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TITLE: Amendment 1 – Wind energy generation systems – Part 6: Tower and foundation design requirements
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PROPOSED STABILITY DATE: 2027

NOTE FROM TC/SC OFFICERS: In 88/926/RQ, Result of 88/914/Q: Proposed amendment to IEC 61400-6:2020, Wind energy generation systems - Part 6: Tower and foundation design requirements, it was concluded that MT 6 will have to further decide on the next step during the preparatory stage of the amendment. MT 6 has during to the development of the amendment, decided to submit the document directly as CDV.
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INTERNATIONAL ELECTROTECHNICAL COMMISSION

WIND ENERGY GENERATION SYSTEMS –

Part 6: Tower and foundation design requirements

AMENDMENT 1

FOREWORD

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Amendment 1 to IEC 61400-6:2020 has been prepared by subcommittee MT 6: Tower and foundation design, of IEC technical committee TC88: Wind energy generation systems.

The text of this Amendment is based on the following documents:

Draft	Report on voting
88/xxxx/FDIS	88/xxxx/RVD

Full information on the voting for its approval can be found in the report on voting indicated in the above table.

The language used for the development of this Amendment is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/publications/.

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INTRODUCTION

Sections as given in this document are replacing or amending the respective sections of IEC 61400-6:2020. The main part of this amendment concerns updated knowledge for the design of L-flanges and modifications required due to changes to IEC 61400-1.

The previous method of fatigue assessment using the Schmidt/Neuper trilinear bolt force curve approximation has been removed from the standard. It has been replaced with a physically more accurate method.

The updated methodology for fatigue assessment of L-flanges has been calibrated such that the target failure probability defined in IEC 61400-1 is achieved. Where existing flange designs are checked with the updated method, over-utilization may be found, which in some cases may show an order of magnitude higher than nominally acceptable damage.

This does not impose an immediate risk for the turbines affected, though, due to the following factors:

- a) In most cases such designs have significant conservatism in the fatigue loads assumed e.g. due to the assumption of uni-directional wind combined with type class turbulence conditions.
- b) Experience shows that broken bolts are almost always found and replaced before a turbine collapses.

Existing flange designs need not be re-assessed using the new method, and existing type or project certification remains valid. In cases where broken bolts are found in operating turbines, the affected flange should be checked with the new methodology. Based on the assessment results and the root causes analysis for the failure, further measures should be defined (e.g. shorter inspection intervals).

2 Normative references

Add the following normative references to IEC 61400-6:2020.

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 898-1, Mechanical properties of fasteners made of carbon steel and alloy steel – Part 1: Bolts, screws and studs with specified property classes – Coarse thread and fine pitch thread

ISO 898-2, Fasteners – Mechanical properties of fasteners made of carbon steel and alloy steel – Part 2: Nuts with specified property classes

ISO 898-3, Mechanical properties of fasteners made of carbon steel and alloy steel - Part 3: Flat washers with specified property classes

ISO 16047, Fasteners - Torque/clamp force testing

ISO 4759-1, Tolerances for fasteners – Part 1: Bolts, screws, studs and nuts – Product grades A, B and C

ISO 4759-3, Tolerances for fasteners - Part 3: Washers for bolts, screws and nuts - Product grades A, C and F

ISO 965 (all parts), ISO general purpose metric screw threads

48 **3 Terms and definitions**

49 *Add the following definitions to IEC 61400-6:2020.*

50 **3.1**

51 **Bolt assembly**

52 Bolt assemblies comprise fastener, nut(s), optionally washer(s), preloading method and lubrication system

54 EXAMPLE A stud assembly for tension-tightening may comprise a stud and two roundnuts on each side, without additional washers

56 NOTE In this standard, the term “bolts” is used for the fastener elements. Instead of (head) bolts, also partially or fully threaded studs with nuts on both ends may be used, if they have the same nominal thread geometry and material properties as bolts from accepted standards.

59 **3.2**

60 **Design gap height**

61 k_{design}

62 Design gap height, defined as the 95% fractile value of the log-normal distribution defined by k_{mean} and COV_k (section 6.7.5.2)

64 **3.3**

65 **Unloaded gap height limit**

66 $k_{\text{limit,unloaded}}$

67 Allowable maximum gap height after mating of flanges, without influence of loading by dead weight of tower section(s) above the flange or preload of bolts

69 **3.4**

70 **Loaded gap height limit**

71 $k_{\text{limit,loaded}}$

72 Allowable maximum gap height after mating of flanges, and after application of e.g. dead weight of tower section(s) above the flange and/or partial preload of bolts

74 NOTE Conditions at time of measuring the loaded gap height shall be defined by the designer

75 **3.5**

76 **Flatness deviation of individual flange**

77 u_{tol}

78 Allowable flatness deviation as defined in section 6.7.3.1 for the individual flange

80 **4 Symbols and abbreviated terms**

81 **Symbols**

82	a	flange dimension (nominal distance from inside of flange to bolt circle diameter)
83		
84	A	nominal area of the bolt shaft with diameter d
85	a*	auxiliary value to compute bolt bending moment
86	a'	reduced effective flange dimension according to Tobinaga/Ishihara
87	A_{cf}	flange cross section area in circumferential direction
88	A_{S}	nominal stress area of the bolt in thread
89	b	weld neck thickness (normally equal to the thickness of the connected tower shell) (in section 6.3.2.3 only)
90		

91	b	flange dimension (nominal distance from bolt circle diameter to middle surface of connected tower shell)
92		
93	$b'_{\{B,D,E\}}$	distance in between plastic hinges for failures modes B, D, E
94	c	flank height of the weld preparation (in section 6.3.2.3 only)
95	c	segment width measured at the middle surface of the shell (tower wall)
96	c_{bcd}	segment width measured at the bolt circle diameter
97	C_D	stiffness of the compression spring q (representing the compressed parts)
98	COV	coefficient of variation
99	COV_k	coefficient of variation of gap height
100	COV_p	coefficient of variation of preload force
101	C_S	spring stiffness of the tension spring (representing the bolts)
102	d	nominal diameter of the bolt
103	D	outer diameter of the flange connection
104	$D_{\{1,2\}}$	auxiliary values to determine coefficients for bolt force polynomial
105	d_b	diameter of the bolt hole
106	DFT_{sbw}	dry film thickness (DFT) of coatings applied to the flange surface beneath washers (sbw), i.e in the contact area between washers and flange
107		outside diameter of the washer
108	D_w	
109	E	Young's modulus of steel
110	F_{p,C^*}	preload bolt force used for modified torque method
111	$F_{p,C'}$	preload bolt force used in the design calculations (design preload)
112	$F_{p,inst.,mean}$	mean preload force after installation
113	$F_{p,mean}$	mean preload after settlement
114	F_S	bolt force
115	$F_S(Z)$	bolt force as a function of external force Z applied on flange segment
116	$F_{S,\{0,1,2,3\}}$	bolt forces for determination of polynomial bolt force model
117	$F_{S,max,FLS}$	bolt force calculated for maximum FLS load level
118	$F_{S,min}$	minimum (constant) bolt force for theoretically fully closed connection under compression
119		
120	$F_{S,loss}$	bolt force used to verify preload loss criterion
121	$F_S'(Z)$	slope (derivative) of bolt force curve as a function of external force Z on flange segment
122		
123	$F_{t,R}$	design value of tension resistance of bolt
124	$F_{U,B}$	limit tension resistance for failure mode B
125	$F_{U,D}$	limit tension resistance for failure mode D
126	f_{ub}	ultimate tensile strength of bolt
127	F_V	preload
128	f_{yb}	nominal yield strength of the bolt material
129	$f_{yb,k}$	characteristic value for yield limit of the bolt
130	$f_{Z,tot}$	total amount of settlement in the connection
131	G	shear modulus of steel
132	G_{RNA}	dead weight of the RNA
133	G_{twr}	dead weight of tower above flange connection considered
134	h_n	flange neck height
135	h_{wp}	distance from flange surface to weld preparation
136	h_{wt}	distance from flange surface to weld toe
137	I_{cf}	flange moment of inertia in circumferential direction (bending moment vector pointing in radial direction)
138		
139	I_{tg}	flange moment of inertia for a bending moment vector pointing in tangential direction
140		
141	k	flange gap height
142	$k(l)$	gap height at position l of total gap length L_{gap}

143	k_{design}	design gap height
144	k_{fac}	stiffness factor to calculate meridional shell stiffness
145	k_{fl}	bending stiffness of the flange
146	$k_{\text{gap,tot}}$	total gap stiffness
147	$k_{\text{limit,loaded}}$	gap height after application of a defined load
148	$k_{\text{limit,unloaded}}$	gap height after mating of flanges without any load
149	k_{mean}	mean gap height
150	k_{measured}	measured gap height
151	k_{seg}	segment stiffness
152	$k_{\text{shell,ini}}$	meridional stiffness of the shell / initial shell stiffness
153	K	shell parameter
154	l	distance from transition radius to weld preparation (in section 6.3-2.3 only)
155	l	length of the bolt between the bolt head and the nut
156	L_{30°	circumferential length measured at mid surface of shell over 30° sector
157	$l_k = L_{\text{gap}}$	spanning length of the gap
158	M	external bending moment
159	m	slope parameter of a fatigue resistance curve
160	M_0	bending moment at $Z = \Delta Z_{dw}$
161	$M_{\text{max,FLS}}$	maximum bending moment included in Markov matrix
162	$M_{\text{mean},i}$	mean value of entry i in the Markov matrix
163	$M_{\text{min,FLS}}$	minimum bending moment included in Markov matrix
164	$M_{\text{pl},3}$	plastic limit bending moment for flange or shell
165	$M_{\text{pl,BI}}$	plastic limit bending moment for shell
166	$M_{\text{pl,FI}}$	plastic limit bending moment for flange
167	$M_{\text{pl,N,BI}}$	plastic limit bending moment for shell, including interaction with external tension force N
168		tension force N
169	$M_{\text{pl,V,FI}}$	plastic limit bending moment for flange, including interaction with shear force V
170		shear force V
171	M_{loss}	bending moment used to calculate bolt force for preload loss check
172	$M_{\text{range},i}$	moment range of entry i in the Markov matrix
173	M_S	bolt moment
174	$M_S(Z)$	bolt moment curve as function of external force Z
175	$M_{S,\text{min}}$	minimum bending moment for theoretically fully closed connection under compression
176		compression
177	N	number of cycles
178	n	shell parameter
179	n_{bolts}	number of bolts in flange connection
180	$N_{\text{pl,BI}}$	plastic limit normal force for shell
181	p	load factor of the tension springs
182	p_{95}	95% quantile of the log-normal distribution
183	R_{shell}	mean radius of shell (tower wall)
184	s	shell (tower wall) thickness
185	t	flange thickness
186	t_w	thickness of the washer
187	u	auxiliary displacement value for computation of flange segment stiffness
188	u_{tol}	flatness tolerance for individual flange
189	$u_{\text{tol},1m}$	flatness tolerance per flange over a circumferential length of 1000mm
190	$u_{\text{tol},30^\circ}$	flatness tolerance per flange over 30° sector
191	$u_{\text{tol},360^\circ}$	flatness tolerance per flange around the entire circumference
192	V	shear force in flange
193	$V_{\text{pl,FI}}$	plastic limit shear force
194	w	flange width

195	W_{twr}	section modulus of the tower with outer diameter D and wall thickness s
196	Z	tower shell force (external force on the segment)
197	$Z_{\{0,1,2,3\}}$	force values to construct tower bolt force model
198	Z_{close}	force at which the connection is theoretically fully closed
199	$Z_{\text{max,FLS}}$	max. segment force from the Markov matrix
200	\tilde{Z}_2	auxiliary value needed to compute segment stiffness k_{seg}
201	Z_{tot}	total segment force
202	$Z_{\text{tot}}(M)$	total segment force as a function of external bending moment M
203		
204	$\alpha_{\{0,1,2\}}$	auxiliary values to determine polynomial coefficients
205	α_{gap}	circumferential angle of the gap
206	α_k	stiffness correction factor
207	α_S	flange surface inclination
208	β_S	bending resilience of bolt
209	δ_P	resilience of the clamped parts
210	δ_S	resilience of the bolt
211	ΔF_{pl}	expected reduction of preload force due plastic strain development
212	ΔF_Z	expected reduction of preload force due to settlements
213	ΔZ	range of external force applied to flange segment
214	ΔZ_{dw}	segment force resulting from the dead weight
215	ΔZ_{gap}	force for theoretical closure of flange gap
216	$\Delta \sigma$	combined stress range
217	$\Delta \sigma_{\text{axial}}$	stress range from axial forces in the bolt
218	$\Delta \sigma_{\text{bending}}$	stress range from bending moments in the bolt
219	$\Delta \sigma_c$	reference stress range of resistance S-N-curve
220	λ'	lever arm ratio taking the action point correction into account
221	μ_k	mean value of log-normal distribution for gap heights
222	ν	Poisson's ratio
223	$\chi_{\text{ini,M}}$	slope of bending moment function
224	$\chi_{\text{ini,mod}}$	modified initial slope of the polynomial approximation
225	$\chi_{\text{ini,true}}$	true slope of the polynomial approximation
226	γ_{M1}	partial safety factor (PSF)
227		

228 **Abbreviated terms**

229		
230	2K-PUR	2 Component Polyurethane
231	BTQP	Bolt Tightening Qualification Procedure
232	COV	Coefficient Of Variation
233	DFT	Dry Film Thickness
234	EP	Epoxy
235	FEA	Finite Element Analysis
236	FLS	Fatigue Limit State
237	HV	“Hochfest vorgespannt“ (German designation for high-strength bolts intended
238		for preloading)
239	PUR	Polyurethane
240	RNA	Rotor Nacelle Assembly
241	SCF	Stress Concentration Factor
242	TSM	Thermal Spray Metallizing
243	ULS	Ultimate Limit State

244 **6.3.3 Bolts and anchors**

245 *Replace entire section 6.3.3 of IEC 61400-6:2020 with the following.*

246 Generally, standardized bolt assemblies should be used as far as practicable.

247 NOTE A comparison of local design codes and industry design guidelines practice may be found in Annex A and
248 Annex C.

249 The material property class for bolt assemblies and anchors shall comply with the requirements
250 stated in ISO 898-1, ISO 898-2 and ISO 898-3. Material properties for bolt sets with metric sizes
251 larger than M39 shall be derived with due consideration of size effects and manufacturing meth-
252 ods.

253 NOTE 1 Large diameters require different materials and manufacturing methods. ISO 898 testing is obtained directly
254 on the fastener or on machined test pieces with max diameter reduction 25 %. For large bolt sizes, the test specimen
255 would still be too large to be conveniently tested, so the specification should be adapted.

256 NOTE 2 The material properties derived as per above procedures are valid in the temperature range from -50 °C
257 to +150 °C.

258 For preloaded connections only bolt sets with either property class 8.8 or 10.9 should be se-
259 lected.

260 When non-standardized bolt assemblies are specified by the designer, the product character-
261 istics of the bolt assembly shall be obtained through type testing on at least 5 samples for each
262 required characteristic.

263 The type testing program shall include at least:

- 264 a) Material properties as per ISO 898-1, ISO 898-2 and ISO 898-3 as applicable
- 265 b) Product grade as per ISO 4759-1, ISO 4759-3, ISO 965-2 and ISO 965-5
- 266 c) Suitability for preloading as per ISO 16047

267 NOTE Non-standardized bolt assemblies may differ due to non-standardized components (fastener, nut, washer(s)),
268 preloading method and lubrication system, among others.

269 Type testing should be repeated in case of different nominal diameters, manufacturing methods,
270 material property class, coating type, type and source of material, tightening method.

271

272 **6.5.2 Partial safety factor**

273 *Replace complete section 6.5.2 including footnote 8 with*

274 Partial safety factors shall be chosen based on the applied verification method.

275 When using EN 1993-1-6:2007 or prEN 1993-1-6:2023, $\gamma_{M1}=1.1$ should be used.

276 When using the modified expressions for meridional buckling (D.1.2.2) according to EN 1993-
277 1-6:2007+A1:2017, $\gamma_{M1}=1.2$ should be used.

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278 6.7 Ring flange connections

279 *Replace entire section 6.7 of IEC 61400-6:2020 with the following.*

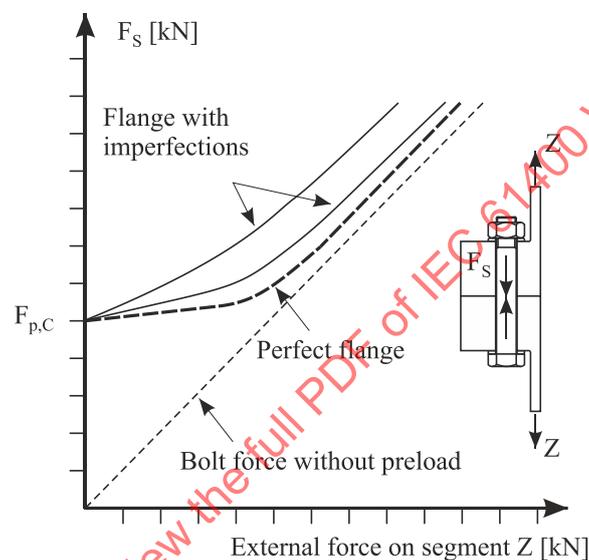
280 6.7.1 General

281 The regulations stated in 6.7 are valid for both L- and T-flange connections, unless otherwise
282 stated.

283 6.7.2 Design assumptions and requirements

284 Ring flange connections shall be tightened in a controlled manner in several steps according to
285 the requirements given in this standard.

286 The fatigue assessment shall be based on the non-linear bolt force function $F_S=f(Z)$ and bolt
287 moment function $M_S=f(Z)$ from which the fatigue ranges of the bolt force F_S and bolt moment
288 M_S can be read off for a given range of the tower shell force Z (see Figure 1 with illustration for
289 the bolt force).



290
291 **Figure 1 – Bolt force F_S as a function of wall force Z**

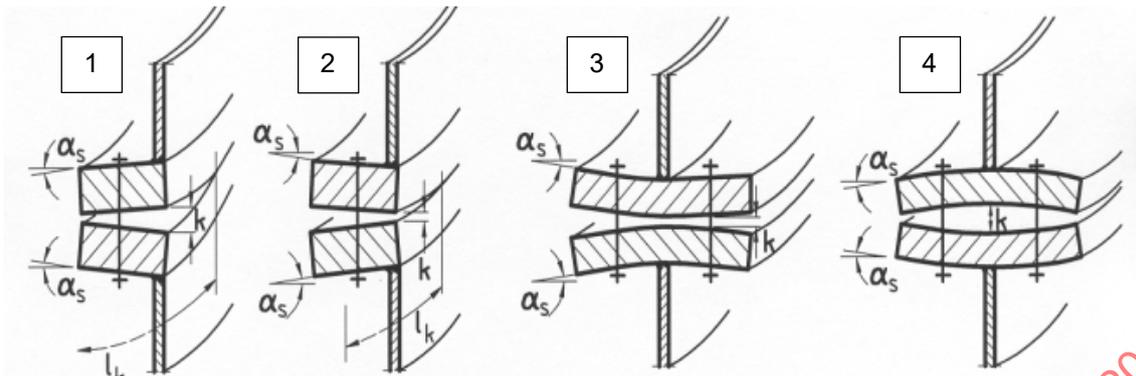
292 The stiffness of the flange connection may be assumed as equivalent to the stiffness of the
293 tower shell, and no negative effect from flange opening needs to be considered e.g. for load
294 simulations.

295 6.7.3 Execution of ring flanges

296 The tolerances for flange flatness and (if applicable) allowable gaps during installation shall be
297 stated in the drawings or manufacturing specifications and/or installation manuals.

298 **NOTE** Flange gaps k in the tower wall region are causing increased fatigue loading of the bolts. Gaps are identified
299 as “parallel gaps” when they occur around part of the circumference with the mating surfaces of the upper and lower
300 flange being parallel to each other. Gaps are identified as “angular gaps” when the mating surfaces are not parallel
301 to each other. Both types can be combined, i.e., a parallel gap can occur on top of an angular gap, see Figure 3. The
302 damage influence of parallel gaps grows with decreasing spanning length l_k over the circumference of the flange for
303 a constant gap height k . Parallel gaps with circumferential lengths of within $\sim 30\text{-}120^\circ$ of the circumference have the
304 largest damaging effect, as the (design) gap height k increases with gap length l_k . To ensure fatigue strength of the
305 connection, it is necessary to limit the size of the gaps in terms of height and length, such that gaps are sufficiently
306 closed and the pressure body in the flange is created in accordance with requirements for fatigue assessment.

307

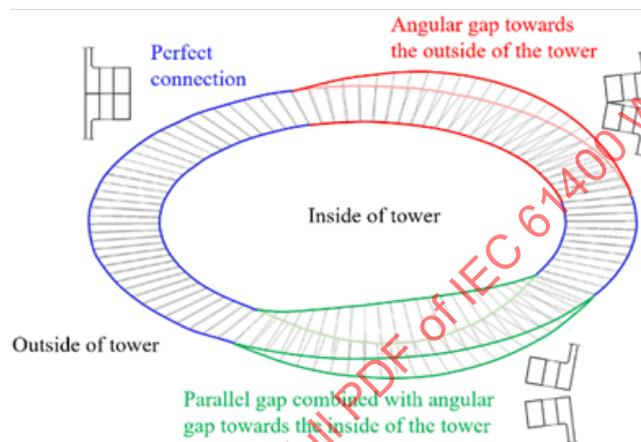


308

309

310

Figure 2 – Flange gaps with gap height k and gap length l_k at the tower wall and flange surface inclination α_s



311

312

Figure 3 – Illustration of parallel gaps and angular gaps

6.7.3.1 Flange tolerances

Following completion of the production of the individual tower sections, the taper to the inside of the connecting surface of each flange (see Figure 2, case 2 & 3) shall be checked and should be within the limits specified in Table 6-1.

For L-Flanges, a minimum taper of 0.2° (opening to the inside, case 2 according to Figure 2) should be specified. Negative taper (case 1 according to Figure 2) is not permitted.

NOTE This is to ensure that the inside gap is not closing at the preload level applied when checking for gaps. Additionally, an inside taper positively influences the bolt force curve. Outside taper (Figure 2, cases 1 and 4) is not allowed.

If required according to section 6.7.3.3, gap limits as specified by the designer shall be checked, noting that the region near to the tower wall is decisive.

Flatness measurements shall be performed with the following procedure.

a) Measurement points in the region of the tower wall, i.e. on the outside of the flange (close to Point II as shown in Figure 9) for L-Flanges and in the centre of the flange for T-Flanges, shall be measured with a maximum distance of 500 mm, evaluated on a circumferential path.

b) A best-fit plane shall be determined, resulting in the smallest mean square error for the distance of the individual measurement points to the best-fit plane.

c) For determining the taper, additional points on the inside (for L-Flanges) and on inside and outside (for T-Flanges) shall be measured.

d) The tolerances according to Table 6-1 shall be evaluated.

The starting point of measurements and the direction shall be defined by the manufacturer and documented in the as-built documentation.

333

334

335 NOTE 1 Measurements should be done clockwise starting from a defined starting position (“zero mark”). This en-
 336 sures that analytical mating of flanges from different manufacturers can be done without uncertainty about the meas-
 337 urement sequence.

338 NOTE 2 The global and local flatness is defined by global flatness $u_{tol,360^\circ}$, which is the largest flatness difference
 339 between two measurement points along the entire circumference and local flatness $u_{tol,1m}$, which is the largest flat-
 340 ness difference between two measurement points within a maximum distance of 1000mm.

341 NOTE 3 When using a distance between measurement points of 500mm, three points at 0mm, 500mm, 1000mm
 342 are evaluated and the distance between any two of those three points is decisive.

343 NOTE 4 An example is given in Figure 4, where the evaluation returns a global flatness value of 2.2 mm and a local
 344 flatness value of 1.16 mm. The x-axis in the middle of the plot shows angle in [°] and the axis shown in the bottom
 345 part shows lengths in [mm] around the circumference.

346 NOTE 5 Different terminology is used in the industry for flatness tolerances. Instead of “flatness”, the term “wavi-
 347 ness” is also used. It should also be noted that this tolerance definition may differ from tolerance definitions in other
 348 standards using the same terminology. The definition described in detail in this section is governing for wind turbine
 349 structures and other definitions do not apply.

350 NOTE 6 The relation between flatness values of the individual flange, as specified in Table 6-1, and the resulting
 351 gap height k between two flanges is illustrated in Figure 5 for clarity. Flatness values u_{tol} are evaluated based on the
 352 individual flanges, the upper left chart in Figure 5 shows flatness measurements for two flanges of a connection.

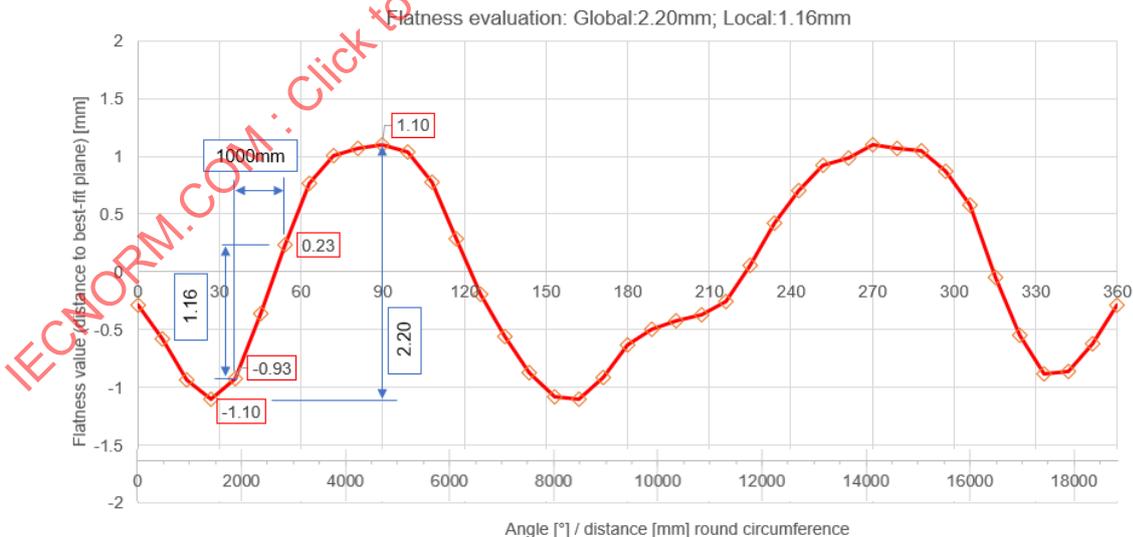
353 NOTE 7 The resulting gap height k between two flanges in the unloaded condition is determined by a mating analys-
 354 is, where the contact points of the flanges are established. The contact between the two flanges is found by both
 355 translations and rotations, such that the resulting gap heights k can't be determined directly from the flatness proto-
 356 cols. Further information on the required steps is provided in [1]. Acceptable gaps are not directly linked to the
 357 flatness tolerances due to the statistical effect when mating two flange surfaces. It is incorrect to assume that allow-
 358 able gaps are twice the flatness tolerance values [1].

359

360

Table 6-1 – Flange tolerances

Characteristic	Limiting value
Flatness deviation $u_{tol,360^\circ}$ per flange around the entire circum- ference	See section 6.7.5.2
Flatness deviation $u_{tol,1m}$ over a circumferential length of 1000mm, using a minimum of 3 measurement points with a maxi- mum distance of 500mm	See section 6.7.5.2
Taper α_s to the inside of the connecting surface of each flange	0.2° to 0.7°
Outer flange surfaces limit α_s before using taper washers	2°



361

362

Figure 4 – Example for flatness measurement evaluation (D=6000mm)

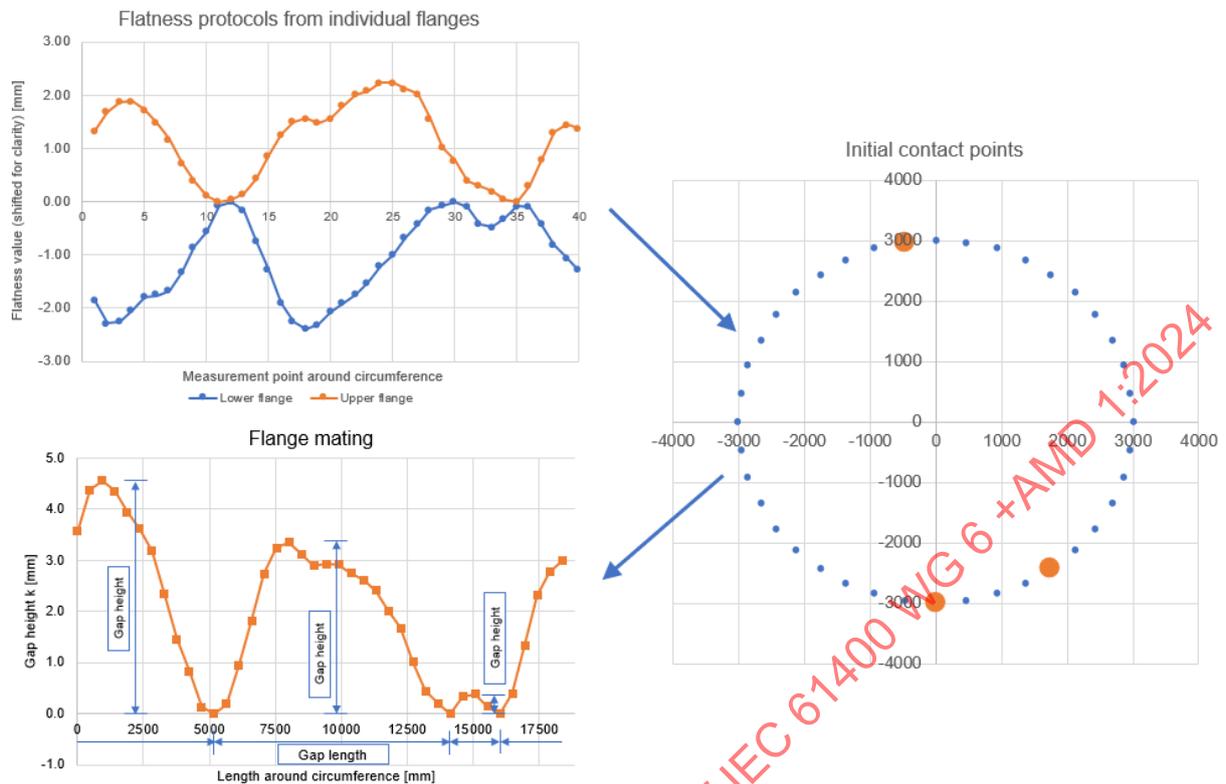


Figure 5 – Clarification of flatness values for the individual flange (u_{tol}) and resulting gap height after mating of two flanges (k)

6.7.3.2 Preloading

For preloading of tower flange bolts, torque-tightening or tension-tightening procedures may be applied.

A Bolt Tightening Qualification Procedure (BTQP) for a specific configuration of bolting assembly shall be developed to determine tightening parameters and the corresponding mean value as well as the COV, see Section 6.7.5.1. In the BTQP, a specific configuration is defined as:

- d) One single bolting assembly type (defined by fastener, nut and washer)
- e) One type of lubricant (optional for tension-tightening)
- f) One tightening method

An example of a BTQP may be found in e.g. ISO 17607-6.

Annex C.2 may be used for HV bolts.

The bolt manufacturer shall establish procedures to ensure that the characteristics of the products considered by the BTQP are maintained during serial production for each applied bolting assembly lot (e.g. analogous to the procedures according to EN 14399-1).

NOTE Verification of friction is not required for tension tightening.

Alternatively, on-site or laboratory test methods may be defined to verify that the bolting assemblies and installation procedures will perform as required. Herein, testing e.g. according to EN 1090-2, Annex H may be carried out. In such case, at least five representative samples from each applied bolting assembly lot shall be tested.

NOTE Where tension tightening tools are used that automatically check and record process parameters such as pressure and nut rotation angle, this may be demonstrated as being sufficient to verify correct preloading.

When tension-tightening is used, flange nuts (also known as roundnuts) or similar nuts with the same characteristics with proven suitability shall be used on the tensioned side.

At least two-stage tightening shall be performed.

NOTE Two complete rounds of tightening are necessary to compensate for the loss of preload induced by sequential tightening. Each stage is to be understood as a complete sequential tightening of all bolts on the 360° circle, where

392 using multiple tools at different positions of the circumference (e.g. spaced 180° apart) at the same time is allowed.
393 Typically, bolts are initially torqued with a low value of ~10% of nominal torque. This is not counted as an additional
394 stage.

395 The following minimum requirements apply for torque-tightened bolts:

396 a) Min. 50% and max. 75% of nominal torque should be applied for the first stage and 100%
397 of the nominal torque for the second (final) stage.

398 b) Torque-tools should undergo suitability testing demonstrating that the tightening process
399 reliably achieves target preload levels.

400 NOTE Suitability testing for torque tools is necessary because achieving the target torque value alone is not suffi-
401 cient. This is e.g. the case when tools are applying the torque very fast and shut down immediately after reaching
402 nominal torque. In that case, time is not sufficient to develop the nut rotation required for the target preload to be
403 achieved.

404

405 The following minimum requirements apply for tension-tightened bolts:

406 a) 100% of the installation preload should be applied on each stage.

407 b) For the second stage, multiple pulls should be executed until the residual nut rotation angle
408 is small; unless proven otherwise, a differential angle of 5° may be used as the criterion to
409 end the process.

410 c) Free rotation of the nuts under the installation tension should be ensured and the turn-down
411 torque must be high enough to overcome potential resistance (e.g. from impurities in hot-
412 dip galvanisation).

413

414 For both torque-tightened and tension-tightened bolts, procedures should be used to document
415 nut rotation angles incl. acceptance levels for the second stage. Acceptance levels should be
416 defined in the BTQP.

417 For all cases, re-tightening of bolts after installation has been completed should be done.

418 Where tension-tightening is used and the reduction of calculated settlement values by 50% as
419 per section 6.7.5.1.2 is applied, re-tightening shall be done after minimum 240 power production
420 hours but, in any case, not later than six months after commissioning.

421 Otherwise, or where torque-tightening is used, re-tightening may also be done earlier but, in
422 any case, not earlier than 72 hours after installation.

423

424 6.7.3.3 Gap height verification during installation

425 Assessment of the gap heights and lengths during the assembly phase may be omitted if the
426 design gap height according to section 6.7.5.2 is used.

427 Alternatively, methods shall be used during execution which ensure that the pressure body is
428 created in the flange in accordance with requirements for fatigue assessment.

429 Shimming may be used as a proven method. Where shimming is required to achieve target
430 fatigue life, the following conditions apply:

431 a) The max. allowable gap heights $k_{\text{limit,unloaded}}$ shall be specified by the designer of the
432 connection as a function of gap angle or gap length.

433 b) For the assessment of the gaps during the assembly phase, the additional influence of
434 self-weight and preload shall be considered to derive $k_{\text{limit,loaded}}$, see Figure 6. The
435 number of preloaded bolts and initial preload at this stage shall be specified by the
436 designer.

437 c) The gap heights and lengths shall be checked using suitable tools, e.g. feeler gauges.
438 Considering the requirement for an inside flange inclination (section 6.7.3.1) the gap on
439 the outside (below or close to the tower wall) shall be measured and evaluated with
440 respect to $k_{\text{limit,loaded}}$.

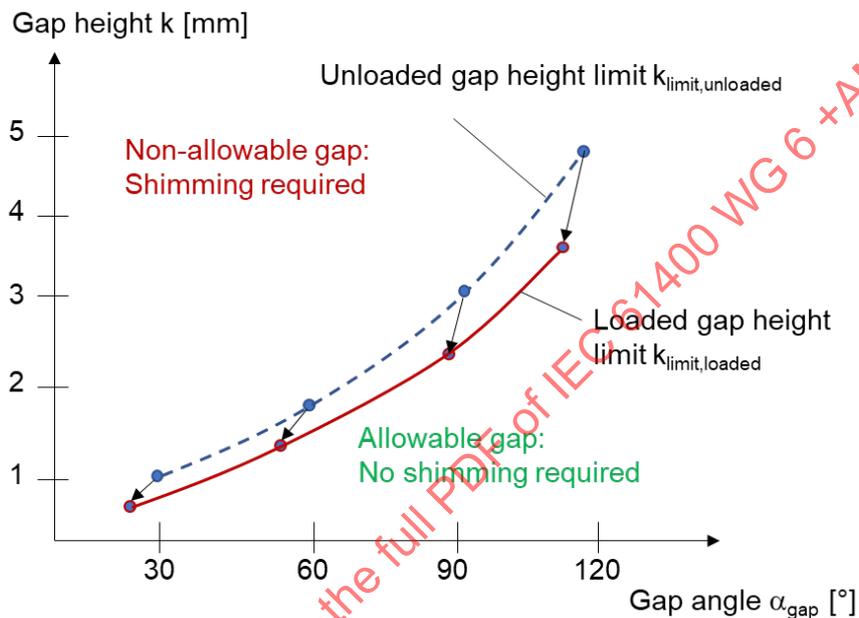
441 d) Where the measured gap height is $k_{\text{measured}} \geq k_{\text{limit,loaded}}$, the gap shall be filled with
442 the largest possible shim plate thickness at each position, see Figure 7.

- 443 e) Thickness increments for the shim plates should not exceed 0.5mm.
- 444 f) Multiple shim plates may be stacked, but the maximum number of shim plates at each
- 445 position should not exceed 3.
- 446 g) Inside gaps shall not be shimmed with higher shim plate thickness as used in the area
- 447 below the tower wall, meaning that shimming shall not be done in a way that earlier
- 448 inside contact is provoked.
- 449 h) The shims or filler material should have sufficient modulus of elasticity and compressive
- 450 strength (yield point under compression) to replicate the effect of the parent flange ma-
- 451 terial.

452 NOTE 1 Due to loading applied, gaps are reducing in both height and length.

453 NOTE 2 Measurements may be done from the inside of the tower, but feeler gauges shall be long enough to reach

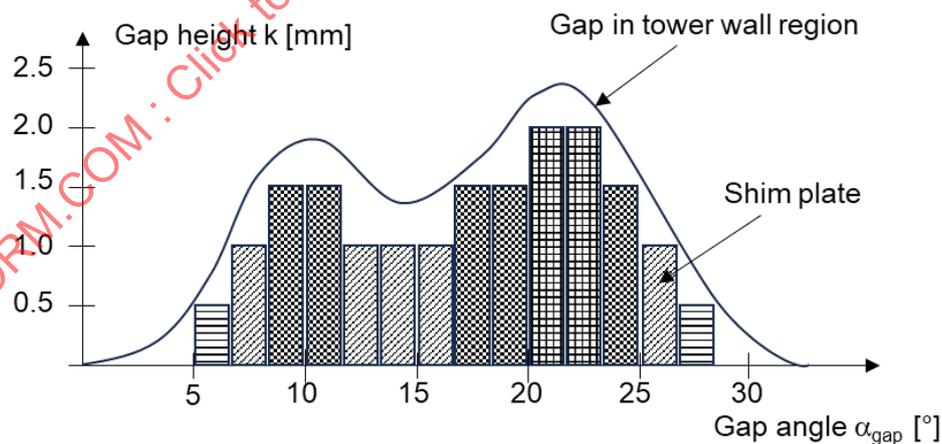
454 the critical region close to the tower wall.



455

456

Figure 6 – Schematic representation of $k_{limit,unloaded}$ and $k_{limit,loaded}$



457

458

Figure 7 – Schematic representation for the correct shimming of an unacceptable gap

459 **6.7.3.4 Inclination of flange surfaces**

460 If, after the preloading, the remaining inclination α_s of the outer flange surfaces (see Figure 2)

461 exceeds the limiting value of 2° , suitable taper washers with sufficient hardness shall be used

462 instead of the normal washers.

463

464 **6.7.4 Ultimate limit state analysis of flange and bolted connection**

465 In the ultimate limit state (ULS) analysis of the flange connections, the preloading force of the
466 bolts need not be considered, i.e. the ultimate limit state analysis may be performed as for a
467 non-preloaded bolted connection. Imperfections (e.g. parallel or angular gaps) may likewise be
468 disregarded for ULS assessment, as they don't alter the failure mechanism.

469 A simplified calculation method according to Petersen / Seidel, considering the extension by
470 Tobinaga / Ishihara (see G.1.3) may be used.

471 The calculation method shall consider at least the following three failure modes:

- 472 1. Failure of bolt due to rupture (exceedance of tensile capacity)
- 473 2. Failure of bolt due to rupture combined with plastic hinge in the tower shell and/or flange
- 474 3. Plastic hinges in tower shell and/or in flange

475 The influence of the axial load in the tower shell shall be considered when calculating the yield
476 bending strength of the tower shell and/or the flange material.

477 Favourable loads (reducing the load on the bolted connection, e.g. dead weight), if included,
478 shall use the partial safety factor for loads for favourable loads.

479

480 **6.7.5 Fatigue limit state analysis of flange and bolted connection**

481 The effect of inclination (out-of-verticality) due to tolerances of the tower and the foundation as
482 described in chapter 5.4.10 may be disregarded for FLS assessment of the flange connections.

483 **6.7.5.1 Design preload**

484 **6.7.5.1.1 Determination of design preload**

485 For the fatigue assessment, the design pretension force of the bolts should be determined
486 based on the installation preload, reduced by losses due to settlements and (if applicable) plas-
487 tic strain in the bolt or flange.

488 The design value for the preload is determined by averaging over $n=5$ bolts as follows:

$$F_{p,C}' = \underbrace{F_{p,inst,mean} \cdot (1 - 0.736 \cdot COV_p)}_{F_{p,mean}} - \Delta F_Z - \Delta F_{pl} \quad (1)$$

489 where

490 $F_{p,inst,mean}$ is the mean preload force after installation

491 ΔF_Z is the expected reduction of preload force due to settlements

492 ΔF_{pl} is the expected reduction of preload force due plastic strain development

493 COV_p is the coefficient of variation (COV) of preload force

494 NOTE. Actual preload values may be significantly higher than the mean values, particularly when torque-tightening
495 or the combined method (torque plus angle) are used. In these cases, values exceeding nominal yield are possible
496 and allowed.

497

498 Where equations (7) and (11) are fulfilled, the reduction in preload due to plastic strain devel-
499 oping in the flange and the bolts may be taken as:

$$\Delta F_{pl} = 0.05 \cdot F_{p,mean} \quad (2)$$

500 where

501 $F_{p,mean}$ is the design preload averaged over 5 bolts after installation

502

503 Eq. (1) for the design preload can then be simplified as:

$$F_{p,C}' = 0.95 \cdot F_{p,inst.,mean} \cdot (1 - 0.736 \cdot COV_p) - \Delta F_Z \quad (3)$$

504

505 Where equations (7) and (11) are not fulfilled, preload losses due to plastic strain should be
506 determined by an appropriate method, e.g. by using an FEA model with demonstrated capability
507 of correctly predicting loss of preload due to plastic strain in the paired thread region. Material
508 modelling as suggested in [2] may be used.

509 Loading should be applied as a load sequence $0 \rightarrow M_{loss} \rightarrow 0 \rightarrow -M_{loss} \rightarrow 0 \rightarrow M_{loss}$, where
510 M_{loss} is defined by Eq. (8). The bolt force curve from the last steps (from $-M_{loss}$ to M_{loss}) shall
511 be used for the assessment, as this includes the loss of preload induced by the first cycle to
512 M_{loss} . Further information can be found in [3].

513 The vertical force resulting from dead weight of RNA and tower sections above the flange con-
514 nection investigated may be included and should be multiplied with a partial safety factor for
515 favorable loads according to IEC 61400-1.

516 For HV bolts preloaded with the modified torque method the design preload shall be limited to:

$$F_{p,C}' \leq 0.9 \cdot F_{p,C}^* = 0.9 \cdot 0.7 \cdot f_{yb} \cdot A_S \quad (4)$$

517 where

518 f_{yb} is the nominal yield strength of the bolt material (e.g. 900MPa for grade 10.9 bolts)

519 A_S is the stress area of the bolt

520 In cases where preloads are verified by measurements, the statistical distribution of measure-
521 ments should be evaluated against the distribution determined by the BTQP and assumed in
522 the design (characterized by mean value and COV), considering the reduction for preload
523 losses which has been accounted for in the design.

524

525 6.7.5.1.2 Loss of preload due to settlements

526 Loss of preload due to settlements ΔF_Z (expressed in [N]) should be calculated based on the
527 expected settlements:

$$\Delta F_Z = \frac{f_{Z,tot}}{\delta_S + \delta_P} \quad (5)$$

528 where

529 $f_{Z,tot}$ is the total amount of settlement in the connection, expressed in [m];

530 δ_S is resilience of the bolt, expressed in [m/N];

531 δ_P is resilience of the clamped parts, expressed in [m/N];

532

533 Where assemblies according to section 6.3.3 are used, the total amount of settlement may be
534 assumed as:

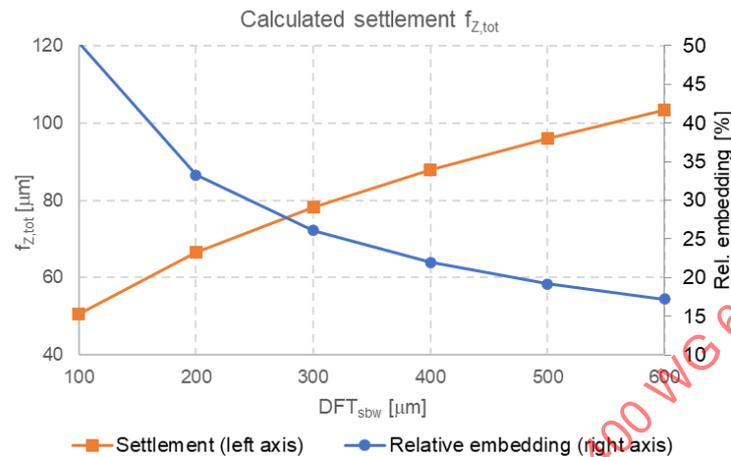
$$f_{Z,tot} = (8 \cdot DFT_{sbw}^{-0.6}) \cdot DFT_{sbw} \geq 50 \mu m \quad (6)$$

535 where

536 DFT_{sbw} is the maximum allowable dry film thickness (DFT) of coatings applied in the contact
537 area between washers and flange (points III & IV in Figure 9), expressed in μm ;

538 NOTE 1 The reference value for the formula is the coating thickness on one side of the flange (not the sum of
539 coating thicknesses). In case coating thicknesses vary on both sides of the flange, the average value should be used.

540 NOTE 2 The settlement calculated with Eq. (6) is shown in Figure 8. The relative embedding, calculated by the term
541 in brackets in Eq. (6), is shown as additional information on the second y-axis.



542

543

Figure 8 – Total settlement $f_{z,tot}$ as function of DFT_{sbw}

544 The following conditions should be fulfilled:

545 a) Coating thickness of the faying surfaces (points I & II in Figure 9) should be less or
546 equal to the coating thickness beneath washers.

547 b) Coating systems covered are EP-/PUR and thermal spray metallizing (TSM). For 2K-
548 PUR systems, the values should be increased by 25%.

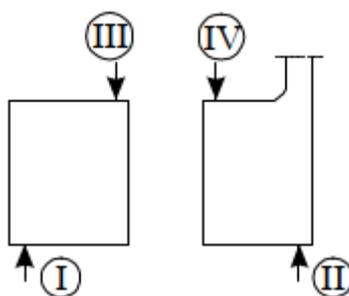
549 c) The maximum actual coating thickness should not exceed $160\mu\text{m}$ for 2K-PUR and
550 $500\mu\text{m}$ for EP-/PUR systems. Higher coating thicknesses should be assessed e.g. by
551 relaxation tests.

552 d) Eq. (6) does not cover settlements in bolted connections that are subjected to an in-
553 creased assembly preload e.g. by applying the yield-controlled tightening or the com-
554 bined method.

555 e) Eq. (6) is not valid for a flange connection with additional coated contact surfaces e.g.
556 due to insertion of a wedge flange to correct structural inclinations.

557 f) Non-coated shim plates may be considered covered.

558



559

560

Figure 9 – Coating thickness reference points

561 In case tension-tightening is used and bolts are re-tightened, the calculated settlement values
562 may be reduced by 50%.

563

564 **6.7.5.1.3 Loss of preload due to plastic strain in the bolt**

565 For bolts where the design preload is in the range $A_S \cdot 0.60 \cdot f_{yb} \leq F_{p,C'} \leq A_S \cdot 0.80 \cdot f_{yb}$, the fol-
566 lowing requirement should be met to avoid significant loss of preload due to plastic strain in the
567 bolt:

$$F_{S,loss} \leq A_S \cdot 0.85 \cdot f_{yb} \quad (7)$$

568 where

569 A_S is the stress area of the bolt;

570 f_{yb} is the nominal yield strength of the bolt material (e.g. 900MPa for grade 10.9 bolts)

571 $F_{S,loss}$ is the bolt force used to check against preload loss

572 NOTE This is based purely on the axial stresses in the bolt, as bending stresses don't cause loss of preload [2].

573

574 The bolt force $F_{S,loss}$ shall be calculated using M_{loss} , which is defined as

$$M_{loss} = \max \begin{cases} M_{\max,S1} \\ M_{\max,FLS} \\ |M_{\min,FLS}| \end{cases} \quad (8)$$

575

576 where

577 $M_{\max,S1}$ is the maximum bending moment from the S1 load case (SLS characteristic load)
578 according to IEC 61400-1 Ed.4 AMD1:2024

579 $M_{\max,FLS}$ is the maximum (most positive) bending moment included in the FLS loads

580 $M_{\min,FLS}$ is the minimum (most negative) bending moment included in the FLS loads

581

582 Maximum and minimum bending moment included in the Markov matrix are calculated as fol-
583 lows.

$$M_{\max,FLS} = \max_{i \in [n]} \left\{ M_{\text{mean},i} + \frac{M_{\text{range},i}}{2} \right\} \quad (9)$$

$$M_{\min,FLS} = \min_{i \in [n]} \left\{ M_{\text{mean},i} - \frac{M_{\text{range},i}}{2} \right\} \quad (10)$$

584 where

585 $M_{\text{mean},i}$ is the mean value of entry i in the Markov matrix;

586 $M_{\text{range},i}$ is the moment range of entry i in the Markov matrix;

587

588 Where the preload loss criterion acc. to Eq. (7) is not fulfilled with the intended preload, the
589 fatigue limit state analysis may conservatively be done with an artificially reduced preload level
590 such that Eq. (7) is fulfilled. Alternatively, numerical assessment should be done.

591

592 6.7.5.1.4 Loss of preload due plastic strain in the flange body

593 To avoid significant loss of preload due to plastic strain in the flange body, the following re-
594 quirement should be fulfilled:

$$\frac{F_{U,D}}{Z_{loss}} \geq 1.2 \quad (11)$$

595 where

596 Z_{loss} is the max. segment force derived from the bending moment M_{loss} as given in Eq.
597 (8)

598 $F_{U,D}$ is the design value of failure mode D, as defined by Eq. (G.4)

599

600 6.7.5.2 Design gap height

601 Design gaps should be assumed to be log-normally distributed, and the design gap height
602 k_{design} should be determined as the 95% quantile of a log-normal distribution for which the
603 mean value k_{mean} and coefficient of variation COV_k may be calculated as a function of the local
604 flatness tolerance $u_{tol,1m}$:

$$k_{mean} = \left(\frac{6.5m}{D} \right) \cdot \left(\frac{u_{tol,1m}}{1.4mm/m} \right) \cdot \left(0.025 \cdot L_{gap}^2 + 0.12 \cdot L_{gap} \right) \quad (12)$$

$$COV_k = 0.35 + 200 \cdot \alpha_{gap}^{-1.6} \quad (13)$$

605 where

606 D is the outer diameter of the flange connection, expressed in [m];

607 $u_{tol,1m}$ is the local flatness tolerance per flange, expressed in [mm/m];

608 L_{gap} is the length of the gap, expressed in [m];

609 α_{gap} is the circumferential angle of the gap, expressed in [degrees];

610 k_{mean} is the mean gap height, expressed in [mm];

611

612 $u_{tol,1m}$ should not be larger than 1.4mm/m where the analytical methods from this standard are
613 used for design.

614 NOTE Flange flatness may also have a negative effect on stress concentrations at the weld neck and on buckling
615 capacity. In case parallel gaps are becoming too large. Therefore, a limitation on the allowable tolerance when using
616 the analytical methods is introduced. Where larger tolerances are used, numerical assessment should be done.

617

618 Tolerance values for flatness over a 30° circumferential angle and entire circumference (global
619 tolerance) shall be derived as:

$$u_{tol,30^\circ} = u_{tol,1m} \cdot \sqrt{\left(\frac{L_{30^\circ}}{1m} \right)} \quad (14)$$

620 where

621 L_{30° is the circumferential length over a 30° sector, expressed in [m];

$$u_{tol,360^\circ} = 1.5 \cdot u_{tol,30^\circ} \quad (15)$$

622

623 During factory acceptance testing of the tower sections, $u_{tol,30^\circ}$ should be evaluated in addition
624 to $u_{tol,1m}$ for $D \geq 6.0m$.

625

626 The parameters for the log-normal distribution are calculated as:

$$\sigma_k = \sqrt{\ln(COV_k^2 + 1)} \quad (16)$$

$$\mu_k = \ln(k_{mean}) - 0.5 \cdot \sigma_k^2 \quad (17)$$

627

628 The 95% quantile of the log-normal distribution is calculated as:

$$p_{95} = \mu_k + 1.6449 \cdot \sigma_k \quad (18)$$

629

630 The design gap height then becomes:

$$k_{design} = e^{p_{95}} \quad (19)$$

631

632 Where FEA is done, the gap shape should be assumed with the following function:

$$k(\ell) = \frac{k_{design}}{2} \cdot \cos\left(2 \cdot \pi \cdot \frac{\ell}{L_{gap}} - \pi\right) + \frac{k_{design}}{2} \quad (20)$$

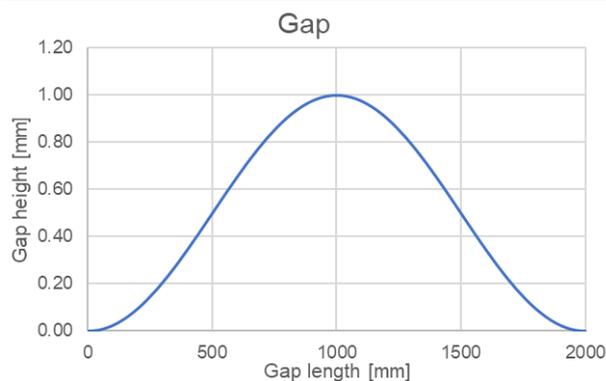
633 where

634 $k(\ell)$ is the gap height at position $0 \leq \ell \leq L_{gap}$;

635 k_{design} is the design gap height, defined as the 95% fractile value of the log-normal distribution
636 defined by k_{mean} and COV_k

637

638 NOTE An example for $L_{gap}=2000mm$ and $k_{design}=1.0mm$ is given in the Figure 10.



639

640

Figure 10 – Gap shape ($L_{\text{gap}}=2000\text{mm}$ / $k_{\text{design}}=1.0\text{mm}$)**6.7.5.3 Bolt force and moment calculation model**

642 For both L- and T-Flanges, bolt forces and moments should be determined either by Finite
643 Element Analysis (FEA) or using a simplified calculation method capable of including the effect
644 of parallel gaps which has been calibrated against FEA models. The polynomial model given in
645 Annex G.3 may be used.

646 Circumferential gap angles of 30°, 60°, 90° and 120° should be considered as potentially de-
647 sign-driving cases, where the case providing the highest fatigue damage is decisive. Values
648 outside this range and intermediate values do not need to be checked.

649 If the taper on the T-flanges is designed such that it ensures that the first point of contact is
650 directly below the tower wall, the effect of taper may be omitted from the calculations. In all
651 other cases, the taper should be included in the model with the worst-case inclination allowed
652 by the manufacturing specification.

653 Stress concentrations from macro-geometric effects should be considered by applying a stress
654 concentration factor (SCF) on the external force Z applied to the flange segment. The SCF may
655 be determined as the average increase of meridional tower stress over a length spanning 5
656 bolts.

657 NOTE Macro-geometric effects can e.g. be related to:

658 a) Door openings: Large cut-outs are leading to local stress increases near the edges of the opening.

659 b) Jacket legs: Transition pieces from jackets with three or four legs often have higher stiffness at the locations
660 where the jackets legs are transitioning into the cylindrical tower shape.

661

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662 6.7.5.4 Damage calculation

663 The combined stress range should be calculated from axial and bending stress contributions
664 as:

$$\Delta\sigma = \Delta\sigma_{axial} + 0.5 \cdot \Delta\sigma_{bending} \quad (21)$$

665 where

666 $\Delta\sigma_{axial}$ is the stress range from axial forces in the bolt

667 $\Delta\sigma_{bending}$ is the stress range from bending moments in the bolt

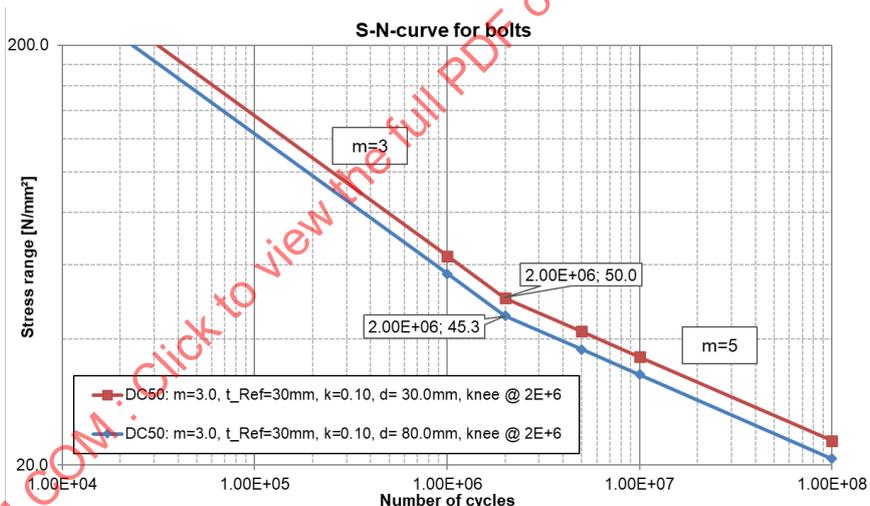
668 NOTE Bending stresses may be extracted in the symmetry plane of the flanges, as this is the common reference
669 point used. Towards the threads, bending stresses may be higher due to geometrical non-linearity. This is inherently
670 included in the evaluation of the effective bending stress.

671 The fatigue safety of the bolt shall then be assessed using detail category 50, i.e. the reference
672 stress range is $\Delta\sigma_C=50\text{MPa}$ at $N=2\text{e}6$ cycles, in case hot-dip galvanized bolts are used.

673 The partial material safety factor should be taken as $\gamma_M=1.1$.

674 The knee point (transition point from $m=3$ to $m=5$ slope) may be assumed to be at $N=2\text{e}6$ cycles
675 (Figure 11). Higher detail categories may be used e.g. for bolts which are rolled after heat
676 treatment or when using other corrosion protection systems, where they are substantiated by
677 testing or where approvals / certificates exist.

678 For bolts larger than M30, a reduction of the S/N curve by the factor $k_S = (30\text{mm}/d)^{0.10}$ shall be
679 used, where d is the nominal diameter of the bolt.



680

681 **Figure 11 – S-N-curve for bolts (examples M30 and M80 shown)**

682 Fatigue assessment shall be performed based on Miner's rule. When directionality of wind (and
683 waves in case of offshore turbines) is considered, the allowable damage is $D=1.0$.

684 For onshore turbines uni-directional wind may be assumed, and then the allowable damage is
685 increased to $D=3.0$, provided that the maximum occurrence probability for one 30° sector from
686 the wind rose does not exceed 40%.

687 Alternatively, methods for load comparison may be used provided that the influence of mean
688 loads is included.

689

6.7.5.5 Fatigue assessment of flange weld and fillet radius

The presence of the flange implies a stress concentration at the weld seam to the tower shell and in the fillet radius of the flange. Such stress concentration should be considered for the fatigue assessment. The method as presented by Seidel [4] may be used for the flange weld if the local flatness tolerance per flange does not exceed $u_{tol,1m}=1.4\text{mm/m}$.

The verification point of the weld should be selected considering the weld preparation.

For L-flanges only, the fatigue resistance of the weld neck radius must not be assessed where the following conditions are fulfilled:

- a) Radius is at least 10mm: $r \geq 10\text{mm}$
- b) Wall thickness of the adjacent shell is limited to: $s \leq 6 \cdot r$
- c) Geometry requirements for the neck height and weld location are fulfilled as shown in Figure 12:
 - i) Distance from flange surface to edge of weld preparation is at least fillet radius plus 15mm:
 $h_{wp} \geq r+15\text{mm}$
 - ii) After welding, the weld toe is at least 10mm away from the start of the radius:
 $h_{wt} \geq r+10\text{mm}$
 - iii) Weld neck height does not exceed $h_n=r+s+20\text{mm}$.
- d) The fatigue assessment of the flange weld has been performed with a detail category not exceeding a reference fatigue strength of $\Delta\sigma_C=125\text{MPa}$ at $N_C=2e6$ cycles.

NOTE Under these conditions, it may be assumed that the increased fatigue resistance in the radius region is sufficient to compensate for the increased fatigue stresses in the radius region compared to the weld.

In all other cases, the flange neck radius should be assessed considering the additional geometric stress concentration from the radius.

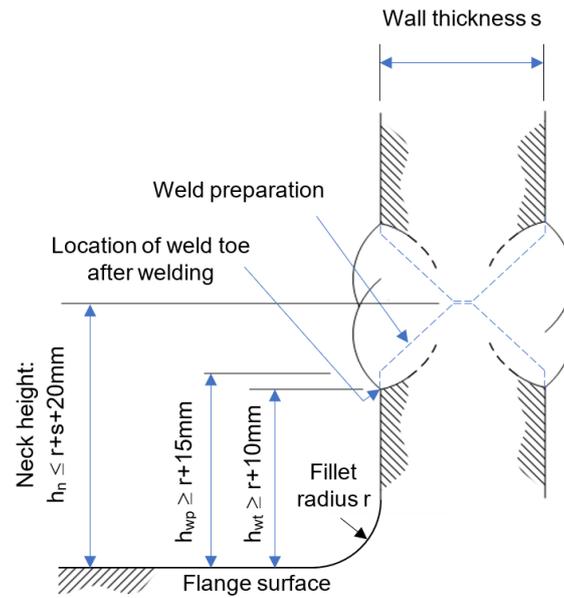
NOTE 1 Flange imperfections may be disregarded, as it has been shown in [5] that the effect is negligible.

NOTE 2 Using a larger radius than $r=10\text{mm}$ or using a lower detail category than DC125 for the weld assessment allows larger wall thickness being used without the necessity of an explicit fatigue assessment in the radius. This may be shown on a generic basis to avoid assessment in all individual cases.

The weld toe to flange surface distance should consider the required distance due to both production and repair welding.

For the fatigue assessment in the radius, the following detail category may be used for forged flanges made from minimum S355 (or equivalent) steel and protected against corrosion:

- a) Reference fatigue strength at $N_C=2e6$ cycles: $\Delta\sigma_C=200\text{MPa}$
- b) Slope $m=5$ up to $N_C=2e6$ cycles, slope $m=9$ thereafter (i.e. knee point of S-N-curve is at $N_D=N_C=2e6$ cycles)
- c) No thickness correction



726

727

728

729

730 **8.5.3.4 Soil degradation under cyclic loading**

731 Replace last sentence in first paragraph:

732 This risk may be addressed by fulfilling a zero ground gap criterion or by other mitigation
733 measures outlined in this section.

734

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Annex C (Informative)

757
758

759 *The following additions are made to Annex C:*

760 **C.2 Use of HV bolt assemblies**

761 Where HV bolt assemblies according to [3] or [4] are used by applying the modified torque
762 method, the mean preload (over all bolts) and COV after installation should be taken from Ta-
763 ble 1.

764 **Table 1 – Mean preload after installation**

	Torque-tightened HV bolts, approved for humidity	Torque-tightened HV bolts, not explicitly approved for humidity
$F_{p,inst.,mean}$	$77\% \cdot A_S \cdot f_{yb,k}$	$0.8 \cdot 77\% \cdot A_S \cdot f_{yb,k}$
COV_p	0.10	0.15

765 where

766 A_S is the nominal stress area of the bolt;

767 $f_{yb,k}$ is the nominal yield limit of the bolt (e.g. 900MPa for a 10.9 bolt);

768
769 NOTE 1 The values provided in Table 1 represent input parameters for the design. A mean preload level of
770 $77\% \cdot A_S \cdot f_{yb,k}$ in combination with $COV=10\%$ leads to a 5% quantile of $71\% \cdot A_S \cdot f_{yb,k}$ when averaging over five bolts.
771 Hence this is consistent with the nominal preload $F_{p,C}^*$ for HV bolts when applying the modified torque method, which
772 is $70\% \cdot A_S \cdot f_{yb,k}$. The limit according to Eq. (4) shall be applied for the design preload.

773 NOTE 2 For HV bolts “not explicitly approved for humidity”, the established requirements according to EN 14399
774 and DAST-Richtlinie 021 apply, see 6.7.3.2.

775 Suitability tests during serial production as defined in 6.7.3.2. shall be performed in both dry
776 and wet conditions for “bolts approved for humidity”.

777 Bolting assemblies shall in any case comply with the requirements set for the serial production
778 for each applied bolting assembly lot (e.g. analogous to the procedures according to EN 14399-
779 1).

780 Suitability for humidity / wet conditions may be demonstrated using the water immersion test as
781 defined in C.3.

782 The higher preload valid for bolts “approved for humidity” may also be used where handling and
783 installation procedures are in place which ensure that bolts are not exposed to moisture (e.g.
784 high humidity or rain) or where preload measurements are made during installation to validate
785 the design assumptions.

786 NOTE Bolts should still be protected against environmental impact even if “approved for humidity”.

787 **C.3 Water immersion test**

788 The water immersion test described in the following may be used to investigate how a bolt
789 assembly performs when the assembly has been exposed to water, with regards to the preload
790 of the bolt assembly when being torqued. For the test, a disassembled bolt assembly shall be
791 immersed into water and the effect on the preload shall be evaluated according to the following
792 paragraph.

793 The test should be executed as follows: Add sufficient water to a tank, suitable for the dimension,
794 either in a vertical or horizontal position, such that the components of the disassembled bolt
795 assembly are fully immersed. The temperature of the water should be $20 \pm 5^\circ\text{C}$. The components
796 shall be immersed between 5 and 10 minutes. After the components have been immersed, the
797 assembly shall be tested with regards to the torque-tension relation according to EN 14399-2.

798 The test shall be conducted within 5 minutes after the components have been removed from
799 the water.

800 C.4 References

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808

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809

Annex G810 *The following corrections and additions are made to Annex G.*811 **G.1.2 Calculation method**812 Failure modes for T-Flanges are as follows:

813 Failure mode A

$$F_u = 2 \cdot F_{t,R} \quad (\text{G.2a})$$

814

815 Failure mode B

$$F_u = 2 \cdot \frac{F_{t,R} \cdot a + M_{pl,3}}{a + b'_B} \quad (\text{G.3a})$$

816

817 Failure mode D

$$F_u = 2 \cdot \frac{M'_{pl,2} + \Delta M_{pl,2} + M_{pl,3}}{b'_D} \quad (\text{G.4a})$$

818

819 Failure mode E

$$F_u = 2 \cdot \frac{M_{pl,2} + M_{pl,3}}{b'_E} \quad (\text{G.5a})$$

820

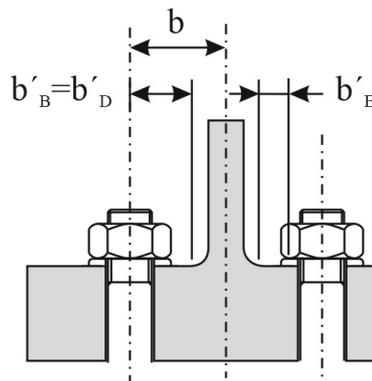
821 For T-Flanges, the location of the plastic hinge for $M_{pl,3}$ is in the flange, see Figure G.6. The
 822 reduced distances in between plastic hinges (b') are given by:

$$b'_B = b'_D = b - \frac{s}{2} - \frac{4}{5} \cdot r \quad (\text{G.24})$$

$$b'_E = b - \frac{D + d_B}{4} - \frac{s}{2} - \frac{4}{5} \cdot r \quad (\text{G.25})$$

823

824 See [7] for further explanation on the method.



825
826 **Figure G.6 – Location of plastic hinges for T-Flanges**

827
828 Ultimate axial design resistance of the bolts:

829
$$F_{t,R} = 0.9 \cdot A_s \cdot \frac{f_{ub}}{1.25} \quad (G.6)$$

830
$$M_{pl,3} = \min \left\{ \begin{array}{l} M_{pl,N,BI} = \left[1 - \left(\frac{N}{N_{pl,BI}} \right)^2 \right] \cdot M_{pl,BI} \\ M_{pl,V,FI} = \left[1 - \left(\frac{V}{V_{pl,FI}} \right)^2 \right] \cdot M_{pl,FI} \end{array} \right. \quad (G.11)$$

831
832 **G.3 Method for fatigue strength analysis according to Seidel (Polynomial**
833 **model)**

834 In this section, an analytical approximation for the calculation of both bolt force and bolt moment
835 is described. The model is illustrated in Figure 13 for L-Flanges and T-Flanges. The bolt force
836 curve is calculated as a function of the gap length L_{gap} and total parallel gap height k (Figure
837 2).

838 When this model is being used for FLS evaluation, the following condition shall be fulfilled for
839 L-Flanges:

$$F_{U,B} \leq \max \{ F_{U,A}; F_{U,D}; F_{U,E} \} \quad (22)$$

840
841 For T-Flanges, the following condition shall be fulfilled:

$$F_{U,A} \leq \max \{ F_{U,B}; F_{U,D}; F_{U,E} \} \quad (23)$$

842

843