinyl chloride | HS: high solid (low solvent)

As can be seen from Tables 3.9 and 3.10, the test results for most of the investigated protective paint systems were part of systematic investigations into preload losses carried out by *Katzung et al.* [148]-[150]. As expected, experimentally determined preload losses show a high variation depending on the type of coating material, number of coating layers as well as the coating thickness. While preload losses for different single layer coatings such as ASI, ESI or 2K-EP-Zn, see investigations carried out by *Sedlacek/Kammel* [83], *Katzung et al.* [148]-[150], *Heistermann* [173] etc., may remain within 10 % or 15 %, especially an increase of the coating thickness or the use of particularly creep prone materials such as PVC-AK or PVC-AY expectedly leads to preload losses of 30 % and more.

A generalized classification of preload losses for some of the common coating systems, as provided by *Katzung et al.* [148]-[150] and partly incorporated in the normative regulations, currently represent the only qualitative recommendations with regard to design and execution of steel structures. However, the range of coating materials has changed considerably in the last years, e.g. due to new rules regarding permissible solvent emissions. The increasing number of new coating materials that have emerged into the market makes it necessary to review their suitability in preloaded bolted connections. Furthermore, currently scientifically validated reference values for preload losses in bolted connections with coated surfaces apply only to a small number of coating systems and cover only a small range of the typical systems used in practice.

Herein, e.g. the listed multilayer 1K-PUR coating systems or systems containing epoxy ester (EPE) primer as well as alkyd paint (AK) are currently used only very sporadically. Systematic investigations into preload losses considering the multitude of coating systems commonly used in steel hall and bridge construction as well as in onshore and offshore wind energy are therefore necessary.

3.4 Summary and conclusions

The performance and the durability of a preloaded bolted connection is mainly dependent on the selection of a suitable corrosion protection and the initiation of a sufficient preload level. As summarized in Chapter 3, a huge amount of the normative regulations considering the handling of preload losses seem to be more reactive and concentrate on rectifying the discrepancies that emerge

from the lack of systematic studies instead of taking proactive measures during design and execution. Considering the normative regulations as well as the experimental investigations with regard to design and execution of preloaded bolted connections presented in this chapter, the following main questions for further development can be identified.

Tightening of bolting assemblies using the modified torque method and combined method

- 1) How high are the actual initial preload values and the resulting system reserves?
- 2) Can prescribed characteristic values of preload be safely achieved by the modified torque method and what reliability can be offered?
- 3) Can a system reserve of at least 10 % (as targeted by EN 1090-2) be met?
- 4) What initial preload values can be achieved after re-tightening using modified torque method?
- 5) Can different tightening tools/coatings and coating systems/clamping length ratios etc. affect the initial preload values?

Preload losses for preloaded tension connections and connections preloaded for serviceability reasons

- 1) Is the required system reserve of 10 % enough to cover preload losses due to loosening (among other things including cyclic loading) for category E connections?
- 2) How high are the expected preload losses for contact surfaces that comply with the coating thickness limitations given in EN 1090-2 and how much overtightening is needed to ensure the required preload level over the service life of the structure?
- 3) How high are the preload losses due to loosening for typical coating systems in steel construction?
- 4) Is there a possibility to reasonably separate the preload losses in bolted connections considering influencing factors such as clamping length ratio

or the common number of faying surfaces for a practical use in steel construction?

- 5) What is the influence on preload losses in case of an overspray (e.g. $2 \times \text{NDFT}$ or $3 \times \text{NDFT}$)?
- 6) Do different tightening methods affect the amount of preload losses in an extent that needs to be considered during design?
- 7) What influence does a re-tightening using modified torque method have on preload losses?

Slip-resistant connections considering the practical application in steel construction

- 1) What influence does an increase in coating thickness of the common faying surfaces have on the slip resistance?
- 2) How do different preload levels (and the natural scattering of the achieved preload values) after the tightening affect the slip resistance in compared to the prescribed preload level $F_{p,C} \pm 5\%$ according to the test procedure of EN 1090-2, Annex G?
- 3) Is a pre-damage of the slip resistance to be expected due to cyclic loading for common surface configurations including a coating or a coating system between washers and connected surfaces?

In pursuit of answers to these questions, systematic investigations have been carried out and are presented in the following chapters.

4 System reserves and preload losses for common applications in steel structures

4.1 General

As described in Chapter 3.3, the corrosion protection on contact surfaces of preloaded bolted connections should be selected in such a way that an unacceptable loss of preload is avoided. Here, connections of categories B/C and E according to EN 1993-1-8 [1] are subjected to strict limitations regarding the coating layer thicknesses on contact surfaces. In practice, this is mainly achieved by using only a priming coat and/or by surface masking underneath the washers.

The normative regulations in EN 1090-2 [2] for bolted connections that are preloaded for serviceability reasons offer more flexibility on how to deal with the corrosion protection with regard to the possible preload losses. However, in order to achieve the maximum improvement in serviceability, preload losses should be kept within certain limits, so that a suitable coating system should be selected wisely.

In the following chapters, systematic investigations into system reserves and preload losses under consideration of different tightening methods and coating systems are presented. Herein, the focus lies within "reference connections" that comply with the limitations for corrosion protection on contact surfaces as provided by EN 1090-2 and are suitable for their application e.g. in towers of wind turbines, bridge constructions etc. Furthermore, connections coated on all surfaces of the connection by using coating systems that are commonly applied e.g. in steel hall construction are investigated.

4.2 Reference connections for fatigue loaded applications in steel structures

4.2.1 General

A comprehensive experimental investigation into preload losses was carried out in the frame of the IGF research project No. 18711 BG "Development of a concept to assess the loss of preload in preloaded bolted connections under fatigue loading" [4] carried out at the Institute for Metal and Lightweight Structures (IML) of the University of Duisburg-Essen (UDE) (project coordinator) and Fraunhofer Institute for Large Structures in Production Engineering IGP in Rostock. Herein, relaxation tests as well as tests under cyclic loading on specimens with different clamping length ratios, tightening methods and surface treatments were carried out, see Figures 4.1 and 4.2.

Next to the reference of grit blasted surfaces, two further surface treatments consisting of zinc spray metallizing and a two-component epoxy primer with zinc phosphate pigmentation were selected:

- GB: grit blasted (GH 40, particle size: $0.42\ \mu\text{m}$ to $1.0\ \mu\text{m}$), Sa $2^{1/2}$, measured average surface roughness $R_{\text{v}5} = 93.7\ \mu\text{m}$,
- ZnSM: grit blasted (Sa 3) + zinc spray metallized (faying surfaces only) with Zn 99.99 according to EN ISO 14919 [197], measured average coating thickness $79.7\ \mu\text{m}$ DFT,
- 2K-EP-ZnPh: grit blasted (Sa $2^{1/2}$) + zinc phosphate primer on faying surfaces (fabric no. 687.06 according to TL/TP-ING [136]), measured average coating thickness $87.6\ \mu\text{m}$ DFT.

As mentioned before, all three surface treatments comply with the limitations for corrosion protection on contact surfaces as required by EN 1090-2.

Tightening of the test specimens was carried out using the combined method and the modified torque method for M20 HV bolting assemblies (EN 14399-4 [29]/EN 14399-6 [31]) in accordance with the specifications given in EN 1090-2 and DAST-Guideline 024. Hereby, a re-tightening was carried out after approx. three days after the initial tightening with the modified torque method. This procedure is described by the meanwhile replaced National Annex of EN 1993-1-8 (2010-12) [45] as well as the German standard DIN 18800-7 [129] and represents the common practical approach. Herein, two different tightening torques were used:

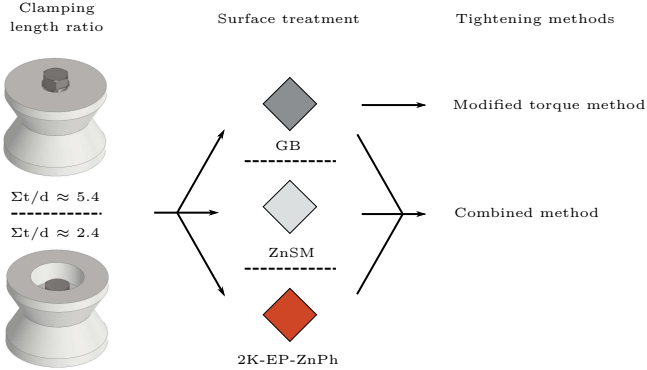


Figure 4.1 Configurations of the test specimens

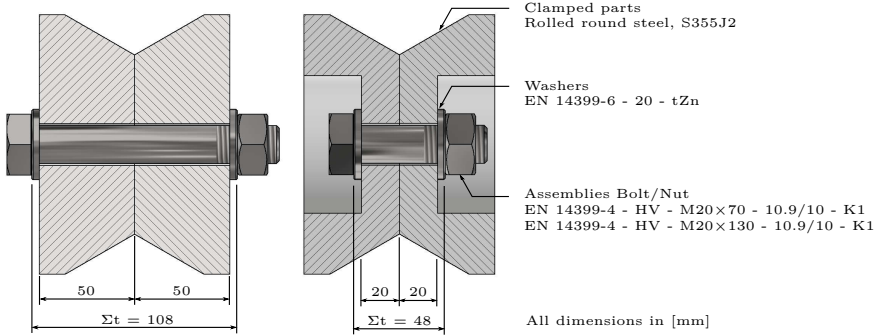


Figure 4.2 Clamped packages of the test specimens used for relaxation tests and tests with cyclic loading

the standard torque of $1.0 M_A$ and a torque used for control measures of $1.1 M_A$, with $M_A = 450 \text{ Nm}$. The preload was continuously measured using bolts with implanted strain gauges (DMS) BTM-6C of Tokyo Measuring Instruments Laboratory Co., Ltd. during and after tightening of the test specimens.

Figure 4.3 shows the experimental approach of the conducted investigations. The test duration of the relaxation tests varied between three days (main preload losses $\Delta F_{p, \text{setting}}$ occurred) and nearly 14 months. After the relaxation tests, the same specimens were tested under cyclic loading in order to determine the loss of preload $\Delta F_{p, \text{cycl}}$, see test setup in Figure 4.4. The cyclic tests were carried out with a stress ratio of $R = 0.1$ up to 2×10^6 load cycles. Finally, the experimentally determined preload losses $\Delta F_{p, \text{setting}}$ and $\Delta F_{p, \text{cycl}}$ were logarithmically

extrapolated to the selected service life for common steel structures of 50 years and 2×10^9 load cycles respectively.

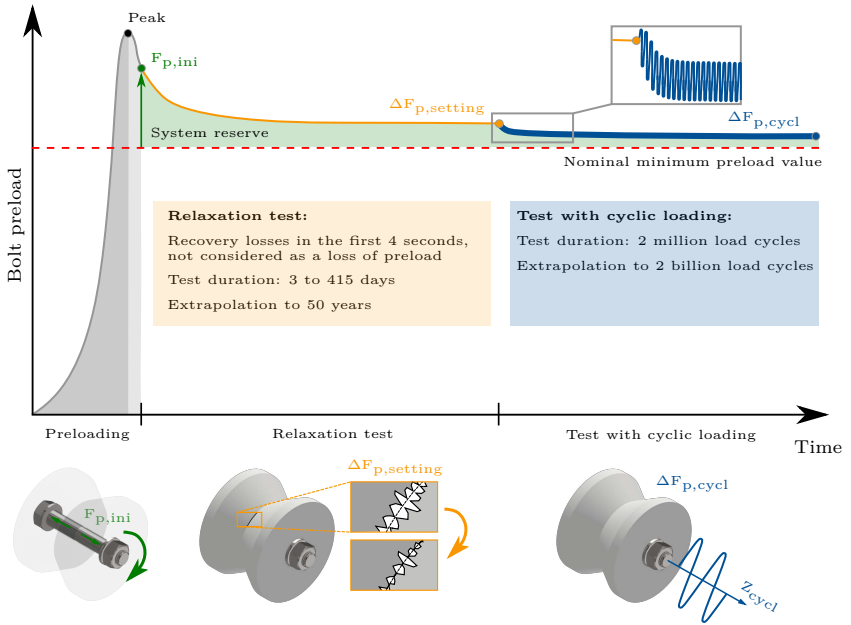


Figure 4.3 Experimental approach for the conducted investigation into preload losses in terms of IGF research project No. 18711 BG

For tests with cyclic loading, load levels between 70 % Z_{crit} and 100 % Z_{crit} were applied, with Z_{crit} describing the critical external load at which an opening of the clamped parts (partly) occurs. In order to calculate Z_{crit} for each connection, the actual load-bearing behaviour of the investigated specimen configurations were determined in static tests. In general, the load-bearing behaviour of an axially loaded preloaded bolted connection can be divided into three areas:

- linear area up to the partial opening at the edges of the concentrically clamped parts,
- nonlinear area caused by system changes in form of a continuous progressive opening of the clamped parts up to the point where the interfaces are completely separated and
- linear area with behaviour of a non-preloaded connection.

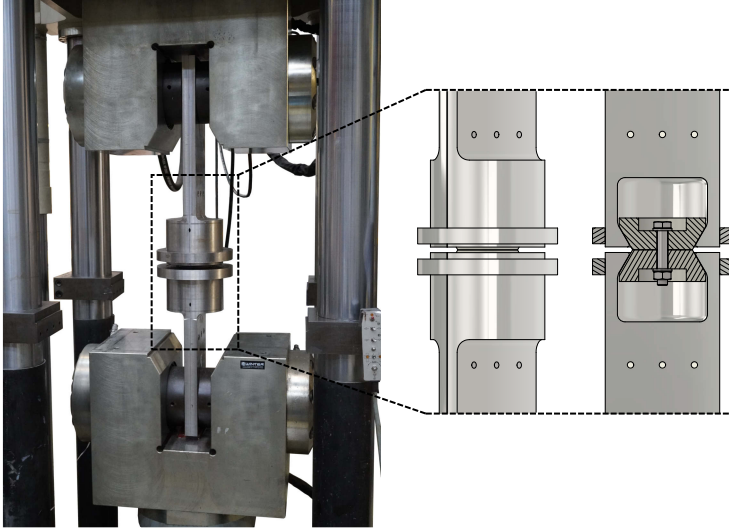


Figure 4.4 Test setup during tests with cyclic loading

In these investigations, the critical load Z_{crit} has not been characterized as the point where the clamped parts are completely separated, since the aim of the tests was to determine preload losses and not the fatigue resistance of the bolt itself. Consequently, the critical load Z_{crit} was based on an analytically assumed load, which considers the actual transition from nonlinear to linear behaviour of the bolt force, as can be seen in Figure 4.5.

Based on the test results of static tests conducted in [4], a generalized load factor Φ of 0.02 was assumed (for more information see [4]). The load factor Φ (acc. to VDI 2230-1 [10]) represents the quotient of the additional bolt load F_{SA} and the axial working load component F_A in the working state, see Figure 2.2. In the frame of this investigation, a generalized load factor Φ enabled an individual determination of the critical load Z_{crit} for each connection, considering the actual preload level at the start of the test:

$$Z_{crit} = \frac{1}{1 - \Phi} \cdot F_{p,start} \approx 1.02 F_{p,start} \text{ [kN]} \quad (4.1)$$

All tests presented within this thesis were carried out at the Institute for Metal and Lightweight Structures (IML) of the University of Duisburg-Essen (UDE). Further tests (with focus on slip-resistant connections) were carried out at the

Fraunhofer Institute for Large Structures in Production Engineering IGP in Rostock and are presented in [4].

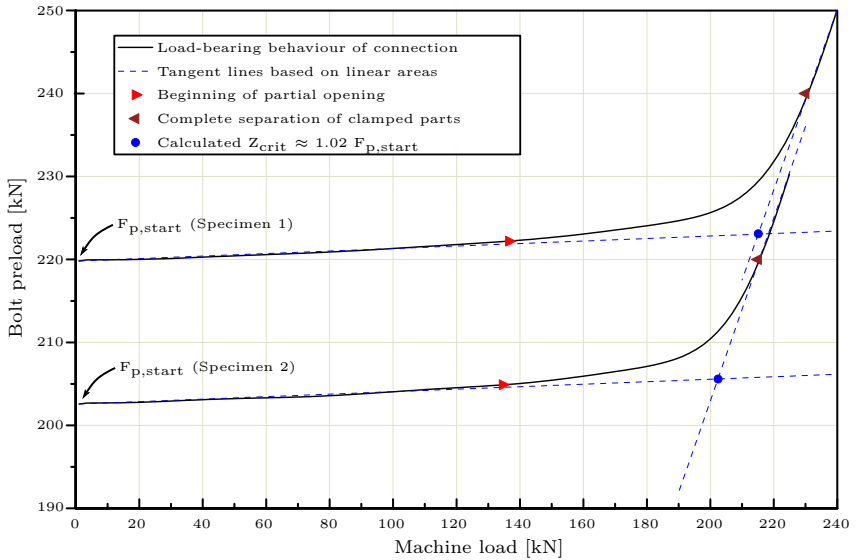


Figure 4.5 Exemplary illustration of the load-bearing behaviour of two concentrically clamped and concentrically loaded test specimens as well as determination of the critical load Z_{crit} [4]

4.2.2 System reserves after tightening

After tightening of bolting assemblies, a considerable drop of the bolt preload can be observed. This can be addressed to the so-called overshoot effect, as described in Chapter 3.3.3.7. Since the drop itself is system-dependent and the tightening has been carried out using the tightening torque testing machine of the Institute for Metal and Lightweight Structures of University of Duisburg-Essen (maximum torque: 15000 Nm and maximum bolt force: 1800 kN), main recovery losses in the first four seconds after achieving the peak value were detected and therefore not considered as loss of preload.

The experimentally determined initial preload levels $F_{p,ini}$ for the modified torque method (MDV) and combined method (KV) are summarized in Table 4.1. Since the HV bolting assemblies for the presented test series contained washers under the rotating nut, the results in Table 4.1 are additionally combined and

presented independent of the actual clamping length ratio (here: MDV) or surface treatment (here: KV) for the complete test series.

Table 4.1 Summary of achieved initial preload levels and system reserves achieved in the IGF research project No. 18711 BG [4]

Tight. method	$\Sigma t/d$ [-]	Surface condition	No. [-]	Phase	Preload level $F_{p,ini}$			$V_{F_{p,ini}}$ [-]	$\gamma_{mean}^{1)}$ [%]
					min [kN]	max [kN]	mean [kN]		
MDV	≈ 5.4	GB	10	in. tight.	149.5	189.2	168.7	0.06	5.4
			5	re. 1.0 M_A	160.8	169.9	166.1	0.02	3.8
			5	re. 1.1 M_A	155.3	199.7	174.1	0.09	8.8
MDV	≈ 2.4	GB	11	in. tight.	162.1	190.1	175.3	0.06	9.6
			5	re. 1.0 M_A	159.1	187.2	172.1	0.06	7.6
			6	re. 1.1 M_A	164.4	196.4	181.2	0.06	13.3
MDV	combined		21	in. tight.	149.5	190.1	172.1	0.06	7.6
			10	re. 1.0 M_A	159.1	187.2	169.1	0.05	5.7
			11	re. 1.1 M_A	155.3	199.7	177.9	0.08	11.2
KV	≈ 5.4 ≈ 2.4	GB	7	tight.	220.8	228.8	224.6	0.01	30.6
			8		227.5	237.2	231.4	0.01	34.5
KV	≈ 5.4 ≈ 2.4	ZnSM	6	tight.	218.1	223.1	220.7	0.01	28.3
			8		205.1	235.7	227.1	0.04	32.0
KV	≈ 5.4 ≈ 2.4	2K-EP-ZnPh	6	tight.	214.4	225.6	219.6	0.02	27.7
			7		222.5	233.0	228.0	0.02	32.6
KV	≈ 5.4 ≈ 2.4	combined	19	tight.	214.4	228.8	221.8	0.02	28.9
			23		205.1	237.2	228.9	0.03	33.1

1) System reserves are based on the nominal minimum preloading force $F_{p,C} = 172$ kN (KV) and $F_{p,C}^* = 160$ kN (MDV) for M20 HV bolting assemblies.

Abbreviations:

MDV: modified torque method | KV: combined method

Modified torque method

As Table 4.1 suggests, the required nominal preload value $F_{p,C}^*$ of 160 kN (M20 HV bolting assemblies) was achieved considering the mean initial preload level $F_{p,ini,mean}$. As expected, procedure-related tightening of bolting assemblies leads to natural fluctuations in the achieved preload values and therefore in the resulting system reserves. Here, the coefficients of variation $V_{F_{p,ini}}$ varied between 2 % and 9 % depending on the test series, where an undercutting of the required preload level $F_{p,C}^*$ was observed only in 1 out of 21 cases after tightening despite the unfavourable scattering of the actual bolt preload for

M20 HV bolting assemblies of k-class K1 using the modified torque method, see Figure 2.6 in Chapter 2.3.3.1.

In comparison to the initial tightening step of the modified torque method, approx. 2 % lower initial preload values $F_{p,ini,mean}$ were determined after re-tightening using the same tightening torque of 1.0 M_A . This can mainly be attributed to the altered frictional resistance after tightening of the connections. On the other hand, a re-tightening using 1.1 M_A expectedly leads to approx. 3 % higher initial preload values compared to the initial tightening.

Considering system reserves, calculated according to Equation (4.2), the modified torque method fails to meet the required 10 % value acc. to EN 1090-2 with an experimentally determined system reserve Υ_{mean} of only 7.6 %.

$$\Upsilon_{mean} = \left(\frac{F_{p,ini,mean}}{F_{p,C*}} - 1 \right) \cdot 100 [\%] \quad (4.2)$$

A re-tightening using 1.0 M_A and 1.1 M_A leads to a system reserve Υ_{mean} of 5.7 % and 11.2 % respectively. The latter suggests that a torque used for control measures might even increase the initial preload value. However, a generalized use of this tightening torque for the purpose of compensation of preload losses is not recommended, since an overtightening of bolting assemblies might not be excluded.

Combined method

As expected, the combined method provides a significant exceedance of the required nominal preload value $F_{p,C}$ of 172 kN (M20 HV bolting assemblies) and therefore offers remarkable system reserves Υ_{mean} for potential preload losses averaging 29 % to 33 % depending on the clamping length ratio. Herewith, the 10 %-demand of EN 1090-2 is clearly fulfilled. In comparison to purely grit blasted test specimens, no significant influence on the achieved preload levels could be determined due to zinc spray metallizing or the epoxy primer (both applied on the faying surfaces). As expected, the tightening into an overelastic range leads to a comparatively low scattering of the individual preload values with coefficients of variation $V_{F_{p,ini}}$ of up to 4 %.

First insights into the reliability of the tightening methods

Table 4.2 summarizes the achieved average initial preload values $F_{p,ini,mean}$ and the corresponding 5 % characteristic values $F_{p,ini,0.05}$, see Equation (4.3).

$$F_{p,ini,0.05} = F_{p,ini,mean} \cdot (1 - k_n \cdot V_{F_{p,ini}}) \text{ [kN]} \quad (4.3)$$

where k_n is a coefficient for the determination of the characteristic 5 % value acc. to EN 1990, Annex D and $V_{F_{p,ini}}$ is the coefficient of variation.

Here, it can be seen that the actual characteristic values achieved by the modified torque method fall short by approx. 4 % to 5 % with regard to the necessary preload level of $F_{p,C}^*$, see system reserves/deficits $\Upsilon_{0.05}$ acc. to Equation (4.4) in Table 4.2. In case of the combined method, a significant exceedance of the required preload $F_{p,C}$ by approx. 25 % can be expected.

$$\Upsilon_{0.05} = \left(\frac{F_{p,ini,0.05}}{F_{p,C}^*} - 1 \right) \cdot 100 \text{ [%]} \quad (4.4)$$

The presented results in Table 4.2 allow only a first insight into possible system reserves, as a meaningful statistical evaluation proves to be difficult due to a comparatively low number of test specimens and a partly high scattering of the test results.

Table 4.2 Achieved average initial preload values and corresponding 5 % fractile values

Tight. method	$\Sigma t/d$ [-]	Surface condition	No. [-]	Phase	$F_{p,ini,mean}$ [kN]	$V_{F_{p,ini}}$ [-]	$k_n^{1)}$ [-]	$F_{p,ini,0.05}^{2)}$ [kN]	$\Upsilon_{0.05}^{3)}$ [%]
MDV	combined		21	in. tight.	172.1	0.06	1.76	153.7	-3.9
			10	re. 1.0 M_A	169.1	0.05	1.92	153.5	-4.1
			11	re. 1.1 M_A	177.9	0.08	1.92	151.9	-5.1
KV	≈ 5.4	combined	19	tight.	221.8	0.02	1.76	214.7	24.8
	≈ 2.4		23		228.9	0.03	1.92	218.0	26.7

1) Coefficient according to EN 1990, Annex D [97] for determination of characteristic 5 % values.

2) Characteristic 5 % value in accordance with $X_{k(n)}$ in EN 1990, Annex D [97].

3) System reserves/deficits are based on the nominal preloading force $F_{p,C} = 172 \text{ kN}$ (KV) and $F_{p,C}^* = 160 \text{ kN}$ (MDV) for M20 HV bolting assemblies considering the characteristic value $F_{p,ini,0.05}$.

Abbreviations:

MDV: modified torque method | KV: combined method

4.2.3 Preload losses

Relaxation tests

Experimentally determined and logarithmically extrapolated preload losses to 50 years $\Delta F_{p,setting,50a}$ for both tightening methods and three different surface treatments are summarized in Table 4.3.

Table 4.3 Summary of extrapolated preload losses $\Delta F_{p,setting,50a}$ determined in the IGF research project No. 18711 BG [4]

Tight. method	$\Sigma t/d$ [-]	Surface condition	No. [-]	Phase	Preload losses $\Delta F_{p,setting,50a}$ ¹⁾			
					min [%]	max [%]	mean [%]	V_X [-]
MDV	≈ 5.4	GB	10	in. tight.	3.7	11.4	7.1	0.36
			5	re. 1.0 M _A	2.9	11.7	6.8	0.50
			5	re. 1.1 M _A	1.9	6.5	3.9	0.44
MDV	≈ 2.4	GB	11	in. tight.	4.9	12.3	7.4	0.27
			5	re. 1.0 M _A	1.1	5.0	3.0	0.50
			6	re. 1.1 M _A	5.1	9.6	7.0	0.23
KV	≈ 5.4 ≈ 2.4	GB	7	tight.	5.5	15.8	10.1	0.45
			8		6.8	13.4	9.7	0.22
KV	≈ 5.4 ≈ 2.4	ZnSM	5	tight.	8.7	11.6	9.9	0.12
			8		12.6	16.4	14.5	0.08
KV	≈ 5.4 ≈ 2.4	2K-EP-ZnPh	6	tight.	6.1	13.3	9.3	0.29
			7		9.1	17.2	11.0	0.26

¹⁾ Calculated considering the respective initial preload value $F_{p,ini}$.

Abbreviations:

MDV: modified torque method | KV: combined method

The mean preload losses $\Delta F_{p,setting,50a,mean}$ for grit blasted compounds varied between 7 % and 10 % after the initial tightening using both, the modified torque method and the combined method respectively. In case of the MDV, it can be mentioned that re-tightening of grit blasted connections only led to partly lower experimental preload losses $\Delta F_{p,setting,50a,mean}$ in comparison to those without re-tightening, although the interpretation proves to be difficult due to a low number of tests ($n = 10$ and $n = 11$ after the initial tightening / $n = 5$ and $n = 6$ after the re-tightening) and a high scattering with a coefficient of variation V_X (here: $X = \Delta F_{p,setting,50a}$) of up to 50 %.

Very similar preload losses $\Delta F_{p,setting,50a,mean}$ of approx. 10 % were observed for zinc spray metallized connections and specimens with epoxy primer (both $\Sigma t/d$

≈ 5.4) tightened by the combined method. This can be mainly attributed to the fact that no coating was applied on the contact surfaces beneath the washers with the associated high surfaces pressures. Furthermore, due to the load distribution in the test specimen, the coated faying surfaces with comparatively low coating thicknesses of around $80 \mu\text{m}$ are only subjected to a fraction of the surface pressures beneath the washers. With the exception of grit blasted test specimens, a tendency to higher preload losses $\Delta F_{p, \text{setting}, 50\text{a}, \text{mean}}$ was observed for specimens with a lower clamping length ratio of $\Sigma t/d \approx 2.4$. Herein, higher pressures on the faying surfaces (will be further discussed in Chapter 4.3.4.3.5) lead to average preload losses of 14.5 % and 11.0 % for connections with ZnSM and 2K-EP-ZnPh surface treatments respectively and therefore to an increase of approx. 5 % and 2 % in comparison to preload losses determined for test specimens with $\Sigma t/d \approx 5.4$. An exemplary illustration of experimentally determined preload losses is given in Figure 4.6 for the combined method (KV).

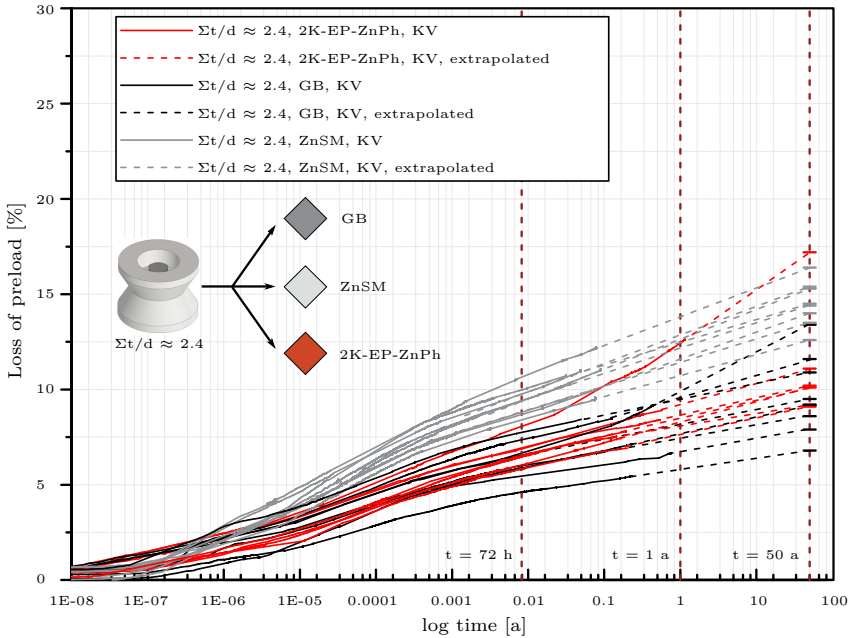


Figure 4.6 Exemplary test results of relaxation tests for specimens tightened by the combined method [4]

Considering some of the boundary conditions for the relaxation tests as well as the determined preload losses, first conclusions can be drawn as followed:

- the assumption of negligible preload losses after 72 hours, as noted by *Ba-Saleem* [164], see Chapter 3.3.3.7, cannot be confirmed even for uncoated test specimens. In this investigation, around 60 % of the total estimated preload losses occurred within the first 72 hours,
- a sufficiently accurate extrapolation of preload losses is mostly possible after 72 hours. After this period of time, the regression line does not change significantly any more, see Figure 4.6,
- considering the fact that an increase of preload losses can be measured even after one year, see Figure 4.6, an estimation of preload losses by logarithmic extrapolation seems to be reasonable,
- compared to the initial tightening by the modified torque method (without re-tightening), only partly lower preload losses were determined after a re-tightening using 1.0 M_A or 1.1 M_A . However, a meaningful interpretation is difficult due to the low number of tests and the high scattering of the test results,
- in comparison with the results of the test specimens tightened by the modified torque method, slightly higher preload losses $\Delta F_{p, \text{setting}, 50a, \text{mean}}$ in a range of up to 3 % were determined for specimens tightened by the combined method (here: grit blasted surfaces),
- compared to purely grit blasted connections, additionally applied coatings on faying surfaces (ZnSM and 2K-EP-ZnPh) notably affected the amount of preload losses only in case of test specimens with a lower clamping length ratio of $\Sigma t/d \approx 2.4$,
- a required system reserve of 10 % acc. to EN 1090-2 that is intended to implicitly cover preload losses, is completely depleted considering grit blasted connections. An exceedance of a system reserve of 10 % can be expected for metallized bolted connections or connections consisting of a priming coat. This corresponds well to other values given in literature considering experimentally determined preload losses for uncoated surfaces, see Table 3.7 in Chapter 3.3.5.2.

Tests with cyclic loading

The results of tests with cyclic loading are summarized in Table 4.4. As expected, preload losses due to cyclic loading $\Delta F_{p,cycl}$ mainly occur within the first load cycles, see Figure 4.7. Furthermore, connections with $\Sigma t/d \approx 5.4$ even showed preload losses that in most cases remained in the range of measurement error and therefore can be rated as negligible despite the load level of 100 % Z_{crit} . Here, extrapolated preload losses $\Delta F_{p,cycl,2E9}$ varied between 0.3 % (ZnSM, KV) and 1.8 % (GB, KV).

Table 4.4 Summary of experimentally determined preload losses at 2 million load cycles $\Delta F_{p,cycl,2E6}$ as well as extrapolated preload losses to 2 billion load cycles $\Delta F_{p,cycl,2E9}$ [4]

Tight. method	$\Sigma t/d$ [-]	Surface condition	$F_{p,start}$ [kN]	Load Z_{crit}	Z_{max} [kN]	Preload losses $\Delta F_{p,cycl}$ ¹⁾	
						$\Delta F_{p,cycl,2E6}$ [%]	$\Delta F_{p,cycl,2E9}$ [%]
MDV	≈ 5.4	GB	163.7	100 %	167.0	1.1	1.5
			163.3	90 %	150.0	0.8	1.0
			161.6	90 %	148.0	1.0	1.4
MDV	≈ 2.4	GB	187.2	90 %	171.8	3.9	4.0
			164.9	70 %	117.7	1.6	2.1
KV	≈ 5.4	GB	207.8	100 %	212.0	1.4	1.8
			202.8	90 %	186.0	0.8	1.1
			205.7	90 %	185.0	0.3	0.4
KV	≈ 2.4	GB	211.8	90 %	194.0	4.7 ²⁾	5.7
			218.2	70 %	155.8	1.6 ³⁾	2.2
KV	≈ 5.4	ZnSM	207.5	90 %	191.0	0.1	0.3
			206.3	90 %	190.0	0.2	0.4
KV	≈ 2.4	ZnSM	204.4	90 %	187.0	3.5	4.8
			206.1	70 %	148.0	1.3	1.9
KV	≈ 5.4	2K-EP-ZnPh	201.8	100 %	206.0	0.5	0.6
			201.7	90 %	185.0	0.3	0.4
KV	≈ 2.4	2K-EP-ZnPh	211.9	70 %	151.2	0.6	0.7

1) Calculated considering the respective preload value at the start of each test $F_{p,start}$.

2) Testing machine-induced termination of the test at 822.160 cycles.

3) Testing machine-induced termination of the test at 915.700 cycles.

Abbreviations:

MDV: modified torque method | KV: combined method

A similar order of preload losses $\Delta F_{p,cycl,2E9}$ was determined for connections with $\Sigma t/d \approx 2.4$ loaded up to 70 % Z_{crit} where the resulting extrapolated values varied between 0.7 % and 2.2 %. Slightly higher preload losses $\Delta F_{p,cycl,2E9}$ in

the range between 4.0 % and 5.7 % were observed for connections with $\Sigma t/d \approx 2.4$ exposed to cyclic loading with a maximum of 90 % Z_{crit} . As can be seen in Figure 4.7, most of these preload losses occurred within the first cycles and therefore can be mainly attributed to minor plastic deformations in the area beneath the washers caused by additional stresses that are introduced by external cyclic loading. Unfortunately, no particular determination of the impact of different surface treatments is possible, since the applied axial cyclic loading decompressed the faying surfaces of the investigated connections (which were partially zinc spray metallized and coated with an epoxy primer).

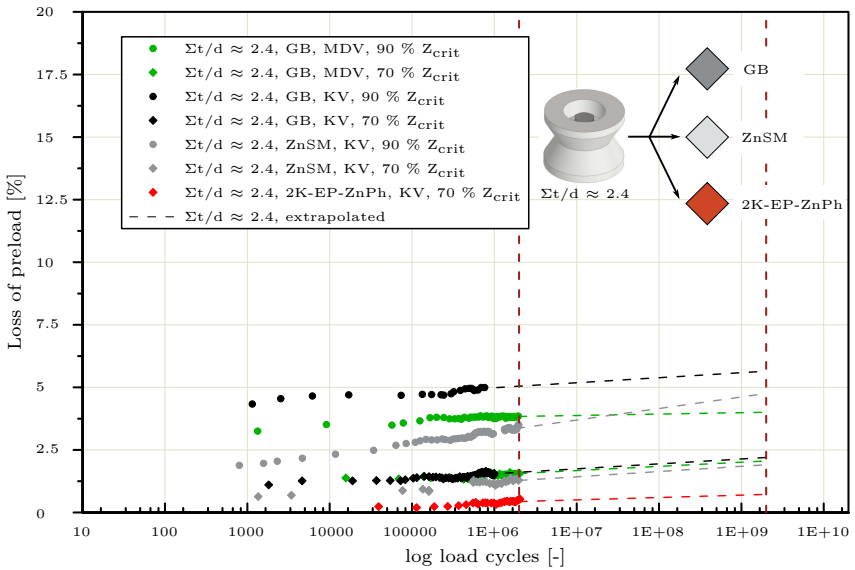


Figure 4.7 Exemplary test results of tests under cyclic loading for specimens with $\Sigma t/d \approx 2.4$ [4]

In all investigated configurations, extrapolated preload losses due to cyclic loading seem to be uncritical despite the unfavourable boundary conditions such as a comparatively low load factor or a partly high utilization of the connection due to high cyclic loading. The latter can be meaningfully compared to the permissible design tension resistance of the bolted connection, which can be expressed as:

$$F_{t,Rd} = \frac{k_2 \cdot f_{ub} \cdot A_s}{\gamma_{M2}} \cdot \frac{0.7}{0.7} = \frac{k_2 \cdot \boxed{0.7 \cdot f_{ub} \cdot A_s}}{0.7 \cdot \gamma_{M2}} = \frac{k_2 \cdot \boxed{F_{p,C}}}{0.7 \cdot \gamma_{M2}} \quad (4.5)$$

Considering that the factor k_2 is 0.9 for hexagonal bolts and the partial factor for resistance γ_{M2} is 1.25, Equation (4.5) can be further expressed as:

$$F_{t,Rd} = \frac{0.9 \cdot F_{p,C}}{0.7 \cdot 1.25} \approx 1.03 F_{p,C} \quad (4.6)$$

The conversion of the permissible design tension resistance $F_{t,Rd}$ to $\approx 1.03 F_{p,C}$ serves as a comparative value and can be used for the estimation of the utilization rate of the maximum applied cyclic load Z_{max} in a cyclic test, see Equation (4.7).

$$X [\%] F_{t,Rd} = \frac{Z_{max}}{1.03 \cdot F_{p,C}} \cdot 100 \quad (4.7)$$

Herewith, the maximum applied cyclic load Z_{max} in this investigation varied between 94 % $F_{t,Rd}$ ($Z_{max} = 167.0$ kN) and 120 % $F_{t,Rd}$ ($Z_{max} = 212.0$ kN) for connections with $\Sigma t/d \approx 5.4$ tightened by the modified torque method and combined method respectively. For connections with $\Sigma t/d \approx 2.4$, the maximum utilization was equal to 97 % $F_{t,Rd}$ ($Z_{max} = 171.8$ kN) for specimens tightened by the modified torque method and 110 % $F_{t,Rd}$ ($Z_{max} = 194.0$ kN) for connections tightened by the combined method.

4.2.4 Consideration of system reserves and preload losses over the service life

The relaxation tests as well as the tests under cyclic loading allow an assessment of the experimentally determined system reserves and preload losses with regard to the required preload value over the service life, see Figures 4.8 and 4.9. Given a comparatively low number of test specimens and a partly high scattering of the test results, average values with regard to their scatter bands are considered in order to draw first conclusions on the reliability of the investigated system configurations. Since the preloaded bolted tension connections may be subjected to high stresses in service, this is represented by considering preload losses due to cyclic loading that are based on tests carried out with $Z_{max} = 90$ % Z_{crit} .

As already mentioned in Chapter 4.2.2, the required system reserve of at least 10 % was only confirmed for the combined method. Furthermore, the combined method possesses enough system reserves Υ_{mean} (of around 28 % and more) to withstand possible preload losses $\Delta F_{p,setting,50a}$ and $\Delta F_{p,cycl,2E9}$ over the service life regardless of the investigated surface treatment. Considering both, system

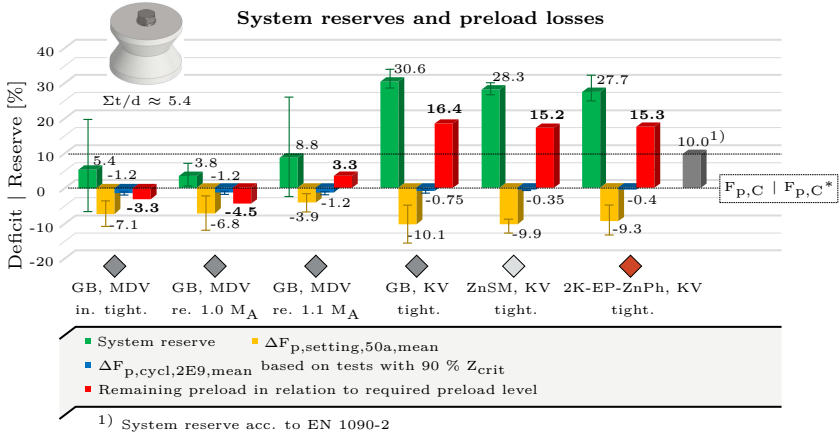


Figure 4.8 Experimentally determined system reserves and preload losses as mean values with scatter band for investigated connections with $\Sigma t/d \approx 5.4$ [4]

reserves Υ_{mean} and total preload losses $\Delta F_{p,setting,50a}$ as well as $\Delta F_{p,cycl,2E9}$, the remaining preload level exceeds the required preload $F_{p,C}$ by at least $\approx 7\%$ (here: ZnSM, $\Sigma t/d \approx 2.4$), see Figure 4.9. However, for the investigated grit blasted connections tightened by the modified torque method, deficits regarding the required preload $F_{p,C}^*$ in a range of up to 5 % can be expected. Herein, comparatively low system reserves due to tightening as well as re-tightening with 1.0 M_A are either completely used up or exceeded due to the resulting total preload losses $\Delta F_{p,setting,50a}$ and $\Delta F_{p,cycl,2E9}$ over the service life. In case of a re-tightening with 1.1 M_A , a convenient overall balance between system reserves and total preload losses was determined. However, this tightening torque (legitimately) does not belong to the common execution practice in steel construction and mainly serves the purpose of control measures on construction site.

An assessment of experimentally determined system reserves and preload losses shows that especially the required preload value $F_{p,C}^*$ for connections tightened by the modified torque method can hardly be maintained even for reference connections that fulfil the strict limitations regarding the coating layer thicknesses on contact surfaces as required by EN 1090-2. Therefore, a counteractive measure of using only a priming coat and/or surface masking beneath the washers of preloaded bolted connections seem to be justified. Furthermore, a structural design with 90 % of the minimum nominal preloading force (here: $F_{p,C}^*$) might be

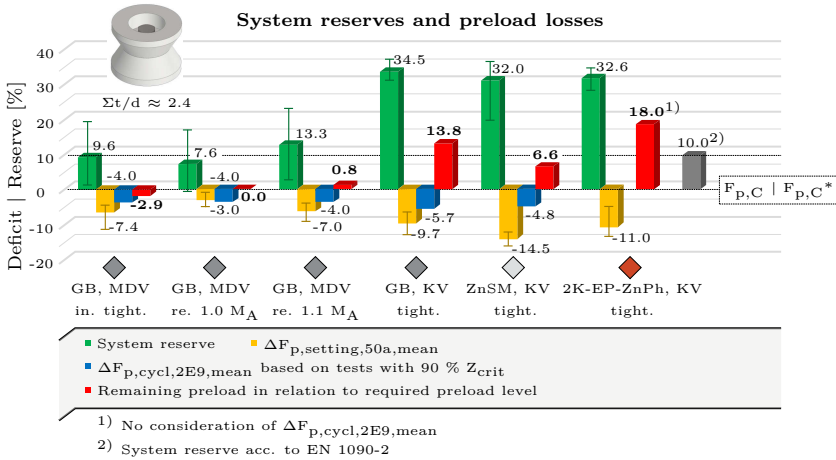


Figure 4.9 Experimentally determined system reserves and preload losses as mean values with scatter band for investigated connections with $\Sigma t/d \approx 2.4$ [4]

considered, as also suggested for (EN) torque method by Table I.1 in EN 1090-2, Annex I. A maximum of 90 % of the preload value $F_{p,C}^*$ is justifiably prescribed for the verification of fatigue resistance of ring flange connections for steel towers according to DIBt-Guideline for wind turbines [155]. A similar approach is also integrated in the IEC 61400-6 [156], as mentioned in Chapter 3.3.4.10. Here, a verification of the fatigue resistance has to be carried out with maximum 90 % of the nominal preload value even in cases where the initial preload losses are compensated by a re-tightening step. If this is not the case, the design must be carried out considering a generalized preload level of 70 % of the nominal preload value.

A pleasing potential is revealed by the combined method, as remarkably higher system reserves offer a sufficient safety against potential preload losses of the investigated specimen configurations. Furthermore, the beneficial influence on the system reserves (which is currently not considered in the normative regulations) can potentially be used in order to compensate a certain amount of preload losses even for connections with coated surfaces. Therefore, a systematic investigation is necessary in order to verify this behaviour and to cover some of the most common coatings and coating systems in steel construction as well as their influence on preload losses.

4.3 Connections with typical coating systems in steel structures

4.3.1 General

In the following, an experimental investigation into system reserves and preload losses, which was conducted in the frame of IGF research project No. 21196 BG "Development of normative fundamentals for consideration of preload losses in preloaded bolted connections with coated faying surfaces in steel construction" [6] carried out at the Institute for Metal and Lightweight Structures (IML) of the University of Duisburg-Essen (UDE) (project coordinator) and Fraunhofer Institute for Large Structures in Production Engineering IGP in Rostock, is presented. The main aim of this investigation was to determine the suitability of various coatings and coating systems commonly used in steel construction with regard to their use in preloaded bolted connections. For this reason, relaxation tests were conducted considering two different ranges of clamping length ratios and tightening methods using single-lap and double-lap specimens, see Figure 4.10.

The tightening of the specimens was carried out using the modified torque method and combined method for M16 HV bolting assemblies (EN 14399-4 [29]/EN 14399-6 [31]) in accordance with the specifications given in EN 1090-2 and DAST-Guideline 024. Here, a pre-tightening torque $M_{A,pre}$ of 190 Nm was chosen for the modified torque method, where after a standby time of around 5 minutes, the initial tightening with $M_A = 250$ Nm was carried out. For a re-tightening step after approx. three days after the initial tightening, the standard torque of $1.0 M_A$ with $M_A = 250$ Nm for M16 HV bolting assemblies was used again. For the combined method, the same pre-tightening torque $M_{A,pre}$ of 190 Nm was applied, as suggested by the DAST-Guideline 024. For the final angle-controlled tightening after a standby time of around 5 minutes, an angle of rotation $\Delta\theta$ of 90° was applied, see Figure 4.11. The tightening by means of the modified torque method was carried out using electric and hydraulic tools, see Figure 4.12, where for the combined method only the hydraulic torque wrench was applied. The preload was continuously measured using bolts with implanted strain gauges (DMS) BTMC-3 of Tokyo Measuring Instruments Laboratory Co., Ltd., see Figure 4.13, during and after the tightening of test specimens.

The experimental approach in this investigation is illustrated in Figure 4.14. The relaxation tests were carried out with a minimum duration of either three days

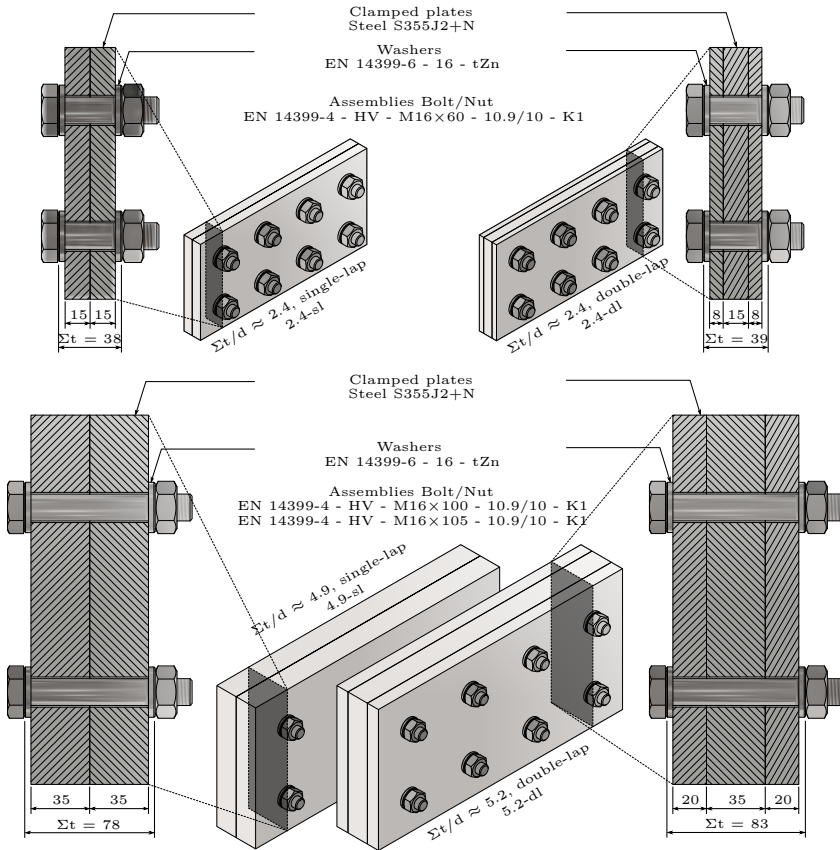


Figure 4.10 Specimen configurations incl. clamped packages used for the relaxation tests in the IGF research project No. 21196 BG at UDE/IML

(initial tightening using the modified torque method) or 14 days (re-tightening using the modified torque method and tightening by the combined method). For some specimens, the loss of preload behaviour was monitored for over a month. All tests were conducted at room temperatures of around 21°C to 23°C. Since the focus of this investigation lies within typical applications e.g. in steel hall construction, no subsequent tests under cyclic loading were intended. Following the approach described in Chapter 4.2.1, experimentally determined preload losses $\Delta F_{p, \text{setting}}$ were logarithmically extrapolated to the selected service life

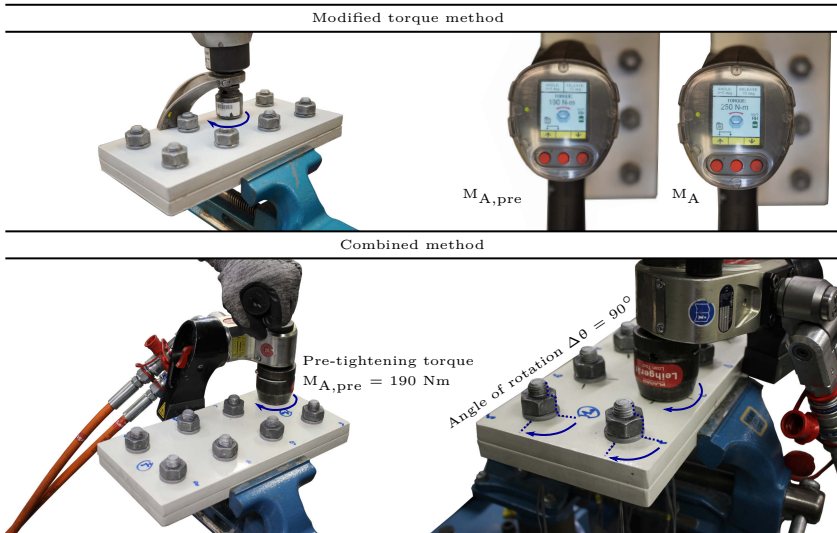


Figure 4.11 Tightening of the specimens by the modified torque method and combined method according to EN 1090-2 and DAST-Guideline 024

for common steel structures of 50 years. All tests presented within this thesis were carried out at the Institute for Metal and Lightweight Structures (IML) of the University of Duisburg-Essen (UDE). Further tests on connections with low-solvent coating systems or coatings on hot dip galvanized steel surfaces were carried out at the Fraunhofer Institute for Large Structures in Production Engineering IGP in Rostock and are presented in [6].

4.3.2 Investigated coating systems

The selection of coatings and coating systems used in this investigation was made in cooperation with German steel manufacturers and, herewith, represents the common practical applications in steel and steel hall construction as well as includes the typical systems according to ZTV-ING.

Considering the type of corrosion protection, the investigated coatings and coating systems can be divided into three groups:

- typical conventional paints and paint systems according to EN ISO 12944 series for steel structures on grit blasted steel substrates,



Figure 4.12 Electric (left) and hydraulic (right) tools used for the tightening of bolting assemblies



Figure 4.13 M16 HV bolts implanted with strain gauges BTMC-3 of Tokyo Measuring Instruments Laboratory Co., Ltd.

- typical powder coating systems according to DIN 55633-1 in steel hall construction on grit blasted steel substrates and
- typical powder coating systems on hot dip galvanized surfaces (duplex-systems) according to EN 13438 and EN 15773.

Table 4.5 summarizes the selected paint systems and gives some information on their expected performance with regard to their corrosion protection. The classification of corrosivity categories and the corresponding expected life of protection are based on practical experience with regard to each coating system and are not necessarily identical with the minimum requirements that are listed in EN ISO 12944-5 [55]. The given information corresponds to the confirmation

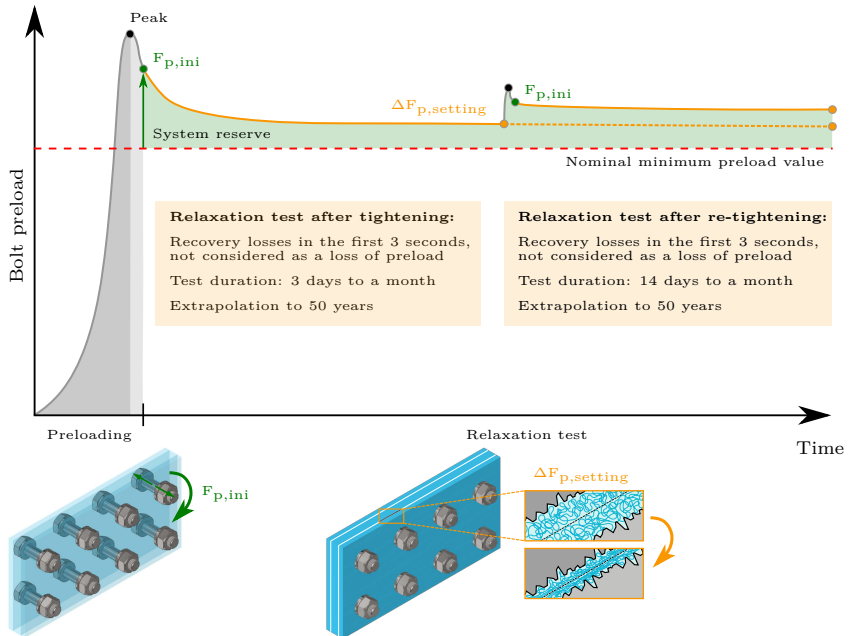


Figure 4.14 Experimental approach for the conducted investigation into preload losses in the IGF research project No. 21196 BG

of suitability for the corrosivity category that is based on testing according to EN ISO 12944-6 [56] and is specified in the associated technical data sheets.

As can be seen from Table 4.5, next to the nominal (nom) dry film thicknesses (NDFT) that are assumed for the compliance with the minimum requirements for corrosion protection, also maximum (max) possible dry film thicknesses are specified. These are based on the experience of practitioners who suggested that the actual coating layer thicknesses on the coated structures are significantly higher. In fact, the industry assumes that the average coating layer thicknesses might be around $1.4 \times \text{NDFT}$. Furthermore, since the surface masking for the relevant areas of bolted connections such as head plates is not necessarily carried out in steel hall construction, the actual layer thickness of $2 \times \text{NDFT}$ to $3 \times \text{NDFT}$ cannot be excluded. In fact, coating layer thicknesses of $2 \times \text{NDFT}$ to $3 \times \text{NDFT}$ correspond to the normative regulations regarding the maximum dry film thickness in EN 1090-2, Annex F as well as EN ISO 12944-5, see explanations in Chapter 3.3.1.

Table 4.5 Selected coatings and coating systems for the investigation within the scope of the IGF research project No. 21196 BG

No.	Binder base/ Chemical type	Corrosivity Category	Expected life of protection	Surface preparation	Coating thickness nom max [μm] ¹⁾
1. Typical conventional paints and paint systems on grit blasted steel substrates					
1.1	2K-PUR	C2/C3	VH/H	grit blasted to Sa 2 ^{1/2} medium (G)	160 -
1.2	2K-EP 2K-PUR	C2/C3	VH/H	grit blasted to Sa 2 ^{1/2} medium (G)	80 - 80 -
1.3	2K-EP-Zn 2K-EP-EG 2K-PUR	C3/C4	VH/H	grit blasted to Sa 2 ^{1/2} medium (G)	80 150 80 240 80 240
1.4	2K-EP-Zn 2K-EP-EG 2K-EP-EG 2K-PUR	C5	VH	grit blasted to Sa 2 ^{1/2} medium (G)	80 - 80 - 80 - 80 -
1.5	2K-EP-HS 2K-EP-HS 2K-PUR	C5	VH	grit blasted to Sa 2 ^{1/2} medium (G)	120 360 120 360 80 240
2. Typical powder coating systems on grit blasted steel substrates					
2.1	EP/SP	C2/C3	H/H	grit blasted to Sa 2 ^{1/2} medium (G)	80 240
2.2	EP SP	C4/C5	H/H	grit blasted to Sa 2 ^{1/2} medium (G)	100 540 80 240
3. Typical powder coating systems on hot dip galvanized surfaces (duplex-systems)					
3.1	EP/SP	C2/C3	H/H	hot dip galvanized sweep blasted	100 -
3.2	EP SP	C4/C5	H/H	hot dip galvanized sweep blasted	80 - 80 -

1) nom: nominal dry film thicknesses (NDFT) that are required in order to meet the requirements on the corrosivity category and protection life | max: possible maximum dry film thicknesses in the practical application.

Abbreviations:

2K: two-pack | EP: epoxy based paint | EP-Zn: epoxy based zinc rich paint | EG: micaceous iron oxide
SP: polyester resin | PUR: polyurethane paint | HS: high solid (low solvent)

The surface preparation for subsequent painting was carried out in accordance with specifications in EN ISO 12944-4 [54] and with the information provided in the technical data sheets of the coating material manufacturers. Herein, the steel surfaces were grit blasted to grade Sa 2^{1/2} according to EN ISO 8501-1,

whereby the roughness of the steel surface corresponded to the profile grade "medium (G)" according to EN ISO 8503-1, as exemplarily shown in Figure 4.15 using ISO Comparator G. Prior to the application of the powder coating, the grit blasted surfaces were additionally subjected to a wet-chemical pre-treatment by zinc phosphating and chrome-free nanopassivation. The application of the paint systems consisting of several layers was carried out under consideration of the curing time as provided in technical data sheets of the coating material manufacturers.

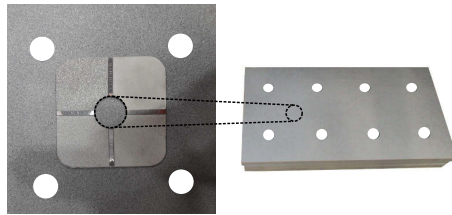


Figure 4.15 Grit blasted surface to Sa 2^{1/2} according to EN ISO 8501-1 with corresponding profile grade "medium (G)" according to EN ISO 8503-1

Hot dip galvanizing was carried out in accordance with EN ISO 1461. Additionally, the zinc melt complied with specifications given in DAST-Guideline 022 "*Hot dip galvanizing of load-bearing steel components*" [198], where the temperature of the molten zinc is defined to be between 450°C and 455°C. It is well-known that the silicon and/or phosphorous content together with the thickness of the steel plates have an influence on the thickness of the zinc layer. The steel plates of $t = 8$ mm, $t = 15$ mm and $t = 20$ mm used for this investigation can be mostly assigned to category B steels according to EN ISO 14713-2 [66] with a silicon content from 0.14 % to 0.25 %. However, the plates with $t = 35$ mm possessed a silicon content of 0.43 % to 0.47 % and therefore can be assigned to category D steels according to EN ISO 14713-2 with a tendency to an increased zinc coating thickness. A high silicon content of 0.43 % to 0.47 % of the plates with $t = 35$ mm is reflected very well in the measured zinc layer thicknesses, see Table 4.6.

Table 4.6 Test programme incl. measured layer thicknesses for the investigated coatings and coating systems in the IGF research project No. 21196 BG

No.	Binder base/ Chemical type	Clamping length ratio	No. of specimens		Measured coating thickness	
		$\Sigma t/d$	MDV nom max	KV nom max	DFT_{mean} nom max [μm] ²⁾	V_X nom max [-]
1. Typical conventional paints and paint systems on grit blasted steel substrates						
1.1	2K-PUR	2.4-sl	2 ¹⁾ -	1 -	125.8 -	0.24 -
		2.4-dl	2 ¹⁾ -	1 -		
		4.9-sl	1 -	1 -		
		5.2-dl	1 -	1 -		
1.2	2K-EP 2K-PUR	2.4-sl	1 -	1 -	159.0 -	0.16 -
		2.4-dl	1 -	1 -		
		4.9-sl	1 -	1 -		
		5.2-dl	1 -	1 -		
1.3	2K-EP-Zn 2K-EP-EG 2K-PUR	2.4-sl	1 1	1 -	336.3 756.1	0.14 0.14
		2.4-dl	1 1	- -		
		4.9-sl	1 1	- 1		
		5.2-dl	1 1	- 1		
1.4	2K-EP-Zn 2K-EP-EG 2K-EP-EG 2K-PUR	2.4-sl	3 ¹⁾ -	- -	434.8 -	0.18 -
		2.4-dl	2 ¹⁾ -	- -		
		4.9-sl	1 -	- -		
		5.2-dl	1 -	- -		
1.5	2K-EP-HS 2K-EP-HS 2K-PUR	2.4-sl	1 1	- -	373.1 823.3	0.06 0.08
		2.4-dl	1 1	- -		
2. Typical powder coating systems on grit blasted steel substrates						
2.1	EP/SP	2.4-sl	1 1	1 1	77.0 233.9	0.14 0.16
		2.4-dl	1 2	1 1		
		4.9-sl	1 1	1 1		
		5.2-dl	1 1	1 1		
2.2	EP SP	2.4-sl	1 2	1 2	202.9 362.7	0.27 0.16
		2.4-dl	1 1	1 1		
		4.9-sl	1 1	2 1		
		5.2-dl	2 1	1 1		
3. Typical powder coating systems on hot dip galvanized surfaces (duplex-systems)						
3.1	EP/SP	2.4-sl	1 -	1 -	333.9 -	0.11 -
		2.4-dl	1 -	1 -	343.3 -	0.12 -
		4.9-sl	1 -	1 -	603.8 -	0.07 -
		5.2-dl	1 -	1 -	466.0 -	0.24 -
3.2	EP SP	2.4-sl	1 -	1 -	365.8 -	0.08 -
		2.4-dl	1 -	1 -	370.9 -	0.09 -
		4.9-sl	1 -	1 -	617.3 -	0.07 -
		5.2-dl	1 -	1 -	480.2 -	0.22 -

1) Two different coating manufacturers.

2) Average measured dry film thicknesses (DFT_{mean}) on specimens with the expected nominal (nom) and maximum (max) layer thicknesses. | DFT_{mean} for duplex systems are given for each specimen configuration due to the increased zinc layer thickness (265 - 266 μm DFT for plates with $t = 8$ mm and $t = 15$ mm), especially for thicker plates with $t = 20$ mm (347 μm DFT) and $t = 35$ mm (557 μm DFT).

Abbreviations:

2K: two-pack | EP: epoxy based paint | EP-Zn: epoxy based zinc rich paint | EG: micaceous iron oxide
SP: polyester resin | PUR: polyurethane paint | HS: high solid (low solvent)

Compared to zinc layer thicknesses of approx. 265 μm DFT and 347 μm DFT measured for plates $t = 8\text{ mm}$, $t = 15\text{ mm}$ and $t = 20\text{ mm}$ thicknesses (category B steels according to EN ISO 14713-2), increased zinc layers with approx. 557 μm DFT were measured for steel plates with $t = 35\text{ mm}$ (category D steel according to EN ISO 14713-2). Prior to the application of the powder coating, the zinc layer was additionally cleaned (and therefore prepared for a subsequent coating) by sweep blasting according to EN ISO 12944-4 using aluminium oxide blasting media with particle sizes of 0.5 mm to 1.0 mm and a blast pressure of around 3 bar to 3.5 bar.

After coating, the steel plates were labeled, documented and their dry film thicknesses (DFT) were measured according to EN ISO 2808 [199] by the use of the magnetic method according to EN ISO 2178 [200] (paints and paint systems as well as powder coating systems on grit blasted surfaces) and the amplitude-sensitive eddy-current method according to EN ISO 2360 [201] (powder coating systems on hot dip galvanized steel). Each plane of the coated plates was measured at five different positions, where every position included five measurements, see Figure 4.16. Next to the number of conducted tests for different tightening methods and intended range of the coating thickness, Table 4.6 summarizes the average measured dry film thicknesses for the investigated coatings and coating systems.

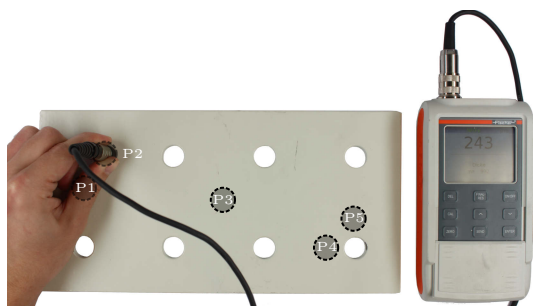


Figure 4.16 Measurement of the dry film thickness using the magnetic method according to EN ISO 2178

4.3.3 System reserves after tightening

As already reported in Chapter 4.2.2, a considerable drop in the bolt preload due to the so-called overshoot effect could be observed directly after the tightening

of the bolting assemblies. Here, in agreement with investigations carried out by *Stranghöner et al.* [159] and *Afzali* [92], the main recovery losses were detected in the first 3 seconds after reaching the peak value and, accordingly, were not considered as a loss of preload.

In the following, the experimentally determined initial preload levels $F_{p,ini}$ achieved for test specimens with different coatings and coating systems specified in Table 4.6 are discussed for both, the modified torque method and the combined method, and a further analysis is provided.

4.3.3.1 Modified torque method

Since the same configuration of M16 HV bolting assemblies was used for all carried out tests (here: k-class K1, hot dip galvanized washers under the rotating nut), a combined evaluation of the initial bolt preloads was possible for test specimens with different coating systems. However, a separate evaluation was conducted with regard to the initial tightening and re-tightening steps as well as for using different tightening tools. An evaluation of a total of 494 tests show that the required nominal preload value $F_{p,C}^*$ of 100 kN (M16 HV 10.9 bolting assemblies) was achieved regarding the mean initial preload level $F_{p,ini,mean}$. This applies to both, the initial tightening ($F_{p,ini,mean} = 105.8$ kN) as well as re-tightening ($F_{p,ini,mean} = 103.4$ kN) of the bolting assemblies, see Table 4.7, where the corresponding coefficients of variation $V_{F_{p,ini}}$ amount to 9 % for both cases. In accordance with the results from Chapter 4.2.2, a re-tightening step leads to approx. 2 % - 3 % lower initial preloads $F_{p,ini,mean}$ in comparison with the values achieved after the initial tightening by using the same tightening torque of $1.0 M_A$ (here: $M_A = 250$ Nm). As mentioned before, this can be mainly attributed to the altered frictional resistance after tightening of the connections.

The average system reserves Υ_{mean} for the initial tightening and re-tightening were determined to 5.8 % and 3.4 % respectively, see the combined evaluation in Table 4.7. Additionally, an exemplary presentation of all identified system reserves and deficits is given in Figure 4.17. With regard to the average system reserves of $\Upsilon_{mean} = 5.8$ % after the initial tightening of the bolting assemblies, the modified torque method fails to meet the average system reserve of 10 % acc. to EN 1090-2. Furthermore, it must be mentioned that the required nominal preload value $F_{p,C}^*$ of 100 kN was not achieved in 136 and 182 cases out of a

Table 4.7 Summary of the achieved initial preload levels and system reserves for the modified torque method for various surface conditions investigated in the IGF research project No. 21196 BG

Tight. method	$\Sigma t/d$ [-]	Surface cond. ¹⁾	Tool	No. [-]	Phase	Preload level $F_{p,ini}$			$\gamma_{mean}^{2)}$ [%]
						min [kN]	max [kN]	mean $V_{F_{p,ini}}$ [-]	
MDV	comb.	comb.	hydr.	132	in. tight.	84.0	132.4	108.9	8.9
			electr.	362	in. tight.	82.8	135.4	104.7	4.7
MDV	comb.	comb.	comb.	494	in. tight.	82.8	135.4	105.8	0.09
MDV	comb.	comb.	hydr.	132	re-tight.	84.1	127.9	105.0	5.0
			electr.	362	re-tight.	78.9	136.8	102.8	2.8
MDV	comb.	comb.	comb.	494	re-tight.	78.9	136.8	103.4	0.09

1) Coating systems in accordance with Table 4.6.
2) System reserves are based on the preloading force $F_{p,C^*} = 100$ kN (M16 HV 10.9 bolting assemblies).
Abbreviations:
MDV: modified torque method | hydr.: hydraulic tool | electr.: electric tool | comb.: combined eval.

total of 494 tests for initial tightening and re-tightening steps respectively and therefore corresponds to approx. 28 % and 37 % of all cases.

Following the example of *Schaumann/Rutkowski*, see Chapter 3.2.4, a separate evaluation was carried out differentiating between the achieved preload levels using electric and hydraulic wrenches. Compared to the tightening using electric wrench, slightly higher average initial preload values $F_{p,ini,mean}$ in a range of approx. 4 % and 2 % were determined by using a hydraulic tool for the initial tightening and re-tightening steps respectively. Possible causes for such a discrepancy might involve the tightening speed as well as the duration of the maximum acting torque in case of a hydraulic wrench, as reported in [132]-[133].

In addition to the evaluation of the initial preload values $F_{p,ini}$, also the peak values and the associated overshoot in the first three seconds after the tightening (described in the following as recovery losses) as well as its dependence on the coating thickness DFT were investigated. Figure 4.18 summarizes recovery losses and the achieved preloads $F_{p,ini}$ for the modified torque method in relation to the actual coating thickness DFT, whereby Figure 4.19 shows the amount of recovery losses depending on the achieved initial preload level $F_{p,ini}$ as well as the actual clamping length ratio. Here, the calculated recovery losses (first 3 seconds after achieving of the peak value) largely remain within approx. 5 % after tightening. However, in some individual cases, recovery losses of up to ≈ 12 %

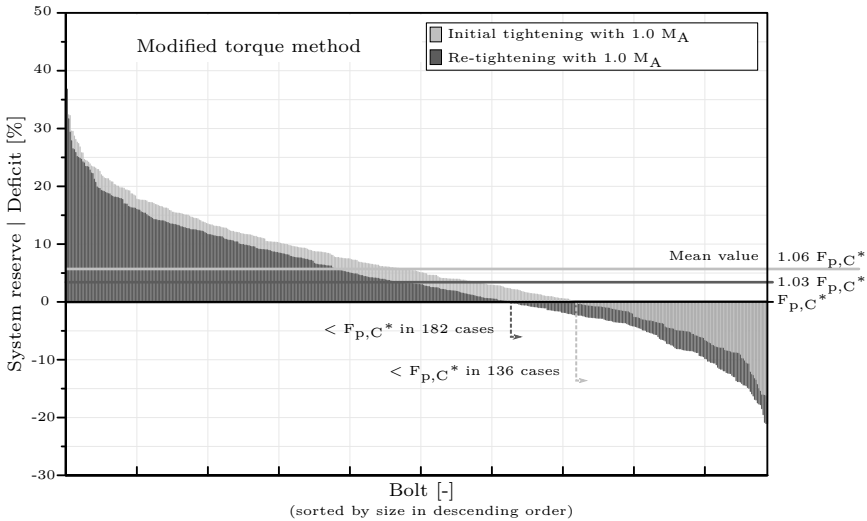


Figure 4.17 Determined system reserves and deficits considering modified torque method after the initial tightening and re-tightening steps

were measured. These high recovery losses, see the grey trendline in Figure 4.18 (left), show a slight influence on the achieved preload level $F_{p,ini}$ (Figures 4.18 (right) and 4.19 (left)) and can be attributed to the increased elasticity of some of the investigated coating systems (here: due to incomplete solvent evaporation, see explanations in Chapter 4.3.4.1.6). In regular cases, however, the influence of the coating thickness on the recovery losses and therefore on the initial preloads $F_{p,ini}$ seems to be negligible, so that an overall evaluation of the initial preload level considering all test series proves to be reasonable. Conversely, the sensitivity of torque-controlled tightening to an increasing coating layer thickness appears to be rather low.

As expected, slightly lower recovery losses can be assigned to higher clamping length ratios $\Sigma t/d$. Furthermore, in comparison to the initial tightening, considerably lower recovery losses can be expected after the re-tightening with major losses remaining within 2 % to 3 %. This, of course, can be mainly attributed to the largely completed setting effects during the first 72 hours after the initial tightening. In general, the determined recovery losses after re-tightening seem to be distributed more evenly, so that the above described correlations of recovery losses with the increasing coating layer thickness as well as the clamping length

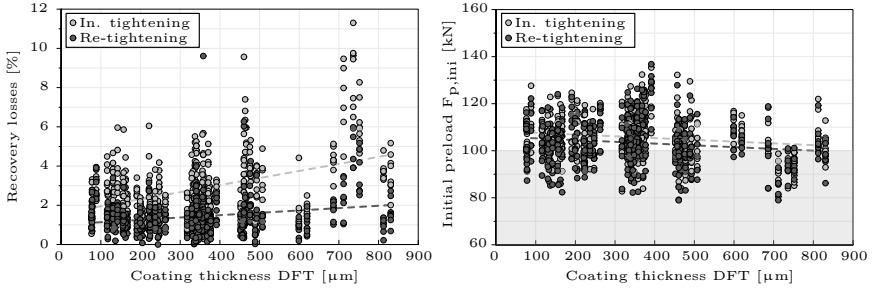


Figure 4.18 Determined recovery losses for the modified torque method (left) as well as the initial preload level $F_{p,ini}$ (right) dependent on the coating thickness DFT

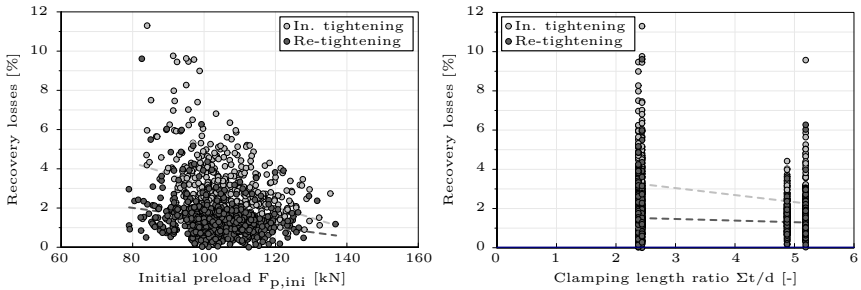


Figure 4.19 Determined recovery losses for the modified torque method dependent on the resulting initial preload level $F_{p,ini}$ (left) as well as the clamping length ratio (right)

ratio are barely reflected even considering the investigated coating systems with an increased elasticity.

A broad data base from the investigation into the modified torque method allows a meaningful statistical evaluation according to EN 1990. The achieved average initial preload values $F_{p,ini,mean}$ and the corresponding 5 % characteristic values $F_{p,ini,0.05}$, see Equation (4.3), are summarized in Table 4.8.

Based on the conducted investigation, the actual characteristic values $F_{p,ini,0.05}$ were determined to 90.4 kN and 87.4 kN for the initial tightening and re-tightening respectively. Herewith, the nominal preloading force $F_{p,C*} = 100$ kN (M16 HV 10.9 bolting assemblies) was undercut by approx. 10 % and 13 %. The respective probability density function as well as the cumulative distribution function of the measured initial preloads $F_{p,ini}$ by means of the modified torque method are shown in Figure 4.20. As can be seen from the cumulative distribution function in Figure 4.20 (right), a reliability of ≈ 73 % (based on the cumulative

Table 4.8 Average initial preload values and the corresponding 5 % fractile values for the modified torque method for various surface conditions investigated in the IGF research project No. 21196 BG

Tight. method	$\Sigma t/d$ [-]	Surface condition	No. [-]	Phase	$F_{p,ini,mean}$ [kN]	$\sqrt{F_{p,ini}}$ [-]	$k_n^{1)}$ [-]	$F_{p,ini,0.05}^{2)}$ [kN]	$\gamma_{0.05}^{3)}$ [%]
MDV	comb.	see Table 4.6	494	in. tight.	105.8	0.09	1.64	90.4	-9.6
			494	re-tight.	103.4	0.09	1.64	87.4	-12.6
Required preload $F_{p,C}^* = 100$ kN (M16 HV 10.9 bolting assemblies)									

1) Coefficient according to EN 1990, Annex D [97] for determination of characteristic 5 % values.

2) Characteristic 5 % value in accordance with $X_{k(n)}$ in EN 1990, Annex D [97].

3) System reserves/deficits are based on the nominal preloading force $F_{p,C}^* = 100$ kN (MDV) considering the characteristic value $F_{p,ini,0.05}$.

Abbreviations:

MDV: modified torque method | comb.: combined evaluation

probability $F(F_{p,ini}) \approx 0.27$ at $F_{p,C}^* = 100$ kN) instead of the desirable 95 % was determined for the modified torque method after the initial tightening. This significant shortfall confirms the results of various experimental investigations including *Scheer et al.* [105], *Lange/Friede* [130]-[131] and others, see Chapter 3.2.4.

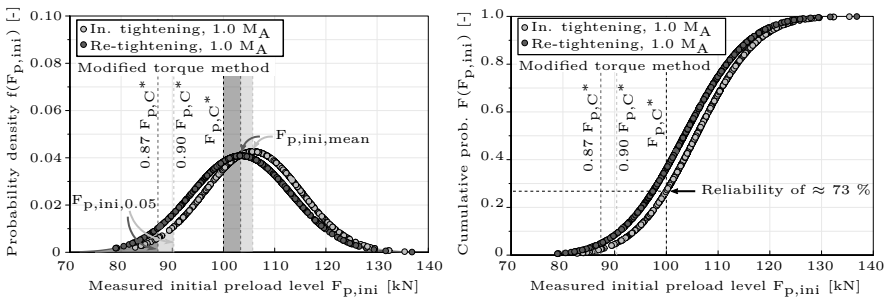


Figure 4.20 Probability density function (left) and cumulative distribution function (right) of the measured initial preloads $F_{p,ini}$ achieved by the modified torque method

Although the resulting 5 % characteristic values $F_{p,ini,0.05}$ correspond to only $0.90 F_{p,C}^*$ and $0.87 F_{p,C}^*$ for initial tightening and re-tightening respectively, it must be mentioned that these values represent bolt preloads for a single bolt within a connection. Using these values for a generalized design of a connection consisting of multiple preloaded bolts would rather represent a conservative case, since a use of $F_{p,ini,0.05}$ would de facto assume that the average preload level in

the complete connection is also equivalent to a 5 % characteristic value. The favourable "balancing effect" of multiple preloaded bolts in a connection with regard to the achieved preload values can be sensibly captured by consideration of a sampling distribution. The approach for a calculation of an effective characteristic preload (described in the following as $F_{p,ini,0.05,eff}$) considering the standard deviation of averaged bolt forces for a certain number of bolts n has been proposed by *Seidel* in a background document for changes to IEC 61400-6 [202].

For the calculation of $F_{p,ini,0.05,eff}$, we assume that multiple random samples of a specific size n (here: number of bolts in a connection) are taken. The distribution of their averages (or the so-called "sampling distribution of the sample mean") is normal and the mean value of the sampling distribution corresponds to the mean value of the original probability distribution (here: $F_{p,ini,mean}$). However, since the averages of the sampling distribution are less variable than the individual observations considered in the original probability distribution, the standard deviation of the sampling distribution can be described by the standard error of the mean $\sigma_{\overline{F_{p,ini}}}$:

$$\sigma_{\overline{F_{p,ini}}} = \frac{\sigma}{\sqrt{n}} \quad (4.8)$$

where σ is the standard deviation of the original probability distribution and n is the size of the sample considered for the sampling distribution.

Analogous to Equation (4.3), a 5 % characteristic value of the sampling distribution (here: effective characteristic preload $F_{p,ini,0.05,eff}$) can be expressed as

$$F_{p,ini,0.05,eff} = F_{p,ini,mean} \cdot (1 - k_n \cdot V_{\overline{F_{p,ini}}}) \text{ [kN]} \quad (4.9)$$

with the coefficient of variation $V_{\overline{F_{p,ini}}}$ calculated as

$$V_{\overline{F_{p,ini}}} = \frac{\sigma_{\overline{F_{p,ini}}}}{\overline{F_{p,ini,mean}}} \text{ [-]} \quad (4.10)$$

Consequently, the effective characteristic preload $F_{p,ini,0.05,eff}$ can be calculated in dependence on the actual number of bolts n in a connection under consideration of the coefficient of variation $V_{F_{p,ini}}$ taken from the original probability distribution, see Equation (4.11).

$$F_{p,ini,0.05,eff} = F_{p,ini,mean} \cdot \left(1 - k_n \cdot \frac{V_{F_{p,ini}}}{\sqrt{n}} \right) \text{ [kN]} \quad (4.11)$$

Figure 4.21 informatively shows the resulting effective characteristic preload $F_{p,ini,0.05,eff}$ for a certain number n of bolts in a connection, calculated by applying Equation (4.11) and considering the coefficient of variation $V_{F_{p,ini}}$ determined from initial tightening and re-tightening, see Table 4.8.

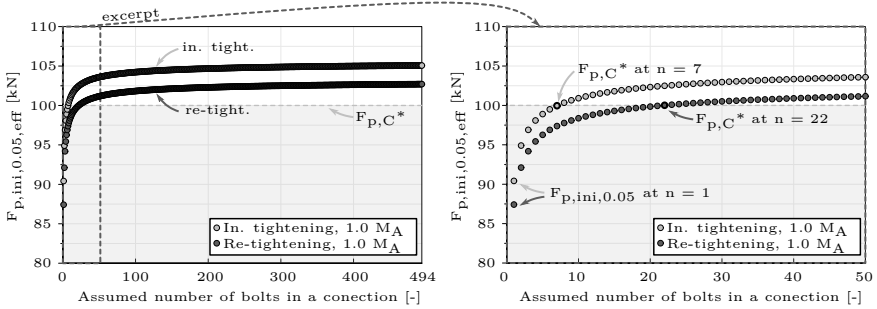


Figure 4.21 Effective characteristic preload $F_{p,ini,0.05,eff}$ considering the sampling distribution approach and a certain size of the sample n for the modified torque method

Herein, the standard error of the mean $\sigma_{\overline{F_{p,ini}}}$ decreases with an increasing number of bolts and therefore leads to higher effective characteristic preload $F_{p,ini,0.05,eff}$ of a connection. Based on the experimental results from initial tightening and re-tightening by the modified torque method, a bolted connection consisting of at least 7 and 22 bolts respectively would be necessary in order to achieve the nominal preload value $F_{p,C}^*$ with a reliability of 95 %. With regard to the possible preload losses and their implicit consideration in combination with the modified torque method, the relationship shown in Figure 4.21 could be meaningfully taken into account during design.

4.3.3.2 Combined method

In compliance with the test results presented in Chapter 4.2.2, the combined method provides a significant amount of system reserves considering the required nominal preload value $F_{p,C}$ (here: 110 kN for M16 HV 10.9 bolting assemblies), see Table 4.9. Since the clamping length ratios of the investigated single-lap (2.4-sl and 4.9-sl) and double-lap (2.4-dl and 5.2-dl) test specimens (see specimen

configurations in Figure 4.10) lie within a similar range of $\Sigma t/d \approx 2.4$ and $\Sigma t/d \approx 5$ and show very similar results with regard to the initial preload levels (a separate evaluation was conducted, but is not presented in this work), it was decided to carry out a combined evaluation for ranges of clamping length ratios of $\Sigma t/d \approx 2.4$ and $\Sigma t/d \approx 5$.

Table 4.9 Summary of the achieved initial preload levels and system reserves for the combined method for various surface conditions investigated in the IGF research project No. 21196 BG

Tight. method	$\Sigma t/d$ [-]	Surface condition ¹⁾	No. [-]	Phase	Preload level $F_{p,ini}$			$V_{F_{p,ini}}$ [-]	γ_{mean} ²⁾ [%]
					min [kN]	max [kN]	mean [kN]		
KV	≈ 5	1.1	15	tight.	141.1	154.9	146.6	0.03	33.3
		1.2	16		135.8	151.2	145.5	0.03	32.3
		1.3 ³⁾	16		121.5	146.4	133.4	0.06	21.3
		2.1	30		138.2	152.4	145.8	0.03	32.5
		2.2	35		135.2	155.1	142.9	0.03	29.9
		3.1	13		139.6	150.8	145.4	0.02	32.2
		3.2	15		137.3	147.7	143.2	0.02	30.2
KV	≈ 5	combined	124	tight.	135.2	155.1	144.7	0.03	31.5
KV	≈ 2.4	1.1	16	tight.	146.5	160.0	152.7	0.03	38.8
		1.2	14		146.3	156.8	150.9	0.02	37.2
		1.3	7		148.4	155.7	153.1	0.02	39.2
		2.1	31		145.5	162.2	154.6	0.03	40.6
		2.2	40		144.3	158.5	150.3	0.03	36.6
		3.1	13		146.1	158.6	154.5	0.02	40.4
		3.2	12		144.3	157.1	150.6	0.03	36.9
KV	≈ 2.4	combined	133	tight.	144.3	162.2	152.2	0.03	38.4

1) Coating system no. in accordance with Table 4.6.
2) System reserves are based on the nominal minimum preloading force $F_{p,C} = 110 \text{ kN}$ (M16 HV 10.9 bolting assemblies).
3) Partially large deformations under the washer during the second, angle-controlled tightening step. Therefore no consideration of this test series in the overall evaluation.

Abbreviations:
KV: combined method

As Table 4.9 shows, a separate evaluation of the average initial preloads $F_{p,ini,mean}$ shows only minor discrepancies between most of the investigated surface conditions. Considering the fact that each test series include various coating thicknesses from $71 \text{ }\mu\text{m}$ to $615 \text{ }\mu\text{m}$ DFT, this difference can be assumed as negligible. However, the investigated test specimens with the coating system 2K-EP-Zn | 2K-EP-EG | 2K-PUR and the associated coating thicknesses of $743 \text{ }\mu\text{m}$ to $813 \text{ }\mu\text{m}$ DFT (here: $\Sigma t/d \approx 5$, surface condition 1.3 in Table 4.9) show, that in particular softer coatings with high coating thicknesses might lead to some large

deformations beneath the washers. This is especially critical considering the second, angle-controlled tightening step of the combined method, since a sudden increase in the resilience of a clamped package caused by coating deformation during tightening means, that the bolting assembly itself cannot be exploited to its full potential. For the affected test specimens (here: surface condition 1.3 in Table 4.9), this results in considerably lower initial preloads $F_{p,ini}$ with a minimum value of just ≈ 121 kN based on 16 tests. Since the investigated coating thicknesses of 743 μm to 813 μm DFT correspond to $3.1 \times \text{NDFT}$ and $3.4 \times \text{NDFT}$ of the coating system 2K-EP-Zn | 2K-EP-EG | 2K-PUR respectively and rather represent an exception in practical application, the results of this test series are not considered in the combined overall evaluation of system reserves, see Table 4.9, but are informatively shown in Figure 4.22.

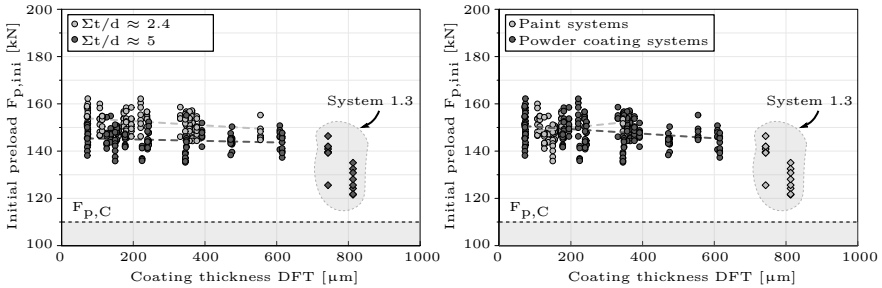


Figure 4.22 Determined recovery losses for the combined method dependent on the coating thickness (left) as well as the clamping length ratio (right)

On the basis of this investigation, a generalized statement on the limit of coating thickness that would not significantly affect the level of preload $F_{p,ini}$ by using the combined method is not possible due to a considerably low number of tests carried out on specimens coated with typical conventional paints and paint systems with thicknesses significantly greater than the nominal range NDFT, see Figure 4.22 (right). However, it seems that the investigated typical powder coating systems including duplex-systems are capable of resisting high surface pressures beneath the washers without showing significant deformations during tightening even up to coating thicknesses of ≈ 615 μm due to their more favourable mechanical properties such as hardness (e.g. quantified by Buchholz indentation resistance according to ISO 2815 [203]).

Considering all investigated coating systems and clamping length ratios, a slight tendency to a decrease in the achieved initial preloads $F_{p,ini}$ of approx. 1 % to

3 % with an increasing coating thickness DFT can be determined, see Figure 4.22 (left). This can be mostly attributed to the fact that higher coating thicknesses increase the total elastic resilience of the connection, which has a detrimental effect on the initial preload due to the angle-controlled tightening. In addition to the initial preload values $F_{p,ini}$, an evaluation of the peak values and the associated overshoot was carried out. Figure 4.23 (left) shows that the recovery losses in the first 3 seconds after reaching the peak value (calculated in relation to the initial preload level $F_{p,ini}$) vary between ≈ 1 % and ≈ 4.5 %. Here, no significant influence of the increasing coating thickness was observed. However, an illustration of the recovery losses in dependence of the clamping length ratio $\Sigma t/d$, see Figure 4.23 (right), confirms that the increasing clamping length (with the associated higher resiliences) can lead to slightly lower recovery losses.

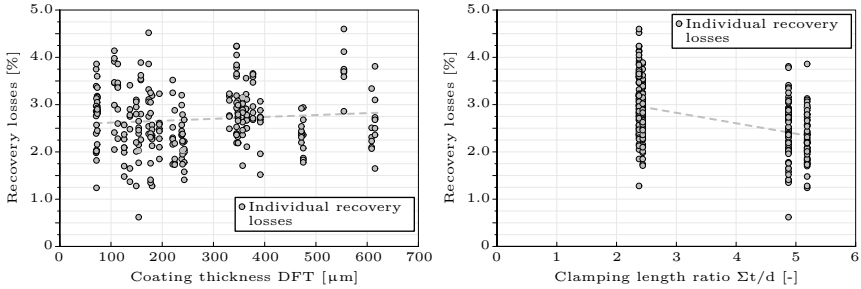


Figure 4.23 Determined initial preload level $F_{p,ini}$ dependent on the coating thickness DFT considering the clamping length ratio (left) and the type of coating (right) for the combined method

A combined analysis for all surface conditions in Table 4.9 shows that the average exceedance of $F_{p,C}$ based on 124 tests for $\Sigma t/d \approx 5$ and 133 tests for $\Sigma t/d \approx 2.4$ is ≈ 32 % and ≈ 38 % respectively, see also Figure 4.24. Considering the average system reserves, it is confirmed that the combined method clearly fulfils a 10 %-demand of EN 1090-2 and even offers significantly higher reserves for possible preload losses. As expected, tightening into an overelastic range can be associated with a low scattering of the individual preload values with coefficients of variation $V_{F_{p,ini}}$ of up to 3 %.

A database built up by 257 tests enables a statistical evaluation of the bolt preloads with regard to their use for normative purposes. Table 4.10 summarizes the achieved average initial preload values $F_{p,ini,mean}$ and the corresponding 5 % characteristic values $F_{p,ini,0.05}$ calculated in accordance with Equation (4.3).

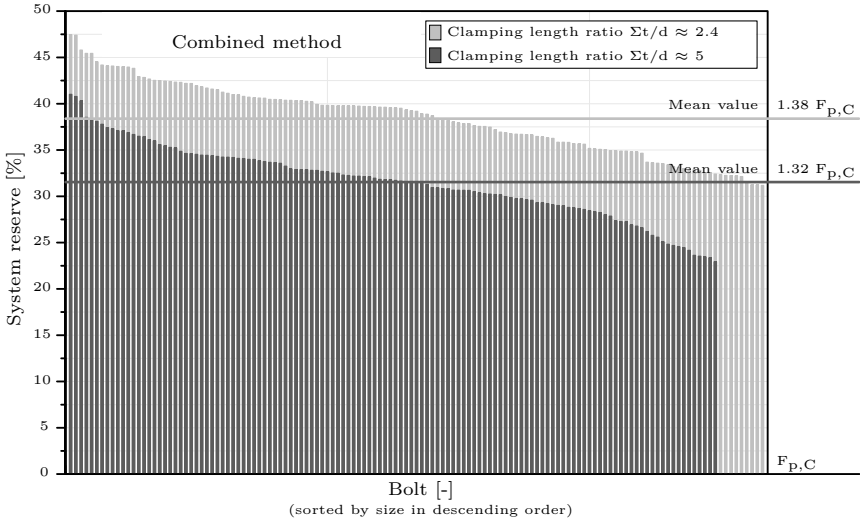


Figure 4.24 Determined system reserves considering the combined method for different clamping length ratios

Herein, it can be seen that the actual characteristic values $F_{p,ini,0.05}$ achieved by the combined method amount to 137.6 kN and 145.3 kN for the respective ranges of clamping length ratios of $\Sigma t/d \approx 5$ and $\Sigma t/d \approx 2.4$. With regard to the nominal minimum preloading force $F_{p,C} = 110$ kN (M16 HV 10.9 bolting assemblies) for the combined method, a preloading force of $1.25 F_{p,C}$ for $\Sigma t/d \approx 5$ and $1.32 F_{p,C}$ for $\Sigma t/d \approx 2.4$ can be determined. In addition, these test results are summarized in Figure 4.25 in form of a probability density function as well as a cumulative distribution function of the measured initial preloads $F_{p,ini}$ based on a normal distribution. Based on the cumulative probability $F(F_{p,ini}) = 0.05$ (corresponds to 5 % characteristic value), a system reserve of at least 25 % could be normatively assumed for tightening by the combined method provided that the clamping length ratio corresponds to the usual practical range of $\Sigma t/d \approx 2$ to $\Sigma t/d \approx 5$ (steel hall construction, connections in wind turbines etc.). Herewith, considering the fractile value of the initial preload, the nominal yield strength of HV 10.9 bolting assemblies in the order of $1.285 F_{p,C}$, see Equation (2.14), may be slightly undercut. However, it is worth mentioning that the experimental values of bolt preload $F_{p,ini}$ considered in this investigation are intended to represent the "real" initial preload, where some of the main influencing factors such as recovery losses (also known as "overshoot") are already implicitly considered.

Table 4.10 Average initial preload values and the corresponding 5 % fractile values for the combined method considering various surface conditions investigated in the IGF research project No. 21196 BG

Tight. method	$\Sigma t/d$ [-]	Surface condition	No. [-]	Phase	$F_{p,ini,mean}$ [kN]	$V_{F_{p,ini}}$ [-]	$k_n^{1)}$ [-]	$F_{p,ini,0.05}^{2)}$ [kN]	$\gamma_{0.05}^{3)}$ [%]
KV	≈ 5	see Table 4.6	124	tight.	144.7	0.03	1.64	137.6	25.1
	≈ 2.4		133		152.2	0.03	1.64	145.3	32.1
Required preload $F_{p,C} = 110$ kN (M16 HV 10.9 bolting assemblies)									

1) Coefficient according to EN 1990, Annex D [97] for determination of characteristic 5 % values.

2) Characteristic 5 % value in accordance with $X_{k(n)}$ in EN 1990, Annex D [97].

3) System reserves are based on the nominal preloading force $F_{p,C} = 110$ kN (KV) considering the characteristic value $F_{p,ini,0.05}$.

Abbreviations:

KV: combined method

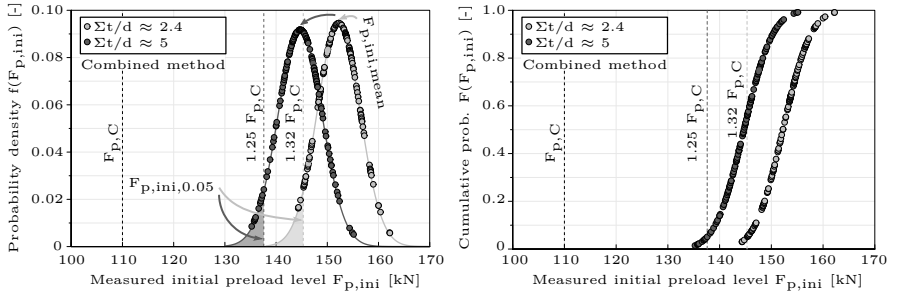


Figure 4.25 Probability density function (left) and cumulative distribution function (right) of the measured initial preloads $F_{p,ini}$ for tightening by the combined method

Analogous to the approach applied for the modified torque method, the effective characteristic preload $F_{p,ini,0.05,eff}$ for connections consisting of more than one bolt can be calculated for the combined method according to Equation (4.11).

Figure 4.26 informatively shows the resulting effective characteristic preload $F_{p,ini,0.05,eff}$ considering a certain number n of bolts in a connection and the coefficient of variation $V_{F_{p,ini}}$ corresponding to the respective ranges of clamping length ratios of $\Sigma t/d \approx 5$ and $\Sigma t/d \approx 2.4$, see Table 4.10.

As already seen from Figure 4.25, a bolted connection with a clamping length ratio $\Sigma t/d \approx 2.4$ exceeds the preload value of $1.3 F_{p,C}$ already considering 5 % characteristic value $F_{p,ini,0.05}$. However, taking into account the experimental

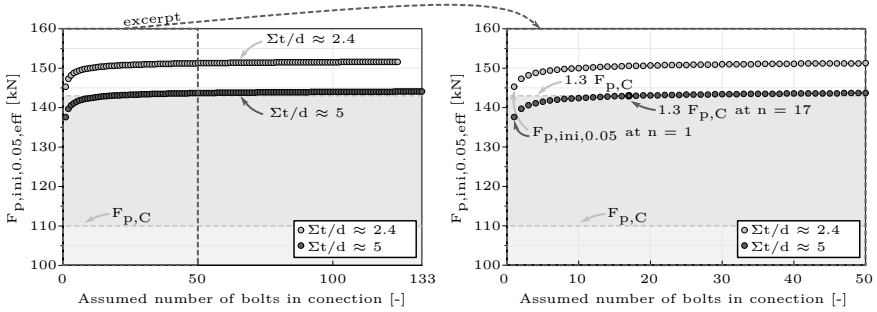


Figure 4.26 Effective characteristic preload $F_{p,ini,0.05,eff}$ considering the sampling distribution approach and a certain size of the sample n for the combined method

results for connections with $\Sigma t/d \approx 5$, a total of at least 17 bolts is necessary in order to achieve a system reserve of 30 % with a reliability of 95 %.

4.3.4 Preload losses

In the following chapters, experimentally determined preload losses $\Delta F_{p,setting,50a}$ achieved in the relaxation tests and extrapolated to 50 years are summarized and discussed for the different investigated coatings and coating systems, see Table 4.6. As shown in Figure 4.14, all preload losses are based on the respective initial preload levels $F_{p,ini}$ that have already been discussed in Chapter 4.3.3.

4.3.4.1 Investigated paint systems

4.3.4.1.1 2K-PUR coating

The experimentally determined and logarithmically extrapolated (here: to 50 years) preload losses $\Delta F_{p,setting,50a}$ for the 2K-PUR coating are summarized in Table 4.11 and graphically presented in Figure 4.27. Next to both tightening methods, KV and MDV, also coatings of two different manufacturers (here: manufacturer (a) and manufacturer (b)) are considered.

A comparison of the preload losses determined after (initial) tightening by the combined method and modified torque method $\Delta F_{p,setting,50a,mean,KV,tight.}$ and $\Delta F_{p,setting,50a,mean,MDV,in.tight.}$ show relative differences of up to $\approx 10\%$, see Table 4.11. For this comparison, the preload losses $\Delta F_{p,setting,50a,mean,KV,tight.}$ were taken as a basis for the calculation, see Equation (4.12).

$$\Delta_{KV/MDV} = \frac{\Delta F_{p,setting,50a,mean,MDV,in.tight.} \cdot 100}{\Delta F_{p,setting,50a,mean,KV,tight.}} - 100 [\%] \quad (4.12)$$

With regard to the selected service life of 50 years that was considered for the linear extrapolation and the fact that the absolute differences of preload losses $\Delta F_{p,setting,50a,mean,KV,tight.}$ and $\Delta F_{p,setting,50a,mean,MDV,in.tight.}$ remain within $\approx 2\%$ (not separately listed in Table 4.11), these slightly higher preload losses in case of the combined method appear to be negligible for a uniform evaluation.

Table 4.11 Summary of the extrapolated preload losses $\Delta F_{p,setting,50a}$ for the coating 2K-PUR investigated in the IGF research project No. 21196 BG

System No. ¹⁾	$\Sigma t/d$ [-]	Tight. method	DFT _{spec} ²⁾ [μm]	No.	Phase	$F_{p,ini}$ mean [kN]	Losses $\Delta F_{p,setting,50a}$ ³⁾					V_X [-]
							min [%]	max [%]	mean [%]	Δ ⁴⁾		
1.1a	2.4-sl	KV	nom	426.1	8	tight.	152.3	18.1	22.2	20.2	-7.6 %	0.07
		MDV	nom	469.9	7	in. tight.	101.9	18.0	19.7	18.7	-45.8 %	0.04
		MDV	nom	469.9	7	re-tight.	101.3	8.7	11.5	10.1		0.09
1.1a	2.4-dl	KV	nom	679.5	8	tight.	153.0	23.9	28.4	26.1	-5.0 %	0.06
		MDV	nom	694.4	8	in. tight.	108.7	21.5	28.9	24.8	-45.0 %	0.11
		MDV	nom	694.4	8	re-tight.	103.8	10.3	16.3	13.6		0.14
1.1a	4.9-sl	KV	nom	547.6	7	tight.	147.7	16.1	23.2	19.7	-8.9 %	0.12
		MDV	nom	546.4	8	in. tight.	107.0	16.6	19.0	17.9	-43.6 %	0.04
		MDV	nom	546.4	8	re-tight.	102.5	8.4	12.5	10.1		0.16
1.1a	5.2-dl	KV	nom	754.3	8	tight.	145.7	21.1	26.0	23.1	-3.5 %	0.08
		MDV	nom	798.5	8	in. tight.	100.4	19.5	25.0	22.3	-51.1 %	0.10
		MDV	nom	798.5	8	re-tight.	97.8	8.8	12.7	10.9		0.15
1.1b	2.4-sl	MDV	nom	522.1	7	in. tight.	107.2	17.4	20.6	18.7	-51.6 %	0.06
		MDV	nom	522.1	7	re-tight.	102.4	7.5	10.1	9.1		0.09
1.1b	2.4-dl	MDV	nom	852.3	8	in. tight.	100.8	24.5	28.3	26.1	-47.2 %	0.05
		MDV	nom	852.3	8	re-tight.	99.9	11.0	16.3	13.8		0.14

1) Coatings and coating systems in accordance with Table 4.6, considering manufacturer a and b.

2) nom: expected nominal layer thickness. Average measured coating thickness per specimen (here: $4 \times DFT_{mean}$ or $6 \times DFT_{mean}$).

3) Calculated considering the respective initial preload value $F_{p,ini}$.

4) Relative difference of $\Delta F_{p,setting,50a,mean,KV,tight.}$ and $\Delta F_{p,setting,50a,mean,MDV,in.tight.}$ determined after (initial) tightening by the combined method and modified torque method as well as preload losses $\Delta F_{p,setting,50a,mean,MDV,in.tight.}$ and $\Delta F_{p,setting,50a,mean,MDV,re-tight.}$ determined after initial tightening and re-tightening by the modified torque method.

Abbreviations:

MDV: modified torque method | KV: combined method.

With regard to the modified torque method, a clearly positive influence on the amount of preload losses $\Delta F_{p,setting,50a,mean}$ can be achieved by re-tightening. In comparison to the values $\Delta F_{p,setting,50a,mean,MDV,in.tight.}$ after initial tightening

(here: based on a measurement of approx. 3 days), approx. 44 % to 52 % lower preload losses $\Delta F_{p,setting,50a,mean,MDV,re-tight.}$ were determined after re-tightening of test specimens (here: based on a measurement of approx. 14 days). For this comparison, the preload losses $\Delta F_{p,setting,50a,mean,MDV,in.tight.}$ were taken as a basis for the calculation, see Equation (4.13).

$$\Delta_{MDV,in.tight/re-tight.} = \frac{\Delta F_{p,setting,50a,mean,MDV,re-tight.} \cdot 100}{\Delta F_{p,setting,50a,mean,MDV,in.tight.}} - 100 [\%] \quad (4.13)$$

A comparison of preload losses $\Delta F_{p,setting,50a,mean}$ determined for the coatings 1.1a and 1.1b (here: initial tightening and re-tightening by the MDV) indicates only minor differences of less than 2 % and shows that the influence of the investigated coating materials of two different manufacturers with the same binder base seems to be rather negligible. This represents a very positive result given the fact that the investigated 2K-PUR coatings do not fall under the concept of frame formulations of ZTV-ING, see explanations in Chapter 3.3.1, so that the actual components of a coating material and their ratios can be individually specified as long as the requirements for corrosion protection are fulfilled.

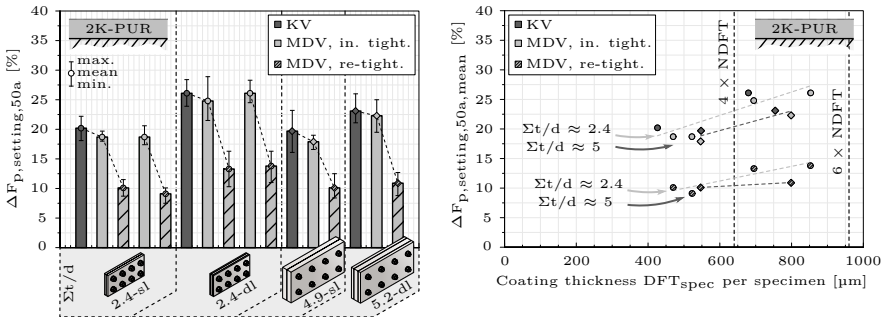


Figure 4.27 Extrapolated preload losses $\Delta F_{p,setting,50a}$ for test specimens with 2K-PUR coating tightened by the combined method and modified torque method (left) as well as mean preload losses $\Delta F_{p,setting,50a,mean}$ depending on the respective coating thickness per specimen DFT_{spec} (right)

As expected, tendentially higher preload losses can be attributed to test specimens with lower clamping length ratios of $\Sigma t/d \approx 2.4$ (here: both, single- and double-lap specimens), see Figure 4.27 (left). Furthermore, a linear correlation between the mean preload losses $\Delta F_{p,setting,50a,mean}$ and the increasing average coating thickness per specimen (here: DFT_{spec} depending on a number of coated surfaces) can be established, see Figure 4.27 (right). Despite the fact that the surface

pressures on the faying surfaces between the clamped plates (not beneath the washers) of the double-lap specimens are nominally higher than those of the single-lap specimens, see specimen configurations in Figure 4.10 and detailed explanations in Chapter 4.3.4.3.5, an influence on the amount of preload losses appears to be low. This corresponds well with the test results presented for (partly coated) reference connections in Chapter 4.2.3 and highlights the major influence of the coated contact surface area under the washers on the total amount of preload losses. Regardless of the tightening method (KV or MDV) or the investigated specimen configuration, the determined preload losses for the 2K-PUR coating appear to remain within 30 % for the specified nominal coating thickness range of $4 \times \text{NDFT}$ (single-lap specimens) and $6 \times \text{NDFT}$ (double-lap specimens), see Figure 4.27 (right).

4.3.4.1.2 Coating system 2K-EP | 2K-PUR

In contrast to the previously described system 1.1 (2K-PUR single layer, $160 \mu\text{m}$ NDFT), the investigated coating system 1.2 consists of a 2K-PUR top coat and a 2K-EP primer, each with $80 \mu\text{m}$ NDFT, and represents a coating system that falls under the concept of framework formulations of ZTV-ING.

Experimentally determined and logarithmically extrapolated preload losses $\Delta F_{p,\text{setting},50a}$ for both tightening methods (MDV and KV) are summarized in Table 4.12 and graphically presented in Figure 4.28.

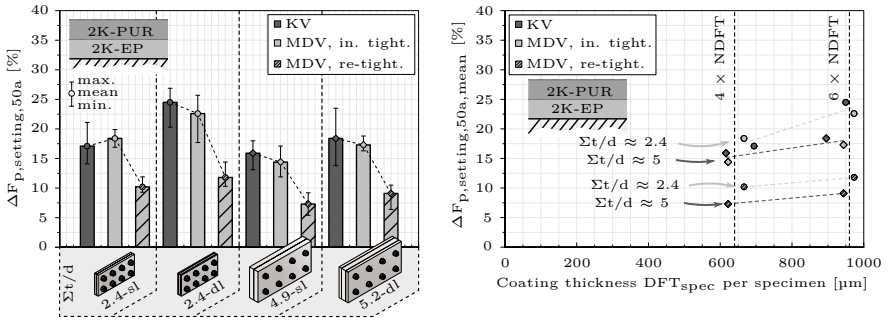


Figure 4.28 Extrapolated preload losses $\Delta F_{p,\text{setting},50a}$ for test specimens with coating system 2K-EP | 2K-PUR tightened by the combined method and modified torque method (left) as well as mean preload losses $\Delta F_{p,\text{setting},50a,\text{mean}}$ depending on the respective coating thickness per specimen DFT_{spec} (right)

Table 4.12 Summary of extrapolated preload losses $\Delta F_{p,setting,50a}$ for the coating system 2K-EP | 2K-PUR investigated in the IGF research project No. 21196 BG

System No. ¹⁾	$\Sigma t/d$ [-]	Tight. method	DFT _{spec} ²⁾		No.	Phase	F _{p,ini}		Losses $\Delta F_{p,setting,50a}$ ³⁾		V _X [-]
				[μm]			mean [kN]	min [%]	max [%]	mean [%]	
1.2a	2.4-sl	KV	nom	694.0	8	tight.	152.9	14.1	21.1	17.1	+7.7 %
		MDV		666.2	8	in. tight.	104.5	16.9	19.9	18.4	-44.7 %
		MDV		666.2	8	re-tight.	104.6	9.3	11.9	10.2	0.10
1.2a	2.4-dl	KV	nom	949.5	6	tight.	148.3	20.3	27.1	24.5	-7.7 %
		MDV		973.0	7	in. tight.	104.9	17.7	25.7	22.6	0.13
		MDV		973.0	7	re-tight.	100.0	10.3	14.4	11.8	-47.8 %
1.2a	4.9-sl	KV	nom	615.9	8	tight.	148.1	13.1	18.0	15.9	-9.2 %
		MDV		621.9	8	in. tight.	108.7	11.9	17.1	14.4	-49.1 %
		MDV		921.9	8	re-tight.	105.8	5.4	9.2	7.3	0.16
1.2a	5.2-dl	KV	nom	895.3	8	tight.	142.9	13.8	23.5	18.4	-6.1 %
		MDV		943.6	8	in. tight.	104.9	16.3	18.8	17.3	0.05
		MDV		943.6	8	re-tight.	101.3	6.4	10.5	9.1	-47.5 %

1) Coatings and coating systems in accordance with Table 4.6, considering manufacturer a and b.

2) nom: expected nominal layer thickness. Average measured coating thickness per specimen (here: $4 \times DFT_{mean}$ or $6 \times DFT_{mean}$).

3) Calculated considering the respective initial preload value F_{p,ini}.

4) Relative difference of $\Delta F_{p,setting,50a,mean,KV,tight.}$ and $\Delta F_{p,setting,50a,mean,MDV,in.tight.}$ determined after (initial) tightening by the combined method and modified torque method as well as preload losses $\Delta F_{p,setting,50a,mean,MDV,in.tight.}$ and $\Delta F_{p,setting,50a,mean,MDV,re-tight.}$ determined after initial tightening and re-tightening by the modified torque method.

Abbreviations:

MDV: modified torque method | KV: combined method.

The test results show that a relative deviation between $\Delta F_{p,setting,50a,mean,KV,tight.}$ and $\Delta F_{p,setting,50a,mean,MDV,in.tight.}$ determined after initial tightening by the combined method and modified torque method lie in a range of $\pm 10 \%$, whereby the absolute differences of $\Delta F_{p,setting,50a,mean,KV,tight.}$ and $\Delta F_{p,setting,50a,mean,MDV,in.tight.}$ remain within $\pm 2 \%$, see Figure 4.28 (left). This result corresponds well with the findings presented for the 2K-PUR coating and shows that preload losses for the KV and MDV can be considered together in an overall evaluation. Analogous to the test results for the 2K-PUR coating, a re-tightening by the MDV leads to a reduction of the preload losses determined after the initial tightening by the MDV of approx. 45 % to 49 % in this investigation, see Table 4.12.

As can be seen from Figure 4.28 (right), test specimens with a clamping length ratio of $\Sigma t/d \approx 2.4$ expectedly show higher preload losses in comparison to the test specimens with $\Sigma t/d \approx 5$. Furthermore, in line with the previously presented results for test specimens with 2K-PUR coating, the mean preload

losses $\Delta F_{p,setting,50a,mean}$ seem to correlate well with an increasing average coating thickness per specimen DFT_{spec} . For the specified nominal coating thickness range of $4 \times NDFT$ (single-lap specimens) and $6 \times NDFT$ (double-lap specimens), a loss of preload $\Delta F_{p,setting,50a,mean}$ of $< 25 \%$ can be estimated regardless of the applied tightening method or the investigated specimen configuration.

4.3.4.1.3 Coating system 2K-EP-Zn | 2K-EP-EG | 2K-PUR

The investigated coating system 2K-EP-Zn | 2K-EP-EG | 2K-PUR represents a further variation of an EP-/PUR-system, which is considered in ZTV-ING [135], see also Chapter 3.3.3 and Table 3.6. In addition to the dry film thicknesses of a nominal (nom) range of $\approx NDFT$, also the maximum (max) possible coating thicknesses ($\approx 3 \times NDFT$) in accordance with normative regulations given in EN 1090-2, Annex F and EN ISO 12944-5 are investigated. Experimentally determined and logarithmically extrapolated preload losses $\Delta F_{p,setting,50a}$ for this test series are summarized in Table 4.13 and graphically presented in Figure 4.29.

As can be seen from Table 4.13, a relative deviation of preload losses determined after initial tightening by the combined method and modified torque method $\Delta F_{p,setting,50a,mean,KV,tight.}$ and $\Delta F_{p,setting,50a,mean,MDV,in.tight.}$ once again amounts to $\pm 10 \%$ and, herewith, agrees with previously presented test results for coating systems 2K-PUR and 2K-EP | 2K-PUR. A re-tightening by the modified torque method leads to a reduction of the preload losses $\Delta F_{p,setting,50a,mean,MDV,in.tight.}$ after the initial tightening of approx. 30 % to 40 %. This result assumes that re-tightening is carried out approx. 3 days after the initial tightening of bolting assemblies.

Considering the test specimens with coating thicknesses of a nominal range (nom), higher preload losses can expectedly be assigned to the test specimens with lower clamping length ratios (here: $\Delta F_{p,setting,50a,mean,\Sigma t/d \approx 2.4} > \Delta F_{p,setting,50a,mean,\Sigma t/d \approx 5}$) and specimens with a higher number of coated surfaces (here: $\Delta F_{p,setting,50a,mean,double-lap} > \Delta F_{p,setting,50a,mean,single-lap}$). Figure 4.29 (right) shows the determined mean preload losses $\Delta F_{p,setting,50a,mean}$ depending on the actual coating thickness per specimen DFT_{spec} . Based on the test results for coating thicknesses of a nominal range (nom), a linear correlation of preload losses with an increasing coating thickness can be established. Furthermore, an assumption of a generalized loss of preload $\Delta F_{p,setting,50a,mean}$

Table 4.13 Summary of extrapolated preload losses $\Delta F_{p, \text{setting}, 50a}$ for the coating system 2K-EP-Zn | 2K-EP-EG | 2K-PUR investigated in the IGF research project No. 21196 BG

System No. ¹⁾	$\Sigma t/d$ [-]	Tight. method	DFT _{spec} ²⁾		No.	Phase	F _{p,ini}		Losses $\Delta F_{p,setting,50a}$ ³⁾		V _X [-]	
			[μm]				mean [kN]	min [%]	max [%]	mean [%]		
1.3a	2.4-sl	KV	nom	1380.0	7	tight.	153.1	21.0	26.1	23.0	-10.2 %	0.07
		MDV	nom	988.0	8	in. tight.	100.7	18.7	23.1	20.7	-40.7 %	0.08
		MDV	nom	988.0	8	re-tight.	102.5	10.5	14.8	12.3		0.13
1.3a	2.4-sl	MDV	max	2846.6	7	in. tight.	92.5	52.8	69.4	63.1	-20.3 %	0.09
		MDV	max	2846.6	7	re-tight.	84.6	44.9	55.7	50.3		0.08
1.3a	2.4-dl	MDV	nom	2136.5	6	in. tight.	108.8	26.1	31.1	28.4	-39.1 %	0.07
		MDV	nom	2136.5	6	re-tight.	113.7	15.5	18.1	17.3		0.06
1.3a	2.4-dl	MDV	max	4116.7	8	in. tight.	102.3	55.1	63.7	59.0	-17.1 %	0.05
		MDV	max	4116.7	8	re-tight.	102.6	45.4	53.7	48.9		0.06
1.3a	4.9-sl	MDV	nom	1363.1	7	in. tight.	109.9	15.1	19.9	16.7	-37.8 %	0.12
		MDV	nom	1363.1	7	re-tight.	106.0	8.1	11.6	10.4		0.11
1.3a	4.9-sl	KV	max	2972.0	8	tight.	139.4	50.4	56.0	53.0	+9.2 %	0.04
		MDV	max	3122.9	8	in. tight.	105.5	48.7	67.8	57.9	-13.5 %	0.13
		MDV	max	3122.9	8	re-tight.	104.6	30.8	61.7	50.1		0.20
1.3a	5.2-dl	MDV	nom	1990.9	8	in. tight.	107.9	18.0	21.8	20.0	-31.0 %	0.08
		MDV	nom	1990.9	8	re-tight.	101.3	11.3	17.4	13.8		0.14
1.3a	5.2-dl	KV	max	4876.6	8	tight.	127.5	52.6	59.7	56.6	+2.1 %	0.04
		MDV	max	4886.3	8	in. tight.	102.4	50.8	62.4	57.8	-20.1 %	0.06
		MDV	max	4886.3	8	re-tight.	103.8	41.1	51.0	46.2		0.07

1) Coatings and coating systems in accordance with Table 4.6.

2) nom: expected nominal layer thickness | max: expected maximum layer thickness. Average measured coating thickness per specimen (here: $4 \times \text{DFT}_{\text{mean}}$ or $6 \times \text{DFT}_{\text{mean}}$).

3) Calculated considering the respective initial preload value $F_{p, \text{ini}}$.

4) Relative difference of $\Delta F_{p, \text{setting}, 50a, \text{mean}, \text{KV}, \text{tight.}}$ and $\Delta F_{p, \text{setting}, 50a, \text{mean}, \text{MDV}, \text{in. tight.}}$ determined after (initial) tightening by the combined method and modified torque method as well as preload losses $\Delta F_{p, \text{setting}, 50a, \text{mean}, \text{MDV}, \text{in. tight.}}$ and $\Delta F_{p, \text{setting}, 50a, \text{mean}, \text{MDV}, \text{re-tight.}}$ determined after initial tightening and re-tightening by the modified torque method.

Abbreviations:

MDV: modified torque method | KV: combined method.

of $< 30 \%$ seems to be possible considering both tightening methods (KV and MDV) and every investigated specimen configuration.

Next to the results for test specimens with coating thicknesses of $\approx \text{NDFT}$, Table 4.13 and Figure 4.29 also consider preload losses determined on test specimens with excessive coating layer thicknesses (here: between $\approx 1.9 \times \text{NDFT}$ and even $\approx 2.9 \times \text{NDFT}$). As expected, a doubling of the nominal coating thickness leads to a significant increase of the loss of preload. In comparison to the above determined preload losses $\Delta F_{p, \text{setting}, 50a, \text{mean}}$ of $< 30 \%$ for coating thicknesses

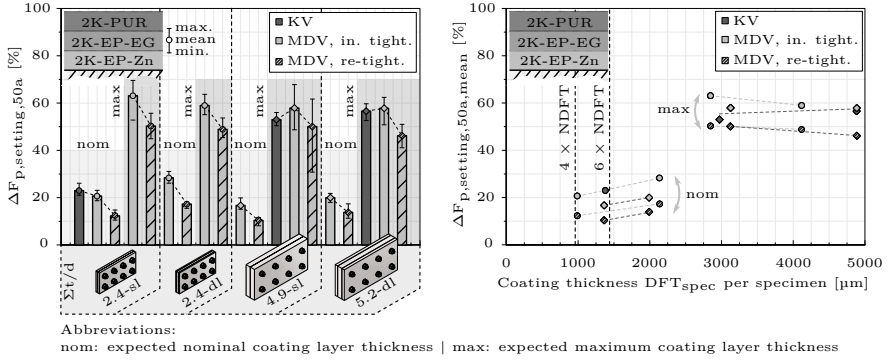


Figure 4.29 Extrapolated preload losses $\Delta F_{p,setting,50a}$ for test specimens with coating system 2K-EP-Zn | 2K-EP-EG | 2K-PUR tightened by the combined method and modified torque method (left) as well as mean preload losses $\Delta F_{p,setting,50a,mean}$ depending on the respective coating thickness per specimen DFT_{spec} (right)

of the nominal range, $\Delta F_{p,setting,50a,mean}$ of 53.0 % to 63.1 % were determined for specimens with excessive coating thicknesses after initial tightening by the modified torque method. This result corresponds to a loss of preload that is two times (at $\approx 1.9 \times NDFT$) to 3.5 times (at $\approx 2.9 \times NDFT$) higher than the preload losses determined for the nominal coating layer thicknesses. Furthermore, the favourable influence of re-tightening by the modified torque method on the amount of preload losses can only be confirmed to a limited extent, since the reduction of preload losses $\Delta F_{p,setting,50a,mean}$ after the initial tightening was determined to approx. 13 % - 20 % for excessive coating layer thicknesses.

The influence on the amount of preload losses due to the coated contact surface area beneath the washers is highlighted by minor differences of determined preload losses $\Delta F_{p,setting,50a,mean}$ between different configurations of test specimens with excessive coating thicknesses. Herein, high surface pressures beneath the washers lead to a deformation of the thick coating, see the example in Figure 4.30. Other than for coating thicknesses of nominal range, a linear correlation of preload losses with an increasing coating thickness DFT_{spec} is no longer given for excessive coating thicknesses, see Figure 4.29 (right). Unfortunately, based on the tests carried out, it is not possible to define the exact limit of the coating thickness at which a sudden increase of loss of preload occurs. However, specimens with a coating thickness of $\approx 1.5 \times NDFT$ did not show any increased preload losses,

so that an exceedance of the nominal coating thickness to this extent seems to be acceptable.

In summary, it can be pointed out that an excessive coating layer thickness does not only lead to high preload losses, but more importantly affects the control over certain parameters and correlations that can be assumed for coating thicknesses of a nominal range. This includes e.g. the favourable influence of a re-tightening by the modified torque method. Furthermore, with regard to the possible deformation of the coating and the resulting cracks, see Figure 4.30, the required corrosion protection can no longer be guaranteed. Additionally, as previously reported in Chapter 4.3.3.2, a negative influence on the amount of system reserves due to deformations beneath the washers cannot be excluded for tightening by the combined method.

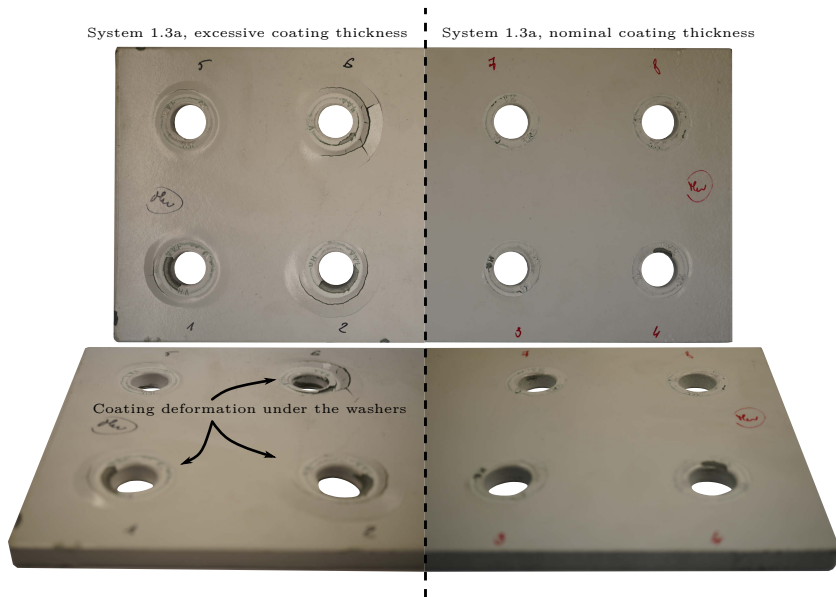


Figure 4.30 Contact surfaces beneath the washers after relaxation test for the specimens with coating system 2K-EP-Zn | 2K-EP-EG | 2K-PUR considering excessive (left) and nominal (right) coating thicknesses

4.3.4.1.4 Coating system 2K-EP-Zn | 2K-EP-EG | 2K-EP-EG | 2K-PUR

According to ZTV-ING [135], a loss of preload of $\leq 30\%$ can be assumed for connections consisting of two clamped parts coated with system 2K-EP-Zn | 2K-EP-EG | 2K-EP-EG | 2K-PUR (referred to as EP-/PUR-system). Experimentally determined and logarithmically extrapolated preload losses $\Delta F_{p,setting,50a}$ for the coating system 2K-EP-Zn | 2K-EP-EG | 2K-EP-EG | 2K-PUR are summarized in Table 4.14. Among other things, coatings of two different coating manufacturers (here: manufacturer (a) and manufacturer (b)) are considered.

Table 4.14 Summary of extrapolated preload losses $\Delta F_{p,setting,50a}$ for the coating system 2K-EP-Zn | 2K-EP-EG | 2K-EP-EG | 2K-PUR investigated in the IGF research project No. 21196 BG

System No. ¹⁾	$\Sigma t/d$ [-]	Tight. method	DFT _{spec} ²⁾		No.	Phase	$F_{p,ini}$ mean [kN]	Losses ΔF_p		$F_{p,setting,50a}$ ³⁾		V_X [-]
			[μm]					min [%]	max [%]	mean [%]	$\Delta^4)$	
1.4a	2.4-sl	MDV MDV	nom nom	1613.2 1613.2	14 14	in. tight. re-tight.	98.1 98.7	24.3 14.6	33.7 24.5	28.8 18.6	-35.4 %	0.09 0.16
1.4a	2.4-dl	MDV MDV	nom nom	2853.7 2853.7	5 5	in. tight. re-tight.	103.9 107.6	32.4 20.4	39.5 26.3	35.8 22.5	-37.1 %	0.09 0.11
1.4a	4.9-sl	MDV MDV	nom nom	1808.9 1808.9	7 7	in. tight. re-tight.	103.4 107.1	19.4 10.7	24.5 16.5	21.8 13.7	-37.2 %	0.08 0.13
1.4a	5.2-dl	MDV MDV	nom nom	2636.2 2636.2	7 7	in. tight. re-tight.	102.1 98.4	22.9 15.4	27.7 20.5	25.1 17.4	-30.6 %	0.06 0.13
1.4b	2.4-sl	MDV MDV	nom nom	1436.3 1436.3	8 8	in. tight. re-tight.	106.6 105.9	19.9 7.9	24.1 11.0	22.7 9.4	-58.5 %	0.05 0.11
1.4b	2.4-dl	MDV MDV	nom nom	2135.2 2135.2	8 8	in. tight. re-tight.	110.3 109.3	24.8 11.2	28.7 15.1	25.8 13.5	-47.8 %	0.05 0.10

1) Coatings and coating systems in accordance with Table 4.6, considering manufacturer a and b.

2) nom: expected nominal layer thickness. Average measured coating thickness per specimen (here: $4 \times DFT_{mean}$ or $6 \times DFT_{mean}$).

3) Calculated considering the respective initial preload value $F_{p,ini}$.

4) Relative difference of preload losses $\Delta F_{p,setting,50a,mean,MDV,in.tight.}$ and $\Delta F_{p,setting,50a,mean,MDV,re-tight.}$ determined after initial tightening and re-tightening by the modified torque method.

Abbreviations:

MDV: modified torque method.

Tightening of the bolting assemblies was carried out only by the modified torque method. Herein, a re-tightening leads to a reduction of preload losses determined after the initial tightening $\Delta F_{p,setting,50a,mean,MDV,in.tight.}$ of approx. 30 % to 60 % depending on the investigated specimen configuration, see Table 4.14. A comparison of the test results achieved for the coating systems 1.4a and 1.4b

shows deviations of preload losses $\Delta F_{p,setting,50a,mean}$ of $\approx 6\%$ for the single-lap and $\approx 10\%$ for the double-lap connections. This noticeable discrepancy can be mainly addressed to significantly higher coating layer thicknesses of the test specimens coated with the coating system 1.4a. Compared to the coating thickness DFT_{spec} of $\approx 1.1 \times NDFT$ that was measured for the test specimens coated with the coating system 1.4b, coating thicknesses DFT_{spec} of approx. $1.26 \times NDFT$ (single-lap connections) and $1.49 \times NDFT$ (double-lap connections) were determined for the test specimens coated with the coating system 1.4a. A graphical presentation of the determined preload losses depending on the coating thickness DFT_{spec} in Figure 4.31 (right) shows that a uniform evaluation of the test results for the coating systems of both coating manufacturers is possible.

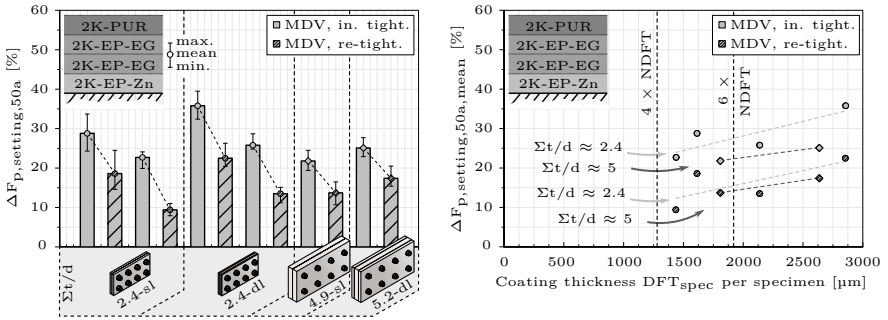


Figure 4.31 Extrapolated preload losses $\Delta F_{p,setting,50a}$ for test specimens with coating system 2K-EP-Zn | 2K-EP-EG | 2K-EP-EG | 2K-PUR tightened by the modified torque method (left) as well as mean preload losses $\Delta F_{p,setting,50a,mean}$ depending on the respective coating thickness per specimen DFT_{spec} (right)

In line with the test results of the previously presented test series, higher preload losses can be attributed to the test specimens with a lower clamping length ratio of $\Sigma t/d \approx 2.4$, see Figure 4.31 (left). Furthermore, the determined mean preload losses $\Delta F_{p,setting,50a,mean}$ show a linear progression with an increasing average coating thickness per specimen DFT_{spec} , see Figure 4.31 (right). With regard to the specified nominal coating thickness range of $4 \times NDFT$ (single-lap specimens) and $6 \times NDFT$ (double-lap specimens), a mean loss of preload $\Delta F_{p,setting,50a,mean}$ of $< 30\%$ seems to be fulfilled regardless of the investigated specimen configuration. Herewith, the reference value of the possible loss of preload given in ZTV-ING can be confirmed for this coating system.

4.3.4.1.5 Coating system 2K-EP-HS | 2K-EP-HS | 2K-PUR

The coating system 2K-EP-HS | 2K-EP-HS | 2K-PUR represents a low-solvent coating system, which is characterized by its high solid body volume. Due to its good abrasion resistance, high-solid coating systems are well suited for their use in hydraulic steel structures.

The test results for the high-solid coating system 2K-EP-HS | 2K-EP-HS | 2K-PUR achieved by the UDE/IML in this investigation are presented in order to confirm the behaviour of preload losses that was already observed for other investigated coating systems e.g. under consideration of the excessive coating thickness, a re-tightening by the MDV etc. However, considering an overall evaluation of the investigated paint systems, the test results for the coating system 2K-EP-HS | 2K-EP-HS | 2K-PUR have an informative character. At this point it should be mentioned that an extensive investigation into different common high-solid coating systems in steel construction was conducted by the Fraunhofer Institute for Large Structures in Production Engineering IGP in Rostock within the frame of the IGF research project No. 21196 BG. The test results of this investigation are presented in [6].

Experimentally determined and logarithmically extrapolated preload losses $\Delta F_{p, \text{setting}, 50a}$ for the coating system 2K-EP-HS | 2K-EP-HS | 2K-PUR are summarized in Table 4.15. All test specimens were tightened by the modified torque method. Next to the dry film thicknesses of a nominal (nom) range (here: $\approx 1.2 \times \text{NDFT}$), also the maximum (max) possible coating thicknesses of $\approx 2.6 \times \text{NDFT}$ were investigated.

A loss of preload $\Delta F_{p, \text{setting}, 50a, \text{mean}}$ of $\leq 20 \%$ was determined for the investigated specimen configurations with coating thicknesses of a nominal range (nom), see Figure 4.32. Compared to other investigated coating systems with similar coating thicknesses (here: coating system 2K-EP-Zn | 2K-EP-EG | 2K-PUR, see Chapter 4.3.4.1.3), $\Delta F_{p, \text{setting}, 50a, \text{mean}}$ of $\leq 20 \%$ represents slightly lower overall preload losses. This can be mostly addressed to a higher solid body volume of the high-solid coatings.

An exceedance of the nominal coating layer thickness by $\approx 2.6 \times \text{NDFT}$ (here: max) leads to preload losses of approx. 50 %. Herewith, the expected loss of preload for test specimens coated with coating thicknesses of $\approx 1.2 \times \text{NDFT}$, see Table 4.15, are nearly tripled. As a result, a linear correlation of preload

Table 4.15 Summary of extrapolated preload losses $\Delta F_{p, \text{setting}, 50a}$ for the coating system 2K-EP-HS | 2K-EP-HS | 2K-PUR investigated in the IGF research project No. 21196 BG

System No. ¹⁾	$\Sigma t/d$ [-]	Tight. method	DFT _{spec} ²⁾		No.	Phase	$F_{p, \text{ini}}$ mean [kN]	Losses $\Delta F_{p, \text{setting}, 50a}$ ³⁾				V_X [-]
								min [%]	max [%]	mean [%]	Δ ⁴⁾ [%]	
1.5b	2.4-sl	MDV	nom	1496.2	8	in. tight.	112.5	15.5	18.2	16.4		0.06
		MDV	nom	1496.2	8	re-tight.	111.0	7.9	10.0	9.3	-43.7 %	0.08
1.5b	2.4-sl	MDV	max	3249.5	8	in. tight.	107.7	49.6	54.4	51.3		0.04
		MDV	max	3249.5	8	re-tight.	104.1	27.6	33.7	30.4	-40.7 %	0.08
1.5b	2.4-dl	MDV	nom	2234.7	8	in. tight.	119.4	18.9	20.7	19.8		0.03
		MDV	nom	2234.7	8	re-tight.	118.3	9.9	11.8	10.9	-44.7 %	0.06
1.5b	2.4-dl	MDV	max	4983.3	8	in. tight.	102.1	47.3	55.8	50.0		0.06
		MDV	max	4983.3	8	re-tight.	97.6	32.3	36.9	34.8	-30.4 %	0.04

1) Coatings and coating systems in accordance with Table 4.6.

2) nom: expected nominal layer thickness | max: expected maximum layer thickness. Average measured coating thickness per specimen (here: $4 \times DFT_{\text{mean}}$ or $6 \times DFT_{\text{mean}}$).

3) Calculated considering the respective initial preload value $F_{p, \text{ini}}$.

4) Relative difference of preload losses $\Delta F_{p, \text{setting}, 50a, \text{mean}, \text{MDV}, \text{in. tight.}}$ and $\Delta F_{p, \text{setting}, 50a, \text{mean}, \text{MDV}, \text{re-tight.}}$ determined after initial tightening and re-tightening by the modified torque method.

Abbreviations:

MDV: modified torque method.

losses with an increasing coating thickness per specimen DFT_{spec} can only be confirmed for coating thicknesses that remain within the nominal range $NDFT$, see Figure 4.32 (right). This finding corresponds very well with the test results presented for coating system 2K-EP-Zn | 2K-EP-EG | 2K-PUR, see Chapter 4.3.4.1.3.

As can be seen from Table 4.15 and Figure 4.32 (left), a re-tightening by the modified torque method carried out on test specimens with coating thicknesses of a nominal range (nom) leads to a reduction of the preload losses $\Delta F_{p, \text{setting}, 50a, \text{mean}, \text{MDV}, \text{in. tight.}}$ after the initial tightening of ≈ 45 %. Unlike for the investigated coating system 2K-EP-Zn | 2K-EP-EG | 2K-PUR presented in Chapter 4.3.4.1.3, test specimens with excessive coating layer thicknesses (max) did not show any high deformations of the thick coating beneath the washers. Herewith, a re-tightening by the modified torque method led to a positive influence of a more usual extent. Compared to preload losses after the initial tightening, a reduction of preload losses $\Delta F_{p, \text{setting}, 50a, \text{mean}, \text{MDV}, \text{in. tight.}}$ of approx. 30 % to 40 % was determined after the re-tightening.

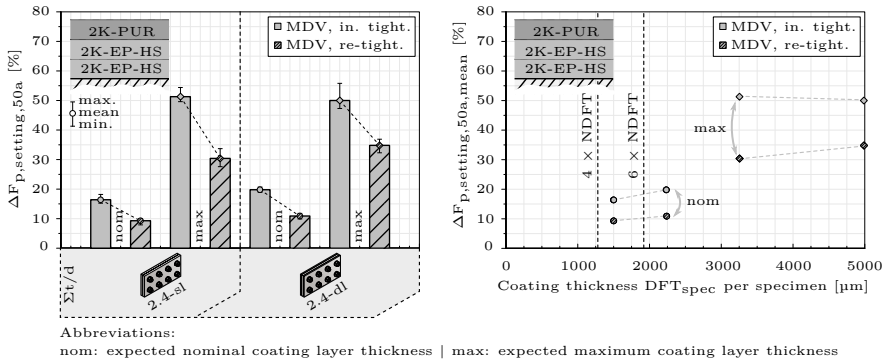


Figure 4.32 Extrapolated preload losses $\Delta F_{p,setting,50a}$ for test specimens with coating system 2K-EP-HS | 2K-EP-HS | 2K-PUR tightened by the modified torque method (left) as well as mean preload losses $\Delta F_{p,setting,50a,mean}$ depending on the respective coating thickness per specimen DFT_{spec} (right)

4.3.4.1.6 Special points to be considered for the execution of paint work with regard to preload losses

EN ISO 12944-5 [55] indicates parameters that might influence the duration of corrosion protection, whereby an increase of the coating layer thickness is addressed as well. Next to the improvement of barrier properties with an increasing coating thickness, also a possible negative effect regarding deterioration of mechanical properties and an increased risk of solvent retention are named. The solvent retention describes an incomplete evaporation of solvents during the curing process of a coating. As noted by EN ISO 12944-5, the drying time of a coating depends on parameters such as the air movement, the relative humidity and the temperature. In order to avoid insufficient drying and to minimize the risk of solvent retention, the application process has to be carried out considering specific requirements. The standard for execution and supervision of paint work EN ISO 12944-7 [57] notes that the requirements specified in the technical data sheet of a coating manufacturer, among other things, considering drying and curing durations have to be met in order to ensure the required corrosion protection. Similar information with regard to environmental conditions is also given in EN 1090-2, Annex F, whereby the reference is made to recommendations of coating manufacturers.

The above mentioned normative explanations are decisive with regard to the use of coatings in preloaded bolted connections, as the presence of solvent retention

results in deterioration of mechanical properties (e.g. increase in elasticity) and, therefore, affect the amount of preload losses. The specifications of coating manufacturers with regard to the drying time (normally based on the modified Bandow-Wolff test acc. to EN ISO 9117-5 [204]) and the waiting time between operations normally rely on a specific coating thickness at a certain temperature. However, in case of an excessive coating thickness, solvents might take much longer to completely evaporate, so that the indicated drying times tend to differ. Additionally, if a subsequent coat of a multi-layer coating system is applied too early, the solvent evaporation from the initial layer is prevented. For this reason, the technical information provided by the coating material manufacturers should serve only as a reference basis for the correct execution of the paint work. Herewith, it can be concluded that the execution of the paint work itself is very much dependent on the experience and the competence of the personnel.

In this investigation, some of the test specimens with coating systems 2K-EP-Zn | 2K-EP-EG | 2K-PUR and 2K-EP-Zn | 2K-EP-EG | 2K-EP-EG | 2K-PUR showed an increased elasticity of the coating. Although no targeted measurements to determine the retained solvent have been carried out, comparative tests as well as hardness measurements on the coated specimens indicate an incomplete solvent evaporation. Figure 4.33 summarizes the determined mean preload losses $\Delta F_{p, \text{setting}, 50a, \text{mean}}$ depending on the respective coating thickness per specimen $DFT_{\text{spec.}}$. Herein, the test results for coating systems 2K-EP-Zn | 2K-EP-EG | 2K-PUR and 2K-EP-Zn | 2K-EP-EG | 2K-EP-EG | 2K-PUR presented in Chapters 4.3.4.1.3 and 4.3.4.1.4 are supplemented by preload losses determined on test specimens with a suspected solvent retention. An increased elasticity of the coating expectedly leads to higher preload losses and, in some cases, even doubles the amount of the loss of preload that can be expected for test specimens with an assumably completed drying of the coating, see red areas in Figure 4.33.

Although crucial with regard to preload losses, parameters such as hardness and elasticity are neither covered by the framework formulations of the coating materials nor by test criteria for their certification. However, among other things,

- Buchholz indentation test according to EN ISO 2815 [203] as well as
- determination of indentation hardness by durometer method (Shore hardness) according to EN ISO 868 [205] and ISO 48-4 [206]

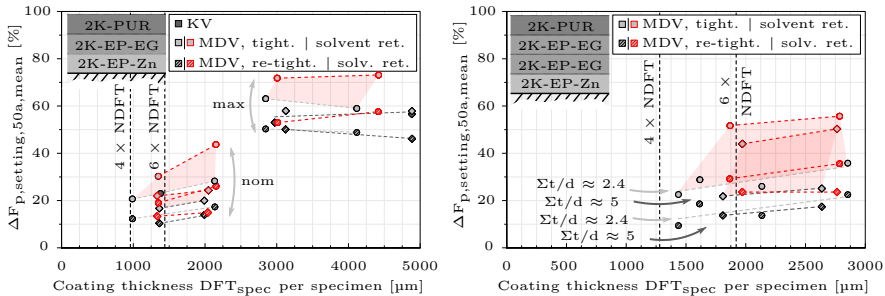


Figure 4.33 Mean preload losses $\Delta F_{p,setting,50a,mean}$ depending on the respective coating thickness per specimen DFT_{spec} for specimens coating systems 2K-EP-Zn | 2K-EP-EG | 2K-PUR (left) and 2K-EP-Zn | 2K-EP-EG | 2K-PUR (right) considering the possibility of a solvent retention

represent a few possibilities for a qualitative assessment of a coating system with regard to hardness and elasticity, see Figure 4.34. While the Buchholz test represents a method specifically developed for a single coating or multicoat systems of paint, varnish or related products, the durometer method is normally used to determine the hardness of plastics and ebonite.

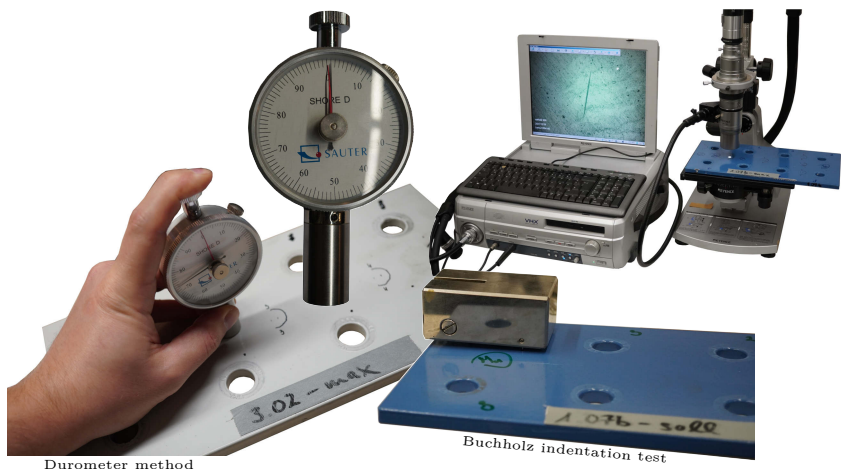


Figure 4.34 Exemplary illustration of the durometer method (left) and the Buchholz indentation test (right)

In this investigation, however, both methods were applied for selected representative test specimens with the coating systems 2K-EP-Zn | 2K-EP-EG | 2K-PUR and 2K-EP-Zn | 2K-EP-EG | 2K-EP-EG | 2K-PUR in order to evaluate whether

the hardness of the coated plates can be assessed and if so, whether a correlation exists. For the Buchholz test, a high scattering of the indentation resistance α_B was determined, so that a meaningful assessment of this method with regard to preload losses does not seem to be purposeful. Therefore, this procedure is not explained in more detail.

However, the durometer method (here: type D durometer) showed some promising results for the investigated test specimens with coating systems 2K-EP-Zn | 2K-EP-EG | 2K-PUR and 2K-EP-Zn | 2K-EP-EG | 2K-EP-EG | 2K-PUR. As can be seen from Figure 4.35 (left), some of the measurements had to be excluded from the final evaluation, as the calculated indentation considering the relationship between hardness reading H_D and the penetration of the indenter was equal to or exceeded the measured coating thickness DFT of the coated surface. Figure 4.35 (right) summarizes the valid measurements for the investigated coating systems 2K-EP-Zn | 2K-EP-EG | 2K-PUR and 2K-EP-Zn | 2K-EP-EG | 2K-EP-EG | 2K-PUR. Herein, a principle relationship between the Shore hardness H_D and the determined preload losses seems to exist. Furthermore, with regard to a similar range of coating thickness DFT, test specimens with the suspected solvent retention expectedly show lower Shore hardness H_D values compared to the test specimens with an assumably completed curing of the coating, see Figure 4.35 (left).

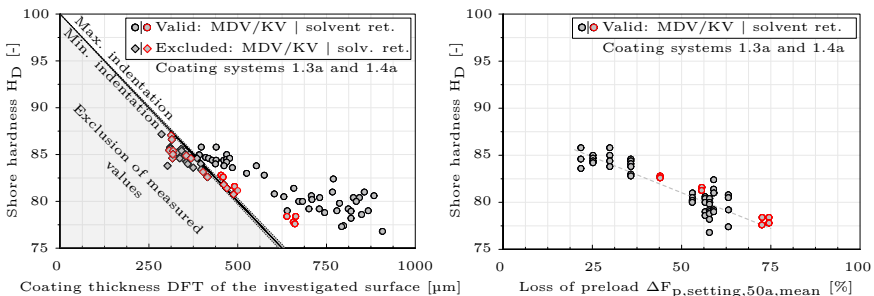


Figure 4.35 Valid and excluded measurements using the durometer method and considering the actual thickness of the coated plates DFT (left) as well as the individual Shore hardness H_D depending on the loss of preload determined for the associated test specimen (right)

The presented results provide a first insight into the possibility of a practical assessment of coating systems for application in preloaded bolted connections with regard to their hardness/elasticity. At this point, it has to be mentioned

that the durometer method according to EN ISO 868 and ISO 48-4 is only partially suitable for measuring the Shore hardness of common coating systems in steel construction using type D durometer, as the fixed geometries of the apparatus with the associated forces of the calibrated spring usually lead to a full penetration of the coating system with thicknesses of approx. $\leq 400 \mu\text{m}$. Some measurements carried out using type C (ASTM D2240 [207]) and type A (EN ISO 868 and ISO 48-4) durometers (which are not presented in the frame of this work) do not provide any transferable results. In this case, the investigated coating materials seem to be too hard in order to measure any noticeable indentation. However, especially because of its ease of use, the durometer method seems to represent a promising subject for the future research with regard to its suitability for an application considering typical coating systems in steel construction. A qualitative estimation of hardness/elasticity of coating systems might be helpful in order to prevent the negative influence on the preload losses due to e.g. solvent retention.

4.3.4.2 Investigated powder coatings and coating systems

4.3.4.2.1 EP/SP Coating

Experimentally determined and logarithmically extrapolated preload losses $\Delta F_{p, \text{setting}, 50a}$ for the EP/SP coating are summarized in Table 4.16. Additionally, the test results are graphically presented in Figure 4.36. Next to both tightening methods (MDV and KV), also different ranges of coating thicknesses are taken into account for this test series.

As can be seen from Figure 4.36 (left), slightly higher preload losses were observed for most of the investigated test specimens tightened by the KV compared to MDV. The relative difference of preload losses $\Delta F_{p, \text{setting}, 50a, \text{mean}, \text{KV}, \text{tight.}}$ and $\Delta F_{p, \text{setting}, 50a, \text{mean}, \text{MDV}, \text{in. tight.}}$ varies between approx. 3 % to 35 %, see Table 4.16. In accordance with the test results presented for 2K-PUR coating and different EP-/PUR coating systems in Chapter 4.3.4.1, a re-tightening by the modified torque method leads to a reduction of the determined preload losses $\Delta F_{p, \text{setting}, 50a, \text{mean}, \text{MDV}, \text{in. tight.}}$ after initial tightening of up to approx. 60 %. As expected, slightly higher preload losses can be assigned to the test specimens with a lower clamping length ratio of $\Sigma t/d \approx 2.4$ compared to $\Sigma t/d \approx 5$ and to test specimens with a higher number of coated surfaces.

Table 4.16 Summary of extrapolated preload losses $\Delta F_{p,setting,50a}$ for the EP/SP coating investigated in the IGF research project No. 21196 BG

System No. ¹⁾	$\Sigma t/d$ [-]	Tight. method	DFT _{spec} ²⁾ [μm]	No.	Phase	$F_{p,ini}$ mean [kN]	Losses $\Delta F_{p,setting,50a}$ ³⁾				V_X [-]
							min [%]	max [%]	mean [%]	Δ ⁴⁾	
2.1	2.4-sl	KV	nom	291.8	8	tight.	156.2	8.4	13.6	10.7	0.20
		MDV		352.6	7	in. tight.	113.6	7.2	9.3	7.8	0.09
		MDV		352.6	7	re-tight.	110.6	6.4	8.2	6.4	0.16
2.1	2.4-sl	KV	max	951.9	7	tight.	154.3	11.4	14.6	12.7	0.08
		MDV		893.1	8	in. tight.	98.7	8.0	12.0	10.1	0.12
		MDV		893.1	6	re-tight.	97.7	3.6	7.1	5.6	0.24
2.1	2.4-dl	KV	nom	426.1	8	tight.	153.2	8.6	14.5	11.4	0.16
		MDV		467.3	6	in. tight.	99.2	8.7	15.1	11.9	0.25
		MDV		467.3	6	re-tight.	94.9	2.1	7.6	5.0	0.43
2.1	2.4-dl	KV	max	1322.4	8	tight.	154.7	12.0	16.1	13.8	0.10
		MDV		1396.1	12	in. tight.	104.7	11.2	15.4	13.4	0.11
		MDV		1396.1	12	re-tight.	100.8	6.5	11.1	9.1	0.16
2.1	4.9-sl	KV	nom	292.8	8	tight.	146.8	8.3	11.9	10.2	0.14
		MDV		309.9	8	in. tight.	105.0	4.1	9.6	7.0	0.34
		MDV		309.9	8	re-tight.	104.0	2.5	5.7	3.8	0.29
2.1	4.9-sl	KV	max	971.7	8	tight.	147.6	9.5	14.3	11.9	0.14
		MDV		1049.8	8	in. tight.	114.7	6.2	9.1	7.8	0.12
		MDV		1049.8	8	re-tight.	112.7	2.0	5.8	4.1	0.30
2.1	5.2-dl	KV	nom	430.1	7	tight.	144.5	7.2	10.9	9.2	0.16
		MDV		457.6	6	in. tight.	109.1	5.7	12.3	8.9	0.34
		MDV		457.6	6	re-tight.	108.2	3.3	9.1	5.4	0.45
2.1	5.2-dl	KV	max	1437.3	7	tight.	143.9	7.2	12.2	10.4	0.18
		MDV		1343.0	8	in. tight.	105.2	7.7	12.0	9.4	0.14
		MDV		1343.0	8	re-tight.	102.4	2.8	5.0	3.7	0.22

1) Coatings and coating systems in accordance with Table 4.6.

2) nom: expected nominal layer thickness | max: expected maximum layer thickness. Average measured coating thickness per specimen (here: $4 \times DFT_{mean}$ or $6 \times DFT_{mean}$).

3) Calculated considering the respective initial preload value $F_{p,ini}$.

4) Relative difference of $\Delta F_{p,setting,50a,mean,KV,tight.}$ and $\Delta F_{p,setting,50a,mean,MDV,in.tight.}$ determined after (initial) tightening by the combined method and modified torque method as well as preload losses $\Delta F_{p,setting,50a,mean,MDV,in.tight.}$ and $\Delta F_{p,setting,50a,mean,MDV,re-tight.}$ determined after initial tightening and re-tightening by the modified torque method.

Abbreviations:

MDV: modified torque method | KV: combined method.

In contrast to the investigated paint systems in Chapter 4.3.4.1, a separate consideration of the test results for test specimens with an excessive coating thickness is not necessary, see Figure 4.36 (right). The determined preload losses $\Delta F_{p,setting,50a,mean}$ tend to increase linearly even up to coating thicknesses of test specimens that correspond to approx. $3 \times NDFT$. Regardless of the investigated specimen configuration, a maximum loss of preload $\Delta F_{p,setting,50a,mean}$ for the

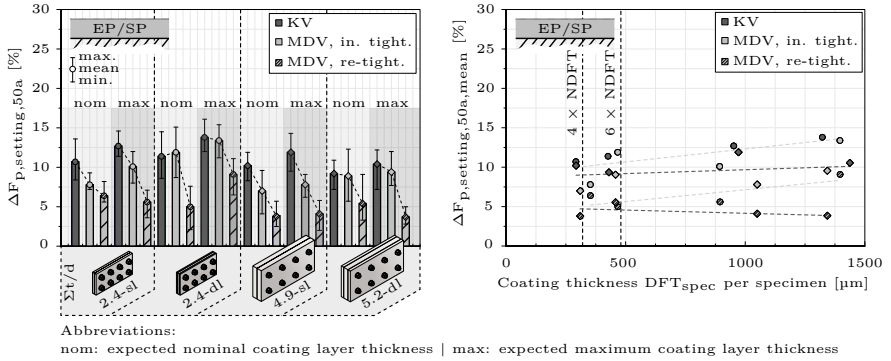


Figure 4.36 Extrapolated preload losses $\Delta F_{p,setting,50a}$ for test specimens with EP/SP coating tightened by the combined method and modified torque method (left) as well as mean preload losses $\Delta F_{p,setting,50a,mean}$ depending on the respective coating thickness per specimen DFT_{spec} (right)

EP/SP coating remains within 15 %. This result corresponds to the range of preload losses that was determined for the reference configurations presented in Chapter 4.2.3. Furthermore, these low preload losses highlight the excellent mechanical properties of the investigated powder coating with its capability to withstand high surface pressures beneath the washers. In contrast to the investigated paint systems in Chapter 4.3.4.1, an exceedance of the nominal coating layer thickness in preloaded bolted connections coated with powder coating EP/SP does not seem to be as critical with regard to both, preload losses and system reserves.

4.3.4.2.2 Coating system EP | SP

The test results of the investigation into preloaded bolted connections with a powder coating system consisting of an epoxy powder coat (EP) and a top coat of polyester powder (SP) are summarized in Table 4.17. Analogous to the test results presented for the EP/SP coating in Chapter 4.3.4.2.1, both tightening methods (MDV and KV) as well as different ranges of coating thicknesses are considered for this test series.

A comparison of the test specimens tightened by the MDV and KV shows that the relative difference between the determined average preload losses $\Delta F_{p,setting,50a,mean,KV,tight.}$ and $\Delta F_{p,setting,50a,mean,MDV,in.tight.}$ remains within approx. 25 %, see Table 4.17 and Figure 4.37 (left). This results agrees well

Table 4.17 Summary of extrapolated preload losses $\Delta F_{p,setting,50a}$ for the coating system EP | SP investigated in the IGF research project No. 21196 BG

System No. ¹⁾	$\Sigma t/d$ [-]	Tight. method	DFT _{spec} ²⁾ [μm]	No.	Phase	$F_{p,ini}$ mean [kN]	Losses $\Delta F_{p,setting,50a}$ ³⁾				V_X [-]
							min [%]	max [%]	mean [%]	Δ ⁴⁾ [%]	
2.2	2.4-sl	KV	nom	720.8	8	tight.	152.1	11.1	13.8	12.6	0.08
		MDV		817.9	8	in. tight.	109.1	8.5	10.1	9.4	0.06
		MDV		817.9	8	re-tight.	104.3	3.4	6.0	4.6	0.22
2.2	2.4-sl	KV	max	1862.9	16	tight.	148.5	14.3	24.3	20.2	0.12
		MDV		1755.7	14	in. tight.	102.7	18.4	30.0	23.3	0.18
		MDV		1755.7	14	re-tight.	102.2	11.1	21.2	14.8	0.22
2.2	2.4-dl	KV	nom	1166.4	8	tight.	151.5	10.6	15.9	13.0	0.15
		MDV		1143.8	8	in. tight.	113.6	9.8	14.2	11.4	0.12
		MDV		1143.8	8	re-tight.	108.2	4.3	7.8	5.6	0.21
2.2	2.4-dl	KV	max	2141.0	8	tight.	150.9	14.4	21.0	17.9	0.13
		MDV		2067.4	6	in. tight.	101.3	14.5	21.6	18.1	0.15
		MDV		2067.4	6	re-tight.	94.3	7.8	15.3	10.8	0.24
2.2	4.9-sl	KV	nom	1044.3	16	tight.	141.2	5.4	11.7	9.5	0.19
		MDV		797.2	8	in. tight.	107.6	6.2	10.6	8.5	0.21
		MDV		797.2	8	re-tight.	105.1	2.4	5.8	4.3	0.24
2.2	4.9-sl	KV	max	1565.3	8	tight.	147.1	8.6	11.6	10.0	0.09
		MDV		1604.1	7	in. tight.	123.0	8.2	16.3	11.1	0.25
		MDV		1604.1	7	re-tight.	123.3	4.3	8.9	6.5	0.26
2.2	5.2-dl	KV	nom	1346.2	5	tight.	138.6	9.1	16.6	12.0	0.24
		MDV		1663.2	16	in. tight.	104.4	9.1	14.3	11.2	0.14
		MDV		1663.2	16	re-tight.	104.4	4.1	8.9	6.9	0.16
2.2	5.2-dl	KV	max	2087.6	6	tight.	145.4	12.3	17.7	15.9	0.12
		MDV		2050.3	7	in. tight.	105.3	11.4	17.7	14.2	0.17
		MDV		2050.3	7	re-tight.	97.9	5.9	9.1	7.2	0.17

1) Coatings and coating systems in accordance with Table 4.6.

2) nom: expected nominal layer thickness | max: expected maximum layer thickness. Average measured coating thickness per specimen (here: $4 \times DFT_{mean}$ or $6 \times DFT_{mean}$).

3) Calculated considering the respective initial preload value $F_{p,ini}$.

4) Relative difference of $\Delta F_{p,setting,50a,mean,KV,tight.}$ and $\Delta F_{p,setting,50a,mean,MDV,in.tight.}$ determined after (initial) tightening by the combined method and modified torque method as well as preload losses $\Delta F_{p,setting,50a,mean,MDV,in.tight.}$ and $\Delta F_{p,setting,50a,mean,MDV,re-tight.}$ determined after initial tightening and re-tightening by the modified torque method.

Abbreviations:

MDV: modified torque method | KV: combined method.

with the experimental findings for bolted connections with the EP/SP coating and, therefore, indicates that a separate consideration of the preload losses is not necessary for both investigated tightening methods. In comparison to preload losses $\Delta F_{p,setting,50a,mean,MDV,in.tight.}$, determined after the initial tightening by the MDV, a relative reduction of $\Delta F_{p,setting,50a,mean,MDV,re-tight.}$ of approx. 36 % to 51 % was observed after re-tightening of the test specimens.

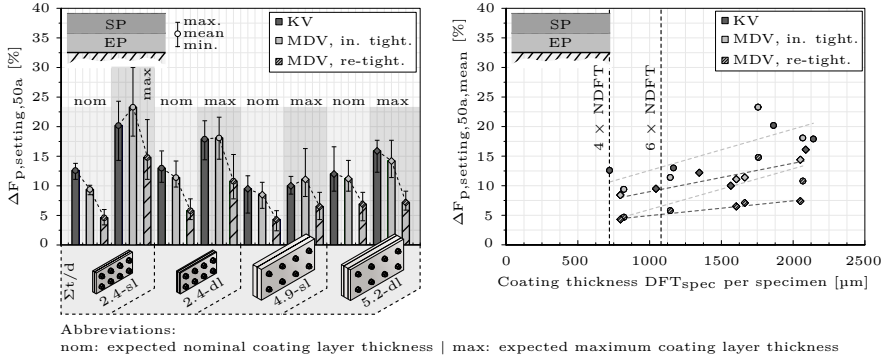


Figure 4.37 Extrapolated preload losses $\Delta F_{p,setting,50a}$ for test specimens with coating system EP | SP tightened by the combined method and modified torque method (left) as well as mean preload losses $\Delta F_{p,setting,50a,mean}$ depending on the respective coating thickness per specimen DFT_{spec} (right)

In accordance with the test results presented for the EP/SP coating in Chapter 4.3.4.2.1, a separate consideration of excessive coating thicknesses with regard to the determined preload losses is not necessary for coating system EP | SP, see Figure 4.36 (right). Despite a few outliers (here: test specimens with $\Sigma t/d \approx 2.4$ (single-lap) and an excessive coating thickness (max) tightened by the MDV, see Figure 4.36 (right)), preload losses $\Delta F_{p,setting,50a,mean}$ seem to increase linearly with an increasing coating thickness up to approx. $\approx 2.6 \times NDFT$. Furthermore, a loss preload of $< 15\%$ can be confirmed for all investigated specimen configurations considering the nominal coating layer thickness (here: $4 \times NDFT$ and $6 \times NDFT$ in Figure 4.36 (right)). Considering the range of coating thickness DFT_{spec} of approx. $700\ \mu m$ to $1500\ \mu m$, in which the test results for both investigated powder coating systems EP/SP (presented in Chapter 4.3.4.2.1) and EP | SP are available, no significant difference of the determined preload losses $\Delta F_{p,setting,50a,mean}$ can be observed. Therefore, the coating system EP | SP can be classified as a continuation of the EP/SP coating presented in Chapter 4.3.4.2.1 with similar mechanical properties.

At this point, it should be mentioned that some of the investigated test specimens were subjected to spalling of the top coat (here: polyester coat SP) during tightening, see exemplary illustration in Figure 4.38. However, several tests carried out on additionally prepared specimens confirmed the comparability of the determined preload losses for both, the affected and the newly prepared connections, and were directly considered in Table 4.17. The possible sources

of error that caused spalling in this investigation may include the soiling (no immediate application of the top coat) and/or the complete cross-linking of the first coating layer. For the latter, a good bond between the first and second coat might be achieved by not fully curing the first coating layer before the final application of the top coat. The spalling around the bolt holes represents a critical case in terms of aesthetics, but especially with regard to the corrosion protection. In practice, however, the incorrect execution of the coating work with regard to the adhesion of the coating can be prevented by some user-friendly tests such as the pull-off test for adhesion according to EN ISO 4624 [208] or the cross-cut test according to EN ISO 2409 [209]. Especially the latter is universally applicable and can serve as a field test with a visual assessment.



Figure 4.38 Exemplary illustration of spalling of the top coat (here: polyester coat) observed for the EP | SP powder coating system

4.3.4.2.3 EP/SP coating on hot dip galvanized surfaces (HDG)

The EP/SP coating, which results have been discussed with regard to grit blasted surfaces in Chapter 4.3.4.2.1, is also considered for the applications on hot dip galvanized surfaces (here: as a duplex-system). Experimentally determined and logarithmically extrapolated preload losses $\Delta F_{p, \text{setting}, 50a}$ are summarized in Table 4.18 and graphically presented in Figure 4.39.

As pointed out in Chapter 4.3.2, the steel plates of $t = 35$ mm that were used for single- and double-lap test specimens with $\Sigma t/d \approx 5$ possessed an increased silicon content of 0.43 % to 0.47 %, which led to a high zinc coating

Table 4.18 Summary of extrapolated preload losses $\Delta F_{p,setting,50a}$ for the EP/SP coating on hot dip galvanized surfaces investigated in the IGF research project No. 21196 BG

System No. ¹⁾	$\Sigma t/d$ [-]	Tight. method	DFT _{spec} ²⁾ [μm]	No.	Phase	$F_{p,ini}$ mean [kN]	Losses $\Delta F_{p,setting,50a}$ ³⁾				V_X [-]
							min [%]	max [%]	mean [%]	Δ ⁴⁾	
3.1	2.4-sl	KV	nom	1324.0	6	tight.	153.6	13.0	15.8	14.8	0.08
		MDV		1340.5	8	in. tight.	104.6	12.7	15.7	13.9	-6.1 %
		MDV		1340.5	8	re-tight.	103.2	5.5	7.9	6.9	-50.3 %
3.1	2.4-dl	KV	nom	2084.4	7	tight.	155.2	14.4	19.2	16.4	-5.5 %
		MDV		2034.9	8	in. tight.	110.4	12.8	17.5	15.5	-51.5 %
		MDV		2034.9	8	re-tight.	104.8	5.8	8.4	7.5	0.13
3.1	4.9-sl	KV	nom	2434.4	6	tight.	146.7	19.3	22.1	20.9	+14.8 %
		MDV		2396.3	8	in. tight.	111.0	22.0	27.4	24.0	-60.6 %
		MDV		2396.3	8	re-tight.	105.9	8.1	11.0	9.4	0.12
3.1	5.2-dl	KV	nom	2851.1	7	tight.	144.3	15.5	18.5	17.2	-18.7 %
		MDV		2741.4	8	in. tight.	115.0	13.0	15.0	14.0	-54.2 %
		MDV		2741.4	8	re-tight.	110.5	4.6	7.6	6.4	0.16

1) Coatings and coating systems in accordance with Table 4.6.

2) nom: expected nominal layer thickness. Average measured coating thickness per specimen (here: $4 \times DFT_{mean}$ or $6 \times DFT_{mean}$).

3) Calculated considering the respective initial preload value $F_{p,ini}$.

4) Relative difference of $\Delta F_{p,setting,50a,mean,KV,tight.}$ and $\Delta F_{p,setting,50a,mean,MDV,in.tight.}$ determined after (initial) tightening by the combined method and modified torque method as well as preload losses $\Delta F_{p,setting,50a,mean,MDV,in.tight.}$ and $\Delta F_{p,setting,50a,mean,MDV,re.tight.}$ determined after initial tightening and re-tightening by the modified torque method.

Abbreviations:

MDV: modified torque method | KV: combined method.

thicknesses of $\approx 557 \mu m$ DFT. These zinc coating thicknesses correspond to an increase of $\approx 200 \mu m$ to $300 \mu m$ compared to the zinc coating thicknesses measured for the steel plates of $t = 8 \text{ mm}$, $t = 15 \text{ mm}$ and $t = 20 \text{ mm}$. An increased zinc coating thickness of the steel plates of $t = 35 \text{ mm}$ is expectedly reflected in the determined preload losses, whereby especially the single-lap test specimens with $\Sigma t/d = 4.9$ are affected, see Figure 4.39, as the high zinc coatings are arranged directly beneath the washers. In fact, the determined mean preload losses $\Delta F_{p,setting,50a,mean}$ are even higher for the single-lap test specimens with $\Sigma t/d = 4.9$ compared to double-lap test specimens with $\Sigma t/d = 5.2$ with $\Delta F_{p,setting,50a,mean}$ of approx. 20 % to 24 % and approx. 14 % to 17 % respectively despite the lower measured coating thickness per specimen DFT_{spec} , see Table 4.18. Herewith, the influence of the coated surfaces beneath the washers on the amount of preload losses shall be highlighted again at this point. Furthermore, the higher zinc coating thicknesses of test specimens with higher clamping length

ratios of $\Sigma t/d \approx 5$ lead to higher preload losses compared to the nominally more critical connections with $\Sigma t/d \approx 2.4$. However, considering the fact that the hot dip galvanizing was carried out in accordance with EN ISO 1461 and DAST-Guideline 022 and under consideration of the practical boundary conditions, this result seems to represent a reasonable case for practical application in steel construction.

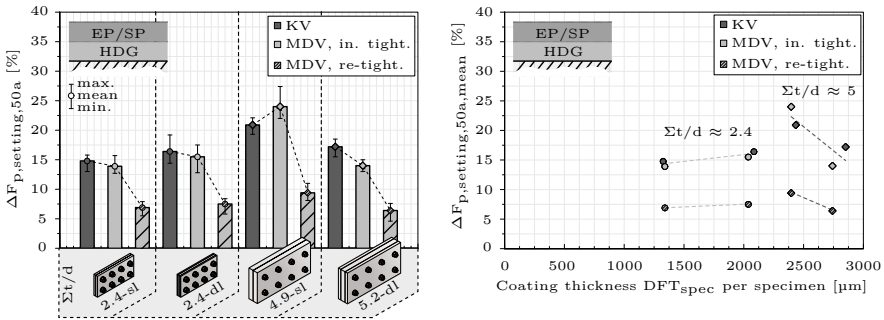


Figure 4.39 Extrapolated preload losses $\Delta F_{p,setting,50a}$ for test specimens with EP/SP coating on hot dip galvanized surfaces (HDG) tightened by the combined method and modified torque method (left) as well as mean preload losses $\Delta F_{p,setting,50a,mean}$ depending on the respective coating thickness per specimen DFT_{spec} (right)

Compared to test specimens with $\Sigma t/d \approx 2.4$ that were coated with EP/SP on grit blasted steel, see Chapter 4.3.4.2.1, the investigated test specimens with EP/SP coating on hot dip galvanized surfaces achieved similar preload losses $\Delta F_{p,setting,50a,mean}$ of approx. 14 % - 15 %. This comparison of both test series applies to the coating thickness range DFT_{spec} of $\approx 1300 \mu m$ to $1400 \mu m$. Herewith, similar mechanical properties of both investigated coating systems are confirmed. Therefore, a consolidated consideration of preload losses with regard to an overall assessment of the powder coating systems seems to be reasonable.

A relative difference of the determined preload losses $\Delta F_{p,setting,50a,mean,MDV,in.tight.}$ and $\Delta F_{p,setting,50a,mean,KV,tight.}$ after the initial tightening by the MDV and KV was determined to $\pm 19 \%$, see Table 4.18. Furthermore, a re-tightening in case of the modified torque method leads to a reduction of the preload losses $\Delta F_{p,setting,50a,mean,MDV,in.tight.}$ after initial tightening of $\approx 50 \%$ to 60% . Since the nominal thickness is not specified for the zinc coating, an assessment of the determined preload losses with regard to such limitation is not possible. However,

regardless of the tightening method or the investigated specimen configuration, a loss of preload $\Delta F_{p,setting,50a,mean}$ of $< 25 \%$ can be estimated.

4.3.4.2.4 Coating system EP | SP on hot dip galvanized surfaces (HDG)

Next to the coating system EP | SP on grit blasted surfaces, see test results in Chapter 4.3.4.2.2, the same coating system EP | SP is also considered for applications on hot dip galvanized surfaces (here: as a duplex-system) in this investigation. Experimentally determined and logarithmically extrapolated preload losses $\Delta F_{p,setting,50a}$ are summarized in Table 4.19 and graphically presented in Figure 4.40.

Table 4.19 Summary of extrapolated preload losses $\Delta F_{p,setting,50a}$ for the coating system EP | SP on hot dip galvanized surfaces investigated in the IGF research project No. 21196 BG

System No. ¹⁾	$\Sigma t/d$ [-]	Tight. method	DFT _{spec} ²⁾ [μm]			F _{p,ini} mean [kN]	Losses $\Delta F_{p,setting,50a}$ ³⁾				V _X [-]	
				No.	Phase		min [%]	max [%]	mean [%]	mean Δ ⁴⁾		
3.2	2.4-sl	KV	nom	1454.4	6	tight.	152.9	16.1	20.3	17.6	-24.7 %	0.09
		MDV		1471.9	8	in. tight.	120.1	12.6	14.7	13.3	-52.5 %	0.06
		MDV		1471.9	8	re-tight.	114.4	4.4	7.5	6.3		0.17
3.2	2.4-dl	KV	nom	2190.2	6	tight.	148.2	15.9	20.6	18.2	-20.1 %	0.11
		MDV		2260.5	8	in. tight.	112.4	13.6	15.3	14.5	-46.8 %	0.04
		MDV		2260.5	8	re-tight.	105.5	6.1	8.4	7.7		0.10
3.2	4.9-sl	KV	nom	2460.5	8	tight.	142.6	20.3	23.3	21.7	+8.5 %	0.05
		MDV		2478.1	8	in. tight.	109.0	21.9	25.4	23.6	-53.6 %	0.05
		MDV		2478.1	8	re-tight.	102.8	9.5	13.2	11.0		0.12
3.2	5.2-dl	KV	nom	2829.1	7	tight.	144.0	13.1	16.7	15.3	+9.8 %	0.08
		MDV		2933.2	8	in. tight.	109.0	14.9	19.0	16.8	-57.9 %	0.10
		MDV		2933.2	8	re-tight.	104.6	5.9	8.7	7.1		0.14

1) Coatings and coating systems in accordance with Table 4.6.
2) nom: expected nominal layer thickness. Average measured coating thickness per specimen (here: $4 \times DFT_{mean}$ or $6 \times DFT_{mean}$).
3) Calculated considering the respective initial preload value $F_{p,ini}$.
4) Relative difference of $\Delta F_{p,setting,50a,mean,KV,tight.}$ and $\Delta F_{p,setting,50a,mean,MDV,in.tight.}$ determined after (initial) tightening by the combined method and modified torque method as well as preload losses $\Delta F_{p,setting,50a,mean,MDV,in.tight.}$ and $\Delta F_{p,setting,50a,mean,MDV,re-tight.}$ determined after initial tightening and re-tightening by the modified torque method.

Abbreviations:
MDV: modified torque method | KV: combined method.

Analogous to the test results presented in Chapter 4.3.4.2.3, the influence of the increased zinc coating thicknesses for single-lap test specimens with $\Sigma t/d = 4.9$ is reflected in this investigation as well. Herein, the preload losses $\Delta F_{p,setting,50a,mean}$

for single-lap test specimens with $\Sigma t/d = 4.9$ were determined to $\approx 22\%$ to 24% , see Figure 4.40 (left). The nominally more critical connections with $\Sigma t/d \approx 2.4$, on the other hand, showed preload losses $\Delta F_{p,setting,50a,mean}$ of $\approx 13\%$ to 18% .

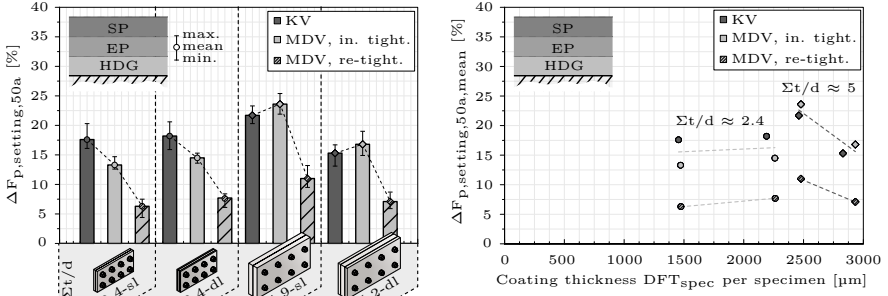


Figure 4.40 Extrapolated preload losses $\Delta F_{p,setting,50a}$ for test specimens with coating system EP | SP on hot dip galvanized surfaces (HDG) tightened by the combined method and modified torque method (left) as well as mean preload losses $\Delta F_{p,setting,50a,mean}$ depending on the respective coating thickness per specimen DFT_{spec} (right)

Considering the range of coating thicknesses of up to $\approx 2260\ \mu m$, a comparison of preload losses determined for the coating system EP | SP on grit blasted and on hot dip galvanized surfaces (here: single- and double-lap specimens with $\Sigma t/d \approx 2.4$) can be carried out. Herein, most of the preload losses $\Delta F_{p,setting,50a,mean}$ lie within 20% for both coating systems and once again indicate similar mechanical properties. Therefore, a uniform evaluation of the preload losses seems to be possible.

As can be seen from Table 4.19, a relative deviation of the preload losses $\Delta F_{p,setting,50a,mean,MDV,in.tight.}$ and $\Delta F_{p,setting,50a,mean,KV,tight.}$ of $\pm 25\%$ can be determined considering test specimens tightened by the MDV and KV. A re-tightening by the modified torque method results in a reduction of the preload losses after initial tightening of $\approx 47\%$ to 58% . These test results are in line with the experimental findings presented for other investigated paint and powder coating systems.

Analogous to the EP/SP coating on hot dip galvanized surfaces, an assesment of preload losses with regard to a nominal zinc layer thickness is not possible. However, preload losses $\Delta F_{p,setting,50a,mean} < 25\%$ were determined regardless of the tightening method and the investigated specimen configuration.

4.3.4.3 Summarizing remarks on experimentally determined preload losses

4.3.4.3.1 Influence of the tightening method

Figure 4.41 shows a comparison of the determined preload losses after (initial) tightening by the combined method $\Delta F_{p, \text{setting}, 50a, \text{mean}, KV, \text{tight.}}$ and the modified torque method $\Delta F_{p, \text{setting}, 50a, \text{mean}, MDV, \text{in. tight.}}$. The comparison considers different investigated paint and powder coating systems (1.1a to 3.2 acc. to Table 4.6) applied on test specimens with $\Sigma t/d \approx 2.4$ and $\Sigma t/d \approx 5$. The test specimens with excessive coating layer thicknesses (here: systems 1.3a and 1.5b acc. to Table 4.6) are not taken into account.

Considering the relative deviation of preload losses $\Delta F_{p, \text{setting}, 50a, \text{mean}, KV, \text{tight.}}$ and $\Delta F_{p, \text{setting}, 50a, \text{mean}, MDV, \text{in. tight.}}$ determined by Equation (4.12), differences in a range of approx. -35 % to 15 % were determined. As can be seen from Figure 4.41, the preload losses $\Delta F_{p, \text{setting}, 50a, \text{mean}, KV, \text{tight.}}$ for the combined method tend to be slightly higher, however, the large majority of the relative deviations remain within 10 %. Even considering the highest indicated relative deviation of approx. 35 %, the absolute difference (here: taking into account the subtracted preload losses $\Delta F_{p, \text{setting}, 50a, KV, \text{tight.}} - \Delta F_{p, \text{setting}, 50a, MDV, \text{in. tight.}}$) amounts to ≈ 4 %. With regard to the selected service life of 50 years for the linear extrapolation of preload losses, these deviations between the test specimens tightened by the combined method and modified torque method appear to be rather negligible for a uniform evaluation of preload losses. Furthermore, the determined deviations are consistent with the test results presented in Chapter 4.2.3.

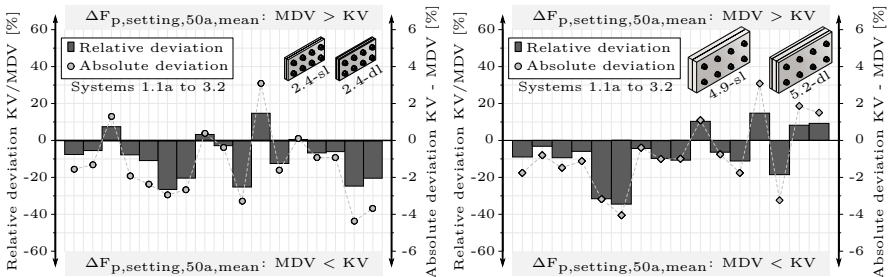


Figure 4.41 Comparison of mean preload losses $\Delta F_{p, \text{setting}, 50a, \text{mean}, KV, \text{tight.}}$ and $\Delta F_{p, \text{setting}, 50a, \text{mean}, MDV, \text{in. tight.}}$ determined after tightening by the combined method and the modified torque method for different investigated paint and powder coating systems

As discussed in Chapter 3.3.3.3, most of the guide values for an estimation of potential preload losses given in Table I.1 of EN 1090-2 are based on a preload level of approx. $F_{p,C}^*$, as these values emerged from investigations carried out by *Katzung et al.* [148]-[150], which considered the torque method acc. to DIN 18800-7 [41] (now equivalent to the modified torque method). Formally, however, the values given in Table I.1 also apply to other tightening methods that are specified by EN 1090-2. Considering the test results for specimens tightened by the combined method and modified torque method, a generalized assumption of preload losses seems to be possible. Furthermore, with regard to the test results of the IGF research project No. 18711 BG presented in [94]-[95], a transferability of the preload losses to other tightening methods such as tension control bolts and lock bolts proves to be conceivable, as the initial preload values after tightening by those tightening methods normally lie within a range of $F_{p,C}^* < F_{p,ini} < 1.3 F_{p,C}$, which was covered in the frame of this investigation by the the modified torque method and the combined method.

4.3.4.3.2 Influence of re-tightening by the modified torque method

A comparison of the mean preload losses $\Delta F_{p,setting,50a,mean,MDV,in.tight.}$ and $\Delta F_{p,setting,50a,mean,MDV,re-tight.}$ between the initial tightening and re-tightening by the modified torque method for different investigated coating systems (1.1a to 3.2 acc. to Table 4.6) and specimen configurations is presented in Figure 4.42. The test specimens with excessive coating layer thicknesses (here: systems 1.3a and 1.5b acc. to Table 4.6) are not taken into account.

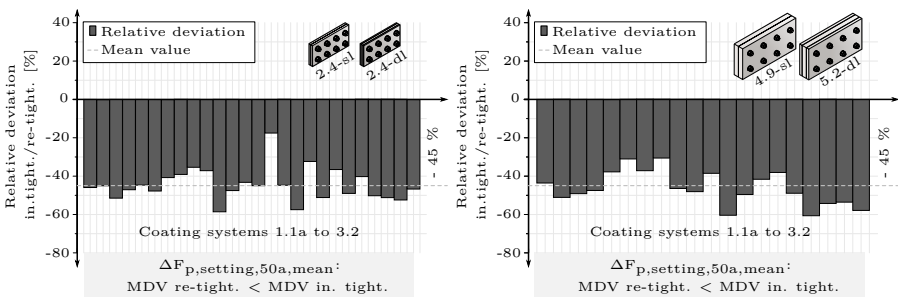


Figure 4.42 Comparison of the mean preload losses $\Delta F_{p,setting,50a,mean}$ considering initial tightening and re-tightening (here: after approx. 3 days) by the modified torque method for different investigated paint and powder coating systems

As can be seen from Figure 4.42, a re-tightening represents a good "instrument" to eliminate the initial preload losses that occurred after initial tightening by the modified torque method. The preload losses $\Delta F_{p,setting,50a,mean,MDV,in.tight.}$ determined after initial tightening by the modified torque method are usually reduced by approx. 40 % to 50 % by re-tightening. These findings presuppose that a re-tightening by the modified torque method is carried out after approx. 3 days after the initial tightening. Considering all test results, a mean reduction of the preload losses $\Delta F_{p,setting,50a,mean,MDV,in.tight.}$ of approx. 45 % was determined after re-tightening by the MDV, see Figure 4.42.

Figure 4.43 exemplarily shows preload losses $\Delta F_{p,setting,50a,mean,MDV,in.tight.}$ and $\Delta F_{p,setting,50a,mean,MDV,re-tight.}$ determined after initial tightening and re-tightening by the MDV for a representative test specimen coated with the coating system 1.4b (acc. to Table 4.6). As can be seen from Figure 4.43 (left), the progression of preload losses over the elapsed time (on a logarithmical scale) is characterized by its linearity. The rate of preload losses, as additionally presented in Figure 4.44 (left), decreases drastically within the first 10 minutes after initial tightening and slowly approaches its horizontal asymptote. However, as reported in [94]-[95], a slight increase in the loss of preload can be detected even after over two years, so that a completely stationary condition of the bolt preload cannot be assumed.

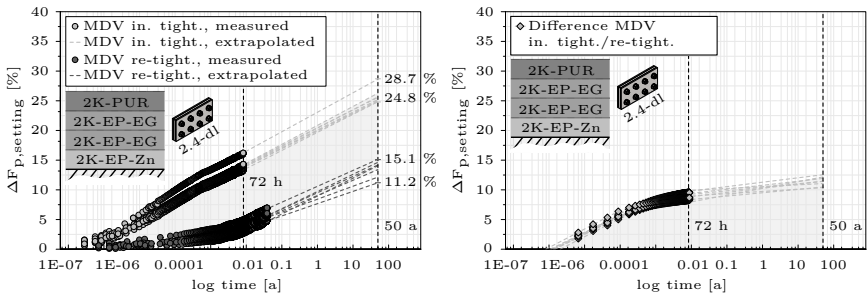


Figure 4.43 Exemplary illustration of preload losses $\Delta F_{p,setting}$ determined after initial tightening and re-tightening by the modified torque method for test specimens with the coating system 1.4b (left) as well as the determined difference of preload losses between the initial tightening and re-tightening as a function of the elapsed time (right)

A re-tightening by the modified torque method eliminates the preload losses after initial tightening and nearly restores the bolt preload to its initial preload level (a re-tightening by the MDV leads to approx. 2 % - 3 % lower initial preloads $F_{p,ini,mean}$ in comparison to the values achieved after the initial tightening, see

Chapter 4.3.3.1). As can be seen from Figure 4.44, the rate of preload losses is expectedly lower after re-tightening compared to the rate of preload losses after initial tightening by the MDV. This behaviour can be attributed to the fact that the main setting effects occur within the first hours after initial tightening. Furthermore, the development of the rate of preload losses is timely offset, see Figure 4.44 (right). This behaviour means that a nearly parallel progression of the preload losses $\Delta F_{p,setting,50a,mean,MDV,re-tight.}$ can be expected after a few days. Therefore, a sufficiently accurate extrapolation of preload losses, as shown for $\Delta F_{p,setting,50a,mean,MDV,re-tight.}$ in Figure 4.43 (left), can be assured by considering preload losses determined after a few days. Furthermore, considering the difference of the measured/extrapolated preload losses after initial tightening and re-tightening by the MDV over the elapsed time, see Figure 4.43 (right), a tendency towards the horizontal progression can be observed.

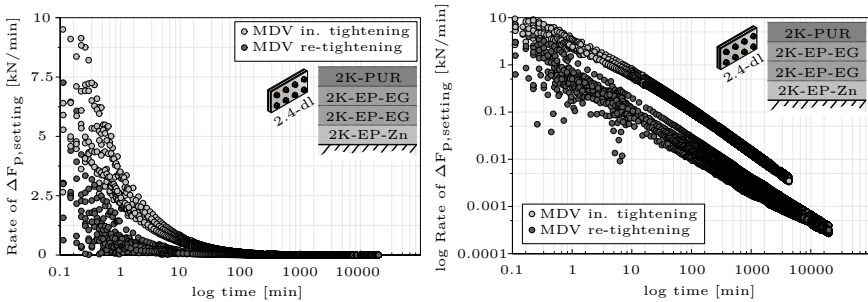


Figure 4.44 Exemplary illustration of the rate of preload losses $\Delta F_{p,setting}$ after initial tightening and re-tightening by the MDV for test specimen with the coating system 1.4b

Following the behaviour of preload losses presented in Figures 4.43 and 4.44, it seems that the amount of preload losses that has been eliminated by the re-tightening after approx. 3 days $\Delta F_{p,setting,3d,mean,MDV,in.tight.}$ affects the remaining amount of preload losses $\Delta F_{p,setting,50a,mean,MDV,re-tight.}$ that is expected to occur after the re-tightening by the MDV. Figure 4.45 shows the mean extrapolated preload losses $\Delta F_{p,setting,50a,mean,MDV,re-tight.}$ after re-tightening by the MDV in relation to the difference of the preload losses $\Delta F_{p,setting,50a,mean,MDV,in.tight.}$ determined after the extrapolation to 50 years and $\Delta F_{p,setting,3d,mean,MDV,in.tight.}$ experimentally determined after approx. 3 days after initial tightening. Here, the individual intersection points for different investigated paint and powder coating systems show that the extrapolated preload losses $\Delta F_{p,setting,50a,mean,MDV,re-tight.}$ after re-tightening by the MDV correspond well to the amount of preload losses

that is expected to occur between 3 days and the intended service life of structures of 50 years after initial tightening by the MDV. Herein, especially the loss of preload range of up to $\approx 15\%$ shows a good agreement with the informatively presented ideal intersection line, see Figure 4.45. This finding leads to the hypothesis that the expected amount of preload losses after re-tightening by the MDV is directly dependent on the elapsed time after initial tightening by the MDV at which the re-tightening is carried out.

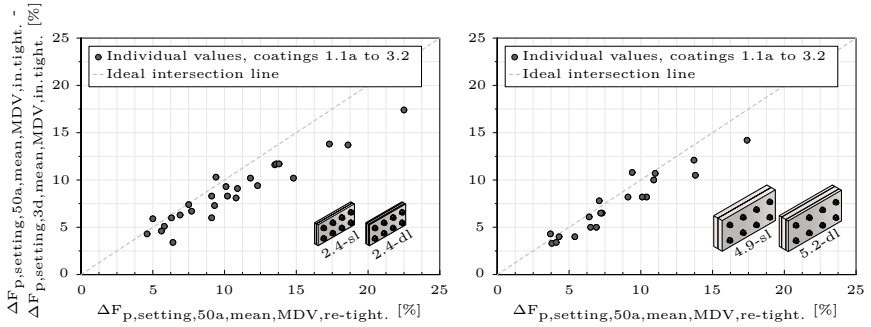


Figure 4.45 Mean preload losses $\Delta F_{p,setting,50a,mean,MDV,re-tight.}$ after re-tightening by the MDV in relation to the difference of the mean preload losses $\Delta F_{p,setting,50a,mean,MDV,in.tight.}$ (extrapolated to 50 years) and $\Delta F_{p,setting,3d,mean,MDV,in.tight.}$ (experimentally determined after approx. 3 days) after initial tightening by the MDV for different investigated paint and powder coating systems

4.3.4.3.3 Suitable boundary conditions for the evaluation of relaxation test

The presented exemplary illustration of preload losses in Figure 4.43 shows that a sufficiently accurate extrapolation of preload losses after initial tightening by the modified torque method (also applies to the combined method) is possible after approx. 72 hours. Herein, no significant changes in the regression line are expected due to the steadily decreasing progression of the rate of preload losses, as shown in Figure 4.44 (right). This behaviour agrees well with the findings presented in Chapter 4.2.3. However, longer measuring times must be considered after re-tightening by the modified torque method, as the rates of preload losses are slightly changed, see Figure 4.44. The test duration after re-tightening by the modified torque method of at least 14 days, which was chosen in this investigation in accordance with the results presented in [4], proves to be sufficient and provides a good basis for the logarithmic extrapolation. Herein, the time span between approx. 3 days and the end of the test (usually 14 days)

was chosen for an estimation of preload losses in order to guarantee a sufficient accuracy of the extrapolation.

Figure 4.46 summarizes the determined preload losses over the elapsed time as scaled values in relation to $\Delta F_{p,setting,50a,mean}$ for different investigated tightening methods as well as paint and powder coating systems. Herein, the preload losses that are based on the measurements carried out for ≈ 3 days (MDV, initial tightening) and ≈ 14 days (KV, tightening / MDV, re-tightening) are considered. Furthermore, extrapolated values are given. With regard to the mean values of the scaled preload losses, see Figure 4.46 (right), approx. 50 % and 60 % of the expected preload losses $\Delta F_{p,setting,50a,mean}$ after (initial) tightening by the combined method and modified torque method occur after the first 3 days and 14 days respectively. Considering re-tightening by the modified torque method, approx. 40 % of the estimated preload losses $\Delta F_{p,setting,50a,mean}$ for the intended service life of 50 years can be expected after a measurement of 14 days.

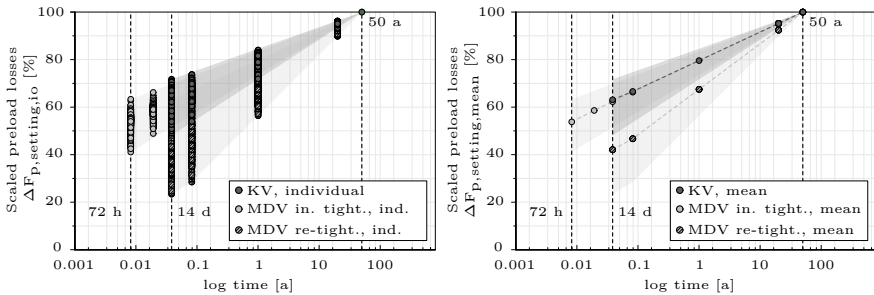


Figure 4.46 Scaled individual preload losses $\Delta F_{p,setting,i}$ (left) and scaled mean preload losses $\Delta F_{p,setting,mean}$ (right) dependent on the elapsed time for different tightening methods and investigated paint and powder coating systems

Based on the experimental results in this investigation, a test duration of at least 14 days can be assumed as adequate for the evaluation of relaxation tests. If a re-tightening by the modified torque method is carried out, it must be ensured that the measurement of preload losses is carried out for at least 14 days regardless of the total elapsed time after the initial tightening by the modified torque method. The test duration of 30 days, as currently prescribed by EN 1090-2, Annex I, might also be applied e.g. for a determination of the loss of preload in case of creep prone materials or coatings/coating systems with an excessive coating layer thickness.

In accordance with experimental findings from other literatures, as discussed in Chapter 3.3.3.7, the occurrence of major preload losses within the first days/weeks after the (initial) tightening can be confirmed. However, the remaining preload losses after the first days/weeks shall not be disregarded. For this reason, a determination of the preload losses by logarithmic extrapolation (under consideration of the intended service life of structures) is recommended.

4.3.4.3.4 Influence of a clamping length ratio

A comparison of test results for the investigated clamping length ratios $\Sigma t/d \approx 2.4$ and $\Sigma t/d \approx 5$ is presented in Figure 4.47. Herein, the individual ratios of determined preload losses $\Delta F_{p,setting,50a,mean}$ are given considering the corresponding ratios of coating thickness per specimen DFT_{spec} for different tightening methods and investigated paint and powder coating systems.

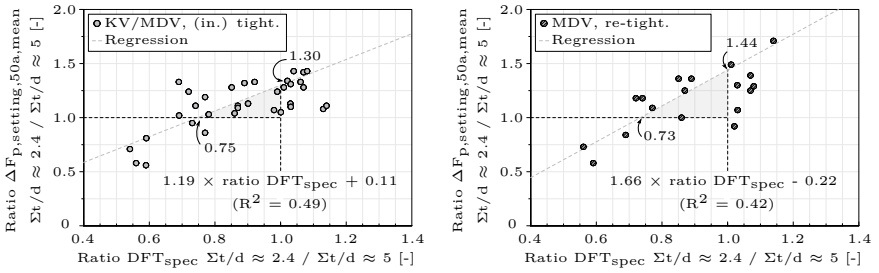


Figure 4.47 Comparison of test results for the investigated clamping length ratios $\Sigma t/d \approx 2.4$ and $\Sigma t/d \approx 5$ considering the ratio of determined preload losses $\Delta F_{p,setting,50a,mean}$ dependent on the ratio of coating thickness per specimen DFT_{spec} for different tightening methods and investigated paint and powder coating systems

By considering the reference points (here: 1.0) for ratios of the preload losses $\Delta F_{p,setting,50a,mean}$ as well as for ratios of the coating thickness DFT_{spec} of the linear regression in Figure 4.47, approx. 25 % to 44 % higher preload losses can be determined for test specimens with the clamping length ratio of $\Sigma t/d \approx 2.4$ in comparison to specimens with $\Sigma t/d \approx 5$.

The plausibility of the observed differences can be verified by considering the elastic resiliances of the test specimens δ_{spec} (consisting of δ_S for the bolt and δ_P for the clamped parts) according to VDI 2230-1 [10], see Figure 2.1 in Chapter 2.1. The determined values of elastic resiliances (the calculation is given in Annex A and is not discussed in detail) for the investigated specimen configurations,

see Figure 4.10, are summarized in Table 4.20. Herein, a comparison of δ_{spec} for the single-lap ($\Sigma t/d = 2.4$ and $\Sigma t/d = 4.9$) and double-lap ($\Sigma t/d = 2.4$ and $\Sigma t/d = 5.2$) specimens leads to a ratio of 0.652 and 0.637 respectively. Based on the calculated ratios of 0.652 and 0.637, the preload losses for the test specimens with $\Sigma t/d \approx 2.4$ shall theoretically correspond to approx. 35 % to 37 % higher values compared to test specimens with $\Sigma t/d \approx 5$.

Table 4.20 Determined elastic resiliances for the investigated test specimen configurations according to VDI 2230-1 [10]

$\Sigma t/d$ [-]	Bolt δ_s [mm/N]	Elastic resiliances		Ratio [-]
		Clamped parts δ_p [mm/N]	Total δ_{spec} [mm/N]	
2.4-sl	$1.562 \cdot 10^{-6}$	$3.144 \cdot 10^{-7}$	$1.876 \cdot 10^{-6}$	0.652
4.9-sl	$2.509 \cdot 10^{-6}$	$3.673 \cdot 10^{-7}$	$2.876 \cdot 10^{-6}$	
2.4-dl	$1.595 \cdot 10^{-6}$	$3.176 \cdot 10^{-7}$	$1.912 \cdot 10^{-6}$	0.637
5.2-dl	$2.627 \cdot 10^{-6}$	$3.723 \cdot 10^{-7}$	$3.000 \cdot 10^{-6}$	

The experimental results presented in Figure 4.47 are supplemented by the analytical estimation acc. to VDI 2230-1 [10] in Figure 4.48. In accordance with the calculation presented in Table 4.20, a difference of elastic resiliances between the clamping length ratios $\Sigma t/d \approx 2.4$ and $\Sigma t/d \approx 5$ was uniformly assumed to ≈ 36 %. As can be seen from Figure 4.48, the experimental values show a comparatively good agreement with the analytical estimation acc. to VDI 2230-1, so that the experimentally determined influence of the clamping length ratio on the amount of preload losses seems to be plausible. However, a majority of the individual values presented in Figure 4.48 fall below the analytical estimation line, so that higher amounts of embedding f_z acc. to VDI 2230-1, see Equation (3.4) in Chapter 3.3.4.9, can be expected for test specimens with $\Sigma t/d \approx 5$ compared to those with $\Sigma t/d \approx 2.4$. This behaviour will be further discussed in Chapter 4.3.4.5.

4.3.4.3.5 Behaviour of preload losses with an increasing coating thickness

An informative linear regression of the extrapolated preload losses $\Delta F_{p,\text{setting},50a}$ as well as the associated explanatory notes for the different investigated coating systems presented in Chapters 4.3.4.1 and 4.3.4.2 show that preload losses $\Delta F_{p,\text{setting},50a,\text{mean}}$ expectedly increase with an increasing coating thickness

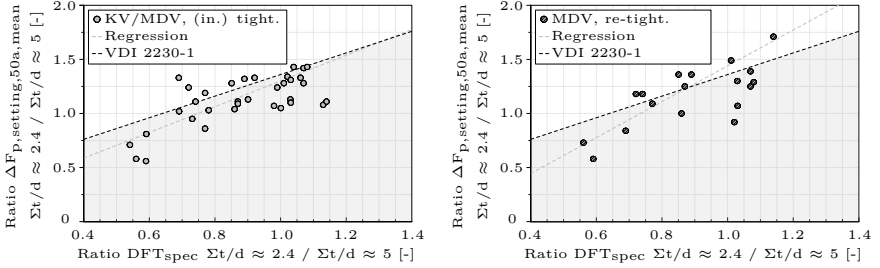


Figure 4.48 Experimentally determined preload losses $\Delta F_{p,setting,50a,mean}$ for different clamping length ratios contrasted to the analytical estimation according to VDI 2230-1 [10]

DFT_{spec} . Since most of the investigated paint systems consist of EP-/PUR based coating materials and the investigated powder coating systems indicate similar mechanical properties, a consolidated consideration of preload losses with an increasing coating thickness seems to be meaningful in order to describe the behaviour of preload losses for EP-/PUR paint systems and powder coating systems. Furthermore, a correlation between preload losses and the increasing coating layer thicknesses would allow a more precise assessment of preload losses regarding a specific nominal coating thickness $NDFT$.

As mentioned in Chapters 4.3.4.1.2 to 4.3.4.1.4, the investigated EP-/PUR systems (here: coating systems 1.2 to 1.4 acc. to Table 4.6) fulfil the requirements for *frame formulations* given by TL/TP-ING [136], see explanations in Chapter 3.3.1. In other words, the investigated coating systems consist of coating materials that possess a similar composition. For this reason, it was decided to treat the investigated 2K-PUR coating (system 1.1 acc. to Table 4.6) separately from the EP-/PUR systems (here: coating systems 1.2 to 1.4 acc. to Table 4.6). Furthermore, test specimens with excessive coating layer thicknesses for the system 1.3a, see Chapter 4.3.4.1.3, as well as high-solid coating system 1.5b (nominal and excessive coating thicknesses), see Chapter 4.3.4.1.5, are presented informatively.

Figure 4.49 shows the mean preload losses $\Delta F_{p,setting,50a,mean}$ based on the corresponding coating thickness per specimen DFT_{spec} for all investigated paint systems acc. to Table 4.6. As can be seen from Figure 4.49, an increase of the preload losses $\Delta F_{p,setting,50a,mean}$ with an increasing coating thickness DFT_{spec} can be sufficiently described by a linear regression. This applies not only to individual EP-/PUR systems (coating systems 1.2 to 1.4 acc. to Table 4.6), but

also to the whole group of EP-/PUR coating systems, whereby the coefficients of determination R^2 of 0.64 and above show a high accuracy of the linear regression for EP-/PUR coating systems, see Figure 4.49.

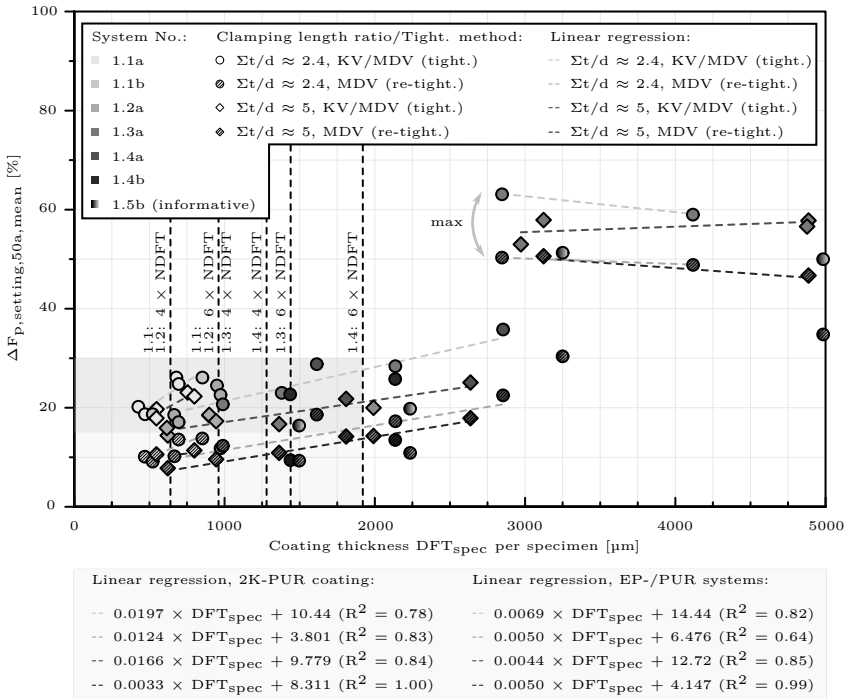


Figure 4.49 Mean preload losses $\Delta F_{p,\text{setting},50a,\text{mean}}$ in relation to the actual coating thickness per specimen DFT_{spec} for the investigated paint systems acc. to Table 4.6

Based on the linear regressions in Figure 4.49, approx. 20 % and 30 % higher preload losses (at approx. 50 % higher coating thicknesses) are determined for double-lap test specimens (six coated surfaces) compared to the single-lap test specimens (four coated surfaces) for clamping length ratios $\Sigma t/d \approx 5$ and $\Sigma t/d \approx 2.4$ respectively. This finding is based on a comparison of the preload losses that can be estimated by the linear regression for coating thicknesses of $4 \times \text{NDFT}$ and $6 \times \text{NDFT}$, see Figure 4.49. The disproportional increase of the preload losses resulting from higher coating thicknesses (50 % higher coating thickness \neq 50 % higher preload losses) in a connection by adding an additional plate can be explained by the actual distribution of surface pressures on the coated

faying surfaces of the investigated test specimens. Figure 4.50 qualitatively presents the resulting scaled surface pressures for the investigated specimen configurations in relation to the pressures of the reference surface beneath the washers. The calculation was carried out in accordance with VDI 2230-1 [10] under consideration of ideally uniformly distributed surface pressures. As can be seen from Figure 4.50, the spread of the compression cone leads to approx. $\frac{1}{2}$ of the reference surface pressure already at the plate thickness of 8 mm (here: double-lap test specimens with $\Sigma t/d = 2.4$). Furthermore, approx. $\frac{1}{3}$ of the reference surface pressure can be assigned to the faying surfaces of the single-lap test specimens with $\Sigma t/d = 2.4$ and the corresponding plate thickness of 15 mm. Finally, approx. 10 % and 20 % of the reference surface pressures can be assumed for the faying surfaces of single-lap test specimens with $\Sigma t/d = 4.9$ and double-lap test specimens with $\Sigma t/d = 5.2$ respectively. With regard to the addressed scale of surface pressures on the coated faying surfaces of the investigated connections, approx. 20 % and 30 % higher preload losses for the double-lap test specimens compared to the single-lap connections seem to be plausible considering the fact that the coating layer thicknesses DFT_{spec} for the double-lap test specimens are approx. 50 % thicker due to an additional plate.

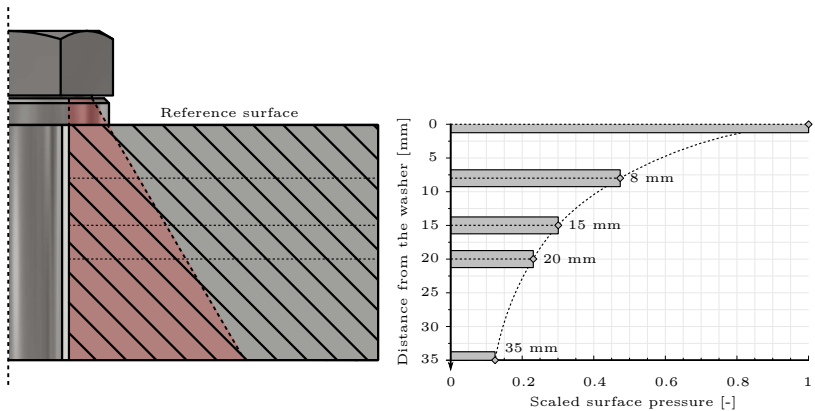


Figure 4.50 Qualitative illustration of the scaled surface pressures for the investigated specimen configurations based on the distance from the washer (here: reference surface) and considering the spread angle of the compression cone of 30° acc. to VDI 2230-1 [10]

The linear correlation between the preload losses $\Delta F_{p, \text{setting}, 50a, \text{mean}}$ and the coating thicknesses DFT_{spec} presented in Figure 4.49 provides a principal approach for an estimation of the preload losses for the investigated paint systems (2K-

PUR and EP-/PUR). However, several boundary conditions must be respected with regard to the validity of the estimates:

- The maximum number of the clamped parts is limited to three,
- an even (or similar) distribution is assumed regarding the coating thicknesses DFT per coated surface,
- coating layer thicknesses of $\approx 1.5 \times \text{NDFT}$ (especially for contact surfaces beneath the washers) shall not be exceeded and
- the maximum coating layer thickness per specimen DFT_{spec} of $\approx 3000 \mu\text{m}$ is assumed.

An evaluation of the mean preload losses $\Delta F_{\text{p,setting,50a,mean}}$ for the investigated powder coating systems considering the actual coating thickness per specimen DFT_{spec} is presented in Figure 4.51. In accordance with the test results for the 2K-PUR coating and EP-/PUR coating systems, the linear regression shows that a correlation between the mean preload losses and the increasing coating thicknesses can be established. In comparison to the evaluation that was carried out for the paint systems (2K-PUR and EP-/PUR), the coefficients of determination R^2 are slightly lower with R^2 of 0.60 to 0.62 after (initial) tightening by the combined method and modified torque method and R^2 of 0.34 to 0.52 after re-tightening by the modified torque method. Herein, the accuracy of the regression model is mainly affected by several outliers that result from high zinc coating thicknesses for the investigated duplex systems and the fact that these coated surfaces were arranged directly beneath the washers. With regard to the practical boundary conditions for hot dip galvanizing that were selected for the investigated test specimens, these slightly increased preload losses seem to represent a possible case for the practical application in steel construction and are, therefore, considered in the overall evaluation of the test results.

In comparison to single-lap test specimens with four coated surfaces, the double-lap specimens with six coated surfaces lead to approx. 10 % and 20 % higher preload losses for most of the investigated test specimens with $\Sigma t/d \approx 5$ and $\Sigma t/d \approx 2.4$ respectively. As discussed above, this increase of the preload losses can be attributed to the surface pressures on the coated faying surfaces. Compared to the investigated paint systems, a tendency towards less influence of an increased number of coated plates on the amount of preload losses can be observed for the investigated powder coating systems. This behaviour can be attributed to the

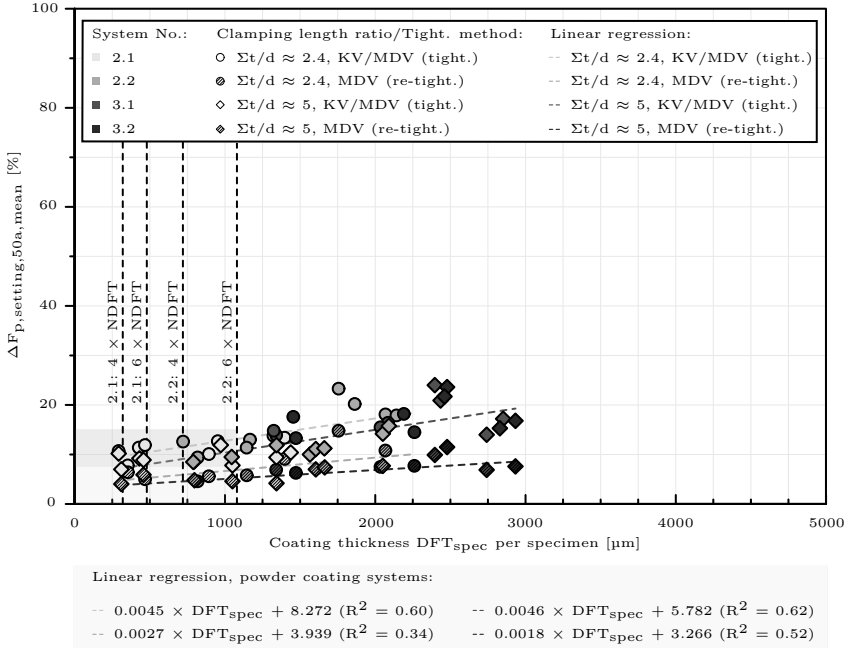


Figure 4.51 Mean preload losses $\Delta F_{p,setting,50a,mean}$ in relation to the actual coating thickness per specimen DFT_{spec} for the investigated powder coating systems acc. to Table 4.6

more favourable mechanical properties of the powder coatings which seem to resist the surface pressures on the faying surfaces even better.

The influence of the coating thickness DFT_{spec} on the amount of preload losses $\Delta F_{p,setting,50a,mean}$ can be described by the linear correlation presented in Figure 4.51. Analogous to the estimation of preload losses for the 2K-PUR coating or EP-/PUR coating systems, several boundary conditions for the validity of the estimates must be respected:

- The maximum number of the clamped parts is limited to three,
- an even (or similar) distribution is assumed regarding the coating thicknesses DFT per coated surface,
- coating layer thicknesses of $\approx 3 \times NDFT$ (especially for contact surfaces beneath the washers) shall not be exceeded and

- the maximum coating layer thickness per specimen DFT_{spec} of $\approx 3000 \mu\text{m}$ is assumed.

The presented correlation between preload losses and the increasing coating thickness in Figures 4.49 and 4.51 serves as a basis for an overall assessment of experimentally determined preload losses. At this point, a verification is necessary, whether an accurate determination of preload losses for specific coating thicknesses is statistically possible by the linear regression.

4.3.4.4 Assessment of the experimentally determined preload losses with regard to their consideration in steel construction

In general, an overall assessment of potential preload losses in steel construction shall be carried out considering the intended target level of preloading, as discussed in Chapter 3.3. Due to the fact that the level of preload is not considered in the design verification of connections with target level II of preloading, it can be assumed that the mean values are suitable for an estimation of the preload losses. In fact, considering the test results achieved by *Katzung et al.* [148]–[150] and their implementation to the normative regulations, it can be concluded that the mean values are taken as a basis for the current estimation of preload losses according to Annex I of EN 1090-2.

If preloading is carried out in order to guarantee the structural safety (here: low-maintenance connections with target level I of preloading), *characteristic values* should be defined and consequently used for the design verification according to EN 1990 [97]. Unfortunately, EN 1990 does not provide an exact definition on what kind of *characteristic values* shall be considered for the handling of preload losses. A consideration of the 95 % fractile values seems to represent one of the options considering the fact that preload losses are influenced by numerous contributing factors such as the composition of the coating, the surface treatment, the coating thickness etc., which might lead to a considerable statistical distribution. At the same time, however, the use of the fractile values would represent a very conservative case, since a certain "balancing effect" in a bolted connection consisting of multiple bolts would be completely disregarded, see explanations in Chapter 4.3.3.1.

The current normative regulations according to EN 1990 indeed leave enough room for other possibilities when it comes to the determination of *characteristic*

values. For example, in addition to the above mentioned consideration of the fractile values, EN 1990 notes that design values can be established directly by using the more adverse values for the probability of occurrence resulting e.g. from slip factor tests. Following this approach, the characteristic values for preload losses should be represented by the maximum values determined for a specific test series. With regard to the structural stiffness parameters (such as creep coefficients), EN 1990 prescribes the use of the mean values. However, attention has to be paid e.g. for the duration of the load, so that different values might be necessary in order to fairly represent the characteristic values. For instance, in this investigation, the duration of the load was taken into account using the logarithmic extrapolation of preload losses.

The above presented observations on the current normative regulations according to EN 1990 indicate that the characteristic value of preload losses shall be represented by values that correspond to a range between the experimentally determined mean preload losses $\Delta F_{p, \text{setting}, 50a, \text{mean}}$ and the 95 % fractile value $\Delta F_{p, \text{setting}, 50a, 0.95}$. Considering the fact that most preloaded bolted connections consist of multiple bolts, the favourable "balancing effect" shall not be entirely disregarded, as e.g. slightly higher preload losses on one part of the connection might be "compensated" by slightly higher remaining preloads of another part. Furthermore, preload losses can be seen as an action that rather accompanies the initial preload level, but does not count as the leading parameter for the reliability of a preloaded bolted connection. Herein, the consideration of the natural distribution for the initial preload level after the tightening or re-tightening shall be put in the foreground when the remaining preload level has to be determined. Herewith, it seems that the use of mean values under consideration of the elapsed time by the logarithmic extrapolation represents a reasonable approach for a practical consideration of preload losses even for the low-maintenance connections with target level I of preloading.

In the following chapters, an assessment of preload losses is carried out considering different investigated coating systems. The aim of this assessment is to verify, whether a sufficiently accurate determination of preload losses can be carried out by the linear regression considering any desired coating thickness. Herein, following the explanations above, the main focus lies on the determination of the mean values of preload losses. The representation of the fractile values, on the other hand, has an informative character and is used for a qualitative comparison of the preload losses.

Therefore, in addition to the extrapolated mean preload losses $\Delta F_{p,setting,50a,mean}$ as well as 95 % fractile values $\Delta F_{p,setting,50a,0.95}$ for different individual test series, preload losses $\Delta F_{p,setting,50a,mean,reg}$ are determined based on the carried out linear regression for the specified 2K-PUR coatings, EP-/PUR coating systems and powder coating systems. For this approach, the determination of preload losses is based on the individual values $\Delta F_{p,setting,50a,i}$, see the exemplary illustration in Figure 4.52 (left). Considering the determined behaviour of preload losses with an increasing coating thickness presented in Chapter 4.3.4.3.5, the linear regression allows an additional estimation of the possible preload losses as 95 % fractiles $\Delta F_{p,setting,50a,0.95,reg}$ for specific coating thicknesses (e.g. NDFT) considering the variability of test results, see Figure 4.52 (right).

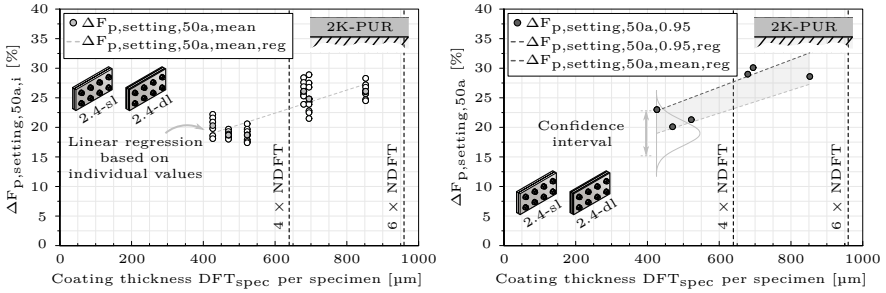


Figure 4.52 Exemplary illustration of the selected approaches for the assessment of preload losses in this investigation (here: 2K-PUR coating, KV/MDV (in.) tight.)

The determination of 95 % fractile values $\Delta F_{p,setting,50a,0.95}$ for different test series was carried out in accordance with EN 1990 by the Equation (4.14):

$$\Delta F_{p,setting,50a,0.95} = \Delta F_{p,setting,50a,mean} \cdot (1 + k_n \cdot V_{\Delta F_{p,setting,50a}}) [\%] \quad (4.14)$$

where k_n is the coefficient for determination of characteristic value acc. to EN 1990, Annex D and $V_{\Delta F_{p,setting,50a}}$ is the coefficient of variation.

Furthermore, a regression analysis was carried out. Herein, analogous to the linear regression presented in Figures 4.49 and 4.51, the model was based on a straight line according to Equation (4.15)

$$y = a + b \cdot x \quad (4.15)$$

considering the independent variable x (here: coating thickness DFT_{spec}) as well as the loss of preload $\Delta F_{p,setting,50a}$ as its response y . Here, the intercept a

represents the expected value of $\Delta F_{p,setting,50a}$ at coating thickness DFT_{spec} of $0 \mu m$, where b describes the slope of the model.

The corresponding upper value of the linear regression $\Delta F_{p,setting,50a,0.95,reg}$ (here: 95 % fractile value in agreement with the approach acc. to EN 1990), see Equation (4.16) was calculated considering standard errors of the intercept SE_a and the slope SE_b as well as the critical value $t_{\alpha/2}$ as a two-tailed inverse of the Student's t -distribution considering the respective degrees of freedom for different test series acc. to Equations (4.17) and (4.18):

$$\Delta F_{p,setting,50a,0.95,reg} = a_{0.95} + b_{0.95} \cdot DFT_{spec} [\%] \quad (4.16)$$

$$a_{0.95} = a + t_{\alpha/2} \cdot SE_a \quad (4.17)$$

$$b_{0.95} = b + t_{\alpha/2} \cdot SE_b \quad (4.18)$$

The regression analysis carried out including a detailed procedure for the calculation is documented in Annex B. For this reason, a presentation of the individual values such as the standard errors of the intercept SE_a and the slope SE_b or the critical value $t_{\alpha/2}$ is not provided here.

4.3.4.4.1 Paint systems

As highlighted in Chapter 4.3.4.3.5, the selected linear regression model shows a promising potential for the estimation of preload losses as a function of the increasing coating thickness. In this chapter, the linear regression approach and the corresponding mean preload losses $\Delta F_{p,setting,50a,mean,reg}$ are statistically verified in a significance test. Furthermore, a qualitative comparison of the mean preload losses $\Delta F_{p,setting,50a,mean,reg}$ as well as the (informative) fractile values $\Delta F_{p,setting,50a,0.95,reg}$ to preload losses $\Delta F_{p,setting,50a,mean}$ and $\Delta F_{p,setting,50a,0.95}$ determined for individual test series are given. The aim of this chapter is to verify, whether an accurate determination of preload losses for any specific coating thickness is statistically possible by linear regression.

A qualitative comparison of the mean preload losses $\Delta F_{p,setting,50a,mean}$ determined for different individual test series and the mean preload losses determined by the linear regression $\Delta F_{p,setting,50a,mean,reg}$ is presented in Figure 4.53. Herein, the coefficients of determination R^2 for the linear regression of $\Delta F_{p,setting,50a,mean,reg}$ mostly lie at approx. 0.5 or above, see Table 4.21. The

significance test for the correlation of preload losses dependent on the increasing coating thickness shows that the null hypothesis (here: "no statistical relationship between preload losses and coating thickness") can be statistically rejected even under consideration of a significance level of $\alpha = 0.01$ for nearly all of the linear regressions, see the statistical evaluation in Table 4.21 and Annex B. Herein, the obtained probability statistic for performing of the significance test, the p-value, corresponds to $p \leq 0.01$ and proves to be highly significant. Herewith, a sufficient relation of the predictor (here: coating thickness DFT_{spec}) to the changes in the response variable (here: $\Delta F_{p,\text{setting},50a,\text{mean},\text{reg}}$) is proven.

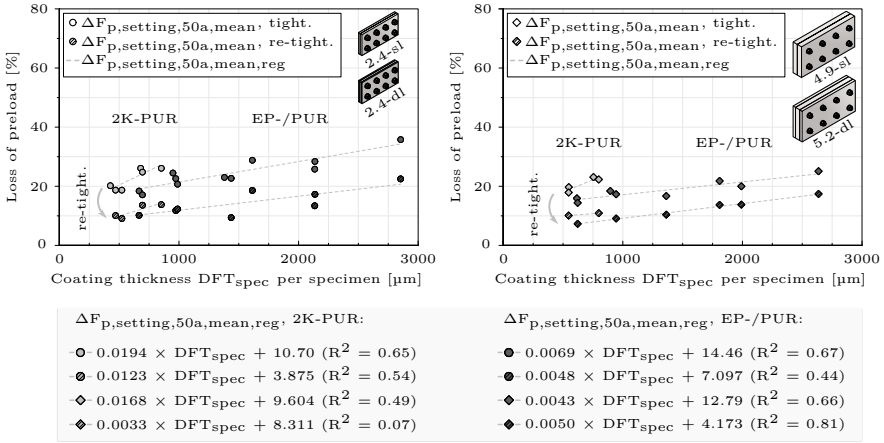


Figure 4.53 Qualitative comparison of the determined preload losses $\Delta F_{p,\text{setting},50a,\text{mean}}$ and $\Delta F_{p,\text{setting},50a,\text{mean},\text{reg}}$ for the investigated 2K-PUR coating and different EP-/PUR coating systems considering test specimens with the clamping length ratio $\Sigma t/d \approx 2.4$ (left) and $\Sigma t/d \approx 5$ (right)

However, as the determined p-value of 0.32 for the investigated 2K-PUR coating (here: test specimens with a clamping length ratio of $\Sigma t/d \approx 5$, re-tightened by the modified torque method) indicates, the null hypothesis cannot be statistically rejected considering the threshold of significance of $p < 0.05$ for this linear regression, see Table 4.21. Taking into account the results of the significance tests for every other test series and considering the fact that the relationship between preload losses and the coating thickness is statistically proven, it is safe to assume that the failure to reject the null hypothesis (and to prove the statistical significance) for the investigated 2K-PUR coating merely means that the available amount of data is not enough to sufficiently interpret the statistics. For this reason, the so-called type II error (here: a non-rejection of the null hypothesis

although it is false) can be concluded. Since the test series for the 2K-PUR coating ($\Sigma t/d \approx 5$, MDV re-tight.) only consists of two test specimens and consequently 16 test results, see Table 4.21, the regression model for $\Delta F_{p, \text{setting}, 50a, \text{mean}, \text{reg}}$ is merely based on the two mean values of the investigated specimens, see Figure 4.53 (right). For this reason, an estimation of the mean preload losses on the basis of the determined function for $\Delta F_{p, \text{setting}, 50a, \text{mean}, \text{reg}}$ seems to be possible despite the failure to reject the null hypothesis.

Table 4.21 Statistical evaluation of the carried out linear regression considering the determined preload losses for the investigated 2K-PUR coating and EP-/PUR coating systems

Test series ¹⁾	$\Sigma t/d$ [-]	Phase	No.	Slope b	Interc. a	R^2 [-]	St. error		p-value ²⁾		$t_{\alpha/2}^{3)}$ [-]
							SE _b [-]	SE _a [-]	b [-]	a [-]	
2K-PUR	≈ 2.4	tight. re-tight.	46	0.0194	10.70	0.65	0.002	1.34	0.000	0.000	1.68
			30	0.0123	3.875	0.54	0.002	1.41	0.000	0.010	1.70
2K-PUR	≈ 5	tight. re-tight.	31	0.0168	9.604	0.49	0.003	2.16	0.000	0.000	1.70
			16	0.0033	8.311	0.07	0.003	2.17	0.320	0.002	1.76 ⁴⁾
EP-/PUR	≈ 2.4	tight. re-tight.	85	0.0069	14.46	0.67	0.001	0.81	0.000	0.000	1.66
			64	0.0048	7.097	0.44	0.001	1.13	0.000	0.000	1.67
EP-/PUR	≈ 5	tight. re-tight.	61	0.0043	12.79	0.66	0.000	0.61	0.000	0.000	1.67
			45	0.0050	4.173	0.81	0.000	0.61	0.000	0.000	1.68

1) Consolidated evaluation for 2K-PUR coating (1.1) and EP-PUR coating systems (1.2 to 1.4).

2) Obtained probability statistic for performing of the significance test.

3) Critical t-value considering the Student's t-distribution with the significance level $\alpha = 0.1$ and the respective degrees of freedom DOF (here: used for calculating $\Delta F_{p, \text{setting}, 50a, 0.95, \text{reg}}$).

4) Determined $\Delta F_{p, \text{setting}, 50a, 0.95, \text{reg}}$ not used for an overall evaluation. Approximation was carried out considering $\Delta F_{p, \text{setting}, 50a, 0.95}$ instead.

Figure 4.54 shows a qualitative comparison of the determined preload losses $\Delta F_{p, \text{setting}, 50a, 0.95}$ and $\Delta F_{p, \text{setting}, 50a, 0.95, \text{reg}}$ for the investigated 2K-PUR coating as well as EP-/PUR coating systems. Considering the results of the significance test presented in Table 4.21, it can be assumed that the 95 % fractile values $\Delta F_{p, \text{setting}, 50a, 0.95, \text{reg}}$ determined by the linear regression provide a sufficient estimation of preload losses considering an increase of the coating thickness. Furthermore, most of the determined fractile values $\Delta F_{p, \text{setting}, 50a, 0.95}$ for individual test series correspond well to the range of preload losses $\Delta F_{p, \text{setting}, 50a, 0.95, \text{reg}}$ that can be estimated by the linear regression function. However, compared to the preload losses $\Delta F_{p, \text{setting}, 50a, 0.95, \text{reg}}$, a higher scattering of the preload losses $\Delta F_{p, \text{setting}, 50a, 0.95}$ can be expected due to the fact that the calculation of $\Delta F_{p, \text{setting}, 50a, 0.95}$ is based on a lower number of measurements with the

corresponding higher coefficients for determination of the characteristic values k_n . For this reason, slightly higher preload losses $\Delta F_{p,setting,50a,0.95}$ cannot be avoided for a few individual test series, see Figure 4.54. An exception to this rule is represented by the determined preload losses $\Delta F_{p,setting,50a,0.95,reg}$ for the 2K-PUR coating (test specimens with $\Sigma t/d \approx 5$, re-tightened by the MDV). Due to a low number of data (two test specimens with a total of 16 measurements, as mentioned before), the 95 % fractile regression function overestimates the preload losses, see the informative regression line in red in Figure 4.54 (right).

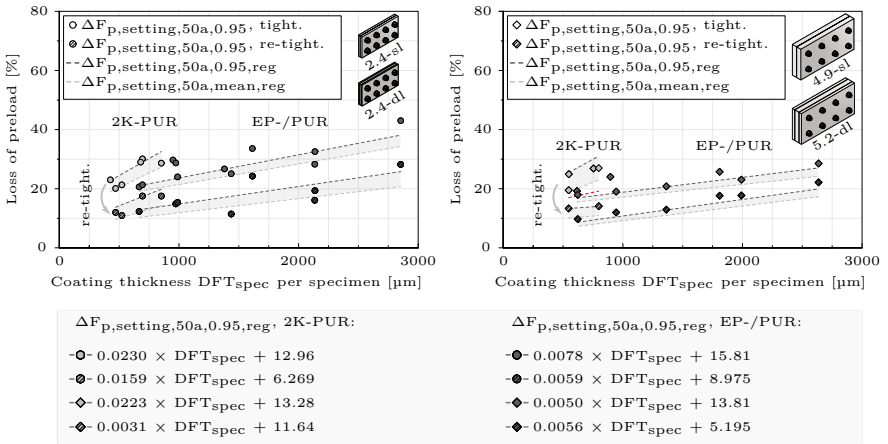


Figure 4.54 Qualitative comparison of the determined preload losses $\Delta F_{p,setting,50a,0.95}$ and $\Delta F_{p,setting,50a,0.95,reg}$ for the investigated 2K-PUR coating and different EP-/PUR coating systems considering test specimens with the clamping length ratio $\Sigma t/d \approx 2.4$ (left) and $\Sigma t/d \approx 5$ (right)

The statistical evaluation of the linear regression shows that an estimation of preload losses in relation to any desired coating thickness is possible. Therefore, an assessment of the experimentally determined preload losses for the investigated paint systems can be carried out by considering the preload losses $\Delta F_{p,setting,50a,mean,reg}$.

Figure 4.55 summarizes the estimated preload losses $\Delta F_{p,setting,50a,mean,reg}$ for the investigated 2K-PUR coating (system 1.1 in Figure 4.55) and different EP-/PUR coating systems (systems 1.2 to 1.4 in Figure 4.55). In addition to that, the fractile values of preload losses $\Delta F_{p,setting,50a,0.95,reg}$ are presented for informative reasons. For the estimation of the preload losses, the nominal coating thicknesses NDFT acc. to Table 4.5 were taken into account. Additionally, an estimation is

provided considering the coating thickness of $1.2 \times \text{NDFT}$. This coating thickness represents a more restrictive limit of the coating thickness than that specified by Clause F.7.2 of EN 1090-2.

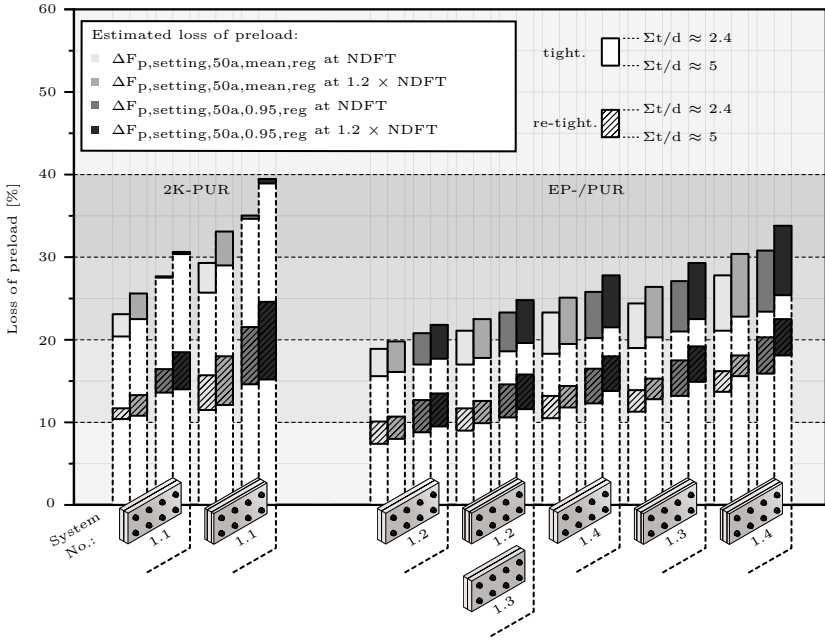


Figure 4.55 Estimated potential preload losses for the 2K-PUR coating and EP-/PUR coating systems considering the mean values $\Delta F_{p, \text{setting}, 50a, \text{mean}, \text{reg}}$ and the 95 % fractile values $\Delta F_{p, \text{setting}, 50a, 0.95, \text{reg}}$ determined by the carried out linear regression at the nominal coating thickness NDFT as well as $1.2 \times \text{NDFT}$

Considering the mean values $\Delta F_{p, \text{setting}, 50a, \text{mean}, \text{reg}}$ of the linear regression, preload losses remain within a range of 20 % to 30 % for both, the 2K-PUR coating and EP-/PUR coating systems with regard to the nominal coating thicknesses NDFT, see Figure 4.55. The same range of preload losses can also be assigned to the 95 % fractile values $\Delta F_{p, \text{setting}, 50a, 0.95, \text{reg}}$ for the investigated EP-/PUR coating systems considering nominal coating thicknesses NDFT. For the 2K-PUR coating, however, fractile values $\Delta F_{p, \text{setting}, 50a, 0.95, \text{reg}}$ of approx. 25 % to 35 % can be estimated. As reported in previous chapters, a re-tightening by the modified torque method leads to a reduction of preload losses after initial tightening. This is well reflected in the estimation in Figure 4.55. Compared to the preload losses $\Delta F_{p, \text{setting}, 50a, \text{mean}, \text{reg}}$ and $\Delta F_{p, \text{setting}, 50a, 0.95, \text{reg}}$

after (initial) tightening (here: abbreviated as *tight.* by the MDV in Figure 4.55), approx. 40 % to 50 % lower preload losses $\Delta F_{p, \text{setting}, 50a, \text{mean}, \text{reg}}$ and $\Delta F_{p, \text{setting}, 50a, 0.95, \text{reg}}$ can be expected after re-tightening.

Considering the coating thickness of $1.2 \times \text{NDFT}$, the 2K-PUR coating shows mean preload losses $\Delta F_{p, \text{setting}, 50a, \text{mean}, \text{reg}}$ of approx. 25 % to 35 %, where the 95 % fractile values of $\Delta F_{p, \text{setting}, 50a, 0.95, \text{reg}}$ correspond to approx. 30 % to 40 %. Furthermore, preload losses of approx. 20 % to 30 % can be estimated for most of the investigated EP-/PUR coating systems considering both, $\Delta F_{p, \text{setting}, 50a, \text{mean}, \text{reg}}$ and $\Delta F_{p, \text{setting}, 50a, 0.95, \text{reg}}$ at $1.2 \times \text{NDFT}$. Herein, merely the estimated loss of preload for the double-lap test specimen of the coating system 2K-EP-Zn | 2K-EP-EG | 2K-EP-EG | 2K-PUR (coating system 1.4 acc. to Table 4.6) slightly exceeds the value of 30 % with $\Delta F_{p, \text{setting}, 50a, \text{mean}, \text{reg}}$ corresponding to 30.8 % and $\Delta F_{p, \text{setting}, 50a, 0.95, \text{reg}}$ to 33.8 %.

As presented in this chapter, a broad data base of the systematic investigations into potential preload losses for the 2K-PUR coating and different EP-/PUR coating systems allows an estimation of preload losses by linear regression. Therefore, the presented results can be taken as a basis for the consideration of preload losses in combination with the determined system reserves presented in Chapter 4.3.3.

4.3.4.4.2 Powder coating systems

In accordance with results for the investigated paint systems presented in Chapter 4.3.4.3.5, an estimation of preload losses by considering a linear regression model seems to be possible for the investigated powder coating systems as well, see Figure 4.56 and Table 4.22. Apart from a few outliers, a regression function for $\Delta F_{p, \text{setting}, 50a, \text{mean}, \text{reg}}$, see Figure 4.56, provides a comparatively good fit for the mean preload losses $\Delta F_{p, \text{setting}, 50a, \text{mean}}$. However, the presence of the mentioned outliers is reflected in the corresponding coefficients of determination R^2 . For the linear regression of $\Delta F_{p, \text{setting}, 50a, \text{mean}, \text{reg}}$, the coefficients of determination vary between $R^2 = 0.24$ and $R^2 = 0.56$. As can be seen from the statistical evaluation presented in Table 4.22, the null hypothesis (here: no statistical relationship between preload losses and coating thickness) can be statistically rejected in all cases, whereby a good relation of the predictor (here: coating thickness DFT_{spec}) to the changes in the response variable (here: $\Delta F_{p, \text{setting}, 50a, \text{mean}, \text{reg}}$) is confirmed by considering the highly significant p-values of $p < 0.001$.

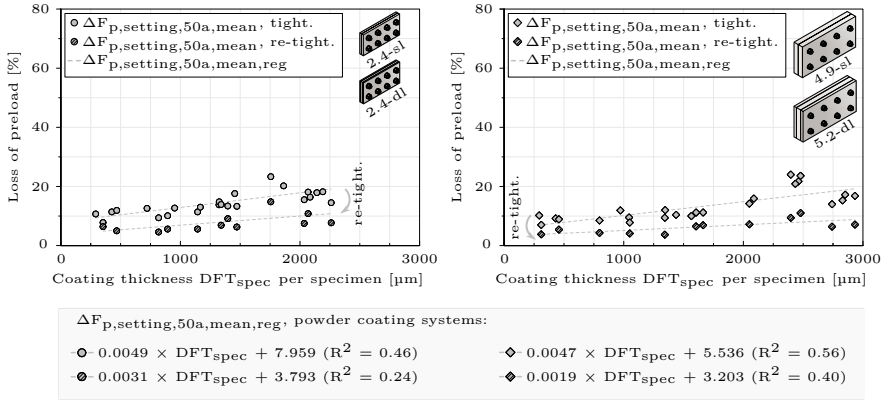


Figure 4.56 Qualitative comparison of the determined preload losses $\Delta F_{p,setting,50a,mean}$ and $\Delta F_{p,setting,50a,mean,reg}$ for the investigated powder coating systems considering test specimens with the clamping length ratio $\Sigma t/d \approx 2.4$ (left) and $\Sigma t/d \approx 5$ (right)

Table 4.22 Statistical evaluation of the carried out linear regression considering the determined preload losses for the investigated powder coating systems

Test series ¹⁾	$\Sigma t/d$ [-]	Phase	No.	Slope		R^2 [-]	St. error		p-value ²⁾		$t^3)$ $t_{\alpha/2}$ [-]
				b	Interc. a		SE _b [-]	SE _a [-]	b	a	
Powder	≈ 2.4	tight.	197	0.0049	7.959	0.46	0.000	0.58	0.000	0.000	1.65
		re-tight.	99	0.0031	3.793	0.24	0.001	0.84	0.000	0.000	1.66
Powder	≈ 5	tight.	193	0.0047	5.536	0.56	0.000	0.54	0.000	0.000	1.65
		re-tight.	100	0.0019	3.203	0.40	0.000	0.43	0.000	0.000	1.66

1) Consolidated evaluation for powder coating systems (2.1 to 3.2).
 2) Obtained probability statistic for performing significance test.
 3) Critical t-value considering the Student's t-distribution with the significance level $\alpha = 0.1$ and the respective degrees of freedom DOF (here: used for calculating $\Delta F_{p,setting,50a,0.95,reg}$).

In comparison to the investigated paint systems presented in Chapter 4.3.4.4.1, the slightly higher scattering of the test results for the investigated powder coating systems, as presented in Chapter 4.3.4.2, consequently leads to a higher scattering of the determined preload losses $\Delta F_{p,setting,50a,0.95}$, see a qualitative comparison of $\Delta F_{p,setting,50a,0.95}$ and $\Delta F_{p,setting,50a,0.95,reg}$ in Figure 4.57. Nevertheless, most of the determined fractile values $\Delta F_{p,setting,50a,0.95}$ lie within the range of the estimated preload losses $\Delta F_{p,setting,50a,0.95,reg}$. Herewith, the statistical evaluation of the linear regression shows that an estimation of preload losses in relation to any desired coating thickness is possible. Analogous to

the investigated paint systems, an assessment of the experimentally determined preload losses for the investigated powder coating systems can be carried out by considering the preload losses $\Delta F_{p,setting,50a,mean,reg}$.

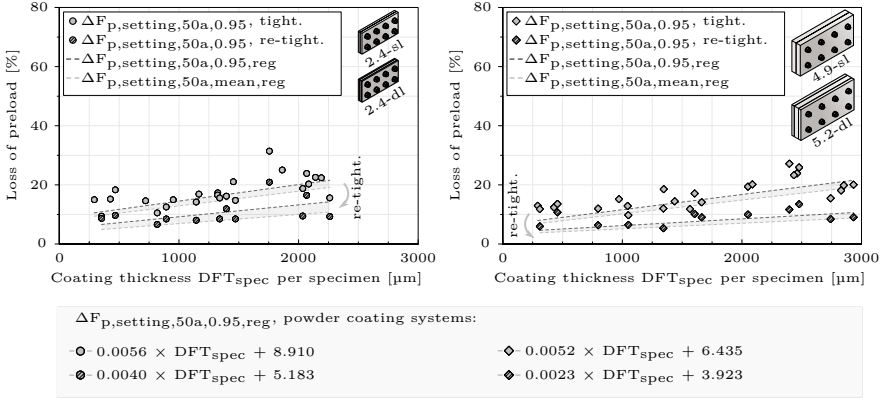


Figure 4.57 Qualitative comparison of the determined preload losses $\Delta F_{p,setting,50a,0.95}$ and $\Delta F_{p,setting,50a,0.95,reg}$ for the investigated powder coating systems considering test specimens with the clamping length ratio $\Sigma t/d \approx 2.4$ (left) and $\Sigma t/d \approx 5$ (right)

Figure 4.58 summarizes the estimated mean preload losses $\Delta F_{p,setting,50a,mean,reg}$ and the informative fractile values of preload losses $\Delta F_{p,setting,50a,0.95,reg}$ for the investigated powder coating systems. Herein, the nominal coating thicknesses NDFT acc. to Table 4.5 as well as the coating thicknesses of $1.2 \times NDFT$ in accordance with the specification of EN 1090-2, Annex I were taken into account.

Based on the linear regression, the preload losses $\Delta F_{p,setting,50a,mean,reg}$ for the powder coating EP/SP as well as for the coating system EP | SP on grit blasted steel surfaces remain within approx. 10 % to 15 % considering the nominal coating thickness NDFT. Furthermore, the range of preload losses of approx. 10 % to 15 % can be assigned to the same powder coating systems considering 95 % fractile values $\Delta F_{p,setting,50a,mean,reg}$ at nominal coating thicknesses NDFT. A re-tightening by the modified torque method expectedly leads to a reduction of the preload losses after initial tightening of approx. 40 % to 50 %. Consequently, a loss of preload $\Delta F_{p,setting,50a,mean,reg}$ and $\Delta F_{p,setting,50a,0.95,reg}$ can be estimated to approx. 5 % to 10 % for the powder coating EP/SP as well as for the coating system EP | SP on grit blasted steel surfaces.

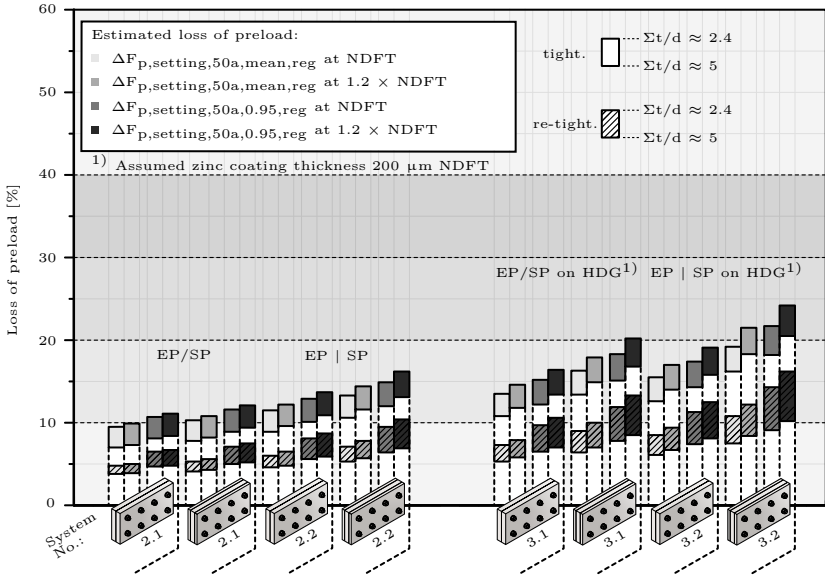


Figure 4.58 Estimated potential preload losses for the investigated powder coating systems considering the mean values $\Delta F_{p,setting,50a,mean,reg}$ and the 95 % fractile values $\Delta F_{p,setting,50a,0.95,reg}$ determined by the carried out linear regression at the nominal coating thickness NDFT as well as $1.2 \times NDFT$

The estimation of preload losses considering the coating thicknesses of $1.2 \times NDFT$, see Figure 4.58, shows that the potential mean preload losses $\Delta F_{p,setting,50a,mean,reg}$ as well as the 95 % fractile values $\Delta F_{p,setting,50a,0.95,reg}$ mostly lie within the range of 10 % to 15 %. Herein, merely the investigated double-lap test specimen slightly exceeds the 15 % loss of preload range with $\Delta F_{p,setting,50a,0.95,reg} = 16.2$ %.

The estimation of potential preload losses for the investigated duplex systems (here: EP/SP and EP | SP on hot dip galvanized surfaces, see Table 4.5) is presented in Figure 4.58. According to EN ISO 1461 [64], the minimum zinc layer thickness is specified to 85 μm for castings with thicknesses of > 6 mm. Considering this specification, it can be assumed that the typical zinc layer thicknesses in the practical application are slightly higher. The investigations cover a range of coating thicknesses per specimen DFT_{spec} of approx. 3000 μm . Considering the nominal coating thicknesses for the EP/SP coating and the EP | SP coating systems, see Table 4.5, the maximum zinc layer thickness is

consequently limited to 200 μm for the estimation of potential preload losses presented in Figure 4.58. In fact, zinc thicknesses up to 200 μm in practical applications are often referred in different publications and worksheets (e.g. [210]-[212]) and seem to represent a sensible range for the assumption carried out for this investigation.

As shown in Figure 4.58, the preload losses $\Delta F_{p,\text{setting},50a,\text{mean},\text{reg}}$ as well as $\Delta F_{p,\text{setting},50a,0.95,\text{reg}}$ can be estimated to approx. 10 % to 20 % for the EP/SP coating on hot dip galvanized surfaces, whereby the estimated preload losses $\Delta F_{p,\text{setting},50a,\text{mean},\text{reg}}$ and $\Delta F_{p,\text{setting},50a,0.95,\text{reg}}$ for the duplex systems (EP | SP coating system on HDG surfaces) lie between 15 % and 25 % considering the mean as well as the 95 % fractile values. These results cover both, nominal coating thicknesses NDFT as well as coating thicknesses of $1.2 \times \text{NDFT}$.

The investigation presented in this chapter allows a meaningful estimation of preload losses by the linear regression. Therefore, the presented results can be taken as a basis for the determination of the remaining preload level considering the determined system reserves presented in Chapter 4.3.3.

4.3.4.5 Preload losses considering elastic resiliences of test specimens

Next to the assessment of preload losses for their estimation in steel construction presented in Chapter 4.3.4.4, an analytical approach acc. to VDI 2230-1 was applied in this investigation in order to determine the amounts of embedding. Herein, the calculation of the amounts of embedding f_z represents an approach that has been established in mechanical engineering for many years and, above all, can be used for an individualized design of preloaded bolted connections. However, as mentioned in Chapter 3.3.4.9, no generalized guide values for the amounts of embedding are available for coated surfaces.

The values for amounts of embedding f_z are primarily dependent on the type of loading, the number of surfaces and the corresponding surface roughness. The calculation of the subsequent loss of preload F_z resulting from the embedment is carried out by Equation (4.19) acc. to VDI 2230-1:

$$F_z = \frac{f_z}{(\delta_S + \delta_P)} [\text{N}] \quad (4.19)$$

where δ_S and δ_P are the elastic resiliences of the bolt and the clamped parts respectively. These parameters have been described in Figure 2.1 and are not

discussed in detail. For the following calculation of the amounts of embedding, the determined elastic resiliences from Table 4.20 were used. A detailed calculation of the elastic resiliences is given in Annex A. Herein, test specimen configurations are considered that were applied in this investigation. The calculation considers only test specimens that were initially tightened as well as re-tightened by the modified torque method, as it is expected (and confirmed considering the determined preload levels $F_{p,ini}$, see Chapter 4.3.3.1) that this tightening method provides initial bolt preloads that remain within the elastic range. Based on the determined preload losses $\Delta F_{p,setting,50a,i}$ [%] and the initial preload levels $F_{p,ini,i}$ [kN], the amounts of embedding $f_{Z,i}$ [μm] for individual measurements were calculated using Equation (4.20):

$$f_{Z,i} = F_{Z,i} \cdot (\delta_S + \delta_P) = F_{p,ini,i} \cdot \Delta F_{p,setting,50a,i} \cdot (\delta_S + \delta_P) \text{ [}\mu\text{m]} \quad (4.20)$$

Furthermore, an informative calculation was carried out for different investigated test series considering the 95 % fractile values of preload losses $\Delta F_{p,setting,50a,0.95}$ [%], see Equation (4.21):

$$f_{Z,0.95} = F_{Z,0.95} \cdot (\delta_S + \delta_P) = F_{p,ini,mean} \cdot \Delta F_{p,setting,50a,0.95} \cdot (\delta_S + \delta_P) \text{ [}\mu\text{m]} \quad (4.21)$$

Figures 4.59 (left) and 4.60 (left) summarize the calculated individual amounts of embedding $f_{Z,i}$ for different coating thicknesses DFT_{spec} . In accordance with test results presented in Chapter 4.3.4.3.5, an increasing coating thickness of test specimens DFT_{spec} expectedly leads to an increase of the amounts of embedding $f_{Z,i}$. This result applies to both, the investigated paint systems, see Figure 4.59, and powder coating systems, see Figure 4.60 (left).

As already presumed in Chapter 4.3.4.3.4, slightly higher amounts of embedding $f_{Z,i}$, mostly in the scale of approx. 10 % to 20 %, can be observed for test specimens with a clamping length ratio of $\Sigma t/d \approx 5$ compared to $\Sigma t/d \approx 2.4$. Considering the fact that the calculated elastic resiliences δ_S and δ_P only include bolts, nuts and clamped parts made of steel, an additional, considerable influence on the amount of elastic resiliences from the applied coating materials in form of a "notional resilience" δ_{coat} cannot be excluded.

The practical estimation of preload losses for the individualized design of bolted connections considering the relative amounts of embedding $f_{Z,i} / DFT_{spec}$ is presented in Figures 4.61 and 4.62. Herein, analogous to the evaluation of preload losses in Chapter 4.3.4.4, a consolidated evaluation for the investigated 2K-PUR

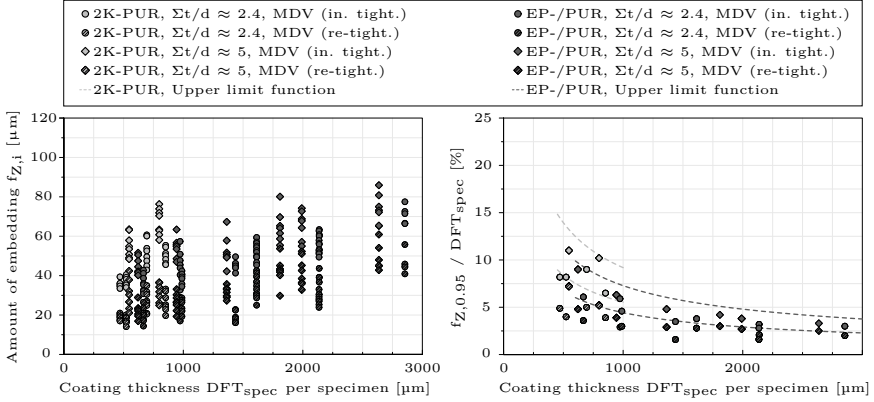


Figure 4.59 Calculated individual amounts of embedding $f_{Z,i}$ for different coating thicknesses DFT_{spec} (left) as well as relative amounts of embedding $f_{Z,0.95} / DFT_{\text{spec}}$ dependent on the coating thickness DFT_{spec} considering 95 % fractile values (right) for different investigated paint systems

coating, EP-/PUR coating systems as well as powder coating systems was carried out.

As can be seen from Figures 4.61 and 4.62, the resulting relative amounts of embedding $f_{Z,i} / DFT_{\text{spec}}$ decreases exponentially and can be described by a power function for the investigated coating thickness range. The specified upper limit functions, see Figures 4.61 and 4.62, were determined conservatively taking into account every individual relative amount of embedding $f_{Z,i} / DFT_{\text{spec}}$. Furthermore, as can be seen from Figures 4.59 (right) and 4.60 (right), the selected upper limit functions correspond to the upper limit of the relative amounts of embedding $f_{Z,0.95} / DFT_{\text{spec}}$ considering 95 % fractile values determined for different investigated test series.

In agreement with the behaviour of experimentally determined preload losses after re-tightening by the modified torque method presented in Chapter 4.3.4.3.2 and later confirmed by evaluations in Chapters 4.3.4.4.1 and 4.3.4.4.2, approx. 40 % lower relative amounts of embedding $f_{Z,i} / DFT_{\text{spec}}$ were assumed for the upper limit function after re-tightening compared to the initial tightening by the modified torque method. Herein, a re-tightening after approx. 3 days after the initial tightening is presupposed.

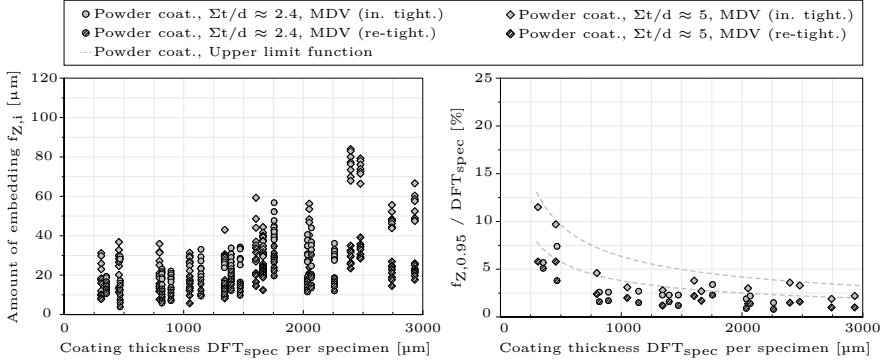


Figure 4.60 Calculated individual amounts of embedding $f_{Z,i}$ for different coating thicknesses DFT_{spec} (left) as well as relative amounts of embedding $f_{Z,0.95} / \text{DFT}_{\text{spec}}$ dependent on the coating thickness DFT_{spec} considering 95 % fractile values (right) for different investigated powder coating systems

The applicability of the estimated relative amounts of embedding $f_{Z,i} / \text{DFT}_{\text{spec}}$ is valid under consideration of the following boundary conditions:

- The maximum number of clamped parts is limited to three,
- an even (or similar) distribution is assumed regarding the coating thicknesses DFT per coated surface,
- coating layer thicknesses of $\approx 1.5 \times \text{NDFT}$ (especially for contact surfaces beneath the washers) shall not be exceeded for the 2K-PUR coating and EP-/PUR coating systems,
- coating layer thicknesses of $\approx 3 \times \text{NDFT}$ (especially for contact surfaces beneath the washers) shall not be exceeded for powder coating systems and
- the maximum coating layer thickness per specimen DFT_{spec} is limited to $\approx 1000 \mu\text{m}$ for the 2K-PUR coating and $\approx 3000 \mu\text{m}$ for EP-/PUR coating systems as well as powder coating systems.

However, especially the above mentioned condition for the estimation of relative amounts of embedding "*an even (or similar) distribution of coating thicknesses DFT per coated surface*" is not necessarily met in practice. For example, the investigations into preload losses for ring flange connections in wind turbine support structures carried out by *Seidel* [213] and *Rutkowski* [133] consider thicker coatings beneath washers than on faying surfaces. Considering the fact

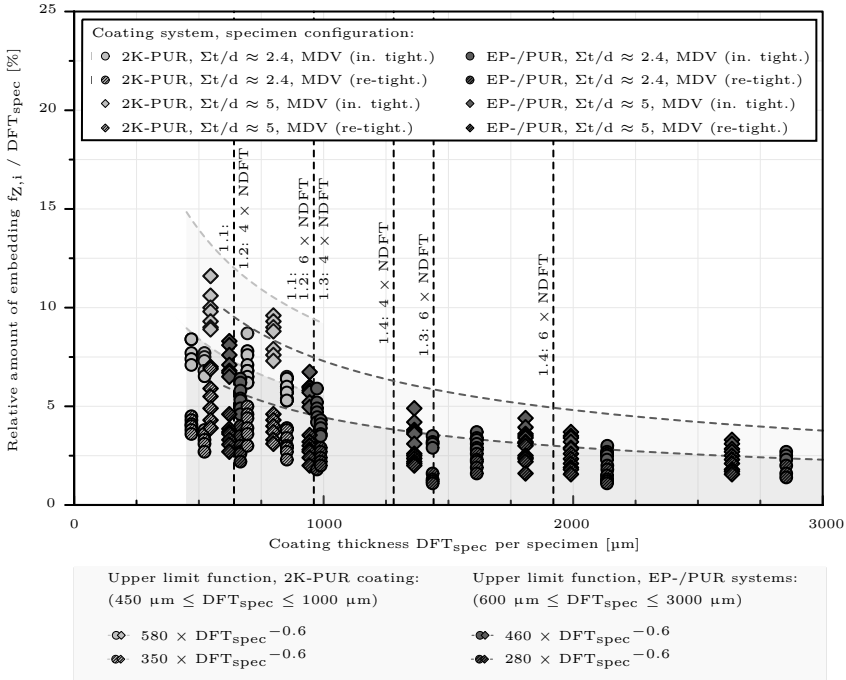


Figure 4.61 Relative individual amounts of embedding $f_{Z,i} / \text{DFT}_{\text{spec}}$ dependent on the coating thickness DFT_{spec} for different investigated paint systems

that surface coatings between washers and connected surfaces lead to a significant influence on the amount of preload losses in a bolted connection, see Figure 4.50, the determination of relative individual amounts of embedding $f_{Z,i} / \text{DFT}_{\text{spec}}$ on the basis of the upper limit functions presented in Figures 4.61 and 4.62 would underestimate the actual preload losses. This is due to the fact that the summation of different, uneven coatings thicknesses to the thickness DFT_{spec} would assume that the coating thickness beneath washers DFT_{sbw} equals the (lower) thicknesses on the faying surfaces $\text{DFT}_{\text{faying}}$.

An alternative approach for the estimation of relative amount of embedding is presented in Figures 4.63 and 4.64. Herein, the calculation is based on the actual coating thickness beneath washers DFT_{sbw} and applies to the 2K-PUR coating, investigated EP-/PUR coating systems as well as different powder coating systems.

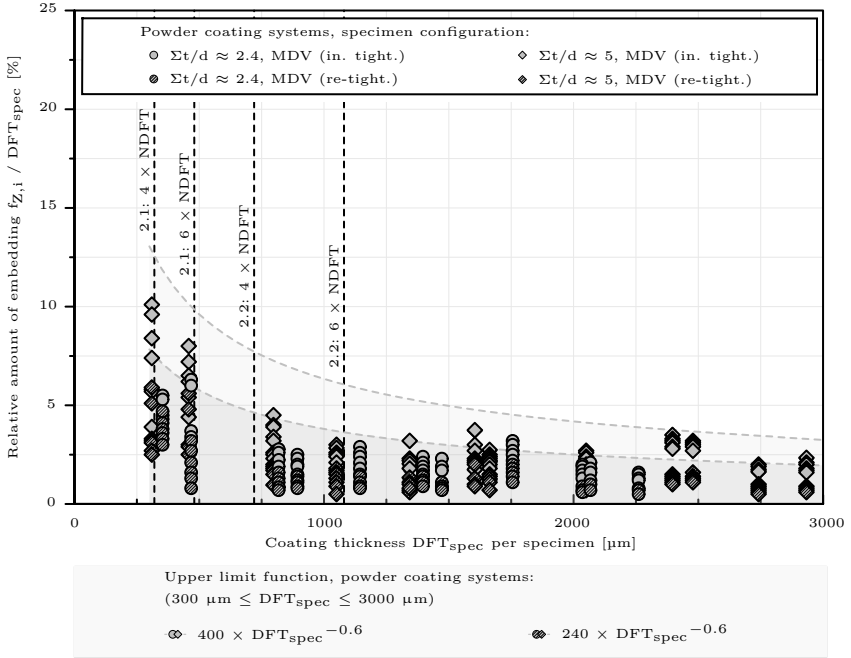


Figure 4.62 Relative individual amounts of embedding $f_{Z,i} / DFT_{spec}$ dependent on the coating thickness DFT_{spec} for different investigated powder coating systems

The applicability of the estimated relative amounts of embedding $f_{Z,i} / DFT_{sbw}$ is valid under consideration of the following boundary conditions:

- The maximum number of clamped parts is limited to two (represents the standard case for ring flange connections in wind turbine support structures),
- individual coating layer thicknesses of $\approx 1.5 \times NDFT$ (applies to DFT_{sbw} and DFT_{faying}) shall not be exceeded for the 2K-PUR coating and EP-/PUR coating systems,
- coating layer thicknesses of $\approx 3 \times NDFT$ (applies to DFT_{sbw} and DFT_{faying}) shall not be exceeded for powder coating systems and
- the maximum coating layer thickness beneath washers DFT_{sbw} is limited to $\approx 160 \mu m$ for the 2K-PUR coating, $\approx 500 \mu m$ for EP-/PUR coating systems as well as $\approx 650 \mu m$ for powder coating systems.

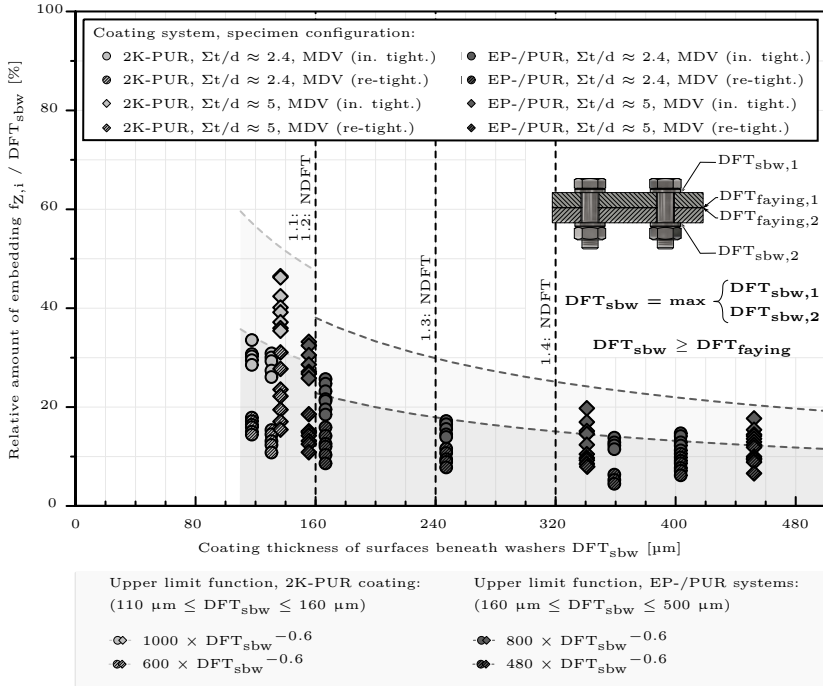


Figure 4.63 Relative individual amounts of embedding $f_{Z,i} / DFT_{sbw}$ dependent on the coating thickness of surfaces beneath washers DFT_{sbw} for different investigated paint systems

The presented approach for the estimation of relative amount of embedding $f_{Z,i} / DFT_{sbw}$ in Figures 4.63 and 4.64 is proposed for the design of ring flange connections in wind turbine support structures acc. to IEC 61400-6.

4.3.5 Consideration of system reserves and preload losses over the service life of steel structures

Analogous to the approach presented in Chapter 4.2.4, the relaxation tests in this investigation allow an assessment of experimentally determined system reserves and preload losses with regard to the required preload value (here: $F_{p,C}$ or $F_{p,C}^*$) over the service life. Since the target level I of preloading serves to guarantee the structural safety quantitatively and bolted connections of target level II are preloaded in order to improve the serviceability qualitatively, the necessary

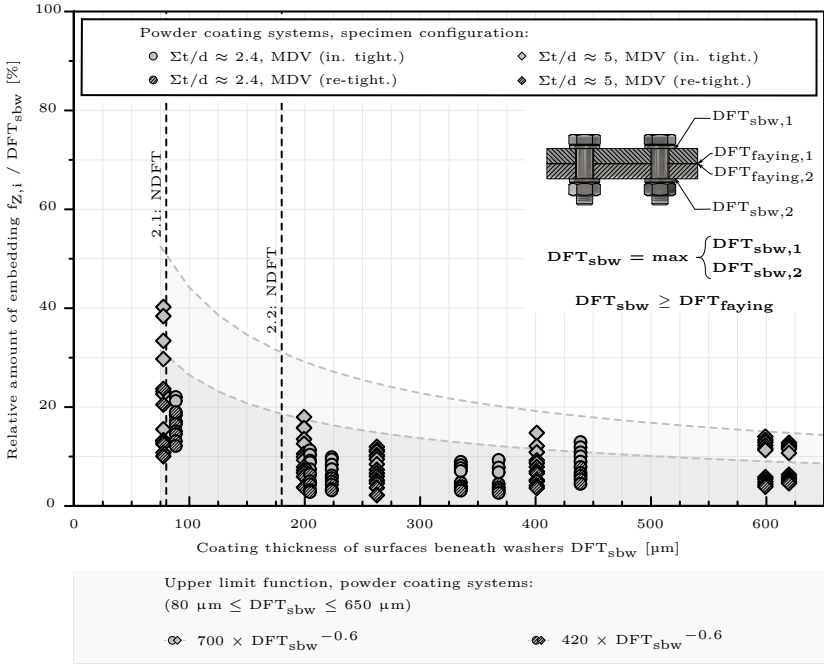


Figure 4.64 Relative individual amounts of embedding $f_{Z,i} / DFT_{sbw}$ dependent on the coating thickness of surfaces beneath washers DFT_{sbw} for different investigated powder coating systems

degree of rigorousness regarding the handling of the remaining preloading force is fairly different.

Connections that are preloaded in order to guarantee the structural safety (low-maintenance connections with target level I of preloading) strictly rely on the preload level that has been considered during design. Consequently, the overall evaluation of experimental test results shall consider the statistical distribution in form of fractile values or, alternatively, effective fractile values (see Chapter 4.3.3.1) for the determination of the initial preload level after tightening (or re-tightening), as it represents the leading parameter for the reliability of a preloaded bolted connection. However, as discussed in Chapter 4.3.4.4, the use of fractile values for the consideration of preload losses would disregard the favourable balancing effect of a bolted connection consisting of multiple bolts and subsequently represent a conservative case for the determination of the remaining preloading force. Since preload losses can be seen as an action that

rather accompanies the initial preload level, the use of their mean values under consideration of the elapsed time by the logarithmic extrapolation seems to agree well with the normative regulations for characteristic values given by EN 1990 [97], see explanations in Chapter 4.3.4.4.

Connections that are preloaded in order to improve the serviceability (target level II of preloading) do not rely on a specific preload level, so that from the point of design verification, the initial preloading forces as well as the preload losses can be handled in a much more flexible manner. For this reason, it can be assumed that the consideration of the mean values are sufficient for an estimation of the remaining preload level for connections that are preloaded for serviceability reasons.

In this chapter, the assessment of system reserves and preload losses over the service life is carried out considering the above mentioned approach for low-maintenance connections with target level I of preloading and connections with target level II of preloading, see Figures 4.66 to 4.69. Herein, the mean initial preload levels $F_{p,ini,mean}$ as well as the mean preload losses $\Delta F_{p,setting,50a,mean,reg}$ based on a linear regression, see Chapter 4.3.4.4, are considered for an estimation of the remaining preload level for the intended service life of 50 years for connections of target level II of preloading. A detailed calculation for every test series is given in Annex C. Furthermore, the fractile values of initial preloads $F_{p,ini,0.05}$ as well as the mean values of preload losses $\Delta F_{p,setting,50a,mean,reg}$ estimated by the linear regression are used in order to determine the remaining preload level for low-maintenance connections with target level I of preloading. Annex D provides a detailed calculation of the remaining bolt preloads considering initial preloads $F_{p,ini,0.05}$ and the mean values of preload losses $\Delta F_{p,setting,50a,mean,reg}$. Additionally, an informative calculation of the remaining preload levels considering the fractile values of the initial preload $F_{p,ini,0.05}$ and preload losses $\Delta F_{p,setting,50a,0.95,reg}$ is given in Annex E.

Figure 4.65 shows an informative comparison of different selected approaches for the estimation of the remaining preload levels. Herein, the relative deviations between the estimated remaining preload levels calculated based on $F_{p,ini,mean}$ and $\Delta F_{p,setting,50a,mean,reg}$ and the remaining preload levels calculated based on $F_{p,ini,0.05}$ and $\Delta F_{p,setting,50a,mean,reg}$ were determined to approx. 15 % considering the modified torque method and approx. 5 % considering the combined method. A consideration of the fractile values $F_{p,ini,0.05}$ and $\Delta F_{p,setting,50a,0.95,reg}$ for an

estimation of the remaining preload level leads to a relative deviation of approx. 18 % considering the modified torque method and approx. 9 % considering the combined method.

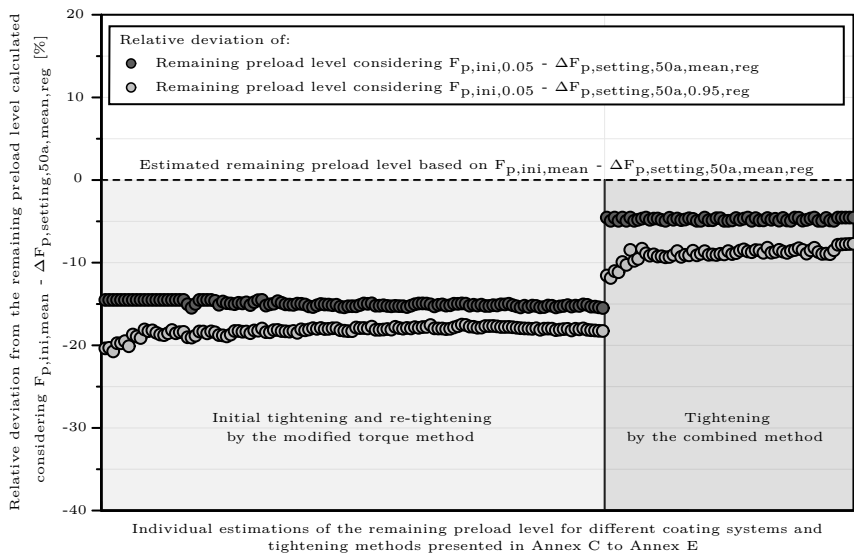


Figure 4.65 Comparison of the remaining preload levels estimated by using different combinations (here: mean and/or fractile values) of the initial preload levels and preload losses

Especially the determined deviation for the modified torque method confirms that the initial preload level represents the leading (critical) parameter for the reliability of a preloaded bolted connection. This finding is backed by the comparatively low additional increase of the relative deviation due to fractile values $F_{p,ini,0.05}$ and $\Delta F_{p,setting,50a,0.95,reg}$. Therefore, the consideration of the natural distribution for the initial preload level is vital when an estimation of the remaining preload level has to be carried out for low-maintenance connections with target level I of preloading. On the part of preload losses, however, a consideration of the mean values represents a reasonable practical approach.

An assessment of experimentally determined initial preload levels in combination with preload losses for different investigated paint and powder coating systems, see Figures 4.66 and 4.68, shows that the nominal preload value $F_{p,C}^*$ (here: 100 kN for M16 HV 10.9 bolting assemblies acc. to EN 14399-4 [29]/EN 14399-6 [31]) can hardly be maintained considering tightening by the modified torque

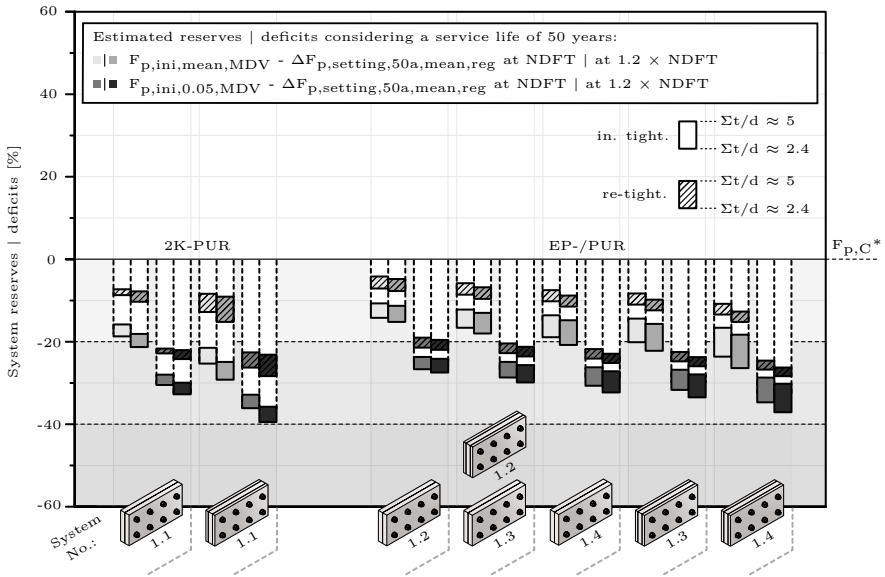


Figure 4.66 Estimated system reserves and deficits with regard to the preload level $F_{p,C}^*$ for different investigated paint systems considering initial tightening as well as re-tightening by the modified torque method

method. This is mainly due to the fact that the nominal preload level $F_{p,C}^*$ in this investigation was achieved only by considering the mean values. Herein, only minor systems reserves of approx. 6 % and 3 % were determined after initial tightening and re-tightening by the modified torque method respectively, see Table 4.7 in Chapter 4.3.3.1. As a result, considering the mean values for connections with target level II of preloading, system deficits of up to 30 % (corresponds to $0.70 F_{p,C}^*$) after initial tightening and up to 15 % (corresponds to $0.85 F_{p,C}^*$) after re-tightening by the modified torque method can be expected for the investigated paint systems depending on the actual coating thickness in a preloaded bolted connection, see Figure 4.66. Slightly lower deficits of up to 20 % (or $0.80 F_{p,C}^*$) after initial tightening and up to 10 % (equals to $0.90 F_{p,C}^*$) after re-tightening by the modified torque method are estimated for the investigated powder coating systems, see Figure 4.68. The presented results apply to both, nominal coating thicknesses NDFT as well as coating thicknesses with a maximum of $1.2 \times NDFT$ for different investigated coating systems.

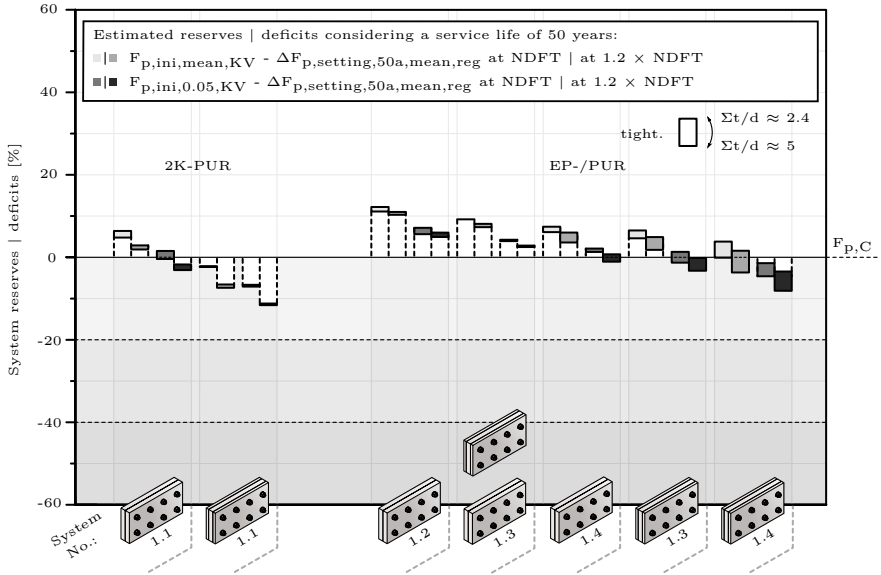


Figure 4.67 Estimated system reserves and deficits with regard to the preload level $F_{p,C}$ for different investigated paint systems considering tightening by the combined method

As reported in Chapter 4.2.4, the combined method offers remarkably higher mean initial preload levels, see Table 4.9, and provides the necessary reserves of $> 30\%$ against potential preload losses for the investigated coating systems. Considering an estimation carried out for connections with target level II of preloading, a full compensation of the mean preload losses $\Delta F_{p,setting,50a,mean,reg}$ can be assumed with regard to the nominal minimum preload value $F_{p,C}$ (here: 110 kN for M16 HV 10.9 bolting assemblies acc. to EN 14399-4 [29]/EN 14399-6 [31]) for most of the investigated coating systems tightened by the combined method. Considering a service life of 50 years, the remaining mean preload values can be estimated to approx. $1.1 F_{p,C}$ and even $1.25 F_{p,C}$ for the investigated paint (Figure 4.67) and powder (Figure 4.69) coating systems. Merely the double-lap connections with the 2K-PUR coating and the four-layer EP-/PUR coating system (based on the coating thickness limit of $1.2 \times NDFT$) show some deficits of up to 10 % (corresponds to $0.90 F_{p,C}$) and 5 % (equals to $0.95 F_{p,C}$) respectively, see Figure 4.67.

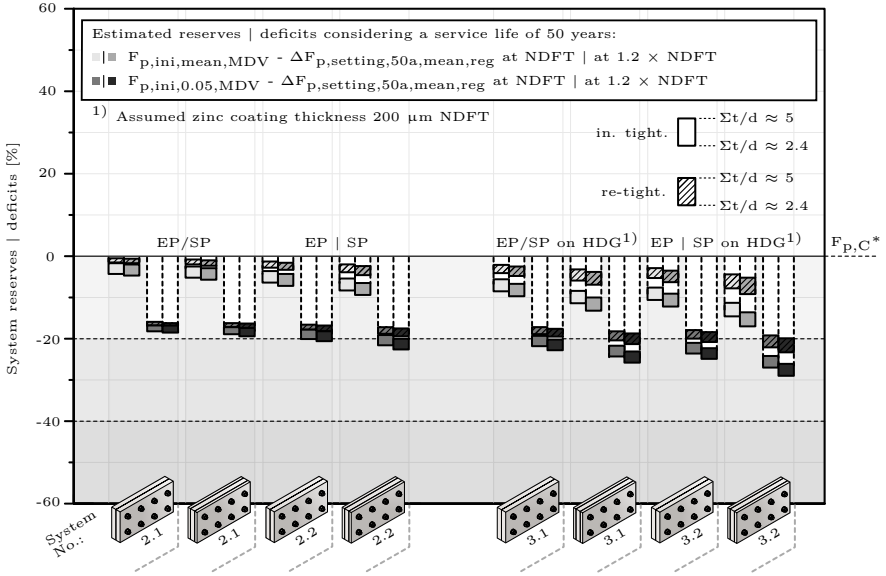


Figure 4.68 Estimated system reserves and deficits with regard to the preload level $F_{p,C}^*$ for different investigated powder coating systems considering initial tightening as well as re-tightening by the modified torque method

A consideration of the characteristic 5 % values for initial preload levels $F_{p,ini,0.05}$ as well as the mean preload losses $\Delta F_{p,setting,50a,mean,reg}$ (here: low-maintenance connections with target level I of preloading), expectedly leads to more conservative remaining bolt preloads. Herein, the favourable "balancing effect" of multiple preloaded bolts in a connection, see explanations in Chapters 4.3.3.1 and 4.3.4.4.1, remains disregarded considering the initial preload level, but can be taken into account using Equation (4.11).

The reliability issues of the modified torque method that were reported in Chapter 4.3.3.1 are reflected in the estimation of the remaining preload level considering a service life of 50 years for connections with target level I of preloading, see Figures 4.66 and 4.68. Considering the investigated paint systems with the coating thickness limit of $1.2 \times \text{NDFT}$, deficits of approx. 30 % to 40 % can be expected after the initial tightening. Herewith, the estimated minimum remaining preload level varies between $0.60 F_{p,C}^*$ and $0.70 F_{p,C}^*$ depending on the coating thickness of a preloaded bolted connection. A re-tightening by the modified torque method expectedly leads to slightly higher overall preload levels

with approx. $0.70 F_{p,C}^*$ to $0.75 F_{p,C}^*$ depending on the applied coating system. Considering the investigated powder coating systems with coating thicknesses of up to $1.2 \times \text{NDFT}$, the estimated deficits amount to approx. 20 % to 30 % after the initial tightening. This corresponds to the remaining preload levels of $0.70 F_{p,C}^*$ and $0.80 F_{p,C}^*$. Compared to the initial tightening, only slightly increased remaining preload levels can be expected after re-tightening by the modified torque method with approx. $0.75 F_{p,C}^*$ to $0.80 F_{p,C}^*$ depending on the applied coating system.

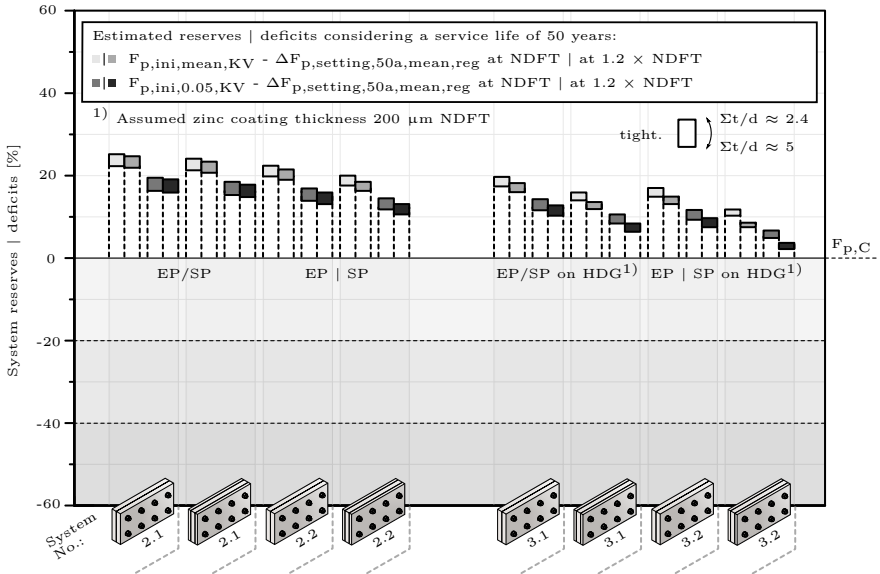


Figure 4.69 Estimated system reserves and deficits with regard to the preload level $F_{p,C}$ for different investigated powder coating systems considering tightening by the combined method

The evaluation of the remaining preload levels for connections tightened by the combined method presented in Figure 4.67 shows that the 2K-PUR coating can lead to deficits (regarding the nominal preload level $F_{p,C}$) of approx. 10 % (or $0.90 F_{p,C}$) considering the service life of 50 years and the coating thickness limit of $1.2 \times \text{NDFT}$. Furthermore, an undercut of the nominal minimum preload value $F_{p,C}$ by up to 10 % can be assigned to the EP-/PUR systems 2K-EP-Zn | 2K-EP-EG | 2K-PUR (system 1.3 in Figure 4.67, double-lap connection) and 2K-EP-Zn | 2K-EP-EG | 2K-EP-EG | 2K-PUR (system 1.4 in Figure 4.67, single-

and double-lap connections). For other investigated paint and powder coating systems tightened by the combined method, some reserves of up to 5 % and 15 % respectively can be estimated considering the coating thickness limit of $1.2 \times \text{NDFT}$.

4.4 Summary and conclusions

The corrosion protection on contact surfaces of preload bolted connections shall be selected in a way that an unacceptable loss of preload is avoided. For connections of categories B/C and E acc. to EN 1993-1-8 [1] (here: target level I of preloading), this can be realized by fulfilling the strict limitations regarding the coating layer thicknesses on contact surfaces that are provided by EN 1090-2. If the specified coating layer thicknesses cannot be complied with, a sensible estimation of the remaining preload level must be carried out e.g. considering experimental test results. In cases, where preloading of bolting assemblies is carried out for serviceability reasons (here: target level II of preloading), the potential preload losses can be handled in a more flexible manner. However, an estimation of the remaining preload level is desirable in order to achieve the maximum improvement in serviceability.

First insights into system reserves and preload losses under consideration of the modified torque method and combined method as well as different surface conditions were provided in Chapter 4.2. Herein, the investigated "reference connections" that comply with the limitations for the corrosion protection on contact surfaces provided by EN 1090-2 showed that the required preload value $F_{p,C}^*$ (here: 160 kN for M20 HV 10.9 bolting assemblies acc. to EN 14399-4 [29]/EN 14399-6 [31]) for connections tightened by the modified torque method can be hardly maintained. Therefore, the practical implementation of the coating thickness limitations by the use of a priming coat and/or surface masking of the contact surfaces seems to be justified. However, a structural design considering 90 % of the nominal preloading force $F_{p,C}^*$ might be necessary for connections tightened by the modified torque method. A tightening by the combined method expectedly leads to high system reserves and offers a sufficient safety against potential preload losses for the investigated "reference connections". The estimated remaining preload level with regard to the intended service life of 50 years clearly exceeds the nominal minimum preloading force $F_{p,C}$.

A comprehensive investigation into preloaded bolted connections coated with different paint and powder coating systems allows an assessment of the determined system reserves and preload losses. Depending on the actual coating thickness of a preloaded bolted connection with target level II of preloading, the remaining bolt preloads of up to $0.70 F_{p,C}^*$ after initial tightening and $0.85 F_{p,C}^*$ after re-tightening by the modified torque method can be estimated for the investigated 2K-PUR coating and different EP-/PUR coating systems. The more favourable mechanical properties of the investigated powder coating systems lead to remaining preloads in the range of up to $0.80 F_{p,C}^*$ after tightening and $0.90 F_{p,C}^*$ after re-tightening by the modified torque method depending on the investigated thickness of the coating system. Tightening by the combined method leads to a complete compensation of the occurring preload losses with regard to the minimum nominal preload value $F_{p,C}$ for most of the investigated coating systems. Herein, merely the 2K-PUR coating and a four-layer EP-/PUR coating system show remaining preload levels of $0.90 F_{p,C}$ and $0.95 F_{p,C}$ respectively considering a service life of 50 years. In cases, where preloading is carried out in order to guarantee the structural safety (here: low-maintenance connections with target level I of preloading), the design value of the remaining preload shall be partly reduced. For the investigated paint and powder coating systems with different coating thicknesses, a reduction of the nominal preload level of up to $0.60 F_{p,C}^*$ and $0.70 F_{p,C}^*$ might be necessary after tightening and re-tightening by the modified torque method respectively. The combined method once again represents the more reliable tightening method and leads to only partial undercuts of the nominal preloading force $F_{p,C}$ of up to 10 % ($0.90 F_{p,C}$) for the investigated 2K-PUR coating and the investigated EP-/PUR coating systems.

5 Slip resistance of bolted connections under consideration of practical boundary conditions

5.1 General

Slip-resistant connections are used in structures whenever slip and deformation must be limited to the minimum. Typical applications include e.g. single and multi-section connections of wind turbines, offshore plants and bridges. As briefly described in Chapter 2.5.3, the load-bearing behaviour of a slip-resistant connection is mainly influenced by the level of preload and the associated slip factor. The latter serves as an experimental value and is dependent on the preload level, but at the same time covers other influencing parameters such as the treatment of the friction surfaces including the composition of the coating material and the coating thickness.

If necessary, the slip factor can be experimentally determined by the test procedure according to EN 1090-2, Annex G. However, the load-bearing behaviour in the test is limited to the prescribed procedure under laboratory conditions and does not consider the practical production-, assembly- and operation-related boundary conditions and their possible affect on the slip resistance.

The following chapters deal with systematic investigations into slip-resistant connections under consideration of different coating layer thicknesses, tightening methods and the influence of cyclic loading. Herein, the above mentioned practical boundary conditions and their possible influence on the slip resistance as well as on the actual preload level are compared to test results achieved by the test procedure according to EN 1090-2, Annex G. The investigations were carried out in the frame of the IGF research project No. 19749 BG "Influence of manufacturing- and assembly-related imperfections on the bearing behaviour of bolted slip-resistant connections in steel structures" [5] (test results also published in [214]) as well as within the preparation of two expert opinions entitled "Determination of slip factors for slip-resistant connections of the cross girder connections in the temporary bridges ZH 26" [7] and "Existing preload level in preloaded bolted connections with HV bolting assemblies M24 in the

area of main girder - end cross beam and main girder - cross beam connections of the temporary bridge ZH 26.105" [8], which results are summarized in [215].

5.2 Practical variation of the coating thickness

5.2.1 General

As specified by EN 1090-2 for various coatings on the friction surfaces, the minimum values for slip factors according to the specified class of friction surface without test assume a dry film thickness with a range of 40 μm to 80 μm or not exceeding 80 μm . However, a practical variation of the actual layer thickness cannot be avoided during the application process. Therefore, it has to be questioned whether a deviation from the normatively specified coating layer thicknesses has an influence on the slip resistance.

In this investigation, some of the main surface treatments for slip-resistant connections specified by EN 1090-2 were selected. Additionally, ethyl-zinc silicate paint, as an alternative for friction surfaces according to ZTV-ING [135], was investigated:

- ASI: grit blasted to grade Sa 3 according to EN ISO 8501-1 [216] (particle size: 0.2 μm to 1.0 μm , profile grade "medium (G)" according to EN ISO 8503-1 [73] with an average surface roughness $R_{y5} \approx 80 \mu\text{m}$) + alkali-zinc silicate paint according to Sheet 85 of TL/TP-ING [136],
- HDG-ASI: hot dip galvanized in accordance with EN ISO 1461 [64] (zinc bath class 1 according to DAST-Guideline 022 [198], temperature of the molten zinc: $\approx 450^\circ\text{C}$, immersion time of 9 to 11 minutes with subsequent cooling by air flow, coating thickness between 90 μm and 268 μm) + sweep blasted according to EN ISO 12944-4 [54] using alumina (particle size: 0.355 μm to 0.5 μm) + alkali-zinc silicate paint according to Sheet 85 of TL/TP-ING [136],
- AlSM: grit blasted to grade Sa 3 according to EN ISO 8501-1 (profile grade "medium (G)" according to EN ISO 8503-1 with an average surface roughness $R_{y5} \approx 60 \mu\text{m}$ - 80 μm) + thermally sprayed with aluminium using Al 99,5 according to EN ISO 14919 [197] (no sealing applied) and
- ESI: grit blasted to grade Sa 3 according to EN ISO 8501-1 (particle size: 0.2 μm to 1.0 μm , profile grade "medium (G)" according to EN ISO 8503-1

with an average surface roughness $R_{y5} \approx 80 \mu\text{m}$) + ethyl-zinc silicate paint according to Sheet 86 of TL/TP-ING [136].

The test specimens for test series ASI, AISM and ESI were coated on the friction surfaces as well as on the surfaces beneath washers. Furthermore, the ASI paint was applied on the friction surfaces of the hot dip galvanized test specimens for test series HDG-ASI. After the application of the coating, the test specimens were labeled, documented and their dry film thicknesses (DFT) were measured according to EN ISO 2808 [199] using the magnetic method acc. to EN ISO 2178 [200], see Figure 5.1. The preparation of the substrates, the subsequent application of the coating as well as the measurement of the coating layer thicknesses for test series ASI, HDG-ASI and ESI were carried out by the Institute for Corrosion Protection Dresden GmbH (*"Institut für Korrosionsschutz Dresden GmbH"*).

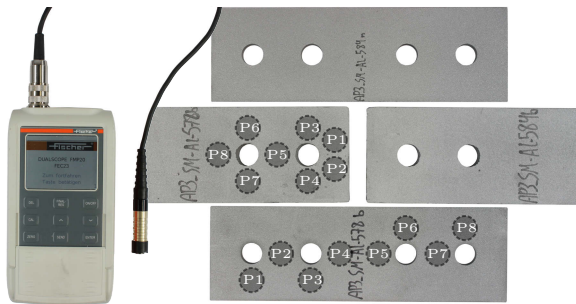


Figure 5.1 Measurement of the dry film thickness (DFT) using the magnetic method according to EN ISO 2178 (here: exemplarily for one inner and one cover plate) for investigated slip-resistant connections

The coating thickness range of $40 \mu\text{m}$ to $80 \mu\text{m}$ NDFT was selected for the reference tests for all investigated test series, as this range corresponds to the minimum slip factor values in EN 1090-2. As indicated by Figure 5.2, two further representative ranges of coating thickness per test series were investigated. Depending on the coating, ranges of $25 \mu\text{m}$ to $40 \mu\text{m}$ NDFT (ASI, HDG-ASI and ESI), $80 \mu\text{m}$ to $130 \mu\text{m}$ NDFT (ASI, HDG-ASI, ESI and AISM) as well as $> 130 \mu\text{m}$ NDFT (AISM) were selected based on the experience of practitioners.

The slip factor tests were carried out according to the test procedure of EN 1090-2, Annex G, see explanatory notes in Chapter 2.5.3 and Figure 2.11. Herein, M16 standard test specimens made of steel S355J2+N in combination with hot dip

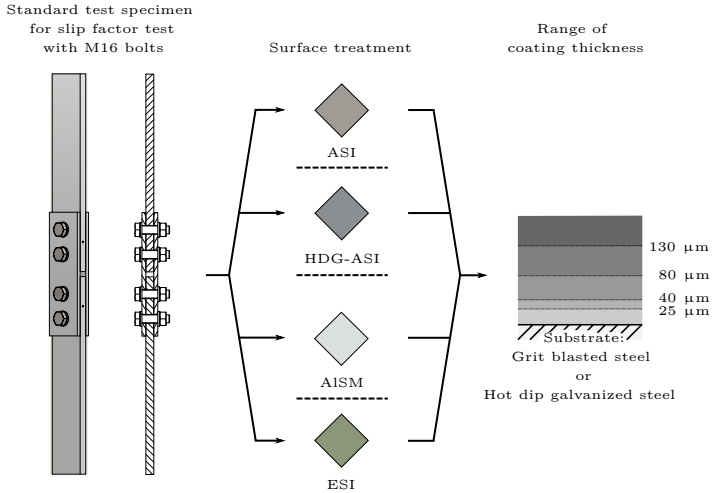


Figure 5.2 Selected configurations of test specimens for the investigation into different coating layer thicknesses

galvanized M16 HV 10.9 bolting assemblies (EN 14399-4 [29]/EN 14399-6 [31]) were selected. For every test, bolts with implanted strain gauges (DMS) BTMC-3 of Tokyo Measuring Instruments Laboratory Co., Ltd. were used. Herewith, the preload could continuously be measured during the tightening of bolting assemblies to $F_{p,C}$ (here: 110 kN for M16 HV 10.9 bolting assemblies) $\pm 5\%$ as well as during the total duration of the slip factor test. The slip displacement was measured as the relative displacement between adjacent points on the inner plate and the cover plates in the direction of the applied load. Deviating from the normative regulations by EN 1090-2, Annex G, the slip displacements were measured at two different positions, see Figure 5.3:

- CBG ("centre bolt group") position: eight linear variable differential transformers (LVDT) at the centre bolts group as prescribed by EN 1090-2 and
- PE ("plate edge") position: four LVDTs at the plate edges as introduced by *Strangh ner et al.* [159] and *Afzali* [92].

The selected procedure for the evaluation of the test results determined using PE position is described in [5]. For this reason, no detailed explanation is provided

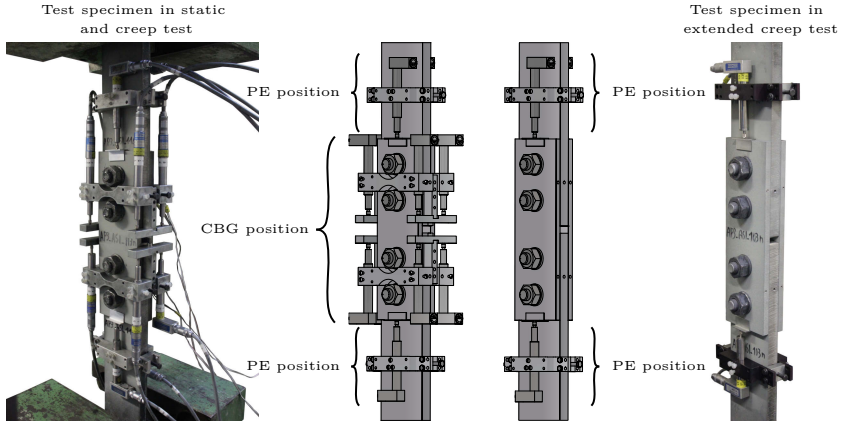


Figure 5.3 Exemplary illustration of test specimens during the slip factor test and the selected position of the linear variable differential transformers (LVDT)

in this work. All slip factor tests were carried out at the Institute for Metal and Lightweight Structures (IML) of the University of Duisburg-Essen (UDE).

5.2.2 Test results

Table 5.1 summarizes the determined slip factors for the different coatings and coating layer thicknesses.

The reference tests (here: range of coating layer thickness of 40 μm - 80 μm) for test series ASI, HDG-ASI and AISM confirm the assumed minimum slip factor values by EN 1090-2 of $\mu \geq 0.4$ for friction surface class B, see slip factors μ_{ect} in Table 5.1. Furthermore, the determined slip factors for test series ASI and AISM even clearly exceed the required minimum value with slip factors μ_{ect} of 0.58 and 0.69 respectively. On the basis of two passed extended creep tests, a slip factor $\mu_{\text{ect}} = 0.42$ was determined for the investigated ESI coating. Therefore, the requirement of $\mu \geq 0.30$ by ZTV-ING [135] is met. However, an explicit classification into a class of friction surface for the ESI coating is deliberately not carried out, since a generalized classification for ESI coating materials of different manufacturers proves to be difficult, as investigations in [92] and [217] indicate.

As expected, the variation of coating thickness is reflected in the load-bearing capacity of slip-resistant connections. Herein, as already experienced in industrial

projects carried out at UDE/IML, it could be confirmed that especially coating thicknesses in the lower range of $< 40 \mu\text{m}$ should be considered critical, as determined slip factors μ_{ect} for test series ASI, HDG-ASI as well as ESI are approx. 20 % lower compared to the reference coating thickness of approx. $40 \mu\text{m}$ - $80 \mu\text{m}$, see Figure 5.4. Thus, next to the reduced corrosion protection, a reduction of the slip resistance can be expected for lower coating thicknesses in slip-resistant connections.

Table 5.1 Summary of test results for the variation of the coating layer thickness [5]

Coating	DFT ¹⁾ [μm]	No. of tests ²⁾ st ct ect	F_{Sm} [kN]	Results - st ³⁾				ct ⁴⁾		ect ⁵⁾	
				μ_{ini} [-]	$V \mu_{\text{ini}}$ [%]	μ_{nom} [-]	μ_{act} [-]	90 % F_{Sm}	μ_{ect} [-]	n	
ASI	35	4 1 3	263.1	0.61	5.1	0.60	0.67	n.p.	0.45	2	
	64	4 1 3	300.9	0.70	1.7	0.68	0.79	n.p.	0.58	2	
	105	4 1 3	289.7	0.69	2.7	0.66	0.79	n.p.	0.59	2	
HDG-ASI	35	4 1 4	250.6	0.57	4.4	0.57	0.62	n.p.	0.37	1	
	65	4 1 4	295.4	0.67	5.2	0.67	0.75	n.p.	0.44	2	
	92	4 1 3	289.2	0.66	6.5	0.66	0.74	n.p.	0.49	2	
AlSM	62	4 1 3	318.2	0.72	4.3	0.72	0.86	n.p.	0.65	3	
	119	4 1 3	339.1	0.77	2.7	0.77	0.96	n.p.	0.69	3	
	232	4 1 3	337.1	0.77	2.4	0.77	1.00	n.p.	0.69	3	
ESI	34	4 1 3	185.0	0.42	3.2	0.42	0.45	n.p.	0.34	2	
	66	4 1 3	215.4	0.49	3.3	0.49	0.53	n.p.	0.42	2	
	111	4 1 3	228.2	0.53	1.9	0.52	0.58	n.p.	0.42	2	

1) Average dry film thickness based on measurements on inner and cover plates.

2) st: static test | ct: creep test | ect: extended creep test.

3) Given results consider mean values. μ_{ini} : slip factor considering the initial preload when the test starts. | μ_{nom} : slip factor considering the nominal minimum preload level $F_{\text{p,C}}$. | μ_{act} : slip factor considering the actual preload at slip.

4) Creep tests at 90 % F_{Sm} failed for all test series (here: n.p.).

5) μ_{ect} : slip factor resulting from the passed extended creep tests. | n: number of passed extended creep tests.

Additional remarks:

Clamping length ratio of test specimens $\Sigma t/d = 2.5$. | Nominal minimum preload level $F_{\text{p,C}} = 110 \text{ kN}$ for M16 HV 10.9 bolting assemblies.

As the test results in Table 5.1 and Figure 5.4 indicate, no significant negative influence on the slip factor could be determined for coating layer thicknesses above $80 \mu\text{m}$. This result corresponds well with the findings in [92] and [217]. Furthermore, a coating thickness of a certain amount even seems to be necessary in order to completely unfold the true potential of a specific coating regarding the load-bearing behaviour of a slip-resistant connection. Considering the test results achieved for test specimens with a measured dry film thickness of $\approx 65 \mu\text{m}$, no

significant change of the slip factor μ_{ect} was observed for the nearly doubled coating thicknesses of 105 μm and 111 μm for test series ASI and ESI respectively. A doubling of the reference coating thickness (here: approx. 119 μm DFT instead of 62 μm DFT) leads to a slightly higher slip factor of $\mu_{\text{ect}} = 0.69$ compared to $\mu_{\text{ect}} = 0.65$ for test series AISM. The same slip factor was determined even in the case of a dry film thickness of 232 μm . The latter corresponds to approx. 3.7 times higher coating thickness compared to the reference coating thickness of 62 μm . Considering the test results achieved for test series HDG-ASI, a slightly different, linear increase of the slip factor μ_{ect} can be observed with an increasing average dry film thickness of the ESI coating from 35 μm to 92 μm , see Figure 5.4. The corresponding slip factors vary between $\mu_{\text{ect}} = 0.37$ and $\mu_{\text{ect}} = 0.49$.

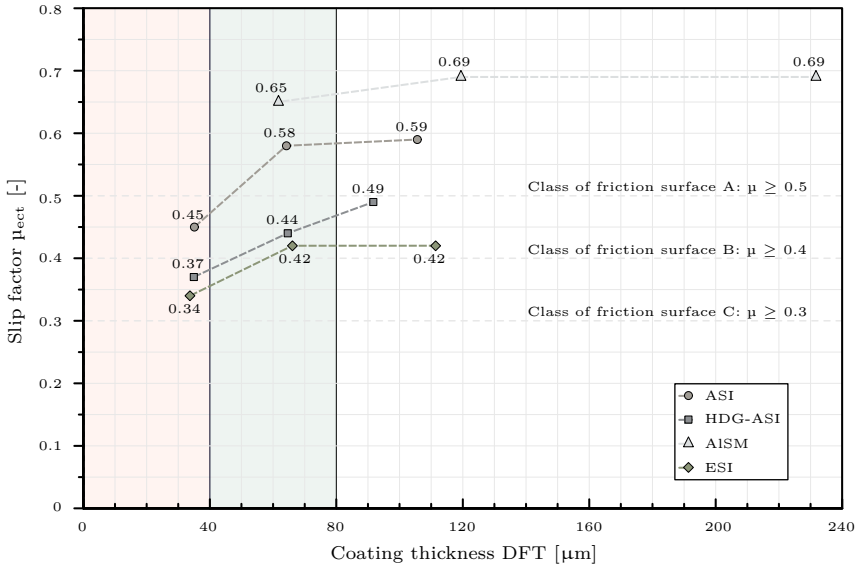


Figure 5.4 Experimentally determined slip factors μ_{ect} as a function of the dry film thickness DFT for the investigated coatings

The presented test results are additionally confirmed by the load-bearing behaviour of the investigated slip-resistant connections during the static tests, see Figure 5.5. Herein, a summary of the individual slip loads F_{Si} dependent on the corresponding slip deformation, see Figure 5.5 (left), and the determined slip deformation with regard to the actual coating thickness, see Figure 5.5 (right),

show a tendency to a significantly higher slip deformation capacity with an increasing coating layer thickness for the investigated test series.

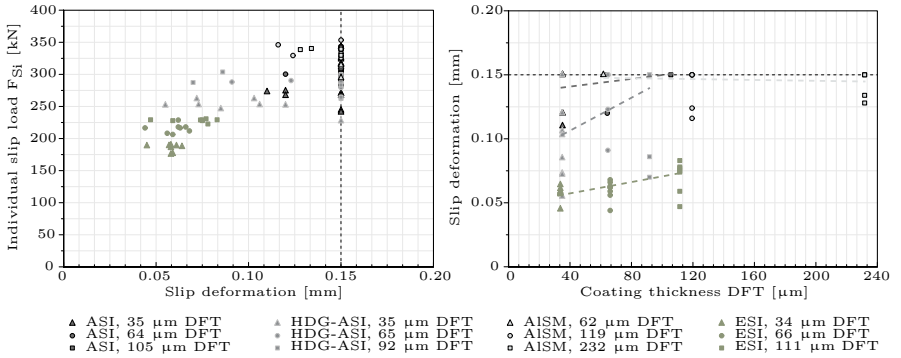


Figure 5.5 Load-bearing behaviour of slip-resistant connections considering individual slip loads in a static test (left) as well as the related slip displacement for investigated test series (right)

Figure 5.6 exemplarily presents the experimentally determined preload losses and the corresponding actual slip factor $\mu_{ect,act}$ for test series ASI. Furthermore, a summary of the determined preload losses for all investigated test series is given in Table 5.2.

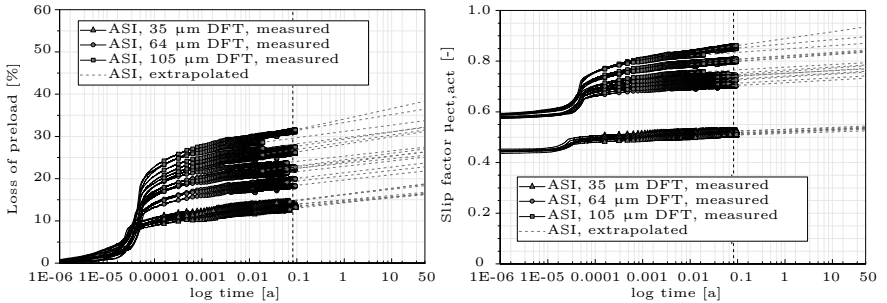


Figure 5.6 Experimentally determined preload losses during the extended creep test (left) and the corresponding actual slip factor $\mu_{ect,act}$ (right) (here: exemplarily for test series ASI)

As expected, an almost linear increase of the preload losses $\Delta F_{p,ect,50a}$ with an increasing coating layer thickness can be observed within every test series. As described in Chapter 3.3.2 and presented in Figure 3.6, the slip factor μ_{ect} determined by the extended creep tests implicitly covers lower preloading forces compared to $F_{p,C}$ and, therefore, considers a certain amount of preload losses that

occurs over the service life of structures. In order to highlight the load-bearing capacity under considerably lower preloading forces, an actual slip factor $\mu_{\text{ect,act}}$ was additionally introduced. A qualitative comparison of the slip factors μ_{ect} and $\mu_{\text{ect,act}}$, see Table 5.2 does not show any negative correlation between the increasing preload losses and the resulting slip resistance for the investigated range of coating thicknesses. Based on this result, it can be even assumed that every coating material possesses some system-related characteristics that are completely unfolded only in the presence of a specific coating layer thickness regardless of the corresponding preload losses that come with that.

Table 5.2 Summary of the determined preload losses $\Delta F_{\text{p,ect,50a}}$ for test specimens that passed the extended creep tests

Coating	DFT ¹⁾ [μm]	No. of bolts	$F_{\text{p,ini,mean}}$ ²⁾ [kN]	$\Delta F_{\text{p,ect,50a}}$ ³⁾			$V(\Delta F_{\text{p}})$ [%]	μ_{ect} ⁴⁾ [-]	$\mu_{\text{ect,act}}$ ⁵⁾ [-]
				min	mean	max			
ASI	35	8	111.3	16.2	17.3	18.7	6.1	0.45	0.54
	64	8	111.2	21.8	24.9	27.5	7.1	0.58	0.77
	105	8	110.9	27.0	32.8	38.3	9.0	0.59	0.88
HDG-ASI	35	4	115.5	17.3	19.4	20.3	7.1	0.37	0.44
	65	8	113.0	18.4	21.3	23.1	7.7	0.44	0.54
	92	8	112.3	20.3	23.7	27.8	9.5	0.49	0.63
AlSM	62	12	111.1	15.1	17.6	21.1	8.7	0.65	0.78
	119	12	111.3	17.2	19.9	23.1	8.7	0.69	0.86
	232	12	111.3	20.8	24.0	26.7	6.8	0.69	0.90
ESI	34	8	111.4	12.6	14.5	15.7	6.3	0.34	0.39
	66	8	111.1	18.3	19.5	20.9	4.9	0.42	0.51
	111	8	111.6	24.6	27.9	31.2	7.0	0.42	0.57

1) Average dry film thickness based on measurements on inner and cover plates.
2) Mean initial preload level at the beginning of the tests.
3) Mean preload losses during extended creep test extrapolated to the intended service life of 50 years.
4) μ_{ect} : slip factor resulting from the passed extended creep tests.
5) $\mu_{\text{ect,act}}$: slip factor resulting from the passed extended creep tests considering the estimated remaining preload level after 50 years.

Additional remarks:
Clamping length ratio of test specimens $\Sigma t/d = 2.5$. | Nominal minimum preload level $F_{\text{p,C}} = 110 \text{ kN}$ for M16 HV 10.9 bolting assemblies.

5.3 Procedure-related tightening of bolting assemblies

5.3.1 General

The preloading force represents one of the most important parameters for the load-bearing capacity of slip-resistant connections. According to the current test procedure of EN 1090-2, Annex G, the bolts shall be tightened to within $\pm 5\%$ of the specified preload $F_{p,C}$ at the beginning of each test. However, with regard to the practical application, the minimum nominal preload level $F_{p,C}$ (or alternatively $F_{p,C}^*$) represents only a normative requirement for the design that must be reliably achieved using different tightening methods. Consequently, some tightening methods might lead to a high scattering of the actual preload in the connection, so that the resulting slip resistance might differ from the one that is determined based on the test procedure according to EN 1090-2, Annex G.

In this investigation, the influence on the slip resistance is examined considering two different tightening methods, the modified torque method and the combined method. Analogous to the investigations presented in Chapter 5.2, test series ASI, AISM and ESI were investigated, see Figure 5.7. For the sake of comparability, the applied surface treatment including the coating materials, the test specimen geometry as well as the preparation and the execution of the tests remained the same as for investigations into different coating layer thicknesses and were already presented in Chapter 5.2.1. The preparation of the steel substrates, the subsequent application of the coating as well as the measurement of the layer thicknesses for test series ASI and ESI were carried out by the Institute for Corrosion Protection Dresden GmbH (*"Institut für Korrosionsschutz Dresden GmbH"*). The tightening of the M16 HV 10.9 bolting assemblies (EN 14399-4 [29]/EN 14399-6 [31]) was carried out in accordance with specifications given by EN 1090-2 [2] and DAST-Guideline 024 [3], see Figure 5.8. The tightening by the modified torque method was carried out using an electric tool, whereby the same tool was used in order to apply a pre-tightening torque for the first step of the tightening by the combined method. The subsequent angle of rotation for the combined method was applied by a hand torque tool with an extension arm, see Figure 5.8. Other than in the investigations presented in Chapters 4.2 and 4.3, no re-tightening by the modified torque method was considered.

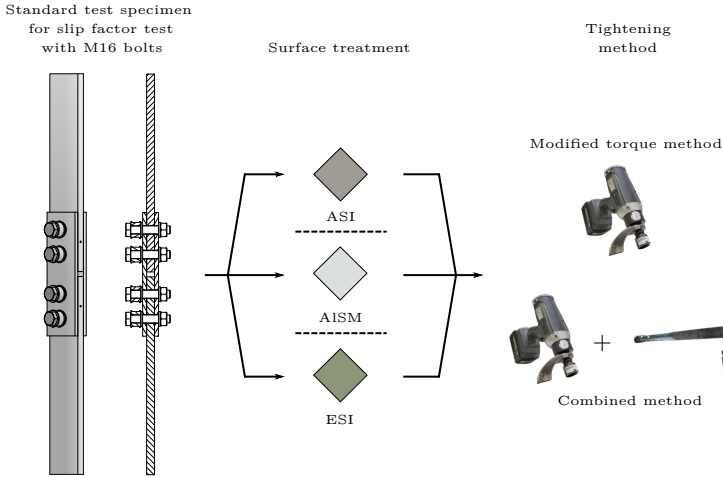


Figure 5.7 Selected configurations of test specimens for the investigation into different tightening methods

The selected coating thicknesses correspond to the ranges that are prescribed for the assumption of the minimum slip factor values by EN 1090-2. In this investigation, no bolts with implanted strain gauges were used, as their reuse after tightening by the combined method is not possible. Instead of bolts with implanted strain gauges, the bolt preload was measured with the help of load cells with a height of 20 mm that were especially manufactured from tool steel 1.2714+QT (working hardness of approx. 40 HRC) at the UDE/IML. Next to a high accuracy regarding the bolt preload measurement, as reported in [92], load cells offer the possibility to reuse them after a re-calibration. Analogous to the investigation into different coating thicknesses presented in Chapter 5.2, the slip displacement was measured at CBG and PE positions, see Figure 5.3. All tests were carried out at the UDE/IML.

5.3.2 Test results

Table 5.3 summarizes the determined slip factors in static tests for both, the modified torque method and the combined method. Herein, the expectedly higher preload levels $F_{p,ini,mean}$ of 139.9 kN to 142.1 kN in case of the combined method lead to approx. 20 % higher slip loads F_{sm} compared to the test specimens tightened by the modified torque method with corresponding preload levels

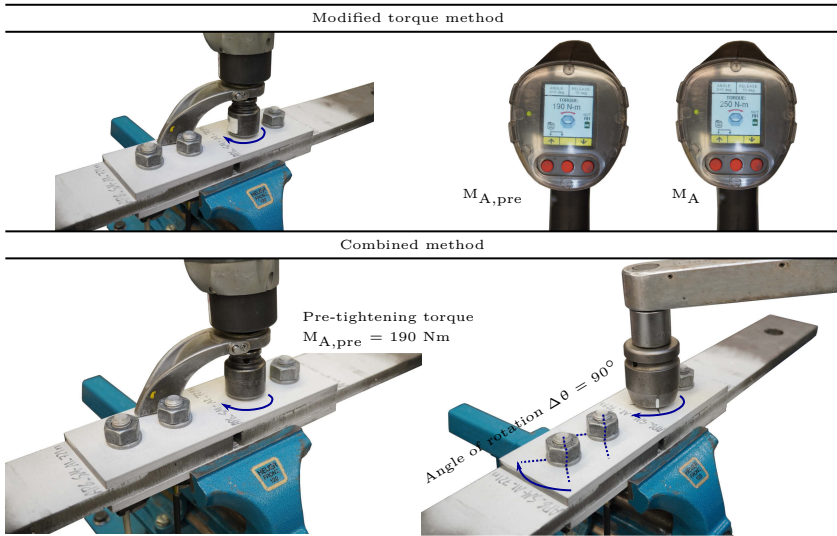


Figure 5.8 Tightening of the specimens by the modified torque method and combined method according to EN 1090-2 and DAST-Guideline 024

$F_{p,ini,mean}$ of 101.9 kN to 102.2 kN. The increase of the mean slip loads F_{Sm} for test specimens tightened by the combined method can be attributed to the higher stress concentration and consequently to higher surface pressures in the bolt hole areas due to increased initial preload levels $F_{p,ini,mean}$. As reported in [92] and [159], the slip factor μ_{ini} (based on the initial preload level at the beginning of each test) decreases with an increasing preload level. The test results in this investigation confirm such a behaviour even for preload levels of up to $\approx 1.3 F_{p,C}$, see Figure 5.9. Furthermore, an analogue behaviour could be observed for the slip factor μ_{act} within the investigated test series.

Despite the use of load cells for the tightening of bolting assemblies by the combined method and the modified torque method and the resulting increase of the clamping length ratio, a comparison of the determined test results in this investigation with the results presented in Chapter 5.2 (listed as reference values "Ref" in Table 5.3 and are characterized by " $F_{p,C} \pm 5\%$ " in Figure 5.9) seems to be reasonable. This is possible due to the fact that the actual surface pressures under the washers and consequently on the friction surfaces remain unchanged for a specific bolt preload regardless of an increase of the clamping length by the load cell. The test results in Table 5.3 show that tightening by the modified

Table 5.3 Summary of test results of static and creep tests for the influence of different tightening methods [5]

Series	DFT ¹⁾ [μm]	Tests ²⁾ st ct	F _{p,ini,mean} [kN]	Results - st ³⁾					ct ⁴⁾	
				F _S m [kN]	μ _{ini} [-]	V μ _{ini} [%]	μ _{nom} [-]	μ _{act} [-]	90 %	F _S m
ASI - KV ASI - MDV	60	4 1 4 1	139.9 101.9	351.7 292.6	0.63 0.72	1.1 3.0	0.80 0.73	0.71 0.81	n.p.	n.p.
ASI - Ref	64	4 1	108.0	300.9	0.70	1.7	0.68	0.79	n.p.	
AISM - KV AISM - MDV	62	4 1 4 1	142.1 102.2	412.7 346.6	0.73 0.85	2.6 4.0	0.94 0.87	0.88 1.03	n.p.	n.p.
AISM - Ref	62	4 1	109.9	318.2	0.72	4.3	0.72	0.86	n.p.	
ESI - KV ESI - MDV	67	4 1 4 1	142.0 102.0	255.9 212.6	0.45 0.52	2.4 3.9	0.58 0.53	0.48 0.56	n.p.	n.p.
ESI - Ref	66	4 1	109.0	215.6	0.49	3.3	0.49	0.53	n.p.	

1) Average dry film thickness based on measurements on inner and cover plates.

2) st: static test | ct: creep test.

3) Given results consider mean values. F_{p,ini,mean}: mean bolt preload at the beginning of static tests. μ_{ini}: slip factor considering the initial preload when the tests start. | μ_{nom}: slip factor considering the nominal minimum preload level F_{p,C}. | μ_{act}: slip factor considering the actual preload at slip.

4) Creep tests at 90 % F_Sm failed for all test series (here: n.p.).

Additional remarks:

Clamping length ratio of test specimens Σt/d = 3.75 (Σt/d = 2.5 for reference tests).

KV: combined method (F_{p,C} = 110 kN). | MDV: modified torque method (F_{p,C}* = 100 kN).

Ref: Reference tests from Chapter 5.2 based on F_{p,C} = 110 kN ± 5 %.

torque method leads to similar load-bearing capacities F_Sm as well as static slip factors μ_{ini,mean} that were achieved for the reference test series. Herein, the relative deviations remain within approx. 5 % for the different investigated surface treatments. As expected, the creep tests at a load level of 90 % F_Sm failed for all test series.

Table 5.4 summarizes the determined slip factors achieved in extended creep tests μ_{ect} for both tightening methods. The determination of the slip factor μ_{ect} was carried out considering the actual preload level F_{p,ini} at the beginning of the respective test. For this reason, in most cases not one value, but a range of slip factors μ_{ect} is given in Table 5.4. However, since the initial bolt preloads in this investigation deviate significantly from the preload level F_{p,C} ± 5 % that is prescribed by the Annex G of EN 1090-2, the values of the slip factor μ_{ect} are only of a limited significance for the further comparison. For this reason, Figure 5.10 shows experimentally determined slip factors μ_{ect} as a function of

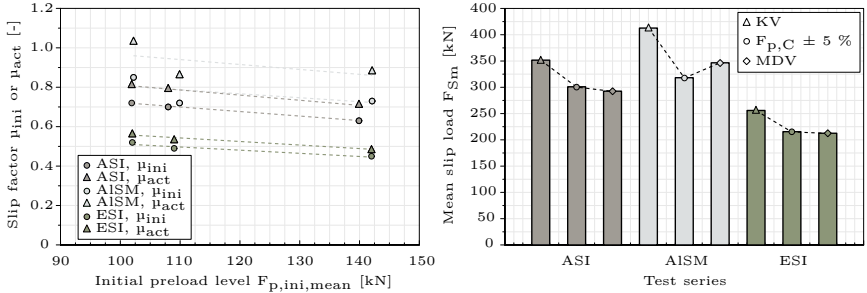


Figure 5.9 Experimentally determined slip factors μ_{ini} and μ_{act} in relation to the initial preload level $F_{p,ini,mean}$ (left) as well as a comparison of the mean slip loads F_{Sm} in static tests (right)

the product $\mu_{ect} \times F_{p,ini,mean}$ as well as a comparison of the test loads F_{ect} of the passed extended creep tests in order to meaningfully reflect on the current design format, as presented in Chapter 3.3.2 and illustrated by Equation (3.3).

As indicated by the test results achieved in static slip tests, tightening by the modified torque method provides comparable results to those of the reference tests presented in Chapter 5.2. However, tightening by the combined method leads to a significant increase of the slip resistance, as can be seen in Figure 5.10 (right). Compared to the preloading to $F_{p,C} \pm 5\%$ (as prescribed by EN 1090-2, Annex G) or by the modified torque method (nominal preload level $F_{p,C}^*$), an increase of the slip resistance of up to $\approx 30\%$ can be expected for connections tightened by the combined method. As highlighted by the static slip tests, this positive influence of the combined method is directly connected to the high initial preload levels at the start of the respective test. Herein, preload levels of $1.16 F_{p,C}$ to $1.26 F_{p,C}$ can be taken as a basis for the combined method, whereby $\approx F_{p,C}^*$ can be considered for the modified torque method in this investigation. With regard to the experimental investigations carried out in [4] and [6], preload levels of such scale seem to be plausible for both investigated tightening methods, so that the test results can be taken as representative with regard to the expected slip resistance. As a comparison of the informative regression lines for KV and MDV in Figure 5.10 (left) with the test results achieved for preload levels of $F_{p,C} \pm 5\%$ indicate, the favourable influence of higher preload levels in case of the combined method on the slip resistance is currently not taken into account during the design of slip-resistant connections.

Table 5.4 Summary of test results of extended creep tests for the influence of different tightening methods [5]

Series	DFT ¹⁾	Tests ²⁾	F _{p,ini,mean}	Results - ect ³⁾		
	[μm]	ect		F _{ect}	μ _{ect}	n
ASI - KV	60	3	127.8	316.5	0.61 - 0.63	2
ASI - MDV		3	99.5	263.4	0.66	1
ASI - Ref	64	3	111.2	255.8	0.58	2
AISM - KV	62	3	138.5	371.4	0.67 - 0.68	3
AISM - MDV		3	102.6	294.6	0.71 - 0.73	3
AISM - Ref	62	3	111.0	286.4	0.65	3
ESI - KV	67	3	136.3	217.5	0.39 - 0.41	3
ESI - MDV		3	98.1	180.7	0.46 - 0.47	3
ESI - Ref	66	3	110.1	183.1	0.42	2

1) Average dry film thickness based on measurements on inner and cover plates.

2) ect: extended creep test.

3) Given results consider mean values. F_{p,ini,mean}: mean bolt preload at the beginning of static tests. | F_{ect}: load level of the passed extended creep test. μ_{ect}: slip factor resulting from the passed extended creep tests. | n: number of passed extended creep tests based on the corresponding initial preload level F_{p,ini}.

Additional remarks:

Clamping length ratio of test specimens Σt/d = 3.75 (Σt/d = 2.5 for reference tests). | KV: combined method (F_{p,C} = 110 kN). | MDV: modified torque method (F_{p,C}* = 100 kN). | Ref: Reference tests from Chapter 5.2 based on F_{p,C} = 110 kN ± 5 %.

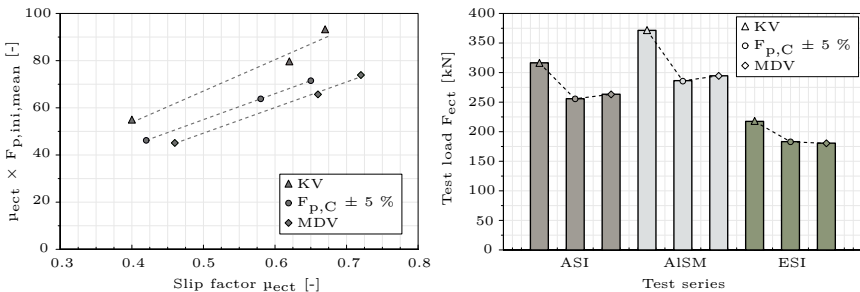


Figure 5.10 Experimentally determined slip factors as a function of the product of the slip factor μ_{ect} and the initial preload level $F_{p,ini,mean}$ (left) as well as a comparison of the test loads F_{ect} of the passed extended creep tests (right)

5.4 Preloads in bolted connections of existing steel bridges

5.4.1 General

The current test procedure for the determination of the slip factor according to EN 1090-2, Annex G ensures that the possibility of creep deformation of a connection is taken into account. Herein, a constant load is applied on the connection, see explanations in Chapter 2.5.3. However, the test procedure does not consider cyclic loading. Considering the fact that slip-resistant connections are primarily designed for their application in structures subjected to cyclic loading, it has to be questioned whether fatigue loads can negatively influence the preload in a connection and consequently the assumed slip factor.

As already reported in Chapter 3.3.2, several experimental investigations up to this date were carried out with regard to the load-bearing characteristics of a slip-resistant connections under fatigue loading. Herein, the test results indicated that the current test procedure according to EN 1090-2, Annex G and especially the (extended) creep test seem to cover the most critical load constellation, so that the resulting slip factors consider not only the potential preload losses, but also the influence of inevitable cyclic loads. The latter two criteria were reviewed in the frame of an industrial project with regard to railway bridges over the German highway A 40 between Duisburg and Mülheim an der Ruhr. The following chapters summarize the main results of experimental investigations into slip factors under consideration of cyclic loading as well as into bolt preloads in existing connections, as reported in [215] and based on expert opinions [7] and [8]. The experimental investigations were carried out at the UDE/IML.

5.4.2 Slip factor under consideration of cyclic loading

For the determination of a slip factor under consideration of the influence of cyclic loading, slip factor tests were carried out on M16 standard test specimens according to EN 1090-2, Annex G considering two different surface treatments [7]-[8]:

- 2K-ESI: grit blasted to grade Sa 2^{1/2} according to EN ISO 8501-1 [216] (profile grade "medium (G)" according to EN ISO 8503-1 [73] with an average surface roughness $R_{y5} \approx 79 \mu\text{m}$) + two-pack ethyl-zinc silicate paint according to Sheet 86 of TL/TP-ING [136] (product GEHODUR-F86-Zink, measured coating thickness $90 \mu\text{m}$ DFT) and

- **1K-ESI:** grit blasted to grade Sa 2^{1/2} according to EN ISO 8501-1 (profile grade "medium (G)" according to EN ISO 8503-1 with an average surface roughness $R_{y5} \approx 79 \mu\text{m}$) + one-pack ethyl-zinc silicate paint according to Sheet 86 of TL/TP-ING [136] (product GEHODUR-F35-Zink for cover plates with a measured coating thickness $\approx 80 \mu\text{m}$ DFT and product SikaCor® Zinc ZS for inner plates with a measured coating thickness $\approx 99 \mu\text{m}$ DFT).

After determination of the slip factor following the test procedure of EN 1090-2, Annex G, three further tests for each surface treatment were carried out in order to confirm the assumed slip factor μ_{ect} under the consideration of a cyclic loading prior to the constant load in an extended creep test, see Figure 5.11. Herein, the maximum shear forces predicted for the real structure from [218] were simulated in form of a sinusoidal cyclic loading with a stress ratio of $R = 0$. Two specimens for each surface treatment were subjected to 1 million load cycles and one test specimen each was addressed to 5 million load cycles before the subsequent extended creep test.

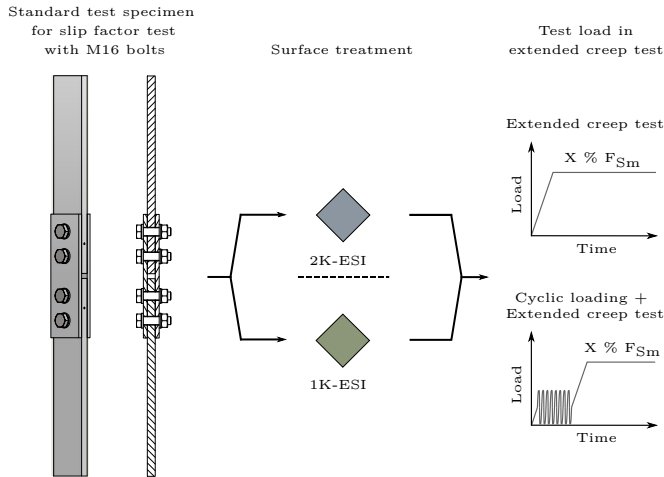


Figure 5.11 Investigated configurations of test specimens and selected load constellations for the extended creep tests

Based on the extended creep tests acc. to EN 1090-2, Annex G, slip factors $\mu_{\text{ect}} = 0.45$ (test load $F_{\text{ect}} = 197.0 \text{ kN}$) and $\mu_{\text{ect}} = 0.36$ (test load $F_{\text{ect}} = 160.2 \text{ kN}$) were determined for test series 2K-ESI and 1K-ESI respectively, see [7].

The cyclic tests showed no significant slip displacements with values of less than 0.01 mm for the corresponding maximum cyclic loads of 42 % F_{ect} and 52 % F_{ect} for test series 2K-ESI and 1K-ESI respectively, see explanations in [7], despite some preload losses in a range of 5 % to 8 % (depending on the number of load cycles). Every subsequent extended creep test considering the test load F_{ect} of 197.0 kN (2K-ESI) and 160.2 kN (1K-ESI) was passed, see exemplary Figure 5.12 for the test series 2K-ESI. This result shows that the determined slip factors μ_{ect} can also be confirmed for test specimens subjected to cyclic loading. Therefore, no negative influence on the slip resistance could be observed. Conversely, cyclic loading rather leads to a better interlocking of the friction surfaces.

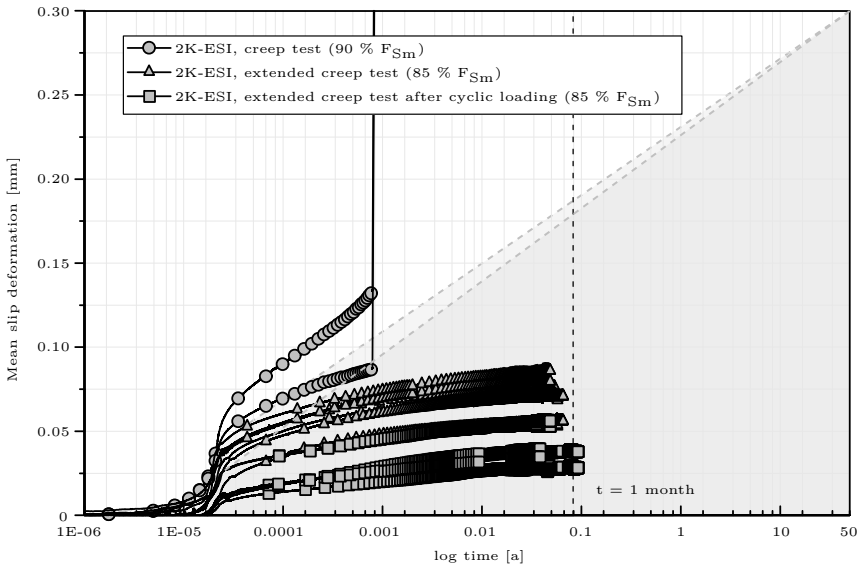


Figure 5.12 Exemplary illustration of test results of a creep test (load level of 90 % F_{Sm}) and passed extended creep tests (load level of 85 % F_{Sm}) under consideration of the cyclic loading for test series 2K-ESI [7], [215]

5.4.3 Determination of existing bolt preloads in slip-resistant connections after a service life of 18 years

In accordance with the approach presented by *de Vries et al.* [219], [159], a special method was developed for the determination of existing bolt preloads in bolted connections [8], see Figure 5.13. This method enabled to carry out the

measurement of the bolt preloads on site and even in the presence of regularly passing high speed trains. The measurement was conducted on a total of ten bolts from a twin girder auxiliary bridge, which dates back to 2003. Figure 5.13 summarizes the main procedure steps for the preparation of the bolts with implanted strain gauges carried out in this investigation. After loosening of the bolts with implanted strain gauges, a calibration step was carried out at the UDE/IML in order to convert the measured strain values into the remaining preload in the bolts. More details can be found in [8] and [215].

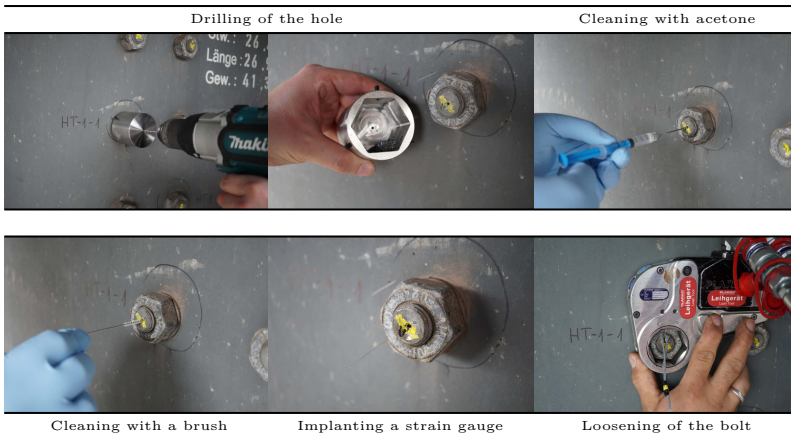


Figure 5.13 Procedure for preparing the bolts with implanted strain gauges under construction site conditions | Photos: © Stranghöner Ingenieure GmbH

The evaluation of the measured bolt preloads $F_{p,act}$, see Figure 5.14, shows that the nominal preload level $F_{p,C}^*$ of 220 kN (here: M24 HV 10.9 bolting assemblies, torque-controlled tightening) is maintained in seven out of ten examined cases, whereby the maximum bolt preload exceeded $F_{p,C}^*$ by approx. 29 %. Three bolts showed some deficits in the range of 1 % to 12 %. However, it should be pointed out that the theoretical bolt preload range for the k-value of 0.10 to 0.16 ranges between $F_{p,k=0.16} = 208.3$ kN and $F_{p,k=0.10} = 333.3$ kN, so that a deficit of approx. 5 % with regard to the preload level $F_{p,C}^*$ may occur even in case of a proper lubrication and a standard-compliant tightening of the bolting assemblies according to the former DIN 18800-7. The average bolt preload $F_{p,act,mean}$ considering all ten bolting assemblies corresponds to a value of $1.06 F_{p,C}^*$.

An overall analysis of the actual bolt preloads indicates that the HV bolting assemblies were properly tightened at the time of the initial commissioning of a twin girder auxiliary bridge, so that a sufficient preload level for the slip-resistant connections can be confirmed even after 18 years. Furthermore, the actual bolt preloads were still within the range of the nominal preload level $F_{p,C}^*$.

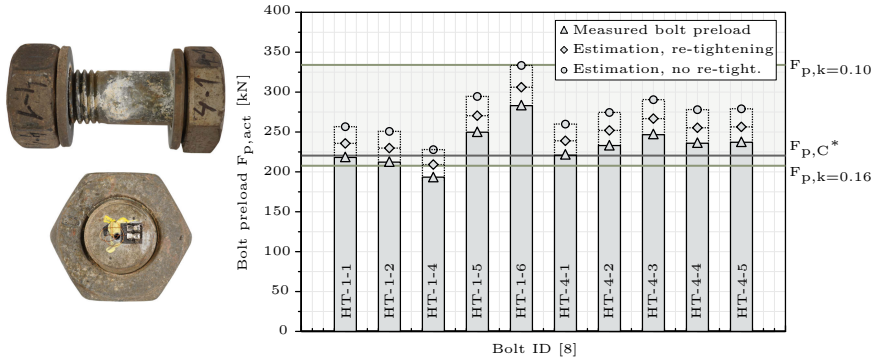


Figure 5.14 Measured bolt preloads $F_{p,act}$ and estimated initial bolt preload after initial tightening as well as considering a re-tightening [8]-[215] | Photos: © Stranghöner Ingenieure GmbH

In addition to the evaluation of the actual bolt preloads $F_{p,act}$, a plausibility analysis was carried out. Herein, possible preload losses over the service life of the connection for the actual preparation of the friction surfaces (2K-ESI, grit blasted to grade Sa 2^{1/2}, coating thickness of 60 μ m to 80 μ m NDFT) considering the findings in the frame of [5] and [6] were estimated, see Figure 5.14. The measured bolt preloads in combination with possible preload losses appear to be plausible for both, initial tightening by the torque method ("*Drehmoment-Vorspannverfahren*") according to DIN 18800-7 without re-tightening as well as initial tightening by the torque method according to DIN 18800-7 with a subsequent re-tightening. In both cases, the estimated initial preload levels correspond to a theoretical bolt preload range of $F_{p,k=0.16} = 208.3$ kN and $F_{p,k=0.10} = 333.3$ kN for k-class K1.

5.5 Summary and conclusions

The main influencing parameters for the load-bearing behaviour of slip-resistant connections include the level of preload and the associated slip factor. The latter

represents an experimental value, which mainly depends on the condition of the friction surfaces including the composition of the coating material as well as the coating thickness.

In this investigation, the slip resistance was determined considering practical boundary conditions such as the variation of coating thickness and the procedure-related tightening of bolting assemblies. It was found that comparatively low coating thicknesses in a range of 25 μm to 40 μm might lead to approx. 20 % lower slip factors compared to the reference coating thickness of 40 μm to 80 μm . Encouragingly, coating layer thicknesses above 80 μm do not show any negative influence on the slip factor. Procedure-related tightening by the combined method leads to a significant increase of the slip resistance of up to 30 % compared to the tightening that is prescribed by the test procedure according to EN 1090 2, Annex G. This procedure-related favourable influence is currently not normatively considered.

In addition to the investigations above, the slip factor under consideration of cyclic loading as well as the actual bolt preloads after a service life of 18 years were determined in the frame of a project with regard to railway bridges [215]. Herein, the test results indicated that a cyclic loading prior to the extended creep test does not affect the slip factor and rather leads to a better interlocking of the friction surfaces. A determination of the actual bolt preloads on the existing connections confirmed a sufficient preload level even after a service life of 18 years.

6 Amendments for standardization

6.1 General

The selection of a suitable corrosion protection and the initiation of a sufficient preload level can have a decisive influence on the performance and the durability of a preloaded bolted connection. Especially with regard to the handling of preload losses, the current normative regulations seem to rather represent a reactive approach instead of taking proactive measures during design and execution. This can mainly be attributed to the lack of systematic studies, especially considering the procedure-related tightening of bolting assemblies and the resulting preload losses.

In the frame of this study, a comprehensive investigation into system reserves and preload losses in preloaded bolted connections was conducted considering different tightening methods as well as paint and powder coating systems that commonly used in steel construction. Following that, an assessment of different coating systems depending on the intended target level of preloading was carried out and was presented in Chapter 4.3.5. Furthermore, the behaviour of slip-resistant connections considering practical boundary conditions and their possible affect on the slip resistance was investigated in Chapters 5.2 and 5.3. Considering these test results, some supplementary recommendations for the execution of slip-resistant connections can be made.

6.2 Consideration of preload losses in steel construction

6.2.1 General

Current normative regulations for the consideration of preload losses in steel construction are very limited. According to EN 1090-2 [2], a loss of preload of no more than 10 % is implicitly considered in the specified tightening methods. Furthermore, EN 1090-2, Annex I provides a list of different coatings/coating systems with associated possible preload losses that may be used as a reference basis to check their suitability in preloaded bolted connections, whereby a similar

list of six verified coating systems is also provided by ZTV-ING [135]. The normative foundations for the provided coatings/coating systems have emerged from the investigations carried out by *Katzung et al.* [148]-[150]. The historical development of the current normative regulations as well as some critical points were extensively discussed in Chapter 3.3.3.

In case of thick coatings with thicknesses of 100 µm NDFt and more, coatings of a particularly creep-prone material or in cases where an assessment of preload losses is not possible (e.g. by using the Table I.1 of EN 1090-2), a test procedure for the experimental determination of preload losses is proposed by the Annex I of EN 1090-2. However, as discussed in Chapter 3.3.3.6, these normative regulations regarding preload losses should be updated considering the latest experimental findings.

In the followings chapters, some additions regarding the handling of preload losses in preloaded bolted connections with typical coating systems as well as an updated test procedure for the determination of preload losses are proposed. Herein, the test results presented in Chapter 4 as well as the current normative regulations of EN 1090-2, Annex I are considered.

6.2.2 Handling of preload losses in bolted connections with typical coating systems

6.2.2.1 Criteria for the consideration of preload losses

Steel surfaces of preloaded bolted connections must be generally protected against corrosion. The suitability of the selected protective coatings or coating systems in preloaded bolted connections depends on the extent of the possible system reserves due to the tightening procedure (here: the actual preload level in relation to the nominal minimum preloading force), preload losses over the service life of a structure, but also on the target level of preloading.

NOTE 1 A reliability of different tightening methods with regard to their ability to achieve the nominal preload level shall be taken into account. Herein, e.g. the combined method can offer significantly higher initial preload values, so that system reserves due to tightening into the overelastic range of approx. 25 % and more can be assumed.

With regard to preloading of bolted connections, a distinction between two target levels can be made:

- **target level I of preloading:** bolted connections are preloaded to ensure the structural safety and
- **target level II of preloading:** bolted connections are preloaded to improve the serviceability.

A distinction between the target levels of preloading intends to emphasize the importance of the preloading force. Furthermore, different possibilities for the execution of preloaded bolted connections including the necessary measures regarding the application and the handling of the preloading force are highlighted.

NOTE 2 Connections of categories B/C acc. to EN 1993-1-8 [1] are directly dependent on a defined and reproducible preload level. Due to the boundary conditions of the creep and extended creep tests acc. to EN 1090-2, Annex G [2], the possibility of the creep deformation in a connection is taken into account, so that a crucial amount of potential preload losses is implicitly considered in the slip factor. If the surfaces beneath washers are executed following the recommendations provided by the Clause 8.4 of EN 1090-2, an explicit consideration of preload losses is not necessary. If alternative surface coatings (among other things with thicknesses of $> 100 \mu\text{m}$) between washers and connected surfaces are applied, it is recommended to consider them directly during the determination of the slip factor acc. to EN 1090-2, Annex G.

Preloaded tension connections of category E acc. to EN 1993-1-8 are directly dependent on a defined and reproducible preload level. In this case, the specified nominal preload value must be maintained over the intended service life of a structure, so that an explicit consideration must be taken regarding potential preload losses.

Bolted connections of target level II of preloading are preloaded for serviceability reasons and shall be treated as non-preloaded bolted connections. In this case, an estimation of potential preload losses is recommended with regard to the advantages that are offered by a sufficient remaining bolt preload e.g. prevention of the opening of the clamped parts or improvement of the deformation behaviour.

Based on the experimental investigations, an estimation of the remaining preload level in preloaded bolted connections considering common paint and powder coating systems is presented in Chapter 6.2.2.2. For other surface treatments or boundary conditions, an updated test procedure for the determination of preload losses presented in Chapter 6.2.3 can be used.

6.2.2.2 Estimation of preload losses

As appropriate, Tables 6.1 and 6.2 may be used as a reference basis to estimate the remaining preload level for different paint and powder coating systems considering tightening by the modified torque method acc. to DAST-Guideline 024 and the combined method acc. to EN 1090-2 as well as different target levels of preloading.

Tables 6.1 and 6.2 assume that the coated surfaces on two/three plies are drawn together by preloaded fasteners with all surfaces coated (i.e. four and six coated surfaces are clamped together including the coated surfaces beneath the washers or nuts/bolt heads). The estimated remaining preload levels assume clamping length ratios of $2.4 \leq \Sigma t/d \leq 5$ and dry film thicknesses (DFT) of $\leq 1.2 \times \text{NDFT}$.

NOTE 3 The selected coating thickness of $1.2 \times \text{NDFT}$ represents a more restrictive limit than that specified in EN 1090-2, Clause F.7.2.

NOTE 4 An excessive coating layer thickness might affect the mechanical properties of the coating/coating system and increase a risk of an incomplete evaporation of solvents during the curing process. Next to an increase of preload losses, the deterioration of mechanical properties are especially critical considering the angle-controlled tightening (here: e.g. second tightening step of the combined method), as the bolting assemblies cannot be exploited to their full potential and high system reserves, see NOTE 1, cannot be guaranteed.

6.2.3 Test to determine the loss of preload

6.2.3.1 General

The purpose of this test procedure is to relate the loss of preload to the maximum permitted thickness of coating layers. It is not the purpose of the test to assess the effect on the slip factor of paint on the faying surfaces of slip-resistant connections.

The validity of the test results is limited to cases where all significant variables are similar to those of the test specimens. Among other things, the following variables shall be taken as significant on the test results:

- a) The composition of the coating;
- b) The surface treatment and treatment of primary layers in case of multi-layer systems;
- c) The maximum thickness of the coating;

Table 6.1 Connections with target level II of preloading: Estimated remaining preload levels for different coatings and coating systems considering the modified torque method (MDV) and the combined method (KV)

No.	Exp. Coating system	Surface prep.	Coating thickness NDFT [μm] ¹⁾	No. of coated surfaces	Estimated remaining preload level ²⁾		
					MDV tight.	MDV re-tight.	KV tight.
1. Typical conventional paints and paint systems on grit blasted steel substrates							
1.1	2K-PUR	Sa 2 ¹ / ₂ medium (G)	160	4 6	0.80 F _{p,C} * 0.70 F _{p,C} *	0.90 F _{p,C} * 0.85 F _{p,C} *	1.0 F _{p,C} 0.90 F _{p,C}
1.2	2K-EP 2K-PUR	Sa 2 ¹ / ₂ medium (G)	80 80	4 6	0.85 F _{p,C} * 0.80 F _{p,C} *	0.90 F _{p,C} * 0.90 F _{p,C} *	1.0 F _{p,C} 1.0 F _{p,C}
1.3	2K-EP-Zn 2K-EP-EG 2K-PUR	Sa 2 ¹ / ₂ medium (G)	80 80 80	4 6	0.80 F _{p,C} * 0.75 F _{p,C} *	0.90 F _{p,C} * 0.85 F _{p,C} *	1.0 F _{p,C} 1.0 F _{p,C}
1.4	2K-EP-Zn 2K-EP-EG 2K-EP-EG 2K-PUR	Sa 2 ¹ / ₂ medium (G)	80 80 80 80	4 6	0.80 F _{p,C} * 0.75 F _{p,C} *	0.90 F _{p,C} * 0.85 F _{p,C} *	1.0 F _{p,C} 0.95 F _{p,C}
2. Typical powder coating systems on grit blasted steel substrates							
2.1	EP/SP	Sa 2 ¹ / ₂ medium (G)	80	4 6	0.95 F _{p,C} * 0.95 F _{p,C} *	0.95 F _{p,C} * 0.95 F _{p,C} *	1.0 F _{p,C} 1.0 F _{p,C}
2.2	EP SP	Sa 2 ¹ / ₂ medium (G)	100 80	4 6	0.90 F _{p,C} * 0.90 F _{p,C} *	0.95 F _{p,C} * 0.95 F _{p,C} *	1.0 F _{p,C} 1.0 F _{p,C}
3. Typical powder coating systems on hot dip galvanized surfaces ³⁾ (duplex-systems)							
3.1	EP/SP	sweep blasted	100	4 6	0.90 F _{p,C} * 0.85 F _{p,C} *	0.95 F _{p,C} * 0.90 F _{p,C} *	1.0 F _{p,C} 1.0 F _{p,C}
3.2	EP SP	sweep blasted	80 80	4 6	0.85 F _{p,C} * 0.80 F _{p,C} *	0.95 F _{p,C} * 0.90 F _{p,C} *	1.0 F _{p,C} 1.0 F _{p,C}

1) NDFT: nominal dry film thicknesses that are required in order to meet the requirements on the corrosivity category and protection life acc. to Table 4.5.

2) Rounded values based on the mean initial preload level F_{p,ini,mean} and mean preload losses ΔF_{p,setting,50a,mean,reg} from the carried out linear regression.

3) Hot dip galvanizing in accordance with EN ISO 1461.

Application limits:

Clamping length ratio: $2.4 \leq \Sigma t/d \leq 5$ | Limit of coating thickness: $1.2 \times \text{NDFT}$.

Abbreviations:

2K: two-pack | EP: epoxy based paint | EP-Zn: epoxy based zinc rich paint | EG: micaceous iron oxide
SP: polyester resin | PUR: polyurethane paint

- d) The curing procedure and the minimum time interval between application of the coating and tightening of the connection;
- e) The preload level in the connection;

Table 6.2 Low-maintenance connections with target level I of preloading: Estimated re-maining preload levels for different coatings and coating systems considering the modified torque method (MDV) and the combined method (KV)

No.	Exp. Coating system	Surface prep.	Coating thickness NDFT [μm] ¹⁾	No. of coated surfaces	Estimated remaining preload level ²⁾		
					MDV tight.	MDV re-tight.	KV tight.
1. Typical conventional paints and paint systems on grit blasted steel substrates							
1.1	2K-PUR	Sa 2 ^{1/2} medium (G)	160	4 6	0.65 F _{p,C} [*] 0.60 F _{p,C} [*]	0.75 F _{p,C} [*] 0.70 F _{p,C} [*]	0.95 F _{p,C} 0.90 F _{p,C}
1.2	2K-EP 2K-PUR	Sa 2 ^{1/2} medium (G)	80 80	4 6	0.70 F _{p,C} [*] 0.70 F _{p,C} [*]	0.75 F _{p,C} [*] 0.75 F _{p,C} [*]	1.0 F _{p,C} 1.0 F _{p,C}
1.3	2K-EP-Zn	Sa 2 ^{1/2} medium (G)	80	4	0.70 F _{p,C} [*]	0.75 F _{p,C} [*]	1.0 F _{p,C}
	2K-EP-EG		80	6	0.65 F _{p,C} [*]	0.75 F _{p,C} [*]	0.95 F _{p,C}
	2K-PUR		80				
1.4	2K-EP-Zn	Sa 2 ^{1/2} medium (G)	80	4	0.65 F _{p,C} [*]	0.75 F _{p,C} [*]	1.0 F _{p,C}
	2K-EP-EG		80				
	2K-EP-EG		80	6	0.60 F _{p,C} [*]	0.70 F _{p,C} [*]	0.90 F _{p,C}
	2K-PUR		80				
2. Typical powder coating systems on grit blasted steel substrates							
2.1	EP/SP	Sa 2 ^{1/2} medium (G)	80	4 6	0.80 F _{p,C} [*] 0.80 F _{p,C} [*]	0.80 F _{p,C} [*] 0.80 F _{p,C} [*]	1.0 F _{p,C} 1.0 F _{p,C}
2.2	EP SP	Sa 2 ^{1/2} medium (G)	100	4	0.80 F _{p,C} [*]	0.80 F _{p,C} [*]	1.0 F _{p,C}
			80	6	0.75 F _{p,C} [*]	0.80 F _{p,C} [*]	1.0 F _{p,C}
3. Typical powder coating systems on hot dip galvanized surfaces ³⁾ (duplex-systems)							
3.1	EP/SP	sweep blasted	100	4 6	0.75 F _{p,C} [*] 0.75 F _{p,C} [*]	0.80 F _{p,C} [*] 0.80 F _{p,C} [*]	1.0 F _{p,C} 1.0 F _{p,C}
3.2	EP SP	sweep blasted	80	4	0.75 F _{p,C} [*]	0.80 F _{p,C} [*]	1.0 F _{p,C}
			80	6	0.70 F _{p,C} [*]	0.75 F _{p,C} [*]	1.0 F _{p,C}

1) NDFT: nominal dry film thicknesses that are required in order to meet the requirements on the corrosivity category and protection life acc. to Table 4.5.

2) Rounded values based on the fracture values of initial preload level F_{p,ini,0.05} and mean preload losses ΔF_{p,setting,50a,mean,reg} from the carried out linear regression.

3) Hot dip galvanizing in accordance with EN ISO 1461.

Application limits:

Clamping length ratio: $2.4 \leq \Sigma t/d \leq 5$ | Limit of coating thickness: $1.2 \times \text{NDFT}$.

Abbreviations:

2K: two-pack | EP: epoxy based paint | EP-Zn: epoxy based zinc rich paint | EG: micaceous iron oxide
SP: polyester resin | PUR: polyurethane paint

f) The number and configuration of washers;

g) The clamping length ratio.

The specified surface treatment and coating shall be applied to the contact surfaces of the test specimens in a manner consistent with the intended structural application. The actual surface roughness and the dry coating thickness shall be documented. The curing procedure shall be documented, either by reference to published recommendations or by description of the actual procedure.

6.2.3.2 Test procedure

The following test procedure is proposed for the determination of preload losses:

- a) Unless otherwise specified, the test specimens can consist of 2 plies 300 mm × 150 mm × 8 mm and 1 ply 300 mm × 150 mm × 16 mm with 8 holes of 18 mm diameter, see Figure 6.1. The test specimen geometries and the corresponding surface condition may differ with regard to the intended use in the structure;
- b) Every test ply shall be coated with the coating system on both sides, unless otherwise specified;
- c) The plies should be fastened together using 8 preloaded M16 × 60 mm bolt/nut/washer assemblies;
- d) The bolting assemblies should be preloaded according to the relevant method, which is intended to be used in the structural application. If a re-tightening is considered, the time duration after initial tightening shall be specified;
- e) The preload in the bolts shall be directly measured with equipment that is accurate to $\pm 4\%$. The loss of preload shall be recorded continuously over a period of at least 14 days so that a "loss of preload-log time" curve can be determined with a subsequent linear extrapolation to the intended service life of the structure, see Figure 6.2.

NOTE 5 A considerable system-dependent drop in the measured preload curve between the maximum peak and the first several seconds (in general, three seconds can be assumed as a simplification) can be observed after the tightening of the bolts. This instant drop is not entirely related to the relaxation behaviour of the bolting assemblies, as this phenomenon can be explained by turning back of the nut and the elastic recovery of the bolt threads when the wrench is removed. For this reason, these recovery losses should not be considered as a loss of preload.

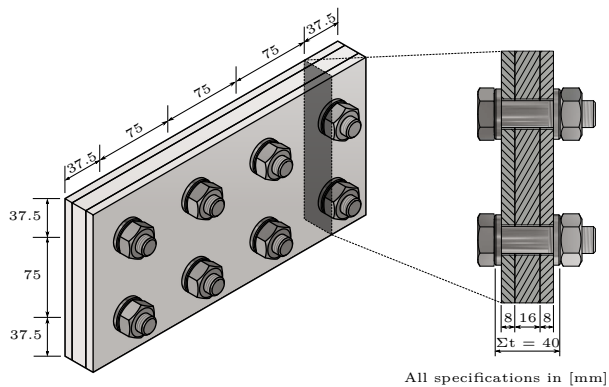


Figure 6.1 Example of the test specimen

NOTE 6 Longer test duration than 14 days might be necessary in order to determine the loss of preload for connections consisting of creep prone materials or coatings with excessive coating thicknesses.

The test results shall be documented.

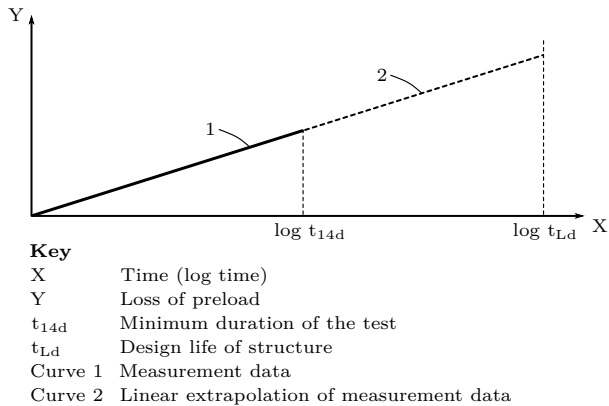


Figure 6.2 Loss of preload-log time curve for determination of the loss of preload

6.2.3.3 Evaluation of the test results

A procedure-related tightening of bolting assemblies (among other things considering a re-tightening, if applicable) enables a verification of the applied tightening

method with regard to its reliability. Furthermore, the procedure-related tightening offers a possibility to check, whether a certain amount of systems reserves can be applied for the compensation of potential preload losses.

The mean value of the determined initial preload $F_{p,ini,mean}$, its standard deviation $\sigma_{F_{p,ini}}$ as well as the associated coefficient of variation $V_{F_{p,ini}}$ are determined by Equations (6.1) to (6.3):

$$F_{p,ini,mean} = \frac{\sum F_{p,ini,i}}{n_{spec}} \text{ [kN]} \quad (6.1)$$

$$\sigma_{F_{p,ini}} = \sqrt{\frac{\sum (F_{p,ini,i} - F_{p,ini,mean})^2}{n_{spec} - 1}} \text{ [kN]} \quad (6.2)$$

$$V_{F_{p,ini}} = \frac{\sigma_{F_{p,ini}}}{F_{p,ini,mean}} [-] \quad (6.3)$$

where $F_{p,ini,i}$ is the individual initial bolt preload and n_{spec} is the number of valid measurements within a test specimen.

A statistical evaluation of the achieved bolt preload shall be carried out in accordance with EN 1990 [97]. Herein, the 5 % characteristic value $F_{p,ini,0.05}$ shall be determined by Equation (6.4):

$$F_{p,ini,0.05} = F_{p,ini,mean} \cdot (1 - k_n \cdot V_{F_{p,ini}}) \text{ [kN]} \quad (6.4)$$

where k_n is the coefficient for determination of characteristic 5 % value acc. to EN 1990, Annex D depending on the actual number of valid measurements n_{spec} within a test specimen and $V_{F_{p,ini}}$ is the coefficient of variation.

The 5 % characteristic value $F_{p,ini,0.05}$ can be used in order to assess the reliability of the tightening procedure regarding the nominal preload level. Furthermore, $F_{p,ini,0.05}$ represents a conservative value (here: it is assumed that the average preload level in the complete connection is equivalent to the 5 % characteristic value) on which a generalized design of a bolted connection can be based.

If a bolted connection consists of multiple preloaded bolts, a calculation of the effective characteristic preload $F_{p,ini,0.05,eff}$ can be conducted according to Equation (6.5):

$$F_{p,ini,0.05,eff} = F_{p,ini,mean} \cdot \left(1 - k_n \cdot \frac{V_{F_{p,ini}}}{\sqrt{n}} \right) \text{ [kN]} \quad (6.5)$$

where n is the actual number of bolts in a connection.

The effective characteristic preload $F_{p,ini,0.05,eff}$ can be used to assess the remaining preload level in the connection over a certain service life of a structure considering the potential preload losses.

After a linear extrapolation to the intended service life of a structure, the mean loss of preload $\Delta F_{p,setting,Ld,mean}$, its standard deviation $\sigma_{\Delta F_{p,setting,Ld}}$ as well as the associated coefficient of variation $V_{\Delta F_{p,setting,Ld}}$ are determined by Equations (6.6) to (6.8):

$$\Delta F_{p,setting,Ld,mean} = \frac{\Sigma \Delta F_{p,setting,Ld,i}}{n_{spec}} [\%] \quad (6.6)$$

$$\sigma_{\Delta F_{p,setting,Ld}} = \sqrt{\frac{\Sigma (\Delta F_{p,setting,Ld,i} - \Delta F_{p,setting,Ld,mean})^2}{n_{spec} - 1}} [\%] \quad (6.7)$$

$$V_{\Delta F_{p,setting,Ld}} = \frac{\sigma_{\Delta F_{p,setting,Ld}}}{\Delta F_{p,setting,Ld,mean}} [-] \quad (6.8)$$

where $\Delta F_{p,setting,Ld,i}$ is the individual loss of preload per bolt.

Depending on the target level of preloading and the actual configuration of a bolted connection, an assessment of the remaining preload level for the intended service life of a structure shall be carried out considering one of the following approaches:

- a) **$F_{p,Ld,mean}$** based on $F_{p,ini,mean}$ and $\Delta F_{p,setting,Ld,mean}$ (e.g. estimation for connections with target level II of preloading);
- b) **$F_{p,Ld,0.05,eff}$** based on $F_{p,ini,0.05,eff}$ and $\Delta F_{p,setting,Ld,mean}$ (e.g. estimation for low-maintenance connections with target level I of preloading consisting of multiple preloaded bolts).

6.3 Recommendations with regard to the execution of slip-resistant connections

6.3.1 General

The load-bearing behaviour of slip-resistant connections is mainly determined by the level of preload and the associated slip factor. The latter represents an experimental value, which can be experimentally determined by the prescribed test procedure under laboratory conditions according to EN 1090-2, Annex G.

Based on the experimental test results presented in Chapter 5, recommendations with regard to the execution of slip-resistant connections considering practical boundary conditions are provided.

6.3.2 Dealing with practical scattering of coating layer thicknesses in slip-resistant connections

The slip factors provided by EN 1090-2 assume a dry film thickness of no more than 80 μm , whereby the validity of surface treatments involving alkali-zinc silicate paint is even limited to a range of 40 μm - 80 μm . However, a practical variation of the coating thickness cannot be avoided during the application process, so that the exceedance or the undercutting of the normatively specified coating thickness range must be critically assessed with regard to the potential influence on the slip resistance.

Experimental investigations into some of the main surface treatments for slip-resistant connections such as alkali-zinc silicate paint on grit blasted and on hot dip galvanized steel, aluminium spray metalizing as well as ethyl-zinc silicate paint according to ZTV-ING [135] could confirm that coating thicknesses in the lower range of < 40 μm are critical. Herein, a reduction of slip factors of approx. 20 % can be expected compared to the reference coating thicknesses of approx. 40 μm to 80 μm .

Furthermore, Annex G of EN 1090-2 states:

"The mean coating thickness on the contact surface of the test specimens shall be at least 25 % thicker than the nominal thickness specified for use in the structure."

Although this requirement justifiably aims at the implicit consideration of the associated preload losses in the test procedure, a special attention shall be paid whenever the determination of a slip factor is carried out for coating thicknesses in the lower range (e.g. < 40 μm), as it might result in an overestimation of the slip factor.

In contrast to low coating thicknesses, no significant negative influence on the slip factor can be confirmed for coating thicknesses of > 80 μm , so that a reasonable exceedance of the reference thickness of 40 μm to 80 μm can be considered as

acceptable. However, a maximum limit of the exceedance of the coating thickness cannot be given here.

6.3.3 Procedure-related tightening and slip resistance

The current test procedure according to EN 1090-2, Annex G relates the determined slip factors to a prescribed preload level of $F_{p,C} \pm 5\%$. With regard to the procedure-related tightening of bolting assemblies in the practical application, the minimum nominal preload level $F_{p,C}$ (or alternatively $F_{p,C}^*$) might be subjected to a high scattering of the actual bolt preload in a connection, so that the resulting slip resistance might differ from the one that is determined by the test procedure according to EN 1090-2, Annex G.

An investigation into the slip resistance under consideration of procedure-related tightening shows that connections tightened by the modified torque method provide comparable slip factors to those of the reference tests carried out considering a prescribed preload level of $F_{p,C} \pm 5\%$. On the other hand, tightening by the combined method expectedly leads to a positive impact on the slip resistance. Due to a considerable amount of the resulting system reserves, an increase of the slip resistance of up to $\approx 30\%$ can be expected. Unfortunately, this procedure-related favourable influence is currently not taken into account during design of slip-resistant connections.

6.4 Summary

Current normative regulations in steel construction acc. to EN 1090-2 and ZTV-ING provide limited guidelines regarding the consideration of preload losses during design and execution of bolted connections with typical coatings and coating systems. In the frame of this study, an assessment of different paint and powder coating systems depending on the intended target level of preloading was conducted. Based on the determined system reserves and preload losses, an estimation of the remaining preload levels considering the intended service life of structures of 50 years was carried out. Furthermore, based on the experimental results, the current test procedure for the determination of preload losses acc. to EN 1090-2, Annex I was updated.

Based on the experimental investigations presented in Chapter 5, recommendations for the execution of slip-resistant connections considering some practical

boundary conditions such as the natural scattering of coating layer thicknesses and the procedure-related tightening were formulated.

7 Conclusions and outlook

General

Bolted connections can be preloaded either to improve the serviceability e.g. by minimizing slip or by increasing the deformation stiffness or to ensure the structural safety. Accordingly, target level I of preloading and target level II of preloading can be distinguished acc. to DAST-Guideline 024. With regard to the design of bolted connections, the preloading force for connections of target level I is directly included in the design verification, whereas no consideration of the actual amount of preload is necessary for connections of target level II of preloading. For connections with target level I of preloading, the nominal value of preloading force should not only be reliably achieved during the tightening of a connection, but a sufficient level of preloading force considering the resulting preload losses must be ensured over the service life of the structure. A special type among the connections with target level I of preloading are represented by the slip-resistant connections. The performance of slip-resistant connections mainly relies on the level of preload and the associated slip factor. The latter can be experimentally determined by the prescribed test procedure under laboratory conditions according to EN 1090-2, Annex G and is intended to implicitly consider the preload losses. However, practical boundary conditions such as the scattering of coating layer thicknesses or the procedure-related tightening and their potential influence on the slip factor are not considered.

It becomes clear that a sufficient design and execution of the so-called low-maintenance connections depend on the knowledge of several influencing factors such as the reliability of different tightening methods, the associated system reserves as well as the estimated loss of preload, e.g. for various coating systems. However, an assessment of potential preload losses is only possible to a very limited extent according to the current state of the art in steel construction, so that a development of suitable verification methods is necessary. Furthermore, recommendations with regard to the execution of slip-resistant connections considering practical boundary conditions are desirable in order to assess their

possible influence on the slip resistance. The objective of this work is to address the gap in the knowledge that currently exists by providing practically applicable solutions for a sufficient design and execution of low-maintenance preloaded bolted connections in steel construction. In order to close the gap of knowledge, experimental results achieved in the frame of three IGF research projects No. 18711 BG [4], No. 19749 BG [5] and No. 21196 BG [6] as well as further experimental investigations presented in [7] and [8] were taken as a basis.

Conclusion

A first insight into system reserves and preload losses was enabled by the experimental investigation carried out within the frame of the IGF research project No. 18711 BG [4]. Herein, purely grit blasted bolted connections as well as grit blasted connections with zinc spray metallized ($\approx 80 \mu\text{m}$ DFT) faying surfaces and faying surfaces with zinc phosphate primer ($\approx 88 \mu\text{m}$ DFT) were investigated (no coatings considered beneath the washers). The selected clamping length ratios of the test specimens correspond to $\Sigma t/d \approx 2.4$ and $\Sigma t/d \approx 5.4$.

The test results indicate that the required system reserve of at least 10 % could not be achieved for the modified torque method acc. to DAST-Guideline 024. However, a tightening by the combined method acc. to EN 1090-2 and DAST-Guideline 024 does not only fulfil a demand of 10 % higher bolt preloads compared to the nominal preload value, but also offers remarkably higher system reserves in the range of $> 25 \%$. These system reserves can be used in order to compensate potential preload losses over the service life.

With regard to both, system reserves and total preload losses resulting from the relaxation tests and tests with cyclic loading, the remaining preload level (based on the mean values) for connections tightened by the combined method exceeded the required preload level $F_{p,C}$ by at least $\approx 7 \%$. Herein, the aforementioned purely grit blasted connections, grit blasted connections with zinc spray metallized faying surfaces as well as grit blasted connections with painted (zinc phosphate primer) faying surfaces were taken into account. An evaluation of connections initially tightened as well as re-tightened by the modified torque method shows that some undercuttings regarding the required preload level $F_{p,C}^*$ (based on the mean values) can be expected over the service life already for grit blasted

surfaces. This is due to the fact that comparatively low system reserves of less than 10 % resulting from the tightening by the modified torque method cannot entirely compensate the total preload losses that were estimated following the relaxation tests as well as tests with cyclic loading. Therefore, a counteractive measure of using only a priming coat and/or surface masking of the contact surfaces (as commonly used in practice) of preloaded bolted connections seems to be justified. Furthermore, a structural design with 90 % of the minimum nominal preloading force $F_{p,C}^*$ or even lower might be necessary for preloaded bolted connections which fulfil the requirements for corrosion protection on contact surfaces acc. to EN 1090-2, but are tightened by the modified torque method.

An extensive investigation into preloaded bolted connections considering common coatings and coating systems in steel construction was conducted within the frame of the IGF research project No. 21196 BG [6]). Herein, the investigated single-lap and double-lap grit blasted bolted connections consisting of four or six plates were coated with different paint (2K-PUR and EP-/PUR based) and powder coating systems (EP and/or SP based) on all sides including surfaces beneath the washers. Furthermore, duplex coating systems consisting of (EP and/or SP based) powder coatings on hot dip galvanized steel plates were considered. The selected clamping length ratios of the test specimens correspond to $\Sigma t/d \approx 2.4$ and $\Sigma t/d \approx 5$. The actual coating thicknesses DFT_{mean} varied between approx. 125 μm and 435 μm for the 2K-PUR coating and different EP-/PUR coating systems, between approx. 80 μm and 200 μm for powder coating systems as well as between approx. 330 μm and 620 μm for the investigated duplex systems with powder coatings.

In accordance with the test results achieved within the frame of the IGF research project No. 18711 BG [4], the required nominal preload level $F_{p,C}^*$ was achieved after tightening by the modified torque method considering mean initial preload values $F_{p,\text{ini},\text{mean}}$. However, a system reserve of at least 10 % could not be confirmed. This applies to both, initial tightening and re-tightening by the modified torque method, whereby a re-tightening led to approx. 2 % to 3 % lower bolt preloads compared to the ones after the initial tightening. A statistical evaluation of the test results acc. to EN 1990 carried out in this investigation shows that the characteristic 5 % preload values $F_{p,\text{ini},0.05}$ correspond to approx. 0.90 $F_{p,C}^*$ and 0.87 $F_{p,C}^*$ considering tightening and re-tightening by the modified torque method respectively. Herewith, a reliability of ≈ 73 % instead of the desirable 95 % (as required by EN 1090-2) can be determined for the

modified torque method. Considering the average system reserves determined for the combined method, a 10 %-demand of EN 1090-2 can be safely confirmed. Furthermore, in accordance with test results of previous investigation presented in [4], significantly higher system reserves in the range of 32 % to 38 % depending on the clamping length ratio can be expected on an average basis. A statistical evaluation of the test results acc. to EN 1990 leads to characteristic 5 % preload values $F_{p,ini,0.05}$ that correspond to approx. $1.25 F_{p,C}$ and $1.32 F_{p,C}$ considering clamping length ratios of $\Sigma t/d \approx 5$ and $\Sigma t/d \approx 2.4$ respectively.

An evaluation of experimentally determined preload losses considering the aforementioned connections with different coatings and coating systems commonly used in steel construction enabled an assessment of different influencing factors. Herein, the influence on the amount of preload losses resulting from the tightening into overelastic range by the combined method seems to be negligible, so that a generalized assumption of preload losses for the modified torque method and the combined method is possible. Furthermore, a transferability of preload losses to other tightening methods such as tension control bolts and lock bolts proves to be conceivable, as the associated initial preload values after the tightening normally correspond to the range that is expected for the modified torque method and the combined method.

With regard to the resulting preload losses, a re-tightening by the modified torque method represents a moderate instrument to eliminate the first preload losses that occurred after initial tightening. According to the test results in this investigation, approx. 40 % to 50 % lower preload losses $\Delta F_{p,setting,50a,mean}$ can be expected after the re-tightening compared to the values after initial tightening by the modified torque method. Herein, a re-tightening of bolting assemblies after approx. 3 days after initial tightening are presupposed.

A representation of the determined preload losses $\Delta F_{p,setting,50a,mean}$ in relation to the respective coating thickness per specimen DFT_{spec} (consisting of $4 \times DFT_{mean}$ for single-lap and $6 \times DFT_{mean}$ for double-lap test specimens) indicates that an estimation of preload losses for specific coating thicknesses is possible based on linear regression. Herein, an assessment of experimentally determined preload losses was carried out using different approaches based on the intended target level of preloading. Considering the mean values of the linear regression and a limit of coating thickness of $1.2 \times NDFT$ that is used for the reference values in Table I.1 of EN 1090-2, preload losses $\Delta F_{p,setting,50a,mean,reg}$ remain

within a range between 25 % and 35 % for both, the 2K-PUR coating and different investigated EP-/PUR coating systems. An estimation of potential preload losses for the investigated powder coating systems shows that EP/SP coating as well as EP | SP coating system on grit blasted surfaces lead to preload losses of approx. 10 % to 15 % considering the mean values $\Delta F_{p, \text{setting}, 50a, \text{mean}, \text{reg}}$. Finally, preload losses of 15 % to 25 % can be estimated for duplex systems consisting of a zinc coating layer with a maximum of 200 μm NDFT and the subsequent EP/SP coating or EP | SP coating system. The carried out estimations form a basis for the consideration of preload losses in combination with determined system reserves.

Next to the assessment of preload losses with regard to their estimation in steel construction, also an analytical approach acc. to VDI 2230-1 was applied. Herein, the calculation of the amounts of embedding f_z allows a practical estimation of preload losses for the individualized design of connections. In this investigation, an exponential decrease was found out by relating the amounts of embedding f_z to the increasing coating layer thicknesses of test specimens DFT_{spec} for different paint and powder coating systems, whereby the resulting relationship can be described by a power function. Herein, upper limit functions were determined considering every individual ratio of $f_{z,i} / \text{DFT}_{\text{spec}}$.

Based on the determined system reserves and preload losses, reference values for the estimation of the remaining preload levels considering the selected service life of structures of 50 years were provided. Herein, depending on the coating thickness, the estimated remaining bolt preloads varied between 0.70 $F_{p,C}^*$ and 0.80 $F_{p,C}^*$ after initial tightening and between 0.85 $F_{p,C}^*$ 0.90 $F_{p,C}^*$ after re-tightening by the modified torque method for the investigated 2K-PUR coating and different EP-/PUR coating systems considering target level II of preloading. The more favourable mechanical properties of the powder coating systems lead to bolt preloads in the range of 0.80 $F_{p,C}^*$ and 0.95 $F_{p,C}^*$ after initial tightening and 0.90 $F_{p,C}^*$ and 0.95 $F_{p,C}^*$ after re-tightening by the modified torque method depending on the coating thickness of a preloaded bolted connection. A full compensation of the estimated preload losses can be assumed for most of the investigated coating systems considering tightening by the combined method due to its high system reserves of > 25 %.

Considering low-maintenance connections with target level I of preloading, the design value of the remaining preload shall be partly reduced. Depending

on the actual coating thickness, the estimated preload levels varied between $0.60 F_{p,C}^*$ and $0.80 F_{p,C}^*$ after initial tightening as well as between $0.70 F_{p,C}^*$ and $0.80 F_{p,C}^*$ after re-tightening by the modified torque method for the investigated paint and powder coating systems. The combined method once again represents the more reliable tightening method. Herein, a partial undercutting of the nominal preloading force $F_{p,C}$ can be expected, whereby the minimum values range up to $0.90 F_{p,C}$ for the investigated 2K-PUR coating and the investigated EP-/PUR coating systems. For other surface treatments or boundary conditions, an updated test procedure for the determination of preload losses considering current regulations in EN 1090-2, Annex I and the extensive findings in course of this work are proposed.

Finally, a possible influence of different practical boundary conditions on the slip resistance was determined in terms of the IGF research project No. 19749 BG [5]. It could be confirmed that especially the coating thicknesses in the lower range of $25 \mu\text{m}$ to $40 \mu\text{m}$ might affect the slip factor compared to the reference coating thickness of $40 \mu\text{m}$ to $80 \mu\text{m}$. On the other hand, higher coating layer thicknesses in the range of approx. $100 \mu\text{m}$ to even $230 \mu\text{m}$ do not show any negative influence on the slip factor and, herewith, on the slip resistance. Furthermore, the procedure-related tightening by the combined method leads to a significant increase of the slip resistance of up to 30 % in comparison to the tightening acc. to the test procedure in EN 1090-2, Annex G. This procedure-related favourable influence is currently not normatively considered. Additionally, investigations into slip-resistant connections under consideration of operational cyclic loads were carried out. The test results indicate that a cyclic loading does not affect the slip factor and rather leads to a better interlocking of friction surfaces for the investigated surface conditions.

Outlook

The presented work aimed at a sufficient design and execution of the so-called low-maintenance preloaded bolted connections considering different tightening methods and coating systems that commonly used in steel construction. However, alternative tightening methods such as the HRC tightening method, the direct tension indicator (DTI) method, the tractive method or lockbolts can also be used. A comprehensive investigation into systems reserves and the reliability of these tightening methods considering the nominal preload value is desirable in

the future. Furthermore, alternative coatings and coating systems not covered in this thesis shall be considered for their assessment with regard to preload losses and an estimation of the remaining preload level, as the surface conditions selected in the frame of this work mainly represent applications in steel hall construction.

The investigated connections with an excessive coating layer thickness (here: approx. $2 \times \text{NDFT}$ to $3 \times \text{NDFT}$) expectedly show a significant increase of the loss of preload. Furthermore, especially for the angle-controlled tightening, the reproducibility of the expected preload levels cannot be guaranteed due to the coating deformation under the washers. For this reason, limitations of coating thicknesses of $\approx 1.5 \times \text{NDFT}$ for the investigated paint systems and $\approx 3 \times \text{NDFT}$ for powder coating systems were introduced regarding the estimation of preload losses in the context of this work. Further investigations considering a narrower gradation of the coating layer thicknesses (especially for paint systems) are meaningful in order to define a more accurate limitation. In this context, systematic investigations into mechanical properties of different coatings and coating systems, e.g. considering durometer method, seem to be meaningful. Herein, a qualitative estimation of the hardness/elasticity of coating systems might be helpful in order to prevent the negative influence on the system reserves and preload losses e.g. due to the increased coating layer thickness or an incomplete curing of the coating. Furthermore, this approach might be helpful in order to determine a point in the elapsed time, at which the coating system can be considered as sufficiently cured/cross-linked for its use in preloaded bolted connections.

The experimental investigations are based on constant room temperatures, which are assumed to reasonably represent the common application of coatings and coating systems in steel hall construction. However, increased temperatures can significantly affect the loss of preload behaviour in bolted connections consisting of organic coatings. Herein, especially the above mentioned curing process and the cross-linking of the coating are expected to significantly influence the temperature stability, so that further investigations, among other things, for the determination of temperature limits for an application of the estimated preload losses, are necessary.

In the investigation into connections that comply with the limitations for corrosion protection on contact surfaces acc to. EN 1090-2, it was found that the

extrapolated preload losses due to cyclic loading seem to be rather uncritical and the main preload losses can be sensibly covered by the relaxation tests. Since the presented preload losses for connections with typical coatings and coating systems rely on relaxation tests, the transferability of the uncritical preload losses due to additional cyclic loading to bolted connections (here: target level I of preloading) consisting of coated surfaces, especially under the washers, should be verified. In addition to the selected constant cyclic loadings in this investigation, multistage load collectives could be further developed in order to better describe the practical load situations.

Systematic investigations into slip-resistant connections regarding different practical boundary conditions enable the first conclusions to be drawn on their influence on the load-bearing behaviour and therefore provide a fundamental basis for their consideration during design and execution in the future. Other production-, assembly- and operation-related influences, that were not presented in the frame of this work, were investigated in IGF research project No. 19749 BG [5]. Herein, a broader data basis, in particular taking into account further typical surface treatments and coatings (e.g. zinc spray metallizing, hot dip galvanizing etc.) as well as test specimen configurations (e.g. variation of the number and the thickness of packing plates) would be useful in order to verify the transferability of the existing experimental findings. Finally, other questions with regard to the refurbishment of existing steel structures such as the reuse of slip-resistant connections should be investigated.

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Annex A - Elastic resiliences for the investigated specimen configurations

Specimen configuration with $\Sigma t/d \approx 2.4$ (single-lap)

Table A.1 Calculation parameters for the single-lap specimen configuration with $\Sigma t/d \approx 2.4$

Calculation parameters	Values
Bolt diameter	$d = 16 \text{ mm}$
Minor diameter of the bolt thread	$d_3 = 13.546 \text{ mm}$
Outside diameter of the plane head bearing surface of the bolt	$d_W = 24.9 \text{ mm}$
Hole diameter of the clamped parts	$d_h = 18 \text{ mm}$
Pitch of the thread	$P = 2 \text{ mm}$
Bolt length	$l = 60 \text{ mm}$
Clamping length	$l_k = 38 \text{ mm}$
Length of the bolt shank	$l_{Sch} = 32 \text{ mm}$
Length of the free loaded thread	$l_{Gew} = 6 \text{ mm}$
Nominal cross section	$A_N = 201.06 \text{ mm}^2$
Cross section of thread at minor diameter	$A_{d3} = 144 \text{ mm}^2$
Substitutional outside diameter of the basic solid	$D_A = D'_A = 75 \text{ mm}$
Young's modulus, based on experimental results	$E_S = E_M = E_P = 2.1 \cdot 10^5 \text{ N/mm}^2$
Joint coefficient for the type of bolted joint	$w = 1$

Individual elastic resiliences of different bolt components:

$$\delta_{SK} = \frac{0.5 \cdot d}{E_S \cdot A_N} = \frac{0.5 \cdot 16}{210.000 \cdot 201.06} = 1.895 \cdot 10^{-7} \text{ mm/N} \quad (\text{A.1})$$

$$\delta_{Sch} = \frac{l_{Sch}}{E_S \cdot A_N} = \frac{32}{210.000 \cdot 201.06} = 7.579 \cdot 10^{-7} \text{ mm/N} \quad (\text{A.2})$$

$$\delta_{Gew} = \frac{l_{Gew}}{E_S \cdot A_{d3}} = \frac{6}{210.000 \cdot 144} = 1.983 \cdot 10^{-7} \text{ mm/N} \quad (\text{A.3})$$

$$\delta_G = \frac{0.5 \cdot d}{E_S \cdot A_{d3}} = \frac{0.5 \cdot 16}{210.000 \cdot 144} = 2.643 \cdot 10^{-7} \text{ mm/N} \quad (\text{A.4})$$

$$\delta_M = \frac{0.4 \cdot d}{E_M \cdot A_N} = \frac{0.4 \cdot 16}{210.000 \cdot 201.06} = 1.516 \cdot 10^{-7} \text{ mm/N} \quad (\text{A.5})$$

Elastic resilience of the bolt:

$$\delta_S = \delta_{SK} + \delta_{Sch} + \delta_{Gew} + \delta_G + \delta_M = 1.562 \cdot 10^{-6} \text{ mm/N} \quad (\text{A.6})$$

Input parameters for the determination of the elastic resilience of the clamped parts:

$$\beta_L = \frac{l_k}{d_W} = \frac{38}{24.9} = 1.526 \quad (\text{A.7})$$

$$y = \frac{D_A}{d_W} = \frac{75}{24.9} = 3.012 \quad (\text{A.8})$$

$$\tan \varphi_D = \frac{D_A}{d_W} = 0.362 + 0.032 \cdot \ln \left(\frac{\beta_L}{2} \right) + 0.153 \cdot \ln y = 0.522 \quad (\text{A.9})$$

$$D_{A,gr} = d_W + w \cdot l_k \cdot \tan \varphi_D = 44.738 \text{ mm} \quad (\text{A.10})$$

$D_{A,gr} = 44.738 \text{ mm} < 75 \text{ mm} = D_A$. The corresponding elastic resilience of concentrically clamped parts is calculated according to Equation (A.11):

$$\delta_P = \frac{2 \cdot \ln \left(\frac{(d_W + d_h) \cdot (d_W + w \cdot l_k \cdot \tan \varphi_D - d_h)}{(d_W - d_h) \cdot (d_W + w \cdot l_k \cdot \tan \varphi_D + d_h)} \right)}{w \cdot E_P \cdot \pi \cdot d_h \cdot \tan \varphi_D} \quad (\text{A.11})$$

Thus the elastic resilience δ_P as well as the elastic resilience of the test specimen δ_{spec} results in:

$$\delta_P = \frac{2 \cdot \ln \left(\frac{(24.9 + 18) \cdot (24.9 + 1 \cdot 38 \cdot 0.522 - 18)}{(24.9 - 18) \cdot (24.9 + 1 \cdot 38 \cdot 0.522 + 18)} \right)}{1 \cdot 210.000 \cdot \pi \cdot 18 \cdot 0.522} = 3.144 \cdot 10^{-7} \text{ mm/N} \quad (\text{A.12})$$

$$\delta_{spec} = \delta_S + \delta_P = 1.562 \cdot 10^{-6} + 3.144 \cdot 10^{-7} = 1.876 \cdot 10^{-6} \text{ mm/N} \quad (\text{A.13})$$

Specimen configuration with $\Sigma t/d \approx 2.4$ (double-lap)

Table A.2 Calculation parameters for the double-lap specimen configuration with $\Sigma t/d \approx 2.4$

Calculation parameters	Values
Bolt diameter	$d = 16 \text{ mm}$
Minor diameter of the bolt thread	$d_3 = 13.546 \text{ mm}$
Outside diameter of the plane head bearing surface of the bolt	$d_W = 24.9 \text{ mm}$
Hole diameter of the clamped parts	$d_h = 18 \text{ mm}$
Pitch of the thread	$P = 2 \text{ mm}$
Bolt length	$l = 60 \text{ mm}$
Clamping length	$l_k = 39 \text{ mm}$
Length of the bolt shank	$l_{Sch} = 32 \text{ mm}$
Length of the free loaded thread	$l_{Gew} = 7 \text{ mm}$
Nominal cross section	$A_N = 201.06 \text{ mm}^2$
Cross section of thread at minor diameter	$A_{d3} = 144 \text{ mm}^2$
Substitutional outside diameter of the basic solid	$D_A = D'_A = 75 \text{ mm}$
Young's modulus, based on experimental results	$E_S = E_M = E_P = 2.1 \cdot 10^5 \text{ N/mm}^2$
Joint coefficient for the type of bolted joint	$w = 1$

Individual elastic resiliances of different bolt components:

$$\delta_{SK} = \frac{0.5 \cdot d}{E_S \cdot A_N} = \frac{0.5 \cdot 16}{210.000 \cdot 201.06} = 1.895 \cdot 10^{-7} \text{ mm/N} \quad (\text{A.14})$$

$$\delta_{Sch} = \frac{l_{Sch}}{E_S \cdot A_N} = \frac{32}{210.000 \cdot 201.06} = 7.579 \cdot 10^{-7} \text{ mm/N} \quad (\text{A.15})$$

$$\delta_{Gew} = \frac{l_{Gew}}{E_S \cdot A_{d3}} = \frac{7}{210.000 \cdot 144} = 2.313 \cdot 10^{-7} \text{ mm/N} \quad (\text{A.16})$$

$$\delta_G = \frac{0.5 \cdot d}{E_S \cdot A_{d3}} = \frac{0.5 \cdot 16}{210.000 \cdot 144} = 2.643 \cdot 10^{-7} \text{ mm/N} \quad (\text{A.17})$$

$$\delta_M = \frac{0.4 \cdot d}{E_M \cdot A_N} = \frac{0.4 \cdot 16}{210.000 \cdot 201.06} = 1.516 \cdot 10^{-7} \text{ mm/N} \quad (\text{A.18})$$

Elastic resilience of the bolt:

$$\delta_S = \delta_{SK} + \delta_{Sch} + \delta_{Gew} + \delta_G + \delta_M = 1.595 \cdot 10^{-6} \text{ mm/N} \quad (\text{A.19})$$

Input parameters for the determination of the elastic resilience of the clamped parts:

$$\beta_L = \frac{l_k}{d_W} = \frac{39}{24.9} = 1.566 \quad (\text{A.20})$$

$$y = \frac{D_A}{d_W} = \frac{75}{24.9} = 3.012 \quad (\text{A.21})$$

$$\tan \varphi_D = \frac{D_A}{d_W} = 0.362 + 0.032 \cdot \ln \left(\frac{\beta_L}{2} \right) + 0.153 \cdot \ln y = 0.523 \quad (\text{A.22})$$

$$D_{A,gr} = d_W + w \cdot l_k \cdot \tan \varphi_D = 45.292 \text{ mm} \quad (\text{A.23})$$

$D_{A,gr} = 45.292 \text{ mm} < 75 \text{ mm} = D_A$. The corresponding elastic resilience of concentrically clamped parts is calculated according to Equation (A.11). Thus the elastic resilience δ_P as well as the elastic resilience of the test specimen δ_{spec} results in:

$$\delta_P = \frac{2 \cdot \ln \left(\frac{(24.9 + 18) \cdot (24.9 + 1 \cdot 39 \cdot 0.523 - 18)}{(24.9 - 18) \cdot (24.9 + 1 \cdot 39 \cdot 0.523 + 18)} \right)}{1 \cdot 210.000 \cdot \pi \cdot 18 \cdot 0.523} = 3.176 \cdot 10^{-7} \text{ mm/N} \quad (\text{A.24})$$

$$\delta_{spec} = \delta_S + \delta_P = 1.595 \cdot 10^{-6} + 3.176 \cdot 10^{-7} = 1.912 \cdot 10^{-6} \text{ mm/N} \quad (\text{A.25})$$

Specimen configuration with $\Sigma t/d \approx 4.9$ (single-lap)

Table A.3 Calculation parameters for the single-lap specimen configuration with $\Sigma t/d \approx 4.9$

Calculation parameters	Values
Bolt diameter	$d = 16 \text{ mm}$
Minor diameter of the bolt thread	$d_3 = 13.546 \text{ mm}$
Outside diameter of the plane head bearing surface of the bolt	$d_W = 24.9 \text{ mm}$
Hole diameter of the clamped parts	$d_h = 18 \text{ mm}$
Pitch of the thread	$P = 2 \text{ mm}$
Bolt length	$l = 100 \text{ mm}$
Clamping length	$l_k = 78 \text{ mm}$
Length of the bolt shank	$l_{Sch} = 72 \text{ mm}$
Length of the free loaded thread	$l_{Gew} = 6 \text{ mm}$
Nominal cross section	$A_N = 201.06 \text{ mm}^2$
Cross section of thread at minor diameter	$A_{d3} = 144 \text{ mm}^2$
Substitutional outside diameter of the basic solid	$D_A = D'_A = 110 \text{ mm}$
Young's modulus, based on experimental results	$E_S = E_M = E_P = 2.1 \cdot 10^5 \text{ N/mm}^2$
Joint coefficient for the type of bolted joint	$w = 1$

Individual elastic resiliences of different bolt components:

$$\delta_{SK} = \frac{0.5 \cdot d}{E_S \cdot A_N} = \frac{0.5 \cdot 16}{210.000 \cdot 201.06} = 1.895 \cdot 10^{-7} \text{ mm/N} \quad (\text{A.26})$$

$$\delta_{Sch} = \frac{l_{Sch}}{E_S \cdot A_N} = \frac{72}{210.000 \cdot 201.06} = 1.705 \cdot 10^{-6} \text{ mm/N} \quad (\text{A.27})$$

$$\delta_{Gew} = \frac{l_{Gew}}{E_S \cdot A_{d3}} = \frac{6}{210.000 \cdot 144} = 1.983 \cdot 10^{-7} \text{ mm/N} \quad (\text{A.28})$$

$$\delta_G = \frac{0.5 \cdot d}{E_S \cdot A_{d3}} = \frac{0.5 \cdot 16}{210.000 \cdot 144} = 2.643 \cdot 10^{-7} \text{ mm/N} \quad (\text{A.29})$$

$$\delta_M = \frac{0.4 \cdot d}{E_M \cdot A_N} = \frac{0.4 \cdot 16}{210.000 \cdot 201.06} = 1.516 \cdot 10^{-7} \text{ mm/N} \quad (\text{A.30})$$

Elastic resilience of the bolt:

$$\delta_S = \delta_{SK} + \delta_{Sch} + \delta_{Gew} + \delta_G + \delta_M = 2.509 \cdot 10^{-6} \text{ mm/N} \quad (\text{A.31})$$

Input parameters for the determination of the elastic resilience of the clamped parts:

$$\beta_L = \frac{l_k}{d_W} = \frac{78}{24.9} = 3.133 \quad (\text{A.32})$$

$$y = \frac{D_A}{d_W} = \frac{110}{24.9} = 4.418 \quad (\text{A.33})$$

$$\tan \varphi_D = \frac{D_A}{d_W} = 0.362 + 0.032 \cdot \ln \left(\frac{\beta_L}{2} \right) + 0.153 \cdot \ln y = 0.604 \quad (\text{A.34})$$

$$D_{A,gr} = d_W + w \cdot l_k \cdot \tan \varphi_D = 71.985 \text{ mm} \quad (\text{A.35})$$

$D_{A,gr} = 71.985 \text{ mm} < 110 \text{ mm} = D_A$. The corresponding elastic resilience of concentrically clamped parts is calculated according to Equation (A.11). Thus the elastic resilience δ_P as well as the elastic resilience of the test specimen δ_{spec} results in:

$$\delta_P = \frac{2 \cdot \ln \left(\frac{(24.9 + 18) \cdot (24.9 + 1 \cdot 78 \cdot 0.604 - 18)}{(24.9 - 18) \cdot (24.9 + 1 \cdot 78 \cdot 0.604 + 18)} \right)}{1 \cdot 210.000 \cdot \pi \cdot 18 \cdot 0.604} = 3.673 \cdot 10^{-7} \text{ mm/N} \quad (\text{A.36})$$

$$\delta_{spec} = \delta_S + \delta_P = 2.509 \cdot 10^{-6} + 3.673 \cdot 10^{-7} = 2.876 \cdot 10^{-6} \text{ mm/N} \quad (\text{A.37})$$

Specimen configuration with $\Sigma t/d \approx 5.2$ (double-lap)

Table A.4 Calculation parameters for the double-lap specimen configuration with $\Sigma t/d \approx 5.2$

Calculation parameters	Values
Bolt diameter	$d = 16 \text{ mm}$
Minor diameter of the bolt thread	$d_3 = 13.546 \text{ mm}$
Outside diameter of the plane head bearing surface of the bolt	$d_W = 24.9 \text{ mm}$
Hole diameter of the clamped parts	$d_h = 18 \text{ mm}$
Pitch of the thread	$P = 2 \text{ mm}$
Bolt length	$l = 105 \text{ mm}$
Clamping length	$l_k = 83 \text{ mm}$
Length of the bolt shank	$l_{Sch} = 77 \text{ mm}$
Length of the free loaded thread	$l_{Gew} = 6 \text{ mm}$
Nominal cross section	$A_N = 201.06 \text{ mm}^2$
Cross section of thread at minor diameter	$A_{d3} = 144 \text{ mm}^2$
Substitutional outside diameter of the basic solid	$D_A = D'_A = 110 \text{ mm}$
Young's modulus, based on experimental results	$E_S = E_M = E_P = 2.1 \cdot 10^5 \text{ N/mm}^2$
Joint coefficient for the type of bolted joint	$w = 1$

Individual elastic resiliences of different bolt components:

$$\delta_{SK} = \frac{0.5 \cdot d}{E_S \cdot A_N} = \frac{0.5 \cdot 16}{210.000 \cdot 201.06} = 1.895 \cdot 10^{-7} \text{ mm/N} \quad (\text{A.38})$$

$$\delta_{Sch} = \frac{l_{Sch}}{E_S \cdot A_N} = \frac{77}{210.000 \cdot 201.06} = 1.824 \cdot 10^{-6} \text{ mm/N} \quad (\text{A.39})$$

$$\delta_{Gew} = \frac{l_{Gew}}{E_S \cdot A_{d3}} = \frac{6}{210.000 \cdot 144} = 1.983 \cdot 10^{-7} \text{ mm/N} \quad (\text{A.40})$$

$$\delta_G = \frac{0.5 \cdot d}{E_S \cdot A_{d3}} = \frac{0.5 \cdot 16}{210.000 \cdot 144} = 2.643 \cdot 10^{-7} \text{ mm/N} \quad (\text{A.41})$$

$$\delta_M = \frac{0.4 \cdot d}{E_M \cdot A_N} = \frac{0.4 \cdot 16}{210.000 \cdot 201.06} = 1.516 \cdot 10^{-7} \text{ mm/N} \quad (\text{A.42})$$

Elastic resilience of the bolt:

$$\delta_S = \delta_{SK} + \delta_{Sch} + \delta_{Gew} + \delta_G + \delta_M = 2.627 \cdot 10^{-6} \text{ mm/N} \quad (\text{A.43})$$

Input parameters for the determination of the elastic resilience of the clamped parts:

$$\beta_L = \frac{l_k}{d_W} = \frac{83}{24.9} = 3.333 \quad (\text{A.44})$$

$$y = \frac{D_A}{d_W} = \frac{110}{24.9} = 4.418 \quad (\text{A.45})$$

$$\tan \varphi_D = \frac{D_A}{d_W} = 0.362 + 0.032 \cdot \ln \left(\frac{\beta_L}{2} \right) + 0.153 \cdot \ln y = 0.606 \quad (\text{A.46})$$

$$D_{A,gr} = d_W + w \cdot l_k \cdot \tan \varphi_D = 75.169 \text{ mm} \quad (\text{A.47})$$

$D_{A,gr} = 75.169 \text{ mm} < 110 \text{ mm} = D_A$. The corresponding elastic resilience of concentrically clamped parts is calculated according to Equation (A.11). Thus the elastic resilience δ_P as well as the elastic resilience of the test specimen δ_{spec} results in:

$$\delta_P = \frac{2 \cdot \ln \left(\frac{(24.9 + 18) \cdot (24.9 + 1 \cdot 83 \cdot 0.606 - 18)}{(24.9 - 18) \cdot (24.9 + 1 \cdot 83 \cdot 0.606 + 18)} \right)}{1 \cdot 210.000 \cdot \pi \cdot 18 \cdot 0.606} = 3.723 \cdot 10^{-7} \text{ mm/N} \quad (\text{A.48})$$

$$\delta_{spec} = \delta_S + \delta_P = 2.627 \cdot 10^{-6} + 3.723 \cdot 10^{-7} = 3.000 \cdot 10^{-6} \text{ mm/N} \quad (\text{A.49})$$

Annex B - Regression analysis of determined preload losses

Variables

a	intercept of the linear regression
a_{0.95}	upper value (95 % fractile) of the intercept a
b	slope of the linear regression
b_{0.95}	upper value (95 % fractile) of the regression slope b
DOF	degrees of freedom (here: number of observations (n) – number of parameters (2))
MSE	mean squared error
n	number of observations
p_a	obtained probability statistic (p-value) for performing of the significance test considering the intercept a
p_b	obtained probability statistic (p-value) for performing of the significance test considering the regression slope b
R²	coefficient of determination (explained variance)
SE_a	standard error of the intercept a
SE_b	standard error of the regression slope b
SSE	error variation (unexplained)
SSR	regression variation (explained)
SS_x	sum of squares around the mean of variable x (here: $\Sigma(x - \bar{x})^2$)
SS_{xy}	sum of products (here: $\Sigma(x - \bar{x}) \cdot (y - \bar{y})$)
SS_y	sum of squares around the mean of variable y (here: $\Sigma(y - \bar{y})^2$), total variation
t_a	t-statistic or t-value for the intercept a

t_b	t-statistic or t-value for the regression slope b
$t_{\alpha/2}$	critical t-value as a two-tailed inverse of the Student's t-distribution
x	explanatory variable = $DFT_{spec,i}$ (average measured coating thickness per specimen)
\bar{x}	average value of the explanatory variable x
y	response variable = $\Delta F_{p,setting,50a,i}$ (individual values of the loss of preload)
\bar{y}	average value of the response variable y
Σx	sum of the values for the variable x (here: $\Sigma DFT_{spec,i}$)
Σy	sum of the values for the variable y (here: $\Sigma \Delta F_{p,setting,50a,i}$)

Formulas

Determination of the slope b:

$$b = \frac{(x - \bar{x}) \cdot (y - \bar{y})}{(x - \bar{x})^2} \quad (B.1)$$

Determination of the intercept a:

$$a = \frac{\Sigma y}{n} - \left(\frac{b \cdot \Sigma x}{n} \right) \quad (B.2)$$

Determination of the (explained) regression variation SSR:

$$SSR = \frac{SS_{xy}^2}{SS_x} \quad (B.3)$$

Determination of the (unexplained) error variation SSE:

$$SSE = SS_y - SSR \quad (B.4)$$

Determination of the mean squared error MSE:

$$MSE = \frac{SSE}{DOF} \quad (B.5)$$

Determination of the coefficient of determination R^2 :

$$R^2 = \frac{SSR}{SS_y} \quad (B.6)$$

Determination of the standard error of the intercept a:

$$SE_a = \sqrt{\frac{MSE \cdot \Sigma x^2}{n \cdot SS_x}} \quad (B.7)$$

Determination of the standard error of the regression slope b:

$$SE_b = \sqrt{\frac{MSE}{SS_x}} \quad (B.8)$$

Determination of the t-statistic for the intercept a:

$$t_a = \frac{a}{SE_a} \quad (B.9)$$

Determination of the t-statistic for the regression slope b:

$$t_b = \frac{b}{SE_b} \quad (B.10)$$

Determination of the upper value of the intercept a:

$$a_{0.95} = a + t_{\alpha/2} \cdot SE_a \quad (B.11)$$

Determination of the upper value of the regression slope b:

$$b_{0.95} = b + t_{\alpha/2} \cdot SE_b \quad (B.12)$$

2K-PUR coating, $\Sigma t/d \approx 2.4$, (initial) tightening

Table B.1 Regression analysis of extrapolated preload losses $\Delta F_{p, \text{setting}, 50a}$ for the 2K-PUR coating after (initial) tightening, test specimens with $\Sigma t/d \approx 2.4$

System No. ¹⁾	$\Sigma t/d$ [-]	Tight. method	Variable		Squares around mean		Product	
			x	y	x^2	$(x - \bar{x})^2$	$(y - \bar{y})^2$	$(x - \bar{x}) \cdot (y - \bar{y})$
1.1a	2.4-sl	KV	426.1	20.9	181540.4	34655.5	2.8	311.0
				20.3	181540.4	34655.5	5.0	417.4
				20.0	181540.4	34655.5	6.5	473.9
				18.6	181540.4	34655.5	15.8	739.9
				22.2	181540.4	34655.5	0.1	69.7
				18.1	181540.4	34655.5	20.0	833.4
				19.8	181540.4	34655.5	8.0	525.0
				21.6	181540.4	34655.5	1.0	182.6
1.1a	2.4-sl	MDV	469.9	19.7	220848.5	20246.5	8.2	406.8
				18.1	220848.5	20246.5	20.2	638.9
				18.3	220848.5	20246.5	18.4	610.0
				18.0	220848.5	20246.5	21.0	652.8
				18.9	220848.5	20246.5	13.5	522.7
				18.3	220848.5	20246.5	18.1	605.1
				19.3	220848.5	20246.5	10.7	465.1
1.1a	2.4-dl	KV	679.5	23.9	461678.7	4520.4	1.8	90.3
				26.9	461678.7	4520.4	18.5	289.1
				25.3	461678.7	4520.4	7.1	179.0
				25.4	461678.7	4520.4	7.8	187.3
				27.6	461678.7	4520.4	24.8	335.0
				25.9	461678.7	4520.4	10.9	221.8
				28.4	461678.7	4520.4	34.2	393.4
				25.4	461678.7	4520.4	7.8	187.8
1.1a	2.4-dl	MDV	694.4	22.5	482240.4	6756.8	0.0	-4.7
				26.8	482240.4	6756.8	17.8	346.4
				27.5	482240.4	6756.8	24.5	406.5
				21.5	482240.4	6756.8	1.2	-89.1
				24.3	482240.4	6756.8	3.0	142.8
				28.9	482240.4	6756.8	39.8	518.6
				23.9	482240.4	6756.8	1.7	106.2
				22.8	482240.4	6756.8	0.0	17.6
1.1b	2.4-sl	MDV	522.1	17.6	272590.2	8124.1	25.3	452.9
				17.9	272590.2	8124.1	22.4	426.6
				18.7	272590.2	8124.1	15.4	353.6
				17.4	272590.2	8124.1	27.0	468.2
				19.7	272590.2	8124.1	8.4	261.3
				19.3	272590.2	8124.1	11.1	300.2
				20.6	272590.2	8124.1	3.9	177.8
1.1b	2.4-dl	MDV	852.3	28.3	726469.4	57646.3	32.5	1368.7
				25.7	726469.4	57646.3	9.8	750.1
				24.5	726469.4	57646.3	3.5	449.0
				27.2	726469.4	57646.3	20.9	1097.4
				26.0	726469.4	57646.3	11.6	816.2
				26.8	726469.4	57646.3	17.5	1004.3
				25.7	726469.4	57646.3	9.4	735.8
				24.7	726469.4	57646.3	4.3	500.0
n = 46	Total Σ		28162.8	1039.2	18269502.1	1027226.2	592.9	19944.1

1) Coatings and coating systems in accordance with Table 4.6.

2K-PUR coating, $\Sigma t/d \approx 2.4$, re-tightening

Table B.2 Regression analysis of extrapolated preload losses $\Delta F_{p, \text{setting}, 50a}$ for the 2K-PUR coating after re-tightening, test specimens with $\Sigma t/d \approx 2.4$

System No. ¹⁾	$\Sigma t/d$ [-]	Tight. method	Variable		Squares around mean		Product	
			x	y	x^2	$(x - \bar{x})^2$	$(y - \bar{y})^2$	$(x - \bar{x}) \cdot (y - \bar{y})$
1.1a	2.4-sl	MDV	469.9	11.5	220848.5	30277.3	0.1	54.0
				10.7	220848.5	30277.3	1.2	191.8
				8.7	220848.5	30277.3	9.3	529.7
				10.1	220848.5	30277.3	3.0	301.2
				10.1	220848.5	30277.3	2.7	286.7
				10.3	220848.5	30277.3	2.2	255.9
			9.5	220848.5	30277.3	5.3	400.6	
1.1a	2.4-dl	MDV	694.4	12.0	482240.4	2548.9	0.0	10.6
				14.2	482240.4	2548.9	6.0	123.7
				14.8	482240.4	2548.9	9.1	152.4
				12.9	482240.4	2548.9	1.3	58.1
				16.3	482240.4	2548.9	20.3	227.5
				15.4	482240.4	2548.9	13.1	183.0
				10.3	482240.4	2548.9	2.3	-75.9
				13.0	482240.4	2548.9	1.5	61.9
1.1b	2.4-sl	MDV	522.1	9.3	272590.2	14846.7	6.0	297.6
				9.0	272590.2	14846.7	7.6	335.8
				9.1	272590.2	14846.7	7.4	331.4
				7.5	272590.2	14846.7	18.6	525.7
				8.6	272590.2	14846.7	9.9	382.9
				10.1	272590.2	14846.7	2.7	200.1
				9.8	272590.2	14846.7	4.0	243.7
1.1b	2.4-dl	MDV	852.3	16.3	726469.4	43423.4	20.1	935.0
				12.0	726469.4	43423.4	0.1	54.1
				11.0	726469.4	43423.4	0.7	-171.3
				16.2	726469.4	43423.4	19.0	909.3
				14.3	726469.4	43423.4	6.1	516.5
				13.9	726469.4	43423.4	4.7	450.0
				12.6	726469.4	43423.4	0.6	166.0
				14.0	726469.4	43423.4	4.9	462.0
n = 30	Total Σ	19318.5	353.6	13123749.3	683646.7	189.9	8400.0	

¹⁾ Coatings and coating systems in accordance with Table 4.6.

2K-PUR coating, $\Sigma t/d \approx 5$, (initial) tightening

Table B.3 Regression analysis of extrapolated preload losses $\Delta F_{p,setting,50a}$ for the 2K-PUR coating after (initial) tightening, test specimens with $\Sigma t/d \approx 5$

System No. ¹⁾	$\Sigma t/d$ [-]	Tight. method	Variable		x^2	Squares around mean		Product $(x - \bar{x}) \cdot (y - \bar{y})$
			x	y		$(x - \bar{x})^2$	$(y - \bar{y})^2$	
1.1a	4.9-sl	KV	547.6	16.1	299902.1	13866.2	22.1	553.4
				19.9	299902.1	13866.2	0.9	108.6
				17.2	299902.1	13866.2	13.0	425.3
				19.2	299902.1	13866.2	2.6	190.3
				23.2	299902.1	13866.2	6.0	-287.9
				20.8	299902.1	13866.2	0.0	-1.3
				21.3	299902.1	13866.2	0.2	-54.6
1.1a	4.9-sl	MDV	546.4	18.0	298565.8	14155.3	8.0	336.4
				18.8	298565.8	14155.3	3.9	234.5
				19.0	298565.8	14155.3	3.2	211.7
				17.3	298565.8	14155.3	12.1	413.9
				18.3	298565.8	14155.3	6.2	297.0
				17.6	298565.8	14155.3	10.1	377.2
				16.6	298565.8	14155.3	17.6	499.2
1.1a	5.2-dl	KV	754.3	26.0	568985.0	7907.3	27.6	466.9
				21.4	568985.0	7907.3	0.3	51.4
				21.6	568985.0	7907.3	0.6	67.6
				24.8	568985.0	7907.3	16.0	355.4
				22.2	568985.0	7907.3	2.1	129.6
				23.4	568985.0	7907.3	6.7	230.4
				21.1	568985.0	7907.3	0.1	24.6
1.1a	5.2-dl	MDV	798.5	24.6	568985.0	7907.3	14.8	342.3
				24.3	637564.2	17712.5	12.4	468.6
				22.0	637564.2	17712.5	1.5	161.4
				20.1	637564.2	17712.5	0.5	-91.5
				23.4	637564.2	17712.5	7.0	352.9
				24.6	637564.2	17712.5	14.6	508.7
				19.5	637564.2	17712.5	1.6	-168.9
1.1a	5.2-dl	MDV	798.5	19.6	637564.2	17712.5	1.4	-159.7
				25.0	637564.2	17712.5	17.8	561.1
				n = 31		Total Σ	20627.0	644.5

1) Coatings and coating systems in accordance with Table 4.6.

2K-PUR coating, $\Sigma t/d \approx 5$, re-tightening

Table B.4 Regression analysis of extrapolated preload losses $\Delta F_{p, \text{setting}, 50a}$ for the 2K-PUR coating after re-tightening, test specimens with $\Sigma t/d \approx 5$

System No. ¹⁾	$\Sigma t/d$ [-]	Tight method	Variable			Squares around mean		Product	
			x	y	x^2	$(x - \bar{x})^2$	$(y - \bar{y})^2$	$(x - \bar{x}) \cdot (y - \bar{y})$	
1.1a	4.9-sl	MDV	546.4	12.5	298565.8	15884.1	4.1	-254.8	
				11.3	298565.8	15884.1	0.6	-98.4	
				8.6	298565.8	15884.1	3.6	239.4	
				8.4	298565.8	15884.1	4.3	261.8	
				11.8	298565.8	15884.1	1.7	-164.4	
				10.2	298565.8	15884.1	0.1	35.7	
				9.3	298565.8	15884.1	1.6	157.2	
				8.6	298565.8	15884.1	3.6	239.4	
1.1a	5.2-dl	MDV	798.5	11.8	637564.2	15884.1	1.6	161.5	
				9.5	637564.2	15884.1	1.0	-124.2	
				9.6	637564.2	15884.1	0.9	-119.8	
				12.5	637564.2	15884.1	3.9	249.1	
				12.7	637564.2	15884.1	4.9	279.3	
				10.1	637564.2	15884.1	0.2	-51.2	
				8.8	637564.2	15884.1	3.0	-216.5	
				12.4	637564.2	15884.1	3.6	237.9	
n = 16			Total Σ	10759.1	168.2	7489040.4	254145.9	38.6	832.0

¹⁾ Coatings and coating systems in accordance with Table 4.6.

2K-PUR coating, overall evaluation

Table B.5 Overall regression analysis for the 2K-PUR coating

Coating system $\Sigma t/d$ Phase	2K-PUR ≈ 2.4 tight.	2K-PUR ≈ 2.4 re-tight.	2K-PUR ≈ 5 tight.	2K-PUR ≈ 5 re-tight.
a	10.70	3.875	9.604	8.311
b	0.0194	0.0123	0.0168	0.0033
SSR	387.2	103.2	117.4	2.72
SSE	205.6	86.66	123.5	35.85
MSE	4.673	3.095	4.258	2.561
R ²	0.653	0.544	0.487	0.071
SE _a	1.344	1.407	2.163	2.172
SE _b	0.002	0.002	0.003	0.003
t _a	7.963	2.754	4.441	3.827
t _b	9.103	5.775	5.251	1.031
Pa	$4.561 \cdot 10^{-10}$	0.0102	$1.196 \cdot 10^{-4}$	0.0018
Pb	$1.118 \cdot 10^{-11}$	$3.359 \cdot 10^{-6}$	$1.264 \cdot 10^{-5}$	0.3199
t _{α/2}	1.680	1.701	1.699	1.761
a0.95	12.962	6.269	13.279	12.136
b0.95	0.0230	0.0159	0.0223	0.0089

EP-/PUR coating systems, $\Sigma t/d \approx 2.4$, (initial) tightening

Table B.6 Regression analysis of extrapolated preload losses $\Delta F_{p, \text{setting}, 50a}$ for EP-/PUR coating systems after (initial) tightening, test specimens with $\Sigma t/d \approx 2.4$

System No. ¹⁾	$\Sigma t/d$ [-]	Tight method	Variable x y	x^2	Squares around mean $(x - \bar{x})^2$	$(y - \bar{y})^2$	Product $(x - \bar{x}) \cdot (y - \bar{y})$	
1.2	2.4-sl	KV	694.0	14.1	481588.3	501784.3	102.0	7153.0
				16.2	481588.3	501784.3	64.6	5692.4
				16.7	481588.3	501784.3	56.7	5331.6
				15.7	481588.3	501784.3	72.2	6018.1
				17.9	481588.3	501784.3	39.9	4472.1
				21.1	481588.3	501784.3	9.5	2187.0
				18.6	481588.3	501784.3	31.1	3952.1
				16.8	481588.3	501784.3	55.0	5253.3
1.2	2.4-sl	MDV	666.2	17.9	443821.9	541892.3	39.6	4633.1
				19.0	443821.9	541892.3	26.7	3805.7
				18.6	443821.9	541892.3	30.8	4085.4
				17.1	443821.9	541892.3	50.5	5229.9
				18.7	443821.9	541892.3	30.6	4075.3
				19.9	443821.9	541892.3	18.5	3165.9
				19.5	443821.9	541892.3	21.8	3437.8
				16.9	443821.9	541892.3	53.5	5384.1
1.2	2.4-dl	KV	949.5	24.3	901533.5	205065.7	0.0	-73.0
				25.1	901533.5	205065.7	0.9	-426.8
				23.7	901533.5	205065.7	0.3	232.2
				20.3	901533.5	205065.7	15.2	1766.2
				27.1	901533.5	205065.7	8.2	-1300.3
				26.5	901533.5	205065.7	5.2	-1030.3
1.2	2.4-dl	MDV	973.0	25.1	946791.3	184299.3	0.8	-375.0
				25.7	946791.3	184299.3	2.4	-663.1
				17.7	946791.3	184299.3	41.6	2769.0
				21.4	946791.3	184299.3	7.6	1184.7
				24.1	946791.3	184299.3	0.0	22.4
				23.5	946791.3	184299.3	0.4	283.6
				20.6	946791.3	184299.3	13.1	1552.9
				1.3	2.4-sl	KV	1380.0	23.6
26.1	1904514.8	496.9	3.5					-41.6
23.1	1904514.8	496.9	1.1					23.4
23.6	1904514.8	496.9	0.3					12.4
22.5	1904514.8	496.9	3.0					38.6
21.3	1904514.8	496.9	8.2					63.7
21.0	1904514.8	496.9	10.3					71.7
1.3	2.4-sl	MDV	988.0	22.0	976176.4	171658.2	4.9	913.1
				18.7	976176.4	171658.2	30.6	2292.4
				19.7	976176.4	171658.2	20.3	1868.4
				22.5	976176.4	171658.2	2.7	682.9
				19.5	976176.4	171658.2	21.7	1931.4
				23.1	976176.4	171658.2	1.1	443.6
				20.6	976176.4	171658.2	12.8	1479.6
				19.4	976176.4	171658.2	22.8	1976.5
continued								

¹⁾ Coatings and coating systems in accordance with Table 4.6.

Table B.7 Regression analysis of extrapolated preload losses $\Delta F_{p, \text{setting}, 50a}$ for EP-/PUR coating systems after (initial) tightening, test specimens with $\Sigma t/d \approx 2.4$ (continued)

System No. ¹⁾	$\Sigma t/d$ [-]	Tight. method	Variable		x^2	Squares around mean		Product $(x - \bar{x}) \cdot (y - \bar{y})$
			x	y		$(x - \bar{x})^2$	$(y - \bar{y})^2$	
1.3	2.4-dl	MDV	2136.5	30.3	4564423.7	538929.6	37.5	4493.7
				31.1	4564423.7	538929.6	48.4	5107.8
				27.4	4564423.7	538929.6	10.2	2339.8
				27.4	4564423.7	538929.6	10.6	2390.9
				27.8	4564423.7	538929.6	13.4	2687.2
				26.1	4564423.7	538929.6	3.6	1396.6
1.4a	2.4-sl	MDV	1613.2	28.3	2602398.8	44462.9	16.8	863.2
				24.3	2602398.8	44462.9	0.0	31.0
				28.9	2602398.8	44462.9	21.9	987.1
				30.5	2602398.8	44462.9	39.9	1332.0
				27.2	2602398.8	44462.9	9.2	640.4
				26.4	2602398.8	44462.9	5.0	470.7
				27.8	2602398.8	44462.9	12.7	751.5
				25.7	2602398.8	44462.9	2.2	309.7
				29.8	2602398.8	44462.9	31.2	1178.4
				27.7	2602398.8	44462.9	12.1	734.0
				30.7	2602398.8	44462.9	42.1	1368.2
				30.7	2602398.8	44462.9	42.5	1374.5
				33.7	2602398.8	44462.9	89.9	1999.3
				31.4	2602398.8	44462.9	52.0	1519.9
1.4a	2.4-dl	MDV	2853.7	32.4	8143571.7	2106450.1	67.7	11943.1
				33.8	8143571.7	2106450.1	93.2	14014.2
				34.5	8143571.7	2106450.1	107.3	15031.2
				38.7	8143571.7	2106450.1	210.5	21058.7
				39.5	8143571.7	2106450.1	233.3	22166.5
1.4b	2.4-sl	MDV	1436.3	22.4	2063100.2	1157.1	3.0	-59.3
				19.9	2063100.2	1157.1	18.0	-144.4
				22.7	2063100.2	1157.1	2.2	-49.9
				22.8	2063100.2	1157.1	2.0	-47.6
				22.9	2063100.2	1157.1	1.7	-43.9
				23.2	2063100.2	1157.1	1.1	-35.1
				23.3	2063100.2	1157.1	0.8	-30.4
				24.1	2063100.2	1157.1	0.0	-4.2
1.4b	2.4-dl	MDV	2135.2	24.8	4559120.0	537108.2	0.4	477.5
				25.6	4559120.0	537108.2	1.9	1016.7
				25.7	4559120.0	537108.2	2.2	1077.9
				24.9	4559120.0	537108.2	0.5	511.3
				28.6	4559120.0	537108.2	19.9	3267.4
				25.0	4559120.0	537108.2	0.7	608.4
				25.2	4559120.0	537108.2	1.1	751.1
				26.3	4559120.0	537108.2	4.4	1531.0
<hr/>								
n = 85	Total Σ	119198.3	2056.0	198096781.7	30941076.8	2215.1	214603.9	
<hr/>								

¹⁾ Coatings and coating systems in accordance with Table 4.6.

EP-/PUR coating systems, $\Sigma t/d \approx 2.4$, re-tightening

Table B.8 Regression analysis of extrapolated preload losses $\Delta F_{p, \text{setting}, 50a}$ for EP-/PUR coating systems after re-tightening, test specimens with $\Sigma t/d \approx 2.4$

System No. ¹⁾	$\Sigma t/d$ [-]	Tight method	Variable x	y	x^2	Squares around mean $(x - \bar{x})^2$	Product $(x - \bar{x}) \cdot (y - \bar{y})$	
1.2	2.4-sl	MDV	666.2	9.7	443821.9	756154.2	22.1	4085.9
				9.3	443821.9	756154.2	26.1	4440.4
				11.6	443821.9	756154.2	7.7	2417.9
				10.5	443821.9	756154.2	15.1	3378.4
				9.4	443821.9	756154.2	24.7	4321.4
				11.9	443821.9	756154.2	6.0	2133.9
				9.5	443821.9	756154.2	24.2	4280.1
				9.6	443821.9	756154.2	23.2	4190.6
1.2	2.4-dl	MDV	973.0	11.5	946791.3	316675.1	8.4	1635.7
				10.3	946791.3	316675.1	16.5	2283.2
				10.4	946791.3	316675.1	16.3	2272.2
				12.2	946791.3	316675.1	4.8	1235.9
				12.7	946791.3	316675.1	3.0	969.2
				14.4	946791.3	316675.1	0.0	20.9
1.3	2.4-sl	MDV	988.0	13.6	976176.4	300035.0	0.6	435.7
				10.5	976176.4	300035.0	15.4	2146.6
				10.6	976176.4	300035.0	14.2	2065.9
				14.8	976176.4	300035.0	0.2	-225.0
				11.0	976176.4	300035.0	11.4	1845.8
				13.0	976176.4	300035.0	2.1	789.3
				11.8	976176.4	300035.0	6.6	1411.7
				12.8	976176.4	300035.0	2.5	873.9
1.3	2.4-dl	MDV	2136.5	17.7	4564423.7	360816.8	11.1	1998.1
				17.5	4564423.7	360816.8	9.7	1869.7
				17.9	4564423.7	360816.8	11.9	2073.7
				15.5	4564423.7	360816.8	1.1	641.4
				17.0	4564423.7	360816.8	6.6	1543.5
				18.1	4564423.7	360816.8	13.5	2209.5
1.4a	2.4-sl	MDV	1613.2	17.2	2602398.8	5994.5	8.1	220.8
				14.6	2602398.8	5994.5	0.1	18.0
				19.0	2602398.8	5994.5	20.9	354.1
				20.4	2602398.8	5994.5	35.6	462.2
				15.8	2602398.8	5994.5	1.9	107.0
				16.2	2602398.8	5994.5	3.2	138.2
				15.7	2602398.8	5994.5	1.8	102.4
				16.9	2602398.8	5994.5	6.3	194.2
				20.3	2602398.8	5994.5	35.3	459.7
				16.1	2602398.8	5994.5	2.7	128.2
				22.7	2602398.8	5994.5	69.1	643.7
				20.2	2602398.8	5994.5	34.1	452.4
				24.5	2602398.8	5994.5	101.7	780.7
				20.6	2602398.8	5994.5	38.9	483.1

continued

¹⁾ Coatings and coating systems in accordance with Table 4.6.

Table B.9 Regression analysis of extrapolated preload losses $\Delta F_{p, \text{setting}, 50a}$ for EP-/PUR coating systems after re-tightening, test specimens with $\Sigma t/d \approx 2.4$ (continued)

System No. ¹⁾	$\Sigma t/d$ [-]	Tight. method	Variable			Squares around mean		Product $(x - \bar{x}) \cdot (y - \bar{y})$	
			x	y	x^2	$(x - \bar{x})^2$	$(y - \bar{y})^2$		
1.4a	2.4-dl	MDV	2853.7	20.4	8143571.7	1736922.4	36.1	7918.4	
				20.7	8143571.7	1736922.4	40.2	8356.5	
				21.7	8143571.7	1736922.4	52.7	9566.7	
				23.5	8143571.7	1736922.4	83.2	12018.8	
				26.3	8143571.7	1736922.4	142.3	15723.7	
1.4b	2.4-sl	MDV	1436.3	11.0	2063100.2	9884.6	11.6	339.2	
				7.9	2063100.2	9884.6	42.5	647.9	
				9.3	2063100.2	9884.6	26.0	507.1	
				8.4	2063100.2	9884.6	36.0	596.7	
				10.4	2063100.2	9884.6	15.6	392.5	
				9.6	2063100.2	9884.6	22.9	475.9	
				9.7	2063100.2	9884.6	22.2	468.1	
				8.9	2063100.2	9884.6	30.7	551.2	
1.4b	2.4-dl	MDV	2135.2	11.2	4559120.0	359326.8	10.3	-1920.5	
				14.1	4559120.0	359326.8	0.1	-193.7	
				14.6	4559120.0	359326.8	0.1	143.8	
				12.8	4559120.0	359326.8	2.7	-976.9	
				15.1	4559120.0	359326.8	0.5	444.0	
				12.1	4559120.0	359326.8	5.1	-1348.1	
				13.4	4559120.0	359326.8	1.0	-588.4	
				14.2	4559120.0	359326.8	0.0	-125.9	
n = 64			Total Σ	98289.3	921.5	175503270.7	24553366.2	1257.3	116730.8

¹⁾ Coatings and coating systems in accordance with Table 4.6.

EP-/PUR coating systems, $\Sigma t/d \approx 5$, (initial) tightening

Table B.10 Regression analysis of extrapolated preload losses $\Delta F_{p, \text{setting}, 50a}$ for EP-/PUR coating systems after (initial) tightening, test specimens with $\Sigma t/d \approx 5$

System No. ¹⁾	$\Sigma t/d$ [-]	Tight method	Variable		Squares around mean		Product	
			x	y	x^2	$(x - \bar{x})^2$	$(y - \bar{y})^2$	$(x - \bar{x}) \cdot (y - \bar{y})$
1.2	4.9-sl	KV	615.9	13.1	379291.4	511574.7	29.3	3874.5
				15.6	379291.4	511574.7	9.0	2148.6
				18.0	379291.4	511574.7	0.4	436.6
				14.2	379291.4	511574.7	19.5	3154.4
				15.3	379291.4	511574.7	10.5	2322.3
				16.9	379291.4	511574.7	2.9	1220.8
				17.8	379291.4	511574.7	0.6	532.2
				16.0	379291.4	511574.7	6.4	1808.1
1.2	4.9-sl	MDV	621.9	17.1	386791.9	502943.2	2.2	1055.4
				14.8	386791.9	502943.2	14.0	2657.6
				16.5	386791.9	502943.2	4.3	1467.4
				14.7	386791.9	502943.2	14.7	2720.6
				13.4	386791.9	502943.2	26.5	3648.4
				12.6	386791.9	502943.2	35.6	4233.9
				14.1	386791.9	502943.2	19.9	3164.0
				11.9	386791.9	502943.2	44.5	4731.4
1.2	5.2-dl	KV	895.3	18.2	801575.2	189924.8	0.1	143.0
				19.6	801575.2	189924.8	1.1	-454.6
				17.7	801575.2	189924.8	0.7	368.7
				17.0	801575.2	189924.8	2.6	703.4
				17.7	801575.2	189924.8	0.7	377.0
				20.0	801575.2	189924.8	2.1	-630.8
				23.5	801575.2	189924.8	24.3	-2146.8
				13.8	801575.2	189924.8	22.8	2080.8
1.2	5.2-dl	MDV	943.6	16.3	890389.3	150161.3	5.0	867.2
				17.1	890389.3	150161.3	2.2	570.1
				17.0	890389.3	150161.3	2.4	597.9
				18.3	890389.3	150161.3	0.1	120.8
				16.7	890389.3	150161.3	3.6	732.1
				16.7	890389.3	150161.3	3.5	723.0
				17.6	890389.3	150161.3	1.0	380.1
				18.8	890389.3	150161.3	0.1	-97.5
continued								

¹⁾ Coatings and coating systems in accordance with Table 4.6.

Table B.11 Regression analysis of extrapolated preload losses $\Delta F_{p, \text{setting}, 50a}$ for EP-/PUR coating systems after (initial) tightening, test specimens with $\Sigma t/d \approx 5$ (continued)

System No. ¹⁾	$\Sigma t/d$ [-]	Tight. method	Variable		Squares around mean		Product	
			x	y	x^2	$(x - \bar{x})^2$	$(y - \bar{y})^2$	$(x - \bar{x}) \cdot (y - \bar{y})$
1.3	4.9-sl	MDV	1363.1	15.1	1858100.5	1024.7	12.3	-112.5
				15.7	1858100.5	1024.7	8.5	-93.2
				15.7	1858100.5	1024.7	8.0	-90.4
				19.9	1858100.5	1024.7	1.8	43.2
				16.2	1858100.5	1024.7	5.4	-74.1
				15.2	1858100.5	1024.7	11.5	-108.7
				18.8	1858100.5	1024.7	0.1	7.9
1.3	5.2-dl	MDV	1990.9	18.0	3963568.1	435283.7	0.3	-362.4
				18.2	3963568.1	435283.7	0.1	-240.2
				21.8	3963568.1	435283.7	10.5	2140.7
				19.5	3963568.1	435283.7	0.8	590.1
				18.7	3963568.1	435283.7	0.0	99.5
				20.7	3963568.1	435283.7	4.5	1399.4
				21.5	3963568.1	435283.7	8.6	1935.5
1.4a	4.9-sl	MDV	1808.9	21.3	3963568.1	435283.7	7.5	1811.4
				22.0	3272000.5	228251.1	11.9	1647.0
				21.2	3272000.5	228251.1	6.7	1241.2
				19.4	3272000.5	228251.1	0.7	410.4
				21.0	3272000.5	228251.1	5.7	1141.2
				20.7	3272000.5	228251.1	4.6	1025.3
				23.9	3272000.5	228251.1	28.4	2546.1
1.4a	5.2-dl	MDV	2636.2	24.5	3272000.5	228251.1	35.3	2840.3
				24.3	6949430.2	1703198.1	32.8	7472.5
				24.2	6949430.2	1703198.1	32.3	7411.6
				22.9	6949430.2	1703198.1	19.0	5695.8
				25.8	6949430.2	1703198.1	52.5	9455.8
				24.3	6949430.2	1703198.1	32.4	7424.0
				27.7	6949430.2	1703198.1	83.1	11895.0
n = 61	Total Σ		81197.8	1132.4	135929646.7	27846417.6	798.3	120805.5

¹⁾ Coatings and coating systems in accordance with Table 4.6.

EP-/PUR coating systems, $\Sigma t/d \approx 5$, re-tightening

Table B.12 Regression analysis of extrapolated preload losses $\Delta F_{p, \text{setting}, 50a}$ for EP-/PUR coating systems after re-tightening, test specimens with $\Sigma t/d \approx 5$

System No. ¹⁾	$\Sigma t/d$ [-]	Tight. method	Variable		x^2	Squares around mean		Product		
			x	y		$(x - \bar{x})^2$	$(y - \bar{y})^2$	$(x - \bar{x}) \cdot (y - \bar{y})$		
1.2	4.9-sl	MDV	621.9	7.2	386791.9	835059.1	20.9	4180.8		
				8.7	386791.9	835059.1	9.8	2860.6		
				9.2	386791.9	835059.1	6.6	2350.9		
				7.0	386791.9	835059.1	23.0	4382.2		
				6.9	386791.9	835059.1	23.8	4456.8		
				5.4	386791.9	835059.1	41.0	5853.4		
				7.5	386791.9	835059.1	18.4	3921.1		
				6.5	386791.9	835059.1	28.3	4864.2		
1.2	5.2-dl	MDV	943.6	10.0	890389.3	350626.5	3.2	1059.6		
				7.8	890389.3	350626.5	15.8	2356.7		
				8.7	890389.3	350626.5	9.6	1833.8		
				10.2	890389.3	350626.5	2.6	947.0		
				10.3	890389.3	350626.5	2.2	875.3		
				6.4	890389.3	350626.5	29.2	3200.3		
				10.5	890389.3	350626.5	1.8	801.6		
				8.7	890389.3	350626.5	9.6	1832.5		
1.3	4.9-sl	MDV	1363.1	8.1	1858100.5	29797.7	14.2	650.5		
				10.6	1858100.5	29797.7	1.5	212.6		
				9.9	1858100.5	29797.7	3.6	328.4		
				11.0	1858100.5	29797.7	0.7	146.1		
				11.6	1858100.5	29797.7	0.1	45.1		
				10.1	1858100.5	29797.7	2.8	290.2		
				11.3	1858100.5	29797.7	0.2	85.1		
1.3	5.2-dl	MDV	1990.9	11.7	3963568.1	207142.9	0.0	-62.9		
				11.3	3963568.1	207142.9	0.2	-217.8		
				17.4	3963568.1	207142.9	30.9	2530.6		
				14.3	3963568.1	207142.9	6.0	1113.4		
				13.1	3963568.1	207142.9	1.6	578.8		
				15.6	3963568.1	207142.9	14.0	1705.8		
				13.6	3963568.1	207142.9	3.1	803.3		
				13.2	3963568.1	207142.9	2.0	642.1		
1.4a	4.9-sl	MDV	1808.9	13.2	3272000.5	74597.6	2.0	382.7		
				14.8	3272000.5	74597.6	8.9	814.4		
				14.4	3272000.5	74597.6	6.6	702.6		
				13.7	3272000.5	74597.6	3.5	510.3		
				12.7	3272000.5	74597.6	0.8	245.0		
				10.7	3272000.5	74597.6	1.3	-314.5		
				16.5	3272000.5	74597.6	21.6	1268.5		
1.4a	5.2-dl	MDV	2636.2	16.6	6949430.2	1210958.4	22.9	5267.1		
				15.4	6949430.2	1210958.4	12.7	3920.7		
				15.8	6949430.2	1210958.4	16.0	4404.7		
				20.5	6949430.2	1210958.4	76.1	9598.5		
				15.9	6949430.2	1210958.4	16.3	4441.0		
				20.5	6949430.2	1210958.4	75.0	9533.2		
				17.2	6949430.2	1210958.4	28.9	5919.0		
n = 45				Total Σ	69108.4	531.9	126482713.7	20350103.3	619.7	101321.4

¹⁾ Coatings and coating systems in accordance with Table 4.6.

EP-/PUR coating systems, overall evaluation

Table B.13 Overall regression analysis for EP-/PUR coating systems

Coating system $\Sigma t/d$ Phase	EP-/PUR ≈ 2.4 tight.	EP-/PUR ≈ 2.4 re-tight.	EP-/PUR ≈ 5 tight.	EP-/PUR ≈ 5 re-tight.
a	14.46	7.097	12.79	4.173
b	0.0069	0.0048	0.0043	0.0050
SSR	1488.5	555.0	524.1	504.5
SSE	726.6	702.4	274.3	115.2
MSE	8.754	11.33	4.648	2.679
R ²	0.672	0.441	0.656	0.814
SE _a	0.812	1.125	0.610	0.608
SE _b	0.001	0.001	0.000	0.000
t _a	17.81	6.309	20.97	6.860
t _b	13.04	6.999	10.62	13.72
p _a	$4.358 \cdot 10^{-30}$	$3.316 \cdot 10^{-8}$	$4.947 \cdot 10^{-29}$	$2.051 \cdot 10^{-8}$
p _b	$8.609 \cdot 10^{-22}$	$2.158 \cdot 10^{-9}$	$2.591 \cdot 10^{-15}$	$2.592 \cdot 10^{-17}$
t _{$\alpha/2$}	1.663	1.670	1.671	1.681
a _{0.95}	15.812	8.975	13.809	5.195
b _{0.95}	0.0078	0.0059	0.0050	0.0056

Powder coating systems, $\Sigma t/d \approx 2.4$, (initial) tightening

Table B.14 Regression analysis of extrapolated preload losses $\Delta F_{p, \text{setting}, 50a}$ for powder coating systems after (initial) tightening, test specimens with $\Sigma t/d \approx 2.4$

System No. ¹⁾	$\Sigma t/d$ [-]	Tight method	Variable x	y	x^2	Squares around mean $(x - \bar{x})^2$	$(y - \bar{y})^2$	Product $(x - \bar{x}) \cdot (y - \bar{y})$
2.1	2.4-sl	KV	291.8	12.8	85175.0	1143248.3	3.7	2052.3
				8.5	85175.0	1143248.3	38.4	6628.3
				13.6	85175.0	1143248.3	1.1	1121.2
				11.6	85175.0	1143248.3	9.7	3336.9
				10.2	85175.0	1143248.3	20.2	4803.9
				8.5	85175.0	1143248.3	38.4	6625.8
				12.3	85175.0	1143248.3	5.8	2564.3
				8.4	85175.0	1143248.3	39.8	6741.9
2.1	2.4-sl	MDV	352.6	7.2	124355.7	1016940.1	55.7	7529.2
				7.3	124355.7	1016940.1	54.9	7475.0
				8.1	124355.7	1016940.1	43.2	6626.0
				7.3	124355.7	1016940.1	55.0	7480.6
				9.3	124355.7	1016940.1	29.0	5434.3
				7.7	124355.7	1016940.1	49.6	7100.5
				7.8	124355.7	1016940.1	47.2	6926.7
2.1	2.4-sl	KV	951.9	12.1	906205.0	167385.3	6.6	1055.0
				13.2	906205.0	167385.3	2.2	601.0
				12.6	906205.0	167385.3	4.2	840.7
				11.4	906205.0	167385.3	10.6	1333.5
				14.6	906205.0	167385.3	0.0	35.5
				11.9	906205.0	167385.3	7.7	1134.4
				13.1	906205.0	167385.3	2.6	660.5
2.1	2.4-sl	MDV	893.1	10.0	797644.0	218992.5	21.7	2178.8
				10.9	797644.0	218992.5	14.6	1788.5
				11.0	797644.0	218992.5	13.9	1745.9
				12.0	797644.0	218992.5	7.1	1245.9
				9.9	797644.0	218992.5	22.7	2231.1
				9.4	797644.0	218992.5	28.3	2488.1
				8.0	797644.0	218992.5	44.3	3113.2
				9.3	797644.0	218992.5	28.8	2512.5
				2.1	2.4-dl	KV	426.1	9.2
12.1	181539.9	874225.9	6.5					2382.2
11.7	181539.9	874225.9	8.8					2771.1
12.4	181539.9	874225.9	5.0					2098.0
14.5	181539.9	874225.9	0.0					165.4
11.2	181539.9	874225.9	12.4					3296.4
8.6	181539.9	874225.9	37.6					5736.6
11.8	181539.9	874225.9	8.5					2724.6
2.1	2.4-dl	MDV	467.3	14.1	218367.5	798838.0	0.3	523.4
				15.1	218367.5	798838.0	0.2	-400.1
				8.7	218367.5	798838.0	35.5	5325.8
				9.8	218367.5	798838.0	24.0	4376.0
				8.9	218367.5	798838.0	33.2	5150.8
				14.4	218367.5	798838.0	0.1	266.6
continued								

¹⁾ Coatings and coating systems in accordance with Table 4.6.

Table B.15 Regression analysis of extrapolated preload losses $\Delta F_{p, \text{setting}, 50a}$ for powder coating systems after (initial) tightening, test specimens with $\Sigma t/d \approx 2.4$ (continued)

System No. ¹⁾	$\Sigma t/d$ [-]	Tight. method	Variable			Squares around mean		Product
			x	y	x^2	$(x - \bar{x})^2$	$(y - \bar{y})^2$	$(x - \bar{x}) \cdot (y - \bar{y})$
2.1	2.4-dl	KV	1322.4	14.4	1748804.2	1494.0	0.1	12.3
				13.7	1748804.2	1494.0	1.0	39.6
				13.2	1748804.2	1494.0	2.1	55.9
				12.5	1748804.2	1494.0	5.0	86.1
				15.3	1748804.2	1494.0	0.3	-22.5
				13.2	1748804.2	1494.0	2.3	58.5
				16.1	1748804.2	1494.0	2.0	-54.3
				12.0	1748804.2	1494.0	7.2	103.7
2.1	2.4-dl	MDV	1396.1	11.8	1949020.4	1224.8	8.6	-102.8
				15.4	1949020.4	1224.8	0.5	25.4
				13.2	1949020.4	1224.8	2.3	-53.1
				13.7	1949020.4	1224.8	1.0	-34.7
				13.7	1949020.4	1224.8	0.9	-33.0
				12.4	1949020.4	1224.8	5.1	-78.9
				12.6	1949020.4	1224.8	4.4	-73.8
				14.3	1949020.4	1224.8	0.1	-12.8
				15.3	1949020.4	1224.8	0.4	22.6
				12.3	1949020.4	1224.8	5.6	-82.7
				11.2	1949020.4	1224.8	12.4	-123.4
				15.2	1949020.4	1224.8	0.3	18.3
2.2	2.4-sl	KV	720.8	13.5	519596.5	409913.8	1.3	742.9
				11.8	519596.5	409913.8	8.5	1862.7
				12.0	519596.5	409913.8	7.2	1717.4
				11.1	519596.5	409913.8	12.9	2298.6
				12.7	519596.5	409913.8	4.1	1291.8
				13.8	519596.5	409913.8	0.7	547.3
				13.7	519596.5	409913.8	1.0	647.8
				12.4	519596.5	409913.8	5.4	1493.1
2.2	2.4-sl	MDV	817.9	9.8	669020.6	294999.7	24.1	2664.4
				8.9	669020.6	294999.7	33.6	3149.6
				9.7	669020.6	294999.7	24.7	2701.0
				9.7	669020.6	294999.7	25.1	2722.4
				9.5	669020.6	294999.7	27.4	2842.6
				10.1	669020.6	294999.7	20.8	2478.5
				8.7	669020.6	294999.7	35.4	3231.8
				8.5	669020.6	294999.7	38.6	3372.9
2.2	2.4-sl	KV	1862.9	14.3	3470426.2	251835.8	0.1	-183.4
				18.1	3470426.2	251835.8	11.8	1722.5
				18.0	3470426.2	251835.8	10.9	1658.7
				18.3	3470426.2	251835.8	13.2	1822.8
				19.1	3470426.2	251835.8	19.3	2206.5
				20.4	3470426.2	251835.8	32.9	2879.5
				20.6	3470426.2	251835.8	35.5	2988.6
				18.7	3470426.2	251835.8	16.2	2021.8
				22.5	3470426.2	251835.8	60.5	3903.7
				21.3	3470426.2	251835.8	43.7	3318.6
				20.6	3470426.2	251835.8	34.6	2953.1
				23.5	3470426.2	251835.8	76.9	4401.8
				24.3	3470426.2	251835.8	92.7	4831.5
				19.2	3470426.2	251835.8	20.4	2264.2
				22.3	3470426.2	251835.8	57.2	3793.8
				22.3	3470426.2	251835.8	57.1	3792.5
continued								

¹⁾ Coatings and coating systems in accordance with Table 4.6.

Table B.16 Regression analysis of extrapolated preload losses $\Delta F_{p, \text{setting}, 50a}$ for powder coating systems after (initial) tightening, test specimens with $\Sigma t/d \approx 2.4$ (continued)

System No. ¹⁾	$\Sigma t/d$ [-]	Tight method	Variable		x^2	Squares around mean		Product
			x	y		$(x - \bar{x})^2$	$(y - \bar{y})^2$	$(x - \bar{x}) \cdot (y - \bar{y})$
2.2	2.4-sl	MDV	1755.7	20.2	3082309.0	155689.5	30.3	2170.6
				22.4	3082309.0	155689.5	59.3	3038.9
				19.2	3082309.0	155689.5	20.4	1783.0
				18.4	3082309.0	155689.5	14.1	1480.9
				18.5	3082309.0	155689.5	14.5	1503.6
				19.9	3082309.0	155689.5	27.1	2052.7
				30.0	3082309.0	155689.5	234.8	6046.7
				28.1	3082309.0	155689.5	178.9	5277.4
				26.0	3082309.0	155689.5	128.5	4473.0
				22.8	3082309.0	155689.5	66.0	3205.4
				29.9	3082309.0	155689.5	229.7	5980.7
				21.7	3082309.0	155689.5	49.8	2783.6
				27.9	3082309.0	155689.5	174.5	5212.3
				21.7	3082309.0	155689.5	48.6	2750.5
2.2	2.4-dl	KV	1166.4	11.2	1360567.2	37885.5	12.5	687.7
				13.5	1360567.2	37885.5	1.5	239.2
				12.9	1360567.2	37885.5	3.3	355.7
				12.6	1360567.2	37885.5	4.3	402.1
				11.9	1360567.2	37885.5	8.0	550.1
				15.9	1360567.2	37885.5	1.3	-225.6
				15.7	1360567.2	37885.5	1.0	-190.2
				10.6	1360567.2	37885.5	17.1	804.8
2.2	2.4-dl	MDV	1143.8	11.7	1308362.6	47192.7	8.9	648.3
				10.7	1308362.6	47192.7	16.2	874.6
				14.2	1308362.6	47192.7	0.2	104.0
				10.5	1308362.6	47192.7	17.6	912.3
				9.8	1308362.6	47192.7	24.4	1072.2
				10.7	1308362.6	47192.7	15.7	861.2
				12.4	1308362.6	47192.7	5.1	489.2
				11.4	1308362.6	47192.7	10.9	716.8
2.2	2.4-dl	KV	2141.0	17.4	4583754.7	608236.2	7.3	2105.2
				19.4	4583754.7	608236.2	22.2	3672.7
				18.9	4583754.7	608236.2	17.8	3292.5
				21.0	4583754.7	608236.2	39.4	4893.0
				14.4	4583754.7	608236.2	0.1	-264.8
				19.5	4583754.7	608236.2	22.9	3732.3
				18.1	4583754.7	608236.2	11.8	2678.8
				14.8	4583754.7	608236.2	0.0	88.6
2.2	2.4-dl	MDV	2067.4	15.7	4274246.1	498929.6	1.0	706.4
				19.7	4274246.1	498929.6	25.5	3565.6
				21.6	4274246.1	498929.6	48.2	4901.4
				14.5	4274246.1	498929.6	0.1	-164.6
				17.5	4274246.1	498929.6	7.8	1976.5
				19.4	4274246.1	498929.6	21.8	3300.1
				continued				

¹⁾ Coatings and coating systems in accordance with Table 4.6.

Table B.17 Regression analysis of extrapolated preload losses $\Delta F_{p, \text{setting}, 50a}$ for powder coating systems after (initial) tightening, test specimens with $\Sigma t/d \approx 2.4$ (continued)

System No. ¹⁾	$\Sigma t/d$ [-]	Tight. method	Variable		x^2	Squares around mean		Product
			x	y		$(x - \bar{x})^2$	$(y - \bar{y})^2$	$(x - \bar{x}) \cdot (y - \bar{y})$
3.1	2.4-sl	KV	1324.0	14.6	1752979.2	1374.5	0.0	3.8
				15.8	1752979.2	1374.5	1.2	-40.4
				13.0	1752979.2	1374.5	3.0	64.0
				15.7	1752979.2	1374.5	1.0	-37.5
				15.8	1752979.2	1374.5	1.1	-39.5
				14.0	1752979.2	1374.5	0.4	24.8
3.1	2.4-sl	MDV	1340.5	13.6	1797027.1	422.0	1.2	22.2
				13.7	1797027.1	422.0	0.9	19.6
				13.8	1797027.1	422.0	0.9	19.3
				15.7	1797027.1	422.0	0.9	-19.8
				13.6	1797027.1	422.0	1.1	21.4
				14.2	1797027.1	422.0	0.3	10.3
				14.0	1797027.1	422.0	0.5	14.7
				12.7	1797027.1	422.0	4.1	41.4
3.1	2.4-dl	KV	2084.4	14.4	4344900.1	523259.6	0.1	-245.5
				18.2	4344900.1	523259.6	12.0	2510.7
				15.1	4344900.1	523259.6	0.2	289.3
				15.4	4344900.1	523259.6	0.5	534.5
				15.7	4344900.1	523259.6	1.0	717.1
				17.2	4344900.1	523259.6	6.3	1816.3
				19.2	4344900.1	523259.6	20.4	3270.1
3.1	2.4-dl	MDV	2034.9	12.8	4140936.8	454078.8	3.8	-1308.2
				14.1	4140936.8	454078.8	0.4	-428.3
				15.3	4140936.8	454078.8	0.4	407.1
				16.6	4140936.8	454078.8	3.7	1297.1
				14.8	4140936.8	454078.8	0.0	65.9
				16.7	4140936.8	454078.8	4.0	1341.1
				17.5	4140936.8	454078.8	8.1	1912.0
				16.7	4140936.8	454078.8	3.9	1328.7
3.2	2.4-sl	KV	1454.4	18.8	2115158.4	8701.7	17.2	387.3
				16.9	2115158.4	8701.7	4.9	207.4
				16.6	2115158.4	8701.7	3.6	177.0
				16.1	2115158.4	8701.7	2.0	132.3
				17.0	2115158.4	8701.7	5.2	213.4
				20.3	2115158.4	8701.7	31.0	519.5
3.2	2.4-sl	MDV	1471.9	13.8	2166397.8	12275.1	0.8	-98.4
				12.7	2166397.8	12275.1	3.8	-215.7
				13.9	2166397.8	12275.1	0.7	-93.3
				12.6	2166397.8	12275.1	4.5	-234.8
				12.7	2166397.8	12275.1	3.8	-215.7
				13.1	2166397.8	12275.1	2.6	-180.3
				14.7	2166397.8	12275.1	0.0	-3.3
				12.7	2166397.8	12275.1	3.8	-216.8
continued								

1) Coatings and coating systems in accordance with Table 4.6.

Table B.18 Regression analysis of extrapolated preload losses $\Delta F_{p, \text{setting}, 50a}$ for powder coating systems after (initial) tightening, test specimens with $\Sigma t/d \approx 2.4$ (continued)

System No. ¹⁾	$\Sigma t/d$ [-]	Tight method	Variable			Squares around mean		Product	
			x	y	x^2	$(x - \bar{x})^2$	$(y - \bar{y})^2$	$(x - \bar{x}) \cdot (y - \bar{y})$	
3.2	2.4-dl	KV	2190.2	16.3	4796997.1	687455.4	2.5	1315.9	
				18.4	4796997.1	687455.4	13.5	3050.2	
				20.3	4796997.1	687455.4	31.1	4627.4	
				20.6	4796997.1	687455.4	34.4	4860.6	
				15.9	4796997.1	687455.4	1.5	1007.7	
				17.7	4796997.1	687455.4	9.0	2492.8	
3.2	2.4-dl	MDV	2260.5	15.1	5109898.2	808979.5	0.2	373.4	
				14.7	5109898.2	808979.5	0.0	7.0	
				14.4	5109898.2	808979.5	0.1	-253.1	
				15.3	5109898.2	808979.5	0.3	529.5	
				14.5	5109898.2	808979.5	0.0	-182.7	
				13.6	5109898.2	808979.5	1.3	-1025.4	
				14.2	5109898.2	808979.5	0.3	-455.5	
				14.5	5109898.2	808979.5	0.0	-177.9	
n = 197			Total Σ	268131.9	2894.5	434391903.3	69444166.2	3735.6	343594.0

¹⁾ Coatings and coating systems in accordance with Table 4.6.

Powder coating systems, $\Sigma t/d \approx 2.4$, re-tightening

Table B.19 Regression analysis of extrapolated preload losses $\Delta F_{p, \text{setting}, 50a}$ for powder coating systems after re-tightening, test specimens with $\Sigma t/d \approx 2.4$

System No. ¹⁾	$\Sigma t/d$ [-]	Tight method	Variable		x^2	Squares around mean		Product
			x	y		$(x - \bar{x})^2$	$(y - \bar{y})^2$	$(x - \bar{x}) \cdot (y - \bar{y})$
2.1	2.4-sl	MDV	352.6	5.9	124355.7	1061792.9	4.7	2226.4
				5.6	124355.7	1061792.9	6.0	2532.9
				6.0	124355.7	1061792.9	4.4	2156.9
				6.1	124355.7	1061792.9	3.8	1996.5
				8.2	124355.7	1061792.9	0.0	-158.4
				7.6	124355.7	1061792.9	0.2	484.4
				5.6	124355.7	1061792.9	6.1	2552.0
2.1	2.4-sl	MDV	893.1	3.6	797644.0	240065.9	19.9	2187.2
				4.6	797644.0	240065.9	11.8	1686.3
				5.0	797644.0	240065.9	9.3	1497.2
				6.6	797644.0	240065.9	2.1	715.0
				6.4	797644.0	240065.9	2.7	800.9
				7.1	797644.0	240065.9	1.0	492.3
				continued				

¹⁾ Coatings and coating systems in accordance with Table 4.6.

Table B.20 Regression analysis of extrapolated preload losses $\Delta F_{p, \text{setting}, 50a}$ for powder coating systems after re-tightening, test specimens with $\Sigma t/d \approx 2.4$ (continued)

System No. ¹⁾	$\Sigma t/d$ [-]	Tight. method	Variable		Squares around mean			Product
			x	y	x^2	$(x - \bar{x})^2$	$(y - \bar{y})^2$	$(x - \bar{x}) \cdot (y - \bar{y})$
2.1	2.4-dl	MDV	467.3	3.9	218367.5	838646.2	17.3	3813.9
				7.1	218367.5	838646.2	0.9	866.7
				5.7	218367.5	838646.2	5.7	2178.3
				3.6	218367.5	838646.2	19.6	4057.9
				2.1	218367.5	838646.2	35.3	5443.3
				7.6	218367.5	838646.2	0.2	390.9
2.1	2.4-dl	MDV	1396.1	10.3	1949020.4	169.0	5.0	29.0
				6.5	1949020.4	169.0	2.6	-20.8
				8.2	1949020.4	169.0	0.0	1.3
				8.7	1949020.4	169.0	0.4	7.8
				9.5	1949020.4	169.0	2.1	18.7
				9.8	1949020.4	169.0	2.9	22.2
				10.0	1949020.4	169.0	3.7	24.9
				11.1	1949020.4	169.0	9.2	39.4
				8.6	1949020.4	169.0	0.3	6.6
				11.0	1949020.4	169.0	8.6	38.1
				6.9	1949020.4	169.0	1.3	-14.5
8.4	1949020.4	169.0	0.1	4.0				
2.2	2.4-sl	MDV	817.9	4.2	669020.6	319380.5	15.0	2187.5
				3.6	669020.6	319380.5	19.8	2517.2
				5.6	669020.6	319380.5	5.8	1366.7
				4.2	669020.6	319380.5	15.2	2206.0
				5.6	669020.6	319380.5	6.1	1395.4
				6.0	669020.6	319380.5	4.2	1159.9
				4.0	669020.6	319380.5	16.6	2303.4
				3.4	669020.6	319380.5	22.1	2655.2
2.2	2.4-sl	MDV	1755.7	14.8	3082309.0	138813.0	45.9	2523.4
				17.9	3082309.0	138813.0	96.4	3658.9
				12.5	3082309.0	138813.0	19.5	1645.4
				11.1	3082309.0	138813.0	9.1	1122.2
				14.1	3082309.0	138813.0	36.5	2252.4
				12.4	3082309.0	138813.0	18.9	1621.5
				15.3	3082309.0	138813.0	52.3	2694.3
				18.6	3082309.0	138813.0	110.4	3915.0
				13.0	3082309.0	138813.0	24.5	1845.6
				11.3	3082309.0	138813.0	10.5	1208.9
				19.0	3082309.0	138813.0	118.9	4062.2
				11.9	3082309.0	138813.0	15.0	1442.5
				21.2	3082309.0	138813.0	173.5	4907.7
				13.6	3082309.0	138813.0	30.9	2069.6
				2.2	2.4-dl	MDV	1143.8	5.1
5.7	1308362.6	57234.6	5.6					564.7
7.8	1308362.6	57234.6	0.1					68.5
4.5	1308362.6	57234.6	12.8					856.2
5.2	1308362.6	57234.6	8.3					690.6
5.5	1308362.6	57234.6	6.6					614.8
7.1	1308362.6	57234.6	1.0					242.5
4.3	1308362.6	57234.6	13.8					889.3
continued								

¹⁾ Coatings and coating systems in accordance with Table 4.6.

Table B.21 Regression analysis of extrapolated preload losses $\Delta F_{p, \text{setting}, 50a}$ for powder coating systems after re-tightening, test specimens with $\Sigma t/d \approx 2.4$ (continued)

System No. ¹⁾	$\Sigma t/d$ [-]	Tight. method	Variable x	y	x^2	Squares around mean $(x - \bar{x})^2$	$(y - \bar{y})^2$	Product $(x - \bar{x}) \cdot (y - \bar{y})$
2.2	2.4-dl	MDV	2067.4	7.8	4274246.1	468335.7	0.1	-176.7
				10.7	4274246.1	468335.7	6.7	1772.6
				10.7	4274246.1	468335.7	6.8	1790.2
				8.6	4274246.1	468335.7	0.3	357.2
				15.3	4274246.1	468335.7	51.7	4921.0
				11.8	4274246.1	468335.7	13.6	2522.6
3.1	2.4-sl	MDV	1340.5	6.4	1797027.1	1809.8	2.7	69.3
				5.5	1797027.1	1809.8	6.6	109.3
				6.6	1797027.1	1809.8	2.1	61.6
				6.7	1797027.1	1809.8	1.9	58.5
				7.9	1797027.1	1809.8	0.0	8.0
				7.9	1797027.1	1809.8	0.0	8.0
				7.2	1797027.1	1809.8	0.7	36.4
3.1	2.4-dl	MDV	2034.9	7.1	1797027.1	1809.8	0.9	40.4
				5.8	4140936.8	424914.7	5.2	-1489.8
				7.8	4140936.8	424914.7	0.1	-184.3
				8.3	4140936.8	424914.7	0.0	145.7
				6.4	4140936.8	424914.7	2.9	-1109.7
				8.3	4140936.8	424914.7	0.0	139.7
				7.6	4140936.8	424914.7	0.2	-322.9
				7.8	4140936.8	424914.7	0.1	-152.5
3.2	2.4-sl	MDV	1471.9	8.4	4140936.8	424914.7	0.1	225.3
				6.3	2166397.8	7884.4	3.2	-159.1
				5.6	2166397.8	7884.4	6.1	-219.0
				4.4	2166397.8	7884.4	13.6	-327.9
				5.6	2166397.8	7884.4	6.3	-222.1
				6.5	2166397.8	7884.4	2.6	-142.7
				7.3	2166397.8	7884.4	0.6	-70.2
				7.5	2166397.8	7884.4	0.3	-48.4
3.2	2.4-dl	MDV	2260.5	7.4	2166397.8	7884.4	0.5	-60.8
				7.8	5109898.2	769890.4	0.1	-270.0
				7.1	5109898.2	769890.4	1.0	-886.5
				8.1	5109898.2	769890.4	0.0	35.8
				8.4	5109898.2	769890.4	0.1	288.5
				7.7	5109898.2	769890.4	0.1	-278.1
				6.1	5109898.2	769890.4	3.7	-1683.4
				8.2	5109898.2	769890.4	0.0	144.2
n = 99	Total Σ		136924.4	798.5	220685752.6	31309163.4	1252.6	96716.4

¹⁾ Coatings and coating systems in accordance with Table 4.6.

Powder coating systems, $\Sigma t/d \approx 5$, (initial) tightening

Table B.22 Regression analysis of extrapolated preload losses $\Delta F_{p, \text{setting}, 50a}$ for powder coating systems after (initial) tightening, test specimens with $\Sigma t/d \approx 5$

System No. ¹⁾	$\Sigma t/d$ [-]	Tight. method	Variable		x^2	Squares around mean		Product
			x	y		$(x - \bar{x})^2$	$(y - \bar{y})^2$	$(x - \bar{x}) \cdot (y - \bar{y})$
2.1	4.9-sl	KV	292.8	11.4	85747.8	1766859.2	3.0	2300.4
				8.3	85747.8	1766859.2	23.2	6398.1
				8.8	85747.8	1766859.2	18.0	5645.4
				9.6	85747.8	1766859.2	12.5	4693.6
				9.2	85747.8	1766859.2	14.9	5138.4
				10.7	85747.8	1766859.2	6.0	3245.2
				11.6	85747.8	1766859.2	2.2	1976.3
				11.9	85747.8	1766859.2	1.5	1601.5
2.1	4.9-sl	MDV	309.9	5.4	96033.7	1721781.3	58.5	10034.5
				4.2	96033.7	1721781.3	79.7	11717.1
				9.3	96033.7	1721781.3	14.2	4941.4
				9.6	96033.7	1721781.3	12.2	4583.8
				4.1	96033.7	1721781.3	81.4	11841.9
				9.5	96033.7	1721781.3	12.7	4675.8
				8.2	96033.7	1721781.3	23.8	6400.4
				5.7	96033.7	1721781.3	54.0	9642.7
2.1	4.9-sl	KV	971.7	13.2	944292.6	422906.4	0.0	-92.3
				11.6	944292.6	422906.4	2.3	981.7
				10.8	944292.6	422906.4	5.1	1474.3
				14.3	944292.6	422906.4	1.4	-761.8
				12.9	944292.6	422906.4	0.0	108.7
				9.5	944292.6	422906.4	12.8	2322.4
				12.6	944292.6	422906.4	0.2	298.8
				10.2	944292.6	422906.4	8.4	1885.1
2.1	4.9-sl	MDV	1049.8	9.1	1102024.6	327511.5	15.7	2267.0
				8.0	1102024.6	327511.5	25.9	2910.4
				8.6	1102024.6	327511.5	20.1	2568.5
				8.4	1102024.6	327511.5	21.6	2656.9
				6.2	1102024.6	327511.5	47.9	3960.0
				7.8	1102024.6	327511.5	28.0	3028.8
				6.9	1102024.6	327511.5	38.5	3549.1
				7.7	1102024.6	327511.5	29.1	3086.8
2.1	5.2-dl	KV	430.1	9.0	185020.8	1420671.7	16.9	4896.8
				10.6	185020.8	1420671.7	6.4	3019.5
				7.2	185020.8	1420671.7	34.3	6980.5
				10.0	185020.8	1420671.7	9.7	3713.2
				9.9	185020.8	1420671.7	10.2	3813.9
				10.9	185020.8	1420671.7	4.9	2635.1
				7.2	185020.8	1420671.7	34.7	7019.5
2.1	5.2-dl	MDV	457.6	12.3	209435.4	1355870.9	0.6	890.7
				8.1	209435.4	1355870.9	25.2	5841.6
				9.8	209435.4	1355870.9	10.8	3830.4
				8.3	209435.4	1355870.9	22.9	5574.6
				5.7	209435.4	1355870.9	54.1	8568.5
				9.0	209435.4	1355870.9	17.1	4819.2
continued								

¹⁾ Coatings and coating systems in accordance with Table 4.6.

Table B.23 Regression analysis of extrapolated preload losses $\Delta F_{p, \text{setting}, 50a}$ for powder coating systems after (initial) tightening, test specimens with $\Sigma t/d \approx 5$ (continued)

System No. ¹⁾	$\Sigma t/d$ [-]	Tight method	Variable x y		x^2	Squares around mean ($x - \bar{x}$) ² ($y - \bar{y}$) ²		Product ($x - \bar{x}$) · ($y - \bar{y}$)
2.1	5.2-dl	KV	1437.3	7.2	2065925.6	34124.1	35.1	1093.8
				11.3	2065925.6	34124.1	3.3	334.6
				11.8	2065925.6	34124.1	1.6	235.7
				9.6	2065925.6	34124.1	12.4	650.7
				11.7	2065925.6	34124.1	1.9	254.2
				9.0	2065925.6	34124.1	16.9	758.5
				12.2	2065925.6	34124.1	0.7	157.7
2.1	5.2-dl	MDV	1343.0	8.8	1803572.7	77890.2	18.1	1187.1
				12.0	1803572.7	77890.2	1.1	299.1
				8.9	1803572.7	77890.2	17.3	1162.4
				7.7	1803572.7	77890.2	29.2	1508.9
				9.4	1803572.7	77890.2	13.6	1028.3
				8.4	1803572.7	77890.2	21.6	1297.7
				9.4	1803572.7	77890.2	13.4	1022.9
2.2	4.9-sl	KV	1044.3	10.3	1803572.7	77890.2	7.7	776.8
				8.7	1090562.7	333806.2	19.0	2517.4
				7.5	1090562.7	333806.2	31.5	3240.9
				11.1	1090562.7	333806.2	4.0	1150.2
				7.3	1090562.7	333806.2	33.2	3331.4
				9.0	1090562.7	333806.2	17.1	2391.9
				9.1	1090562.7	333806.2	15.8	2295.5
				9.3	1090562.7	333806.2	14.3	2188.5
				5.4	1090562.7	333806.2	58.7	4426.4
				10.4	1090562.7	333806.2	7.2	1545.4
				8.1	1090562.7	333806.2	24.5	2861.0
				11.6	1090562.7	333806.2	2.3	885.6
				10.2	1090562.7	333806.2	8.4	1673.5
				11.5	1090562.7	333806.2	2.5	913.0
				10.1	1090562.7	333806.2	8.8	1716.1
10.5	1090562.7	333806.2	6.6	1489.5				
11.7	1090562.7	333806.2	1.9	800.7				
2.2	4.9-sl	MDV	797.2	6.3	635453.2	680470.9	45.9	5588.4
				6.2	635453.2	680470.9	47.7	5696.2
				8.7	635453.2	680470.9	19.6	3655.7
				9.1	635453.2	680470.9	15.9	3291.3
				7.1	635453.2	680470.9	35.8	4935.8
				10.6	635453.2	680470.9	6.1	2039.1
				10.3	635453.2	680470.9	7.8	2308.9
9.6	635453.2	680470.9	12.2	2884.1				
2.2	4.9-sl	KV	1565.3	9.9	2450205.4	3220.2	9.9	178.6
				10.1	2450205.4	3220.2	8.8	168.0
				10.6	2450205.4	3220.2	6.2	140.9
				11.6	2450205.4	3220.2	2.1	82.6
				10.4	2450205.4	3220.2	7.1	151.7
				8.6	2450205.4	3220.2	20.1	254.1
				9.6	2450205.4	3220.2	12.2	198.3
9.4	2450205.4	3220.2	13.4	207.9				
continued								

1) Coatings and coating systems in accordance with Table 4.6.

Table B.24 Regression analysis of extrapolated preload losses $\Delta F_{p, \text{setting}, 50a}$ for powder coating systems after (initial) tightening, test specimens with $\Sigma t/d \approx 5$ (continued)

System No. ¹⁾	$\Sigma t/d$ [-]	Tight. method	Variable		x^2	Squares around mean $(x - \bar{x})^2$	$(y - \bar{y})^2$	Product $(x - \bar{x}) \cdot (y - \bar{y})$
			x	y				
2.2	4.9-sl	MDV	1604.1	8.9	2573141.9	322.5	17.9	76.0
				8.2	2573141.9	322.5	24.2	88.4
				12.5	2573141.9	322.5	0.4	10.7
				10.8	2573141.9	322.5	5.1	40.4
				9.4	2573141.9	322.5	13.3	65.5
				16.3	2573141.9	322.5	10.1	-57.1
11.8	2573141.9	322.5	1.6	22.7				
2.2	5.2-dl	KV	1346.2	10.5	1812254.4	76098.6	6.5	701.7
				9.1	1812254.4	76098.6	16.0	1102.4
				16.6	1812254.4	76098.6	12.4	-970.6
				11.8	1812254.4	76098.6	1.6	353.2
11.8	1812254.4	76098.6	1.8	365.7				
2.2	5.2-dl	MDV	1663.2	11.1	2766278.1	1693.6	3.8	-80.1
				12.1	2766278.1	1693.6	1.0	-40.4
				13.5	2766278.1	1693.6	0.2	17.8
				14.3	2766278.1	1693.6	1.6	51.5
				12.1	2766278.1	1693.6	0.9	-39.3
				9.1	2766278.1	1693.6	16.1	-165.0
				11.7	2766278.1	1693.6	2.0	-58.3
				12.0	2766278.1	1693.6	1.3	-46.2
				11.6	2766278.1	1693.6	2.2	-61.2
				10.1	2766278.1	1693.6	9.1	-124.3
				9.7	2766278.1	1693.6	11.7	-141.0
				12.4	2766278.1	1693.6	0.5	-30.3
				10.3	2766278.1	1693.6	8.0	-116.4
				9.5	2766278.1	1693.6	13.2	-149.2
				9.8	2766278.1	1693.6	11.0	-136.2
10.1	2766278.1	1693.6	9.0	-123.6				
2.2	5.2-dl	KV	2087.6	12.3	4358088.8	216731.1	0.6	-347.7
				17.1	4358088.8	216731.1	16.1	1869.4
				16.4	4358088.8	216731.1	10.9	1534.1
				16.9	4358088.8	216731.1	14.4	1768.7
				17.7	4358088.8	216731.1	21.5	2159.7
				15.0	4358088.8	216731.1	3.6	889.2
2.2	5.2-dl	MDV	2050.3	12.4	4203715.3	183386.6	0.5	-314.0
				12.2	4203715.3	183386.6	0.9	-398.0
				15.7	4203715.3	183386.6	7.0	1129.4
				13.3	4203715.3	183386.6	0.0	95.1
				11.4	4203715.3	183386.6	2.7	-709.5
				16.4	4203715.3	183386.6	10.7	1403.1
17.7	4203715.3	183386.6	21.3	1978.4				
continued								

¹⁾ Coatings and coating systems in accordance with Table 4.6.

Table B.25 Regression analysis of extrapolated preload losses $\Delta F_{p, \text{setting}, 50a}$ for powder coating systems after (initial) tightening, test specimens with $\Sigma t/d \approx 5$ (continued)

System No. ¹⁾	$\Sigma t/d$ [-]	Tight method	Variable			Squares around mean		Product
			x	y	x^2	$(x - \bar{x})^2$	$(y - \bar{y})^2$	$(x - \bar{x}) \cdot (y - \bar{y})$
3.1	4.9-sl	KV	2434.4	19.7	5926186.5	659857.6	43.9	5379.8
				21.6	5926186.5	659857.6	72.0	6892.6
				20.9	5926186.5	659857.6	60.6	6326.0
				22.1	5926186.5	659857.6	80.3	7280.0
				19.3	5926186.5	659857.6	38.7	5055.9
				21.7	5926186.5	659857.6	73.6	6969.6
3.1	4.9-sl	MDV	2396.3	23.8	5742468.4	599517.3	113.8	8261.1
				22.0	5742468.4	599517.3	79.9	6922.5
				22.9	5742468.4	599517.3	97.0	7624.4
				23.1	5742468.4	599517.3	100.5	7761.1
				24.7	5742468.4	599517.3	134.4	8977.5
				23.9	5742468.4	599517.3	117.7	8401.2
				23.8	5742468.4	599517.3	114.2	8274.6
				27.4	5742468.4	599517.3	204.8	11080.3
3.1	5.2-dl	KV	2851.1	17.9	8129044.9	1510657.9	22.9	5879.3
				18.2	8129044.9	1510657.9	25.7	6233.1
				15.5	8129044.9	1510657.9	5.7	2937.7
				15.9	8129044.9	1510657.9	8.0	3475.7
				18.1	8129044.9	1510657.9	24.6	6095.5
				16.7	8129044.9	1510657.9	12.7	4382.7
				18.5	8129044.9	1510657.9	29.2	6647.1
3.1	5.2-dl	MDV	2741.4	14.8	7515289.3	1252928.8	2.8	1867.6
				13.0	7515289.3	1252928.8	0.0	-126.2
				13.9	7515289.3	1252928.8	0.6	897.6
				14.6	7515289.3	1252928.8	2.2	1668.6
				13.2	7515289.3	1252928.8	0.0	74.3
				13.7	7515289.3	1252928.8	0.4	681.1
				14.0	7515289.3	1252928.8	0.8	1025.5
				15.0	7515289.3	1252928.8	3.5	2090.0
3.2	4.9-sl	KV	2460.5	20.4	6054274.8	703055.1	53.3	6122.0
				20.3	6054274.8	703055.1	51.7	6026.8
				23.3	6054274.8	703055.1	104.8	8585.0
				22.5	6054274.8	703055.1	89.5	7930.4
				21.6	6054274.8	703055.1	73.1	7168.8
				21.2	6054274.8	703055.1	66.3	6828.8
				21.8	6054274.8	703055.1	75.8	7301.7
				22.6	6054274.8	703055.1	90.7	7987.2
3.2	4.9-sl	MDV	2478.1	23.0	6141148.1	732863.1	98.3	8488.0
				22.9	6141148.1	732863.1	95.7	8372.6
				22.9	6141148.1	732863.1	95.4	8363.5
				24.7	6141148.1	732863.1	135.7	9973.7
				25.4	6141148.1	732863.1	151.4	10534.5
				24.3	6141148.1	732863.1	125.1	9575.8
				23.7	6141148.1	732863.1	112.0	9058.8
				21.9	6141148.1	732863.1	77.1	7519.3
continued								

1) Coatings and coating systems in accordance with Table 4.6.

Table B.26 Regression analysis of extrapolated preload losses $\Delta F_{p, \text{setting}, 50a}$ for powder coating systems after (initial) tightening, test specimens with $\Sigma t/d \approx 5$ (continued)

System No. ¹⁾	$\Sigma t/d$ [-]	Tight. method	Variable		x^2	Squares around mean		Product $(x - \bar{x}) \cdot (y - \bar{y})$
			x	y		$(x - \bar{x})^2$	$(y - \bar{y})^2$	
3.2	5.2-dl	KV	2829.1	14.7	8003557.9	1456839.9	2.5	1900.4
				16.0	8003557.9	1456839.9	8.7	3557.1
				13.1	8003557.9	1456839.9	0.0	57.9
				16.4	8003557.9	1456839.9	11.1	4019.7
				16.7	8003557.9	1456839.9	13.1	4365.1
				14.4	8003557.9	1456839.9	1.8	1621.1
				15.9	8003557.9	1456839.9	8.1	3433.9
3.2	5.2-dl	MDV	2933.2	18.9	8603397.1	1718970.2	33.7	7614.9
				17.0	8603397.1	1718970.2	15.2	5116.0
				16.2	8603397.1	1718970.2	9.9	4130.7
				19.0	8603397.1	1718970.2	35.3	7786.1
				15.1	8603397.1	1718970.2	4.1	2659.0
				15.7	8603397.1	1718970.2	7.0	3474.4
				14.9	8603397.1	1718970.2	3.2	2329.3
				17.7	8603397.1	1718970.2	21.7	6106.1
				n = 193		Total Σ	313057.5	2526.7

¹⁾ Coatings and coating systems in accordance with Table 4.6.

Powder coating systems, $\Sigma t/d \approx 5$, re-tightening

Table B.27 Regression analysis of extrapolated preload losses $\Delta F_{p, \text{setting}, 50a}$ for powder coating systems after re-tightening, test specimens with $\Sigma t/d \approx 5$

System No. ¹⁾	$\Sigma t/d$ [-]	Tight. method	Variable			Squares around mean		Product
			x	y	x^2	$(x - \bar{x})^2$	$(y - \bar{y})^2$	$(x - \bar{x}) \cdot (y - \bar{y})$
2.1	4.9-sl	MDV	309.9	2.6	96033.7	1858842.0	14.2	5144.9
				3.4	96033.7	1858842.0	8.8	4049.8
				3.5	96033.7	1858842.0	8.0	3866.2
				5.7	96033.7	1858842.0	0.5	973.2
				3.6	96033.7	1858842.0	7.8	3795.7
				5.1	96033.7	1858842.0	1.6	1721.5
				3.6	96033.7	1858842.0	7.5	3726.7
				2.5	96033.7	1858842.0	15.0	5274.4
2.1	4.9-sl	MDV	1049.8	5.0	1102024.6	388768.5	1.9	854.6
				4.4	1102024.6	388768.5	4.0	1253.6
				5.8	1102024.6	388768.5	0.4	374.0
				3.9	1102024.6	388768.5	6.2	1555.8
				2.0	1102024.6	388768.5	19.2	2730.0
				3.5	1102024.6	388768.5	8.1	1776.7
				4.9	1102024.6	388768.5	2.0	889.8
				3.1	1102024.6	388768.5	10.8	2047.8
continued								

¹⁾ Coatings and coating systems in accordance with Table 4.6.

Table B.28 Regression analysis of extrapolated preload losses $\Delta F_{p, \text{setting}, 50a}$ for powder coating systems after re-tightening, test specimens with $\Sigma t/d \approx 5$ (continued)

System No. ¹⁾	$\Sigma t/d$ [-]	Tight method	Variable x y	x^2	Squares around mean $(x - \bar{x})^2$	$(y - \bar{y})^2$	Product $(x - \bar{x}) \cdot (y - \bar{y})$	
2.1	5.2-dl	MDV	457.6	4.6	209435.4	1477794.2	3.3	2197.3
				3.8	209435.4	1477794.2	6.6	3125.8
				9.1	209435.4	1477794.2	7.4	-3311.4
				7.9	209435.4	1477794.2	2.3	-1850.9
				3.3	209435.4	1477794.2	9.7	3790.6
				4.1	209435.4	1477794.2	5.3	2801.1
2.1	5.2-dl	MDV	1343.0	4.2	1803572.7	109108.0	4.6	705.8
				5.0	1803572.7	109108.0	2.0	461.5
				2.8	1803572.7	109108.0	12.5	1166.6
				3.1	1803572.7	109108.0	10.9	1088.5
				4.7	1803572.7	109108.0	2.9	559.5
				3.5	1803572.7	109108.0	8.4	959.6
				3.5	1803572.7	109108.0	8.6	966.3
				3.0	1803572.7	109108.0	11.5	1120.7
2.2	4.9-sl	MDV	797.2	2.4	635453.2	767609.9	16.1	3513.7
				4.4	635453.2	767609.9	3.9	1728.7
				4.1	635453.2	767609.9	5.0	1960.9
				3.9	635453.2	767609.9	6.0	2137.2
				5.8	635453.2	767609.9	0.3	479.8
				3.7	635453.2	767609.9	7.3	2360.4
				5.0	635453.2	767609.9	1.9	1208.6
				4.9	635453.2	767609.9	2.2	1285.2
2.2	4.9-sl	MDV	1604.1	5.3	2573141.9	4786.6	1.2	77.3
				4.3	2573141.9	4786.6	4.4	145.3
				8.1	2573141.9	4786.6	2.8	-116.0
				5.9	2573141.9	4786.6	0.2	34.5
				7.5	2573141.9	4786.6	1.4	-81.2
				8.9	2573141.9	4786.6	6.6	-177.3
				5.5	2573141.9	4786.6	0.7	58.7
2.2	5.2-dl	MDV	1663.2	6.8	2766278.1	101.5	0.2	-4.4
				7.3	2766278.1	101.5	0.9	-9.3
				7.2	2766278.1	101.5	0.7	-8.6
				8.1	2766278.1	101.5	3.0	-17.5
				6.8	2766278.1	101.5	0.2	-4.7
				6.3	2766278.1	101.5	0.0	0.5
				7.2	2766278.1	101.5	0.7	-8.3
				4.1	2766278.1	101.5	5.4	23.4
				6.8	2766278.1	101.5	0.2	-4.5
				7.2	2766278.1	101.5	0.7	-8.6
				8.9	2766278.1	101.5	6.4	-25.5
				8.2	2766278.1	101.5	3.2	-18.0
				6.4	2766278.1	101.5	0.0	-0.7
				5.7	2766278.1	101.5	0.4	6.7
				7.3	2766278.1	101.5	0.8	-9.1
				6.6	2766278.1	101.5	0.0	-2.1
continued								

1) Coatings and coating systems in accordance with Table 4.6.

Table B.29 Regression analysis of extrapolated preload losses $\Delta F_{p, \text{setting}, 50a}$ for powder coating systems after re-tightening, test specimens with $\Sigma t/d \approx 5$ (continued)

System No. ¹⁾	$\Sigma t/d$ [-]	Tight. method	Variable		Squares around mean		Product	
			x	y	x^2	$(x - \bar{x})^2$	$(y - \bar{y})^2$	$(x - \bar{x}) \cdot (y - \bar{y})$
2.2	5.2-dl	MDV	2050.3	9.1	4203715.3	142136.3	7.2	1014.6
				7.0	4203715.3	142136.3	0.4	239.8
				6.4	4203715.3	142136.3	0.0	13.1
				6.3	4203715.3	142136.3	0.0	-40.5
				5.9	4203715.3	142136.3	0.3	-193.7
				8.9	4203715.3	142136.3	6.2	936.7
				7.1	4203715.3	142136.3	0.6	288.3
3.1	4.9-sl	MDV	2396.3	8.1	5742468.4	522813.1	2.9	1237.6
				10.3	5742468.4	522813.1	15.2	2818.7
				11.0	5742468.4	522813.1	21.6	3356.8
				9.2	5742468.4	522813.1	8.2	2074.8
				10.7	5742468.4	522813.1	18.4	3100.7
				8.4	5742468.4	522813.1	4.0	1452.8
				8.4	5742468.4	522813.1	4.2	1483.6
3.1	5.2-dl	MDV	2741.4	9.3	5742468.4	522813.1	8.8	2142.9
				7.6	7515289.3	1140872.1	1.6	1330.0
				5.7	7515289.3	1140872.1	0.5	-734.5
				4.6	7515289.3	1140872.1	3.0	-1853.0
				5.8	7515289.3	1140872.1	0.4	-665.1
				6.4	7515289.3	1140872.1	0.0	-15.8
				6.9	7515289.3	1140872.1	0.3	601.7
3.1	4.9-sl	MDV	2478.1	7.0	7515289.3	1140872.1	0.4	672.4
				7.3	7515289.3	1140872.1	0.8	973.6
				11.3	6141148.1	647779.2	23.9	3933.3
				9.8	6141148.1	647779.2	11.9	2779.9
				9.5	6141148.1	647779.2	9.8	2525.8
				11.0	6141148.1	647779.2	21.3	3716.1
				13.2	6141148.1	647779.2	46.5	5487.8
3.2	5.2-dl	MDV	2933.2	10.1	6141148.1	647779.2	13.9	2995.7
				10.5	6141148.1	647779.2	16.9	3307.1
				12.3	6141148.1	647779.2	34.8	4747.5
				8.7	8603397.1	1587267.7	5.3	2905.3
				6.7	8603397.1	1587267.7	0.1	379.4
				6.0	8603397.1	1587267.7	0.2	-504.4
				7.6	8603397.1	1587267.7	1.5	1557.2
3.2	5.2-dl	MDV	2933.2	5.9	8603397.1	1587267.7	0.3	-637.0
				7.8	8603397.1	1587267.7	2.0	1765.1
				7.6	8603397.1	1587267.7	1.4	1513.7
				6.6	8603397.1	1587267.7	0.0	246.0
n = 100		Total Σ	167328.7	637.5	346070161.1	66081333.0	589.5	125294.6

¹⁾ Coatings and coating systems in accordance with Table 4.6.

Powder coating systems, overall evaluation

Table B.30 Overall regression analysis for powder coating systems

Coating system $\Sigma t/d$ Phase	Powder ≈ 2.4 tight.	Powder ≈ 2.4 re-tight.	Powder ≈ 5 tight.	Powder ≈ 5 re-tight.
a	7.959	3.793	5.536	3.203
b	0.0049	0.0031	0.0047	0.0019
SSR	1700.0	298.8	2852.3	237.6
SSE	2035.6	953.8	2246.0	351.9
MSE	10.44	9.833	11.76	3.591
R²	0.455	0.239	0.559	0.403
SE_a	0.576	0.837	0.544	0.434
SE_b	0.000	0.001	0.000	0.000
t_a	13.82	4.534	10.17	7.386
t_b	12.76	5.512	15.57	8.134
p_a	$9.626 \cdot 10^{-31}$	$1.657 \cdot 10^{-5}$	$1.087 \cdot 10^{-19}$	$5.061 \cdot 10^{-11}$
p_b	$1.648 \cdot 10^{-27}$	$2.925 \cdot 10^{-7}$	$7.678 \cdot 10^{-36}$	$1.312 \cdot 10^{-12}$
t_{$\alpha/2$}	1.653	1.661	1.653	1.661
a_{0.95}	8.910	5.183	6.435	3.923
b_{0.95}	0.0056	0.0040	0.0052	0.0023

Annex C - Determination of the remaining bolt preloads considering the mean initial preload level $F_{p,ini,mean}$ and mean preload losses $\Delta F_{p,setting,50a,mean,reg}$

Formulas

Determination of the remaining bolt preload (here: $F_{p,50a,mean}$):

$$F_{p,50a,mean} = F_{p,ini,mean} - \frac{F_{p,ini,mean} \cdot \Delta F_{p,setting,50a,mean,reg}}{100} \quad (C.1)$$

Determination of the reserve/deficit regarding the nominal preload level:

$$\Upsilon = \left(\frac{F_{p,50a,mean}}{F_{p,C}^* \text{ or } F_{p,C}} - 1 \right) \cdot 100 \text{ [\%]} \quad (C.2)$$

2K-PUR coating | EP-/PUR coating systems, (initial) tightening by the modified torque method

Table C.1 Estimation of remaining preload levels for the 2K-PUR coating and EP-/PUR coating systems after (initial) tightening by the modified torque method based on the average initial preload level $F_{p,ini,mean,MDV,in.tight.}$ and preload losses $\Delta F_{p,setting,50a,mean,reg}$

Coating system	Coating thickness	Coating thickness DFT _{spec} [µm] ¹⁾	No. of coated surfaces	Initial preload ²⁾ for $\Sigma t/d$ $\approx 2.4 \mid \approx 5$ [kN]	Loss of preload ³⁾ for $\Sigma t/d$ $\approx 2.4 \mid \approx 5$ [%]	Remaining preload ⁴⁾ for $\Sigma t/d$ $\approx 2.4 \mid \approx 5$ [kN]	Reserve/ deficit regarding $F_{p,C}^*$ [%]	Selected preload level $\Sigma F_{p,C}^*$ [-]
1. Typical conventional paints and paint systems on grit blasted steel substrates								
2K-PUR	NDFT 1.2 NDFT	640 768	4	105.8	23.1 24.1 25.6 22.5	81.3 80.2 78.7 81.9	-18.7 -19.8 -21.3 -18.1	0.80
2K-PUR	NDFT 1.2 NDFT	960 1152	6	105.8	29.3 25.7 33.1 29.0	74.7 78.5 70.8 75.1	-25.3 -21.5 -29.2 -24.9	0.70
2K-EP 2K-PUR	NDFT 1.2 NDFT	640 768	4	105.8	18.9 15.6 19.8 16.1	85.8 89.3 84.8 88.7	-14.2 -10.7 -15.2 -11.3	0.85
2K-EP 2K-PUR	NDFT 1.2 NDFT	960 1152	6	105.8	21.1 17.0 22.5 17.8	83.4 87.8 82.0 87.0	-16.6 -12.2 -18.0 -13.0	0.80
2K-EP-Zn 2K-EP-EG 2K-PUR	NDFT 1.2 NDFT	960 1152	4	105.8	21.1 17.0 22.5 17.8	83.4 87.8 82.0 87.0	-16.6 -12.2 -18.0 -13.0	0.80
2K-EP-Zn 2K-EP-EG 2K-PUR	NDFT 1.2 NDFT	1440 1728	6	105.8	24.4 19.0 26.4 20.3	79.9 85.6 77.8 84.3	-20.1 -14.4 -22.2 -15.7	0.75
2K-EP-Zn 2K-EP-EG 2K-EP-EG 2K-PUR	NDFT 1.2 NDFT	1280 1536	4	105.8	23.3 18.3 25.1 19.5	81.1 86.4 79.2 85.2	-18.9 -13.6 -20.8 -14.8	0.80
2K-EP-Zn 2K-EP-EG 2K-EP-EG 2K-PUR	NDFT 1.2 NDFT	1920 2304	6	105.8	27.8 21.1 30.4 22.8	76.4 83.4 73.6 81.7	-23.6 -16.6 -26.4 -18.3	0.75

1) DFT_{spec}: assumed average coating thickness per connection
2) Initial preload level $F_{p,ini,mean,MDV,in.tight.}$
3) Loss of preload $\Delta F_{p,setting,50a,mean,reg}$
4) Remaining preload value based on $F_{p,ini,mean,MDV,in.tight.}$ and $\Delta F_{p,setting,50a,mean,reg}$

Abbreviations:

2K: two-pack | EP: epoxy based paint | EP-Zn: epoxy based zinc rich paint | EG: micaceous iron oxide
SP: polyester resin | PUR: polyurethane paint

2K-PUR coating | EP-/PUR coating systems, re-tightening by the modified torque method

Table C.2 Estimation of remaining preload levels for the 2K-PUR coating and EP-/PUR coating systems after re-tightening by the modified torque method based on the average initial preload level $F_{p,ini,mean,MDV,re-tight.}$ and preload losses $\Delta F_{p,setting,50a,mean,reg}$

Coating system	Coating thickness	Coating thickness DFT _{spec} [µm] ¹⁾	No. of coated surfaces	Initial preload ²⁾ for $\Sigma t/d \approx 2.4 \approx 5$ [kN]	Loss of preload ³⁾ for $\Sigma t/d \approx 2.4 \approx 5$ [%]	Remaining preload ⁴⁾ for $\Sigma t/d \approx 2.4 \approx 5$ [kN]	Reserve/ deficit regarding $F_{p,C}^*$ [%]	Selected preload level $X F_{p,C}^*$ [-]
1. Typical conventional paints and paint systems on grit blasted steel substrates								
2K-PUR	NDFT	640	4	103.4	11.7 10.4 13.3 10.8	91.3 92.7 89.7 92.2	-8.7 -7.3 -10.3 -7.8	0.90
	1.2 NDFT	768						
2K-PUR	NDFT	960	6	103.4	15.7 11.5 18.0 12.1	87.2 91.6 84.8 90.9	-12.8 -8.4 -15.2 -9.1	0.85
	1.2 NDFT	1152						
2K-EP	NDFT	640	4	103.4	10.1 7.4 10.7 8.0	92.9 95.8 92.3 95.2	-7.1 -4.2 -7.7 -4.8	0.90
2K-PUR	1.2 NDFT	768						
2K-EP	NDFT	960	6	103.4	11.7 9.0 12.6 9.9	91.4 94.2 90.4 93.2	-8.6 -5.8 -9.6 -6.8	0.90
2K-PUR	1.2 NDFT	1152						
2K-EP-Zn	NDFT	960	4	103.4	11.7 9.0 12.6 9.9	91.4 94.2 90.4 93.2	-8.6 -5.8 -9.6 -6.8	0.90
2K-EP-EG	1.2 NDFT	1152						
2K-PUR								
2K-EP-Zn	NDFT	1440	6	103.4	13.9 11.3 15.3 12.8	89.0 91.7 87.6 90.2	-11.0 -8.3 -12.4 -9.8	0.85
2K-EP-EG	1.2 NDFT	1728						
2K-PUR								
2K-EP-Zn	NDFT	1280	4	103.4	13.2 10.5 14.4 11.8	89.8 92.5 88.5 91.2	-10.2 -7.5 -11.5 -8.8	0.90
2K-EP-EG	1.2 NDFT	1536						
2K-PUR								
2K-EP-Zn	NDFT	1920	6	103.4	16.2 13.7 18.1 15.6	86.6 89.2 84.8 87.3	-13.4 -10.8 -15.2 -12.7	0.85
2K-EP-EG	1.2 NDFT	2304						
2K-PUR								

1) DFT_{spec}: assumed average coating thickness per connection
2) Initial preload level $F_{p,ini,mean,MDV,re-tight.}$
3) Loss of preload $\Delta F_{p,setting,50a,mean,reg}$
4) Remaining preload value based on $F_{p,ini,mean,MDV,re-tight.}$ and $\Delta F_{p,setting,50a,mean,reg}$

Abbreviations:
2K: two-pack | EP: epoxy based paint | EP-Zn: epoxy based zinc rich paint | EG: micaceous iron oxide
SP: polyester resin | PUR: polyurethane paint

2K-PUR coating | EP-/PUR coating systems, tightening by the combined method

Table C.3 Estimation of remaining preload levels for the 2K-PUR coating and EP-/PUR coating systems after tightening by the combined method based on the average initial preload level $F_{p,ini,mean,KV,tight.}$ and preload losses $\Delta F_{p,setting,50a,mean,reg}$

Coating system	Coating thickness	Coating thickness DFT _{spec} [μm] ¹⁾	No. of coated surfaces	Initial preload ²⁾ for $\Sigma t/d$ ≈ 2.4 ≈ 5 [kN]	Loss of preload ³⁾ for $\Sigma t/d$ ≈ 2.4 ≈ 5 [%]	Remaining preload ⁴⁾ for $\Sigma t/d$ ≈ 2.4 ≈ 5 [kN]	Reserve/ deficit regarding $F_{p,C}$ [%]	Selected preload level $X F_{p,C}$ [-]
1. Typical conventional paints and paint systems on grit blasted steel substrates								
2K-PUR	NDFT 1.2 NDFT	640 768	4	152.2 144.7	23.1 24.1 25.6 22.5	117.0 109.8 113.2 112.1	6.4 0.2 2.9 1.9	1.0
2K-PUR	NDFT 1.2 NDFT	960 1152	6	152.2 144.7	29.3 25.7 33.1 29.0	107.6 107.4 101.9 102.8	-2.2 -2.3 -7.4 -6.6	0.90
2K-EP 2K-PUR	NDFT 1.2 NDFT	640 768	4	152.2 144.7	18.9 15.6 19.8 16.1	123.5 122.2 122.1 121.4	12.2 11.1 11.0 10.3	1.0
2K-EP 2K-PUR	NDFT 1.2 NDFT	960 1152	6	152.2 144.7	21.1 17.0 22.5 17.8	120.1 120.2 118.1 119.0	9.2 9.2 7.3 8.1	1.0
2K-EP-Zn 2K-EP-EG 2K-PUR	NDFT 1.2 NDFT	960 1152	4	152.2 144.7	21.1 17.0 22.5 17.8	120.1 120.2 118.1 119.0	9.2 9.2 7.3 8.1	1.0
2K-EP-Zn 2K-EP-EG 2K-PUR	NDFT 1.2 NDFT	1440 1728	6	152.2 144.7	24.4 19.0 26.4 20.3	115.0 117.1 112.0 115.3	4.6 6.5 1.8 4.9	1.0
2K-EP-Zn 2K-EP-EG 2K-EP-EG 2K-PUR	NDFT 1.2 NDFT	1280 1536	4	152.2 144.7	23.3 18.3 25.1 19.5	116.7 118.2 114.0 116.5	6.1 7.4 3.6 6.0	1.0
2K-EP-Zn 2K-EP-EG 2K-EP-EG 2K-PUR	NDFT 1.2 NDFT	1920 2304	6	152.2 144.7	27.8 21.1 30.4 22.8	109.9 114.1 105.9 111.7	-0.1 3.8 -3.7 1.6	0.95

1) DFT_{spec}: assumed average coating thickness per connection

2) Initial preload level $F_{p,ini,mean,KV,tight.}$

3) Loss of preload $\Delta F_{p,setting,50a,mean,reg}$

4) Remaining preload value based on $F_{p,ini,mean,KV,tight.}$ and $\Delta F_{p,setting,50a,mean,reg}$

Abbreviations:

2K: two-pack | EP: epoxy based paint | EP-Zn: epoxy based zinc rich paint | EG: micaceous iron oxide

SP: polyester resin | PUR: polyurethane paint

Powder coating systems, (initial) tightening by the modified torque method

Table C.4 Estimation of remaining preload levels for powder coating systems after (initial) tightening by the modified torque method based on the average initial preload level $F_{p,ini,mean,MDV,in.tight.}$ and preload losses $\Delta F_{p,setting,50a,mean,reg}$

Coating system	Coating thickness	Coating thickness	No. of coated surfaces	Initial preload ²⁾	Loss of preload ³⁾	Remaining preload ⁴⁾	Reserve/ deficit regarding	Selected preload level
		DFT _{spec} ¹⁾ [μm]		for Σt/d	for Σt/d	for Σt/d	F _{p,C} * [%]	X F _{p,C} * [-]
2. Typical powder coating systems on grit blasted steel substrates								
EP/SP	NDFT	320	4	105.8	9.5 7.0	95.7 98.3	-4.3 -1.7	0.95
	1.2 NDFT	384			9.9 7.3	95.3 98.0	-4.7 -2.0	
EP/SP	NDFT	480	6	105.8	10.3 7.8	94.8 97.5	-5.2 -2.5	0.95
	1.2 NDFT	576			10.8 8.2	94.3 97.1	-5.7 -2.9	
EP SP	NDFT	720	4	105.8	11.5 8.9	93.6 96.4	-6.4 -3.6	0.90
	1.2 NDFT	864			12.2 9.6	92.8 95.7	-7.2 -4.3	
EP SP	NDFT	960	6	105.8	13.3 10.6	91.7 94.6	-8.3 -5.4	0.90
	1.2 NDFT	1152			14.4 11.6	90.6 93.5	-9.4 -6.5	
3. Typical powder coating systems on hot dip galvanized surfaces (duplex-systems)								
EP/SP	NDFT	1120	4	105.8	13.5 10.8	91.5 94.4	-8.5 -5.6	0.90
	1.2 NDFT	1344			14.6 11.8	90.3 93.3	-9.7 -6.7	
EP/SP	NDFT	1680	6	105.8	16.3 13.4	88.6 91.6	-11.4 -8.4	0.85
	1.2 NDFT	2016			17.9 14.9	86.8 90.0	-13.2 -10.0	
EP SP	NDFT	1520	4	105.8	15.5 12.6	89.4 92.4	-10.6 -7.6	0.85
	1.2 NDFT	1824			17.0 14.0	87.8 90.9	-12.2 -9.1	
EP SP	NDFT	2280	6	105.8	19.2 16.2	85.4 88.7	-14.6 -11.3	0.80
	1.2 NDFT	2736			21.5 18.3	83.0 86.4	-17.0 -13.6	

1) DFT_{spec}: assumed average coating thickness per connection

2) Initial preload level $F_{p,ini,mean,MDV,in.tight.}$

3) Loss of preload $\Delta F_{p,setting,50a,mean,reg}$

4) Remaining preload value based on $F_{p,ini,mean,MDV,in.tight.}$ and $\Delta F_{p,setting,50a,mean,reg}$

Abbreviations:

2K: two-pack | EP: epoxy based paint | EP-Zn: epoxy based zinc rich paint | EG: micaceous iron oxide

SP: polyester resin | PUR: polyurethane paint

Powder coating systems, re-tightening by the modified torque method

Table C.5 Estimation of remaining preload levels for powder coating systems after re-tightening by the modified torque method based on the average initial preload level $F_{p,ini,mean,MDV,re-tight.}$ and preload losses $\Delta F_{p,setting,50a,mean,reg}$

Coating system	Coating thickness	Coating thickness	No. of coated surfaces	Initial preload ²⁾	Loss of preload ³⁾	Remaining preload ⁴⁾	Reserve/ deficit regarding	Selected preload level
		DFT _{spec} [μm] ¹⁾		for Σt/d ≈ 2.4 ≈ 5 [kN]	for Σt/d ≈ 2.4 ≈ 5 [%]	for Σt/d ≈ 2.4 ≈ 5 [kN]	F _{p,C} * [%]	X F _{p,C} * [-]
2. Typical powder coating systems on grit blasted steel substrates								
EP/SP	NDFT	320	4	103.4	4.8 3.8 5.0 3.9	98.5 99.5 98.3 99.4	-1.5 -0.5 -1.7 -0.6	0.95
	1.2 NDFT	384						
EP/SP	NDFT	480	6	103.4	5.3 4.1 5.6 4.3	98.0 99.2 97.7 99.0	-2.0 -0.8 -2.3 -1.0	0.95
	1.2 NDFT	576						
EP SP	NDFT	720	4	103.4	6.0 4.6 6.5 4.8	97.2 98.7 96.7 98.4	-2.8 -1.3 -3.3 -1.6	0.95
	1.2 NDFT	864						
EP SP	NDFT	960	6	103.4	7.1 5.3 7.8 5.7	96.1 98.0 95.4 97.6	-3.9 -2.0 -4.6 -2.4	0.95
	1.2 NDFT	1152						
3. Typical powder coating systems on hot dip galvanized surfaces (duplex-systems)								
EP/SP	NDFT	1120	4	103.4	7.3 5.3 7.9 5.8	95.9 97.9 95.2 97.5	-4.1 -2.1 -4.8 -2.5	0.95
	1.2 NDFT	1344						
EP/SP	NDFT	1680	6	103.4	9.0 6.4 10.0 7.0	94.1 96.8 93.1 96.2	-5.9 -3.2 -6.9 -3.8	0.90
	1.2 NDFT	2016						
EP SP	NDFT	1520	4	103.4	8.5 6.1 9.4 6.7	94.7 97.1 93.7 96.5	-5.3 -2.9 -6.3 -3.5	0.95
	1.2 NDFT	1824						
EP SP	NDFT	2280	6	103.4	10.8 7.5 12.2 8.4	92.2 95.6 90.8 94.8	-7.8 -4.4 -9.2 -5.2	0.90
	1.2 NDFT	2736						

1) DFT_{spec} : assumed average coating thickness per connection
2) Initial preload level $F_{p,ini,mean,MDV,re-tight.}$
3) Loss of preload $\Delta F_{p,setting,50a,mean,reg}$
4) Remaining preload value based on $F_{p,ini,mean,MDV,re-tight.}$ and $\Delta F_{p,setting,50a,mean,reg}$

Abbreviations:
2K: two-pack | EP: epoxy based paint | EP-Zn: epoxy based zinc rich paint | EG: micaceous iron oxide
SP: polyester resin | PUR: polyurethane paint

Powder coating systems, tightening by the combined method

Table C.6 Estimation of remaining preload levels for powder coating systems after tightening by the combined method based on the average initial preload level $F_{p,ini,mean,KV,tight.}$ and preload losses $\Delta F_{p,setting,50a,mean,reg}$

Coating system	Coating thickness	Coating thickness	No. of coated surfaces	Initial preload ²⁾	Loss of preload ³⁾	Remaining preload ⁴⁾	Reserve/deficit regarding	Selected preload level
		DFT _{spec} [μm] ¹⁾		for Σt/d ≈ 2.4 ≈ 5 [kN]	for Σt/d ≈ 2.4 ≈ 5 [%]	for Σt/d ≈ 2.4 ≈ 5 [kN]	F _{P,C} [%]	X F _{P,C} [-]
2. Typical powder coating systems on grit blasted steel substrates								
EP/SP	NDFT	320	4	152.2 144.7	9.5 7.0	137.7 134.5	25.2 22.3	1.0
	1.2 NDFT	384			9.9 7.3	137.2 134.1	24.7 21.9	
EP/SP	NDFT	480	6	152.2 144.7	10.3 7.8	136.5 133.4	24.1 21.3	1.0
	1.2 NDFT	576			10.8 8.2	135.8 132.8	23.4 20.7	
EP SP	NDFT	720	4	152.2 144.7	11.5 8.9	134.7 131.8	22.4 19.8	1.0
	1.2 NDFT	864			12.2 9.6	133.6 130.9	21.5 19.0	
EP SP	NDFT	960	6	152.2 144.7	13.3 10.6	132.0 129.4	20.0 17.6	1.0
	1.2 NDFT	1152			14.4 11.6	130.4 127.9	18.5 16.3	
3. Typical powder coating systems on hot dip galvanized surfaces (duplex-systems)								
EP/SP	NDFT	1120	4	152.2 144.7	13.5 10.8	131.7 129.1	19.7 17.4	1.0
	1.2 NDFT	1344			14.6 11.8	130.0 127.6	18.2 16.0	
EP/SP	NDFT	1680	6	152.2 144.7	16.3 13.4	127.5 125.4	15.9 14.0	1.0
	1.2 NDFT	2016			17.9 14.9	124.9 123.1	13.6 11.9	
EP SP	NDFT	1520	4	152.2 144.7	15.5 12.6	128.7 126.4	17.0 14.9	1.0
	1.2 NDFT	1824			17.0 14.0	126.4 124.4	14.9 13.1	
EP SP	NDFT	2280	6	152.2 144.7	19.2 16.2	122.9 121.3	11.8 10.3	1.0
	1.2 NDFT	2736			21.5 18.3	119.5 118.2	8.6 7.5	

1) DFT_{spec} : assumed average coating thickness per connection

2) Initial preload level $F_{p,ini,mean,KV,tight.}$

3) Loss of preload $\Delta F_{p,setting,50a,mean,reg}$

4) Remaining preload value based on $F_{p,ini,mean,KV,tight.}$ and $\Delta F_{p,setting,50a,mean,reg}$

Abbreviations:

2K: two-pack | EP: epoxy based paint | EP-Zn: epoxy based zinc rich paint | EG: micaceous iron oxide

SP: polyester resin | PUR: polyurethane paint

Annex D - Determination of the remaining bolt preloads considering fractile values of the initial preload level $F_{p,ini,0.05}$ and mean preload losses $\Delta F_{p,setting,50a,mean,reg}$

Formulas

Determination of the remaining bolt preload (here: $F_{p,50a,0.05}$):

$$F_{p,50a,0.05} = F_{p,ini,0.05} - \frac{F_{p,ini,0.05} \cdot \Delta F_{p,setting,50a,mean,reg}}{100} \quad (D.1)$$

Determination of the reserve/deficit regarding the nominal preload level:

$$\Upsilon = \left(\frac{F_{p,50a,0.05}}{F_{p,C}^* \text{ or } F_{p,C}} - 1 \right) \cdot 100 \text{ [\%]} \quad (D.2)$$

2K-PUR coating | EP-/PUR coating systems, (initial) tightening by the modified torque method

Table D.1 Estimation of remaining preload levels for the 2K-PUR coating and EP-/PUR coating systems after (initial) tightening by the modified torque method based on the fractile value of the initial preload $F_{p,ini,0.05,MDV,in.tight.}$ and preload losses $\Delta F_{p,setting,50a,mean,reg}$

Coating system	Coating thickness	Coating thickness DFT _{spec} [µm] ¹⁾	No. of coated surfaces	Initial preload ²⁾ for Σt/d ≈ 2.4 ≈ 5 [kN]	Loss of preload ³⁾ for Σt/d ≈ 2.4 ≈ 5 [%]	Remaining preload ⁴⁾ for Σt/d ≈ 2.4 ≈ 5 [kN]	Reserve/ deficit regarding $F_{p,C}^*$ [%]	Selected preload level $\Sigma F_{p,C}^*$ [-]
1. Typical conventional paints and paint systems on grit blasted steel substrates								
2K-PUR	NDFT 1.2 NDFT	640 768	4	90.4	23.1 24.1 25.6 22.5	69.5 68.6 67.3 70.1	-30.5 -31.4 -32.7 -29.9	0.65
2K-PUR	NDFT 1.2 NDFT	960 1152	6	90.4	29.3 25.7 33.1 29.0	63.9 67.1 60.5 64.2	-36.1 -32.9 -39.5 -35.8	0.60
2K-EP 2K-PUR	NDFT 1.2 NDFT	640 768	4	90.4	18.9 15.6 19.8 16.1	73.3 76.3 72.5 75.8	-26.7 -23.7 -27.5 -24.2	0.70
2K-EP 2K-PUR	NDFT 1.2 NDFT	960 1152	6	90.4	21.1 17.0 22.5 17.8	71.3 75.1 70.1 74.3	-28.7 -24.9 -29.9 -25.7	0.70
2K-EP-Zn 2K-EP-EG 2K-PUR	NDFT 1.2 NDFT	960 1152	4	90.4	21.1 17.0 22.5 17.8	71.3 75.1 70.1 74.3	-28.7 -24.9 -29.9 -25.7	0.70
2K-EP-Zn 2K-EP-EG 2K-PUR	NDFT 1.2 NDFT	1440 1728	6	90.4	24.4 19.0 26.4 20.3	68.3 73.2 66.5 72.1	-31.7 -26.8 -33.5 -27.9	0.65
2K-EP-Zn 2K-EP-EG 2K-EP-EG 2K-PUR	NDFT 1.2 NDFT	1280 1536	4	90.4	23.3 18.3 25.1 19.5	69.3 73.8 67.7 72.8	-30.7 -26.2 -32.3 -27.2	0.65
2K-EP-Zn 2K-EP-EG 2K-EP-EG 2K-PUR	NDFT 1.2 NDFT	1920 2304	6	90.4	27.8 21.1 30.4 22.8	65.3 71.3 62.9 69.8	-34.7 -28.7 -37.1 -30.2	0.60

1) DFT_{spec}: assumed average coating thickness per connection
2) Fractile value of the initial preload $F_{p,ini,0.05,MDV,in.tight.}$
3) Loss of preload $\Delta F_{p,setting,50a,mean,reg}$
4) Remaining preload value based on $F_{p,ini,0.05,MDV,in.tight.}$ and $\Delta F_{p,setting,50a,mean,reg}$

Abbreviations:
2K: two-pack | EP: epoxy based paint | EP-Zn: epoxy based zinc rich paint | EG: micaceous iron oxide
SP: polyester resin | PUR: polyurethane paint

2K-PUR coating | EP-/PUR coating systems, re-tightening by the modified torque method

Table D.2 Estimation of remaining preload levels for the 2K-PUR coating and EP-/PUR coating systems after re-tightening by the modified torque method based on the fractile value of the initial preload $F_{p,ini,0.05,MDV, re-tight.}$ and preload losses $\Delta F_{p,setting,50a,mean,reg}$

Coating system	Coating thickness	Coating thickness DFT _{spec} [µm] ¹⁾	No. of coated surfaces	Initial preload ²⁾ for $\Sigma t/d \approx 2.4$ ≈ 5 [kN]	Loss of preload ³⁾ for $\Sigma t/d \approx 2.4$ ≈ 5 [%]	Remaining preload ⁴⁾ for $\Sigma t/d \approx 2.4$ ≈ 5 [kN]	Reserve/ deficit regarding $F_{p,C}^*$ [%]	Selected preload level $X F_{p,C}^*$ [-]
1. Typical conventional paints and paint systems on grit blasted steel substrates								
2K-PUR	NDFT 1.2 NDFT	640 768	4	87.4	11.7 10.4 13.3 10.8	77.2 78.3 75.8 78.0	-22.8 -21.7 -24.2 -22.0	0.75
2K-PUR	NDFT 1.2 NDFT	960 1152	6	87.4	15.7 11.5 18.0 12.1	73.7 77.4 71.7 76.9	-26.3 -22.6 -28.3 -23.1	0.70
2K-EP 2K-PUR	NDFT 1.2 NDFT	640 768	4	87.4	10.1 7.4 10.7 8.0	78.6 81.0 78.0 80.4	-21.4 -19.0 -22.0 -19.6	0.75
2K-EP 2K-PUR	NDFT 1.2 NDFT	960 1152	6	87.4	11.7 9.0 12.6 9.9	77.2 79.6 76.4 78.8	-22.8 -20.4 -23.6 -21.2	0.75
2K-EP-Zn 2K-EP-EG 2K-PUR	NDFT 1.2 NDFT	960 1152	4	87.4	11.7 9.0 12.6 9.9	77.2 79.6 76.4 78.8	-22.8 -20.4 -23.6 -21.2	0.75
2K-EP-Zn 2K-EP-EG 2K-PUR	NDFT 1.2 NDFT	1440 1728	6	87.4	13.9 11.3 15.3 12.8	75.2 77.5 74.0 76.3	-24.8 -22.5 -26.0 -23.7	0.75
2K-EP-Zn 2K-EP-EG 2K-PUR	NDFT 1.2 NDFT	1280 1536	4	87.4	13.2 10.5 14.4 11.8	75.9 78.2 74.8 77.1	-24.1 -21.8 -25.2 -22.9	0.75
2K-EP-Zn 2K-EP-EG 2K-PUR	NDFT 1.2 NDFT	1920 2304	6	87.4	16.2 13.7 18.1 15.6	73.2 75.4 71.6 73.7	-26.8 -24.6 -28.4 -26.3	0.70

1) DFT_{spec}: assumed average coating thickness per connection

2) Fractile value of the initial preload $F_{p,ini,0.05,MDV, re-tight.}$

3) Loss of preload $\Delta F_{p,setting,50a,mean,reg}$

4) Remaining preload value based on $F_{p,ini,0.05,MDV, re-tight.}$ and $\Delta F_{p,setting,50a,mean,reg}$

Abbreviations:

2K: two-pack | EP: epoxy based paint | EP-Zn: epoxy based zinc rich paint | EG: micaceous iron oxide

SP: polyester resin | PUR: polyurethane paint

2K-PUR coating | EP-/PUR coating systems, tightening by the combined method

Table D.3 Estimation of remaining preload levels for the 2K-PUR coating and EP-/PUR coating systems after tightening by the combined method based on the fractile value of the initial preload $F_{p,ini,0.05,KV,tight.}$ and preload losses $\Delta F_{p,setting,50a,mean,reg}$

Coating system	Coating thickness	Coating thickness DFT _{spec} [µm] ¹⁾	No. of coated surfaces	Initial preload ²⁾ for $\Sigma t/d$ ≈ 2.4 ≈ 5 [kN]	Loss of preload ³⁾ for $\Sigma t/d$ ≈ 2.4 ≈ 5 [%]	Remaining preload ⁴⁾ for $\Sigma t/d$ ≈ 2.4 ≈ 5 [kN]	Reserve/ deficit regarding $F_{p,C}$ [%]	Selected preload level $X F_{p,C}$ [-]
1. Typical conventional paints and paint systems on grit blasted steel substrates								
2K-PUR	NDFT 1.2 NDFT	640 768	4	145.3 137.6	23.1 24.1 25.6 22.5	111.7 104.4 108.1 106.6	1.5 -5.1 -1.7 -3.1	0.95
2K-PUR	NDFT 1.2 NDFT	960 1152	6	145.3 137.6	29.3 25.7 33.1 29.0	102.7 102.2 97.3 97.7	-6.7 -7.1 -11.6 -11.2	0.90
2K-EP 2K-PUR	NDFT 1.2 NDFT	640 768	4	145.3 137.6	18.9 15.6 19.8 16.1	117.9 116.2 116.6 115.4	7.1 5.6 6.0 4.9	1.0
2K-EP 2K-PUR	NDFT 1.2 NDFT	960 1152	6	145.3 137.6	21.1 17.0 22.5 17.8	114.6 114.2 112.7 113.1	4.2 3.9 2.4 2.8	1.0
2K-EP-Zn 2K-EP-EG 2K-PUR	NDFT 1.2 NDFT	960 1152	4	145.3 137.6	21.1 17.0 22.5 17.8	114.6 114.2 112.7 113.1	4.2 3.9 2.4 2.8	1.0
2K-EP-Zn 2K-EP-EG 2K-PUR	NDFT 1.2 NDFT	1440 1728	6	145.3 137.6	24.4 19.0 26.4 20.3	109.8 111.4 106.9 109.7	-0.2 1.3 -2.8 -0.3	0.95
2K-EP-Zn 2K-EP-EG 2K-EP-EG 2K-PUR	NDFT 1.2 NDFT	1280 1536	4	145.3 137.6	23.3 18.3 25.1 19.5	111.4 112.3 108.8 110.8	1.3 2.1 -1.1 0.7	1.0
2K-EP-Zn 2K-EP-EG 2K-EP-EG 2K-PUR	NDFT 1.2 NDFT	1920 2304	6	145.3 137.6	27.8 21.1 30.4 22.8	104.9 108.5 101.1 106.2	-4.6 -1.4 -8.1 -3.4	0.90

1) DFT_{spec}: assumed average coating thickness per connection
2) Fractile value of the initial preload $F_{p,ini,0.05,KV,tight.}$
3) Loss of preload $\Delta F_{p,setting,50a,mean,reg}$
4) Remaining preload value based on $F_{p,ini,0.05,KV,tight.}$ and $\Delta F_{p,setting,50a,mean,reg}$

Abbreviations:

2K: two-pack | EP: epoxy based paint | EP-Zn: epoxy based zinc rich paint | EG: micaceous iron oxide
SP: polyester resin | PUR: polyurethane paint

Powder coating systems, (initial) tightening by the modified torque method

Table D.4 Estimation of remaining preload levels for powder coating systems after (initial) tightening by the modified torque method based on the fractile value of the initial preload $F_{p,ini,0.05,MDV,in.tight.}$ and preload losses $\Delta F_{p,setting,50a,mean,reg}$

Coating system	Coating thickness	Coating thickness	No. of coated surfaces	Initial preload ²⁾	Loss of preload ³⁾	Remaining preload ⁴⁾	Reserve/ deficit	Selected
		DFT _{spec} [µm] ¹⁾		for Σt/d ≈ 2.4 ≈ 5 [kN]	for Σt/d ≈ 2.4 ≈ 5 [%]	for Σt/d ≈ 2.4 ≈ 5 [kN]	regarding F _{p,C} * [%]	preload level X F _{p,C} * [-]
2. Typical powder coating systems on grit blasted steel substrates								
EP/SP	NDFT	320	4	90.4	9.5 7.0	81.8 84.1	-18.2 -15.9	0.80
	1.2 NDFT	384			9.9 7.3	81.5 83.8	-18.5 -16.2	
EP/SP	NDFT	480	6	90.4	10.3 7.8	81.1 83.4	-18.9 -16.6	0.80
	1.2 NDFT	576			10.8 8.2	80.6 83.0	-19.4 -17.0	
EP SP	NDFT	720	4	90.4	11.5 8.9	80.0 82.4	-20.0 -17.6	0.80
	1.2 NDFT	864			12.2 9.6	79.4 81.8	-20.6 -18.2	
EP SP	NDFT	960	6	90.4	13.3 10.6	78.4 80.9	-21.6 -19.1	0.75
	1.2 NDFT	1152			14.4 11.6	77.4 80.0	-22.6 -20.0	
3. Typical powder coating systems on hot dip galvanized surfaces (duplex-systems)								
EP/SP	NDFT	1120	4	90.4	13.5 10.8	78.2 80.7	-21.8 -19.3	0.75
	1.2 NDFT	1344			14.6 11.8	77.2 79.8	-22.8 -20.2	
EP/SP	NDFT	1680	6	90.4	16.3 13.4	75.7 78.3	-24.3 -21.7	0.75
	1.2 NDFT	2016			17.9 14.9	74.2 76.9	-25.8 -23.1	
EP SP	NDFT	1520	4	90.4	15.5 12.6	76.4 79.0	-23.6 -21.0	0.75
	1.2 NDFT	1824			17.0 14.0	75.1 77.7	-24.9 -22.3	
EP SP	NDFT	2280	6	90.4	19.2 16.2	73.0 75.8	-27.0 -24.2	0.70
	1.2 NDFT	2736			21.5 18.3	71.0 73.9	-29.0 -26.1	

1) DFT_{spec}: assumed average coating thickness per connection
2) Fractile value of the initial preload $F_{p,ini,0.05,MDV,in.tight.}$
3) Loss of preload $\Delta F_{p,setting,50a,mean,reg}$
4) Remaining preload value based on $F_{p,ini,0.05,MDV,in.tight.}$ and $\Delta F_{p,setting,50a,mean,reg}$

Abbreviations:

2K: two-pack | EP: epoxy based paint | EP-Zn: epoxy based zinc rich paint | EG: micaceous iron oxide
SP: polyester resin | PUR: polyurethane paint

Powder coating systems, re-tightening by the modified torque method

Table D.5 Estimation of remaining preload levels for powder coating systems after re-tightening by the modified torque method based on the fractile value of the initial preload $F_{p,ini,0.05,MDV, re-tight.}$ and preload losses $\Delta F_{p,setting,50a,mean,reg}$

Coating system	Coating thickness	Coating thickness	No. of coated surfaces	Initial preload ²⁾	Loss of preload ³⁾	Remaining preload ⁴⁾	Reserve/ deficit regarding	Selected preload level
		DFT _{spec} [μm] ¹⁾		for Σt/d ≈ 2.4 ≈ 5 [kN]	for Σt/d ≈ 2.4 ≈ 5 [%]	for Σt/d ≈ 2.4 ≈ 5 [kN]	F _{P,C} * [%]	X F _{P,C} * [-]
2. Typical powder coating systems on grit blasted steel substrates								
EP/SP	NDFT 1.2 NDFT	320	4	87.4	4.8 3.8	83.2 84.1	-16.8 -15.9	0.80
		384			5.0 3.9	83.1 84.0	-16.9 -16.0	
EP/SP	NDFT 1.2 NDFT	480	6	87.4	5.3 4.1	82.8 83.8	-17.2 -16.2	0.80
		576			5.6 4.3	82.6 83.7	-17.4 -16.3	
EP SP	NDFT 1.2 NDFT	720	4	87.4	6.0 4.6	82.2 83.4	-17.8 -16.6	0.80
		864			6.5 4.8	81.8 83.2	-18.2 -16.8	
EP SP	NDFT 1.2 NDFT	960	6	87.4	7.1 5.3	81.2 82.8	-18.8 -17.2	0.80
		1152			7.8 5.7	80.6 82.5	-19.4 -17.5	
3. Typical powder coating systems on hot dip galvanized surfaces (duplex-systems)								
EP/SP	NDFT 1.2 NDFT	1120	4	87.4	7.3 5.3	81.1 82.8	-18.9 -17.2	0.80
		1344			7.9 5.8	80.5 82.4	-19.5 -17.6	
EP/SP	NDFT 1.2 NDFT	1680	6	87.4	9.0 6.4	79.6 81.8	-20.4 -18.2	0.80
		2016			10.0 7.0	78.7 81.3	-21.3 -18.7	
EP SP	NDFT 1.2 NDFT	1520	4	87.4	8.5 6.1	80.0 82.1	-20.0 -17.9	0.80
		1824			9.4 6.7	79.2 81.6	-20.8 -18.4	
EP SP	NDFT 1.2 NDFT	2280	6	87.4	10.8 7.5	77.9 80.8	-22.1 -19.2	0.75
		2736			12.2 8.4	76.7 80.1	-23.3 -19.9	

1) DFT_{spec}: assumed average coating thickness per connection
2) Fractile value of the initial preload $F_{p,ini,0.05,MDV, re-tight.}$
3) Loss of preload $\Delta F_{p,setting,50a,mean,reg}$
4) Remaining preload value based on $F_{p,ini,0.05,MDV, re-tight.}$ and $\Delta F_{p,setting,50a,mean,reg}$

Abbreviations:

2K: two-pack | EP: epoxy based paint | EP-Zn: epoxy based zinc rich paint | EG: micaceous iron oxide
SP: polyester resin | PUR: polyurethane paint

Powder coating systems, tightening by the combined method

Table D.6 Estimation of remaining preload levels for powder coating systems after tightening by the combined method based on the fractile value of the initial preload $F_{p,ini,0.05,KV,tight.}$ and preload losses $\Delta F_{p,setting,50a,mean,reg}$

Coating system	Coating thickness	Coating thickness	No. of coated surfaces	Initial preload ²⁾	Loss of preload ³⁾	Remaining preload ⁴⁾	Reserve/deficit regarding	Selected preload level
		DFT _{spec} [μm] ¹⁾		for Σt/d ≈ 2.4 ≈ 5 [kN]	for Σt/d ≈ 2.4 ≈ 5 [%]	for Σt/d ≈ 2.4 ≈ 5 [kN]	F _{P,C} [%]	X F _{P,C} [-]
2. Typical powder coating systems on grit blasted steel substrates								
EP/SP	NDFT	320	4	145.3 137.6	9.5 7.0	131.4 127.9	19.5 16.3	1.0
	1.2 NDFT	384			9.9 7.3	131.0 127.5	19.1 15.9	
EP/SP	NDFT	480	6	145.3 137.6	10.3 7.8	130.3 126.9	18.5 15.3	1.0
	1.2 NDFT	576			10.8 8.2	129.6 126.3	17.8 14.8	
EP SP	NDFT	720	4	145.3 137.6	11.5 8.9	128.6 125.3	16.9 13.9	1.0
	1.2 NDFT	864			12.2 9.6	127.5 124.4	15.9 13.1	
EP SP	NDFT	960	6	145.3 137.6	13.3 10.6	126.0 123.0	14.5 11.8	1.0
	1.2 NDFT	1152			14.4 11.6	124.4 121.6	13.1 10.6	
3. Typical powder coating systems on hot dip galvanized surfaces (duplex-systems)								
EP/SP	NDFT	1120	4	145.3 137.6	13.5 10.8	125.7 122.8	14.3 11.6	1.0
	1.2 NDFT	1344			14.6 11.8	124.1 121.3	12.8 10.3	
EP/SP	NDFT	1680	6	145.3 137.6	16.3 13.4	121.7 119.2	10.6 8.4	1.0
	1.2 NDFT	2016			17.9 14.9	119.3 117.0	8.4 6.4	
EP SP	NDFT	1520	4	145.3 137.6	15.5 12.6	122.8 120.2	11.7 9.3	1.0
	1.2 NDFT	1824			17.0 14.0	120.6 118.3	9.7 7.5	
EP SP	NDFT	2280	6	145.3 137.6	19.2 16.2	117.4 115.3	6.7 4.9	1.0
	1.2 NDFT	2736			21.5 18.3	114.1 112.4	3.7 2.2	

1) DFT_{spec}: assumed average coating thickness per connection

2) Fractile value of the initial preload $F_{p,ini,0.05,KV,tight.}$

3) Loss of preload $\Delta F_{p,setting,50a,mean,reg}$

4) Remaining preload value based on $F_{p,ini,0.05,KV,tight.}$ and $\Delta F_{p,setting,50a,mean,reg}$

Abbreviations:

2K: two-pack | EP: epoxy based paint | EP-Zn: epoxy based zinc rich paint | EG: micaceous iron oxide

SP: polyester resin | PUR: polyurethane paint

Annex E - Determination of the remaining bolt preloads considering fractile values of the initial preload level $F_{p,ini,0.05}$ and preload losses $\Delta F_{p,setting,50a,0.95,reg}$

Formulas

Determination of the remaining bolt preload (here: $F_{p,50a,0.05}$):

$$F_{p,50a,0.05} = F_{p,ini,0.05} - \frac{F_{p,ini,0.05} \cdot \Delta F_{p,setting,50a,0.95,reg}}{100} \quad (E.1)$$

Determination of the reserve/deficit regarding the nominal preload level:

$$\Upsilon = \left(\frac{F_{p,50a,0.05}}{F_{p,C}^* \text{ or } F_{p,C}} - 1 \right) \cdot 100 \text{ [\%]} \quad (E.2)$$

2K-PUR coating | EP-/PUR coating systems, (initial) tightening by the modified torque method

Table E.1 Estimation of remaining preload levels for the 2K-PUR coating and EP-/PUR coating systems after (initial) tightening by the modified torque method based on the fractile values of the initial preload $F_{p,ini,0.05,MDV,in.tight.}$ and preload losses $\Delta F_{p,setting,50a,0.95,reg}$

Coating system	Coating thickness	Coating thickness DFT _{spec} [µm] ¹⁾	No. of coated surfaces	Initial preload ²⁾ for Σt/d ≈ 2.4 ≈ 5 [kN]	Loss of preload ³⁾ for Σt/d ≈ 2.4 ≈ 5 [%]	Remaining preload ⁴⁾ for Σt/d ≈ 2.4 ≈ 5 [kN]	Reserve/ deficit regarding $F_{p,C}^*$ [%]	Selected preload level $\times F_{p,C}^*$ [-]
1. Typical conventional paints and paint systems on grit blasted steel substrates								
2K-PUR	NDFT 1.2 NDFT	640 768	4	90.4	26.1 24.1 29.0 26.7	66.8 68.6 64.2 66.3	-33.2 -31.4 -35.8 -33.7	0.65
2K-PUR	NDFT 1.2 NDFT	960 1152	6	90.4	33.3 30.6 37.7 34.5	60.3 62.7 56.4 59.2	-39.7 -37.3 -43.6 -40.8	0.55
2K-EP 2K-PUR	NDFT 1.2 NDFT	640 768	4	90.4	22.4 19.2 23.4 19.7	70.2 73.1 69.3 72.6	-29.8 -26.9 -30.7 -27.4	0.70
2K-EP 2K-PUR	NDFT 1.2 NDFT	960 1152	6	90.4	24.8 20.6 26.3 21.4	68.0 71.8 66.6 71.1	-32.0 -28.2 -33.4 -28.9	0.65
2K-EP-Zn 2K-EP-EG 2K-PUR	NDFT 1.2 NDFT	960 1152	4	90.4	24.8 20.6 26.3 21.4	68.0 71.8 66.6 71.1	-32.0 -28.2 -33.4 -28.9	0.65
2K-EP-Zn 2K-EP-EG 2K-PUR	NDFT 1.2 NDFT	1440 1728	6	90.4	28.5 22.6 30.7 23.9	64.6 69.9 62.6 68.8	-35.4 -30.1 -37.4 -31.2	0.60
2K-EP-Zn 2K-EP-EG 2K-EP-EG 2K-PUR	NDFT 1.2 NDFT	1280 1536	4	90.4	27.3 22.0 29.3 23.1	65.7 70.6 64.0 69.6	-34.3 -29.4 -36.0 -30.4	0.65
2K-EP-Zn 2K-EP-EG 2K-EP-EG 2K-PUR	NDFT 1.2 NDFT	1920 2304	6	90.4	32.2 24.7 35.2 26.4	61.3 68.1 58.6 66.6	-38.7 -31.9 -41.4 -33.4	0.60

1) DFT_{spec}: assumed average coating thickness per connection
2) Fractile value of the initial preload $F_{p,ini,0.05,MDV,in.tight.}$
3) Fractile value of the loss of preload $\Delta F_{p,setting,50a,0.95,reg}$
4) Remaining preload value based on $F_{p,ini,0.05,MDV,in.tight.}$ and $\Delta F_{p,setting,50a,0.95,reg}$

Abbreviations:

2K: two-pack | EP: epoxy based paint | EP-Zn: epoxy based zinc rich paint | EG: micaceous iron oxide
SP: polyester resin | PUR: polyurethane paint

2K-PUR coating | EP-/PUR coating systems, re-tightening by the modified torque method

Table E.2 Estimation of remaining preload levels for the 2K-PUR coating and EP-/PUR coating systems after re-tightening by the modified torque method based on the fractile values of the initial preload $F_{p,ini,0.05,MDV, re-tight.}$ and preload losses $\Delta F_{p,setting,50a,0.95,reg}$

Coating system	Coating thickness	Coating thickness DFT _{spec} [µm] ¹⁾	No. of coated surfaces	Initial preload ²⁾ for $\Sigma t/d \approx 2.4$ ≈ 5 [kN]	Loss of preload ³⁾ for $\Sigma t/d \approx 2.4$ ≈ 5 [%]	Remaining preload ⁴⁾ for $\Sigma t/d \approx 2.4$ ≈ 5 [kN]	Reserve/ deficit regarding $F_{p,C}^*$ [%]	Selected preload level $X F_{p,C}^*$ [-]
1. Typical conventional paints and paint systems on grit blasted steel substrates								
2K-PUR	NDFT 1.2 NDFT	640 768	4	87.4	14.6 13.6 16.9 14.0	74.7 75.5 72.6 75.2	-25.3 -24.5 -27.4 -24.8	0.70
2K-PUR	NDFT 1.2 NDFT	960 1152	6	87.4	20.4 14.6 23.9 15.2	69.6 74.7 66.5 74.1	-30.4 -25.3 -33.5 -25.9	0.65
2K-EP 2K-PUR	NDFT 1.2 NDFT	640 768	4	87.4	12.1 9.7 12.8 10.5	76.9 79.0 76.2 78.3	-23.1 -21.0 -23.8 -21.7	0.75
2K-EP 2K-PUR	NDFT 1.2 NDFT	960 1152	6	87.4	13.9 11.6 15.1 12.8	75.2 77.2 74.2 76.2	-24.8 -22.8 -25.8 -23.8	0.75
2K-EP-Zn 2K-EP-EG 2K-PUR	NDFT 1.2 NDFT	960 1152	4	87.4	13.9 11.6 15.1 12.8	75.2 77.2 74.2 76.2	-24.8 -22.8 -25.8 -23.8	0.75
2K-EP-Zn 2K-EP-EG 2K-PUR	NDFT 1.2 NDFT	1440 1728	6	87.4	16.8 14.6 18.5 16.4	72.7 74.6 71.3 73.1	-27.3 -25.4 -28.7 -26.9	0.70
2K-EP-Zn 2K-EP-EG 2K-PUR	NDFT 1.2 NDFT	1280 1536	4	87.4	15.8 13.6 17.4 15.2	73.6 75.5 72.2 74.1	-26.4 -24.5 -27.8 -25.9	0.70
2K-EP-Zn 2K-EP-EG 2K-PUR	NDFT 1.2 NDFT	1920 2304	6	87.4	19.6 17.6 21.9 20.0	70.3 72.1 68.3 70.0	-29.7 -27.9 -31.7 -30.0	0.65

1) DFT_{spec}: assumed average coating thickness per connection

2) Fractile value of the initial preload $F_{p,ini,0.05,MDV, re-tight.}$

3) Fractile value of the loss of preload $\Delta F_{p,setting,50a,0.95,reg}$

4) Remaining preload value based on $F_{p,ini,0.05,MDV, re-tight.}$ and $\Delta F_{p,setting,50a,0.95,reg}$

Abbreviations:

2K: two-pack | EP: epoxy based paint | EP-Zn: epoxy based zinc rich paint | EG: micaceous iron oxide

SP: polyester resin | PUR: polyurethane paint

2K-PUR coating | EP-/PUR coating systems, tightening by the combined method

Table E.3 Estimation of remaining preload levels for the 2K-PUR coating and EP-/PUR coating systems after tightening by the combined method based on the fractile values of the initial preload $F_{p,ini,0.05,KV,tight.}$ and preload losses $\Delta F_{p,setting,50a,0.95,reg}$

Coating system	Coating thickness	Coating thickness DFT _{spec} [μm] ¹⁾	No. of coated surfaces	Initial preload ²⁾ for Σt/d ≈ 2.4 ≈ 5 [kN]	Loss of preload ³⁾ for Σt/d ≈ 2.4 ≈ 5 [%]	Remaining preload ⁴⁾ for Σt/d ≈ 2.4 ≈ 5 [kN]	Reserve/ deficit regarding F _{p,C} [%]	Selected preload level X F _{p,C} [-]
1. Typical conventional paints and paint systems on grit blasted steel substrates								
2K-PUR	NDFT 1.2 NDFT	640 768	4	145.3 137.6	26.1 24.1 29.0 26.7	107.4 104.4 103.2 100.8	-2.4 -5.1 -6.2 -8.4	0.90
2K-PUR	NDFT 1.2 NDFT	960 1152	6	145.3 137.6	33.3 30.6 37.7 34.5	96.9 95.5 90.6 90.1	-11.9 -13.2 -17.6 -18.1	0.80
2K-EP 2K-PUR	NDFT 1.2 NDFT	640 768	4	145.3 137.6	22.4 19.2 23.4 19.7	112.8 111.2 111.4 110.4	2.5 1.1 1.2 0.4	1.0
2K-EP 2K-PUR	NDFT 1.2 NDFT	960 1152	6	145.3 137.6	24.8 20.6 26.3 21.4	109.2 109.3 107.1 108.1	-0.7 -0.7 -2.7 -1.7	0.95
2K-EP-Zn 2K-EP-EG 2K-PUR	NDFT 1.2 NDFT	960 1152	4	145.3 137.6	24.8 20.6 26.3 21.4	109.2 109.3 107.1 108.1	-0.7 -0.7 -2.7 -1.7	0.95
2K-EP-Zn 2K-EP-EG 2K-PUR	NDFT 1.2 NDFT	1440 1728	6	145.3 137.6	28.5 22.6 30.7 23.9	103.9 106.4 100.7 104.7	-5.6 -3.3 -8.5 -4.8	0.90
2K-EP-Zn 2K-EP-EG 2K-EP-EG 2K-PUR	NDFT 1.2 NDFT	1280 1536	4	145.3 137.6	27.3 22.0 29.3 23.1	105.7 107.4 102.8 105.8	-4.0 -2.4 -6.5 -3.8	0.95
2K-EP-Zn 2K-EP-EG 2K-EP-EG 2K-PUR	NDFT 1.2 NDFT	1920 2304	6	145.3 137.6	32.2 24.7 35.2 26.4	98.5 103.6 94.2 101.3	-10.4 -5.8 -14.3 -7.9	0.85

1) DFT_{spec}: assumed average coating thickness per connection
2) Fractile value of the initial preload $F_{p,ini,0.05,KV,tight.}$
3) Fractile value of the loss of preload $\Delta F_{p,setting,50a,0.95,reg}$
4) Remaining preload value based on $F_{p,ini,0.05,KV,tight.}$ and $\Delta F_{p,setting,50a,0.95,reg}$

Abbreviations:

2K: two-pack | EP: epoxy based paint | EP-Zn: epoxy based zinc rich paint | EG: micaceous iron oxide
SP: polyester resin | PUR: polyurethane paint

Powder coating systems, (initial) tightening by the modified torque method

Table E.4 Estimation of remaining preload levels for powder coating systems after (initial) tightening by the modified torque method based on the fractile values of the initial preload $F_{p,ini,0.05,MDV,in.tight.}$ and preload losses $\Delta F_{p,setting,50a,0.95,reg}$

Coating system	Coating thickness	Coating thickness	No. of coated surfaces	Initial preload ²⁾	Loss of preload ³⁾	Remaining preload ⁴⁾	Reserve/ deficit regarding	Selected preload level	
		DFT _{spec} [μm] ¹⁾		for Σt/d ≈ 2.4 ≈ 5 [kN]	for Σt/d ≈ 2.4 ≈ 5 [%]	for Σt/d ≈ 2.4 ≈ 5 [kN]	F _{p,C} * [%]	X F _{p,C} * [-]	
2. Typical powder coating systems on grit blasted steel substrates									
EP/SP	NDFT	320	4	90.4	12.5 11.3	79.1 80.2	-20.9 -19.8	0.80	
	1.2 NDFT	384			12.9 11.5	78.8 80.0	-21.2 -20.0		
EP/SP	NDFT	480	6	90.4	13.4 11.9	78.3 79.6	-21.7 -20.4	0.75	
	1.2 NDFT	576			13.8 12.3	77.9 79.3	-22.1 -20.7		
EP SP	NDFT	720	4	90.4	14.6 12.9	77.3 78.7	-22.7 -21.3	0.75	
	1.2 NDFT	864			15.3 13.5	76.6 78.2	-23.4 -21.8		
EP SP	NDFT	960	6	90.4	16.4 14.4	75.6 77.4	-24.4 -22.6	0.75	
	1.2 NDFT	1152			17.5 15.3	74.6 76.6	-25.4 -23.4		
3. Typical powder coating systems on hot dip galvanized surfaces (duplex-systems)									
EP/SP	NDFT	1120	4	90.4	16.6 14.6	75.4 77.3	-24.6 -22.7	0.75	
	1.2 NDFT	1344			17.7 15.5	74.4 76.4	-25.6 -23.6		
EP/SP	NDFT	1680	6	90.4	19.4 16.9	72.9 75.2	-27.1 -24.8	0.70	
	1.2 NDFT	2016			21.1 18.3	71.4 73.9	-28.6 -26.1		
EP SP	NDFT	1520	4	90.4	18.6 16.2	73.6 75.8	-26.4 -24.2	0.70	
	1.2 NDFT	1824			20.1 17.5	72.2 74.6	-27.8 -25.4		
EP SP	NDFT	2280	6	90.4	22.4 19.4	70.2 72.9	-29.8 -27.1	0.65	
	1.2 NDFT	2736			24.7 21.2	68.1 71.2	-31.9 -28.8		

1) DFT_{spec}: assumed average coating thickness per connection

2) Fractile value of the initial preload $F_{p,ini,0.05,MDV,in.tight.}$

3) Fractile value of the loss of preload $\Delta F_{p,setting,50a,0.95,reg}$

4) Remaining preload value based on $F_{p,ini,0.05,MDV,in.tight.}$ and $\Delta F_{p,setting,50a,0.95,reg}$

Abbreviations:

2K: two-pack | EP: epoxy based paint | EP-Zn: epoxy based zinc rich paint | EG: micaceous iron oxide
SP: polyester resin | PUR: polyurethane paint

Powder coating systems, re-tightening by the modified torque method

Table E.5 Estimation of remaining preload levels for powder coating systems after re-tightening by the modified torque method based on the fractile values of the initial preload $F_{p,ini,0.05,MDV,re-tight.}$ and preload losses $\Delta F_{p,setting,50a,0.95,reg}$

Coating system	Coating thickness	Coating thickness	No. of coated surfaces	Initial preload ²⁾ for Σt/d	Loss of preload ³⁾ for Σt/d	Remaining preload ⁴⁾ for Σt/d	Reserve/ deficit regarding	Selected preload level	
		DFT _{spec} [µm] ¹⁾		≈ 2.4 ≈ 5 [kN]	≈ 2.4 ≈ 5 [%]	≈ 2.4 ≈ 5 [kN]	F _{p,C} * [%]	X F _{p,C} * [-]	
2. Typical powder coating systems on grit blasted steel substrates									
EP/SP	NDFT 1.2 NDFT	320	4	87.4	7.6 7.0 7.8 7.1	80.8 81.3 80.6 81.2	-19.2 -18.7 -19.4 -18.8	0.80	
		384							
EP/SP	NDFT 1.2 NDFT	480	6	87.4	8.0 7.2 8.3 7.3	80.4 81.1 80.1 81.0	-19.6 -18.9 -19.9 -19.0	0.80	
		576							
EP SP	NDFT 1.2 NDFT	720	4	87.4	8.7 7.5 9.2 7.8	79.8 80.8 79.4 80.6	-20.2 -19.2 -20.6 -19.4	0.80	
		864							
EP SP	NDFT 1.2 NDFT	960	6	87.4	9.8 8.1 10.4 8.4	78.9 80.4 78.3 80.1	-21.1 -19.6 -21.7 -19.9	0.75	
		1152							
3. Typical powder coating systems on hot dip galvanized surfaces (duplex-systems)									
EP/SP	NDFT 1.2 NDFT	1120	4	87.4	9.9 8.1 10.6 8.4	78.8 80.3 78.2 80.0	-21.2 -19.7 -21.8 -20.0	0.75	
		1344							
EP/SP	NDFT 1.2 NDFT	1680	6	87.4	11.6 8.9 12.5 9.4	77.3 79.6 76.5 79.2	-22.7 -20.4 -23.5 -20.8	0.75	
		2016							
EP SP	NDFT 1.2 NDFT	1520	4	87.4	11.1 8.7 12.0 9.1	77.7 79.8 76.9 79.4	-22.3 -20.2 -23.1 -20.6	0.75	
		1824							
EP SP	NDFT 1.2 NDFT	2280	6	87.4	13.3 9.8 14.7 10.4	75.8 78.9 74.6 78.3	-24.2 -21.1 -25.4 -21.7	0.75	
		2736							

1) DFT_{spec}: assumed average coating thickness per connection
2) Fractile value of the initial preload $F_{p,ini,0.05,MDV,re-tight.}$
3) Fractile value of the loss of preload $\Delta F_{p,setting,50a,0.95,reg}$
4) Remaining preload value based on $F_{p,ini,0.05,MDV,re-tight.}$ and $\Delta F_{p,setting,50a,0.95,reg}$

Abbreviations:

2K: two-pack | EP: epoxy based paint | EP-Zn: epoxy based zinc rich paint | EG: micaceous iron oxide
SP: polyester resin | PUR: polyurethane paint

Powder coating systems, tightening by the combined method

Table E.6 Estimation of remaining preload levels for powder coating systems after tightening by the combined method based on the fractile values of the initial preload $F_{p,ini,0.05,KV,tight.}$ and preload losses $\Delta F_{p,setting,50a,0.95,reg}$

Coating system	Coating thickness	Coating thickness	No. of coated surfaces	Initial preload ²⁾	Loss of preload ³⁾	Remaining preload ⁴⁾	Reserve/ deficit	Selected
		DFT _{spec} [μm] ¹⁾		for Σt/d	for Σt/d	for Σt/d	regarding	preload level
2. Typical powder coating systems on grit blasted steel substrates								
EP/SP	NDFT	320	4	145.3 137.6	12.5 11.3	127.1 122.1	15.5 11.0	1.0
	1.2 NDFT	384			12.9 11.5	126.6 121.7	15.1 10.7	
EP/SP	NDFT	480	6	145.3 137.6	13.4 11.9	125.9 121.2	14.5 10.2	1.0
	1.2 NDFT	576			13.8 12.3	125.2 120.6	13.8 9.7	
EP SP	NDFT	720	4	145.3 137.6	14.6 12.9	124.2 119.8	12.9 8.9	1.0
	1.2 NDFT	864			15.3 13.5	123.1 119.0	11.9 8.2	
EP SP	NDFT	960	6	145.3 137.6	16.4 14.4	121.5 117.8	10.5 7.1	1.0
	1.2 NDFT	1152			17.5 15.3	120.0 116.5	9.0 5.9	
3. Typical powder coating systems on hot dip galvanized surfaces (duplex-systems)								
EP/SP	NDFT	1120	4	145.3 137.6	16.6 14.6	121.2 117.5	10.2 6.8	1.0
	1.2 NDFT	1344			17.7 15.5	119.6 116.3	8.7 5.7	
EP/SP	NDFT	1680	6	145.3 137.6	19.4 16.9	117.1 114.4	6.5 4.0	1.0
	1.2 NDFT	2016			21.1 18.3	114.7 112.4	4.3 2.2	
EP SP	NDFT	1520	4	145.3 137.6	18.6 16.2	118.3 115.3	7.6 4.8	1.0
	1.2 NDFT	1824			20.1 17.5	116.1 113.5	5.5 3.2	
EP SP	NDFT	2280	6	145.3 137.6	22.4 19.4	112.8 110.9	2.5 0.9	1.0
	1.2 NDFT	2736			24.7 21.2	109.4 108.4	-0.5 -1.5	

1) DFT_{spec}: assumed average coating thickness per connection
2) Fractile value of the initial preload $F_{p,ini,0.05,KV,tight.}$
3) Fractile value of the loss of preload $\Delta F_{p,setting,50a,0.95,reg}$
4) Remaining preload value based on $F_{p,ini,0.05,KV,tight.}$ and $\Delta F_{p,setting,50a,0.95,reg}$

Abbreviations:

2K: two-pack | EP: epoxy based paint | EP-Zn: epoxy based zinc rich paint | EG: micaceous iron oxide
SP: polyester resin | PUR: polyurethane paint