Structural Engineering - Towers

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Wind Turbine Certification

Essen, October 21, 2014

ENERGY
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Agenda

Introduction

What is it all about?

- Design evaluation as part of the component or type **certification**
- Towers for **onshore** wind turbines

Introduction

Supporting structures of the towers of wind turbines

- Steel tower: tube tower and lattice tower
- Concrete tower: reinforced concrete tower and hybrid tower

Introduction

Steel towers

- Tube tower

- Lattice tower

Introduction

Steel towers – tube tower

- Cylindrical tube with graduated diameter (conicity) and wall thickness
- Manufactured from individual segments which are assembled at the tower on the construction site
- Prefabrication of segments out of individual pole sections (usually 3 m) in the factory: cutting, bending and welding of heavy plates
- Dimensions limited by transportation: length 25 m and more but diameter <4.30 m!
- Connecting the segments by L flanges (threaded connection)
- Connection foundation by L or T flange at anchor cage or foundation component
- Typically ring foundations possibly with pile foundation

Introduction

Steel towers – lattice tower

- Spatial framework (similar to overhead line pylon)
- Manufactured from commercially available angle profiles that are assembled on site
- Prefabrication of the individual components in the factory: cutting and production of screw holes
- Galvanizing: zinc bath limits the size of the components
- Installation on construction site in sections with hoisting
- Connection of the components only by (pre-stressed) bolted joints for galvanization (influences production of hole and contact surfaces)
- Adapter piece for connecting the nacelle to framework
- Individual foundations (corner legs encased in concrete)

Concrete towers

- Reinforced concrete towers

- Hybrid tower

Introduction

Concrete towers - reinforced concrete tower

- Cylindrical tube with graduated diameter (conicity); wall thickness and concrete quality
- Onsite concrete construction or segmental construction
- Prefabrication of the segments or segment components in the factory: dimensions limited by transportation
- Prestressing with subsequent bond or external prestressing
- Horizontal and vertical joints in segmental construction
- Adapter piece for connecting the nacelle to the concrete structure
- Connection of tower segment / foundation with mortar joint; prestressing strands in reinforced cellar
- Typically ring foundations possibly with pile foundation

Introduction

Concrete towers – hybrid tower

- Prestressed concrete shaft with mounted steel tower shaft
- Development due to the diameter restrictions on towers over 100 meters
- Construction of tubular steel tower and reinforced concrete tower shall apply accordingly
- Connection area of the steel component to the prestressed concrete component (adaptation area)

Introduction

Underlying standards

- IEC 61400-22: Wind Turbines – Part 22: Conformity testing and certification (2010)
- IEC 61400-1: Wind Turbines – Part 1: Design requirements (2005)
  (+ Amendement 1 (2010))
- Guidelines of the certifying company (eg. GL, DNV)
- Eurocodes DIN EN 1991, DIN EN 1992, DIN EN 1993
- Guidelines of the German Institute for Construction (DIBt) for wind turbines
- Secondary literature on standards (eg, German Committee for Reinforced Concrete (DAfStb)
- Approvals (eg. European Technical Approval (ETA) for the clamping system)

Introduction

Underlying standards – German building regulations

- A certification according to IEC 61400 and Eurocodes does not satisfy German building regulations

- According to German building regulations, the requirements of the DIBt guideline must be met for wind turbines:

  eg. additional load cases, DIN EN with country-specific additions, concrete design models, general building inspection approvals

- Inspection by the authorities or an inspection engineer

Agenda

1	Introduction
2	Documents
3	Certification
4	Steel Towers - Verifications
5	Concrete Towers & Hybrid Towers - Verifications

Documents

Required documents for the certification of the tower design

- Certified load report of the wind turbine
- Certification report of the tower head flange (tower head interface = mechanical engineering)
- Proof of stability (structural analysis)
- Detailed drawings of all tower types
- Interfaces (eg, components, clamping system, foundation) must be clarified

Agenda

1	Introduction
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3	Certification
4	Steel Towers - Verifications
5	Concrete Towers & Hybrid Towers - Verifications

Certification

Procedure for the certification

- Completeness of the documents
- Plausibility
- Execution of comparison calculations
- The objective is the confirmation of the correctness and completeness of the documents submitted for examination:

  → Certification report

Certification

Certification Body Wind Turbines

TÜVRheinland®
Precisely Right.

Certification Report
Design Evaluation

Tower of Wind Turbine

Report-No.:	159/123456789-1 Rev1
Revision:	1
TÜV Rheinland Order-No.:	12345678
Date of the report:	2014-067-3
Pages:	12
Applicant / Manufacturer:	WEA AG Müllerstr. 23 12345 Hochhausen Germany
Order-No. of Applicant:	DL0123456789
Turbine type:	TYP W-94 3,5 MW
Type of certification:	Type Certification
Module:	Design Evaluation
Element:	Tower W-94 3,5 MW 120m
Scope of evaluation:	Design evaluation according to: IEC 61400-22 (2010) IEC 61400-1 (2005) + Amendment 1 (2010)
Inspector(s):	Dipl.-Ing. M. Gehlhaar (Ge)

The test results are exclusively related to the evaluated samples.

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Report-No.: 159/123456789-1 Rev1 Page 2 of 12

Content of a certification report

- Basis for the certification
- Examined documents
- Brief description of the wind turbine
- Description of the tower (geometry, materials, components)
- Constraints: base torsion spring, natural frequencies, loads, temperatures, life span (operation; lateral vibrations)
- Inspection descriptions and restrictions, (eg, to natural frequencies; idle time)
- Typically in English

Agenda

Steel Towers - Verifications

Natural frequencies

- Load reports or certification reports specify a frequency band for the calculated natural frequency of the tower and wind turbine so that the load calculation is valid
- Sufficient spacing of the natural frequencies of the tower to the excitation frequencies from the turbine operation (1P to NP with P = frequency of the sheet continuity) to avoid resonance effects
- Validation of the compliance with the natural frequencies

Steel Towers - Verifications

Ultimate limit state (ULS) - Strength

- Strength of the tower shell according to DIN EN 1993-1-1

- Normal force and bending moment: normal stress σ
  Lateral force and torsion: shear stress τ
  Interaction: equivalent stress σ_v

- Verification:
  $\sigma / \sigma_{R,d} \leq 1$
  $\tau / \tau_{R,d} \leq 1$
  $\sigma_v / \sigma_{R,d} \leq 1$

- Verification with $\gamma_M = 1$:
  $\sigma_{R,d} = f_{y,k} / \gamma_M$
  $\tau_{R,d} = \sigma_{R,d} / \sqrt{3}$

Steel Towers - Verifications

Ultimate limit state (ULS) - Stability

- Stability of the tower shell according to DIN EN 1993-1-6
- Decisive in the context of strength verification
- Analytical verification of the tower section
- Consideration of the production quality (quality class of the manufacturing tolerance) through the reduction factors
- Verification in the form of a stress analysis of fictitious steel segments with a constant diameter and wall thickness with $\gamma_M = 1.1$

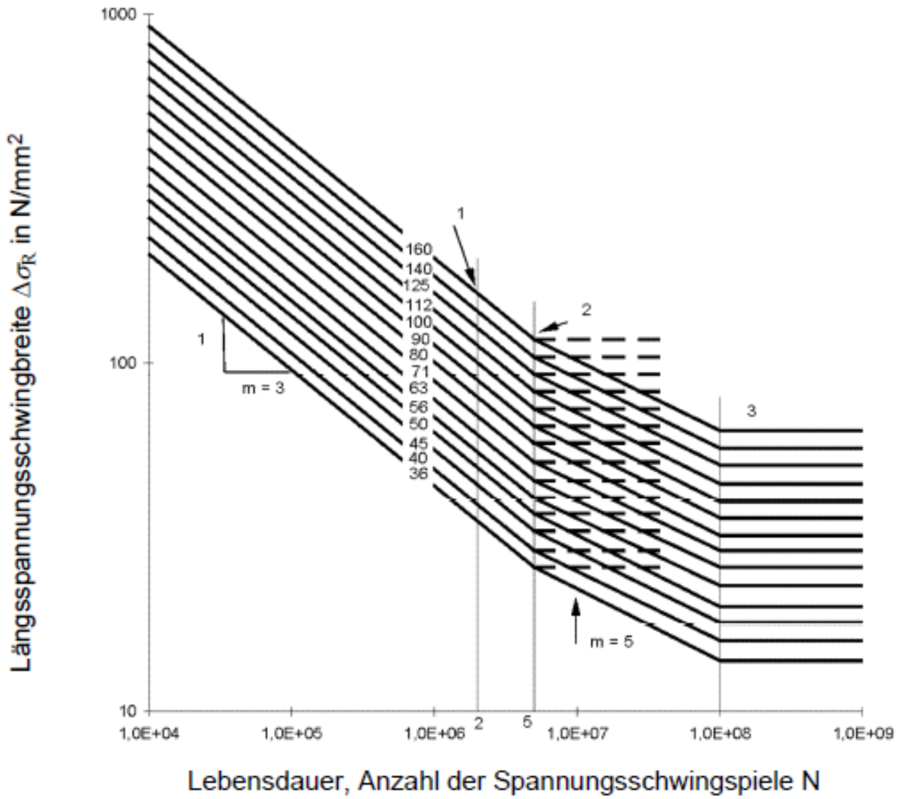
Steel Towers - Verifications

Ultimate limit state (ULS) - Fatigue

- Fatigue limit state (FLS) of the tower shell according to DIN EN 1993-1-9 with $\gamma_F = 1$
- Verification of welding seams and welding points for platforms and internal components with nominal stress with associated detail category tables
- Verification of the welding seams in the door area or openings with structural stresses and detail category tables (Appendix B)
- Calculation of the tower tubing in the door area by the FE method with evaluation of the stress components
- In the area of openings also with analytical notch stress

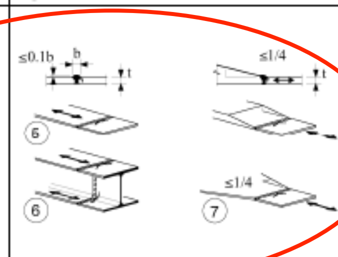
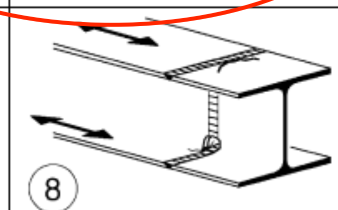
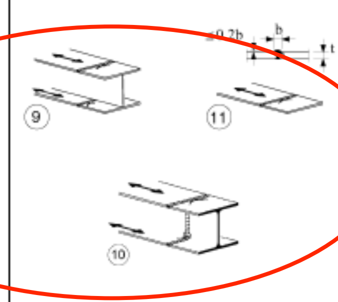
Steel Towers - Verifications

Ultimate limit state (ULS) - Fatigue



Steel Towers - Verifications

Ultimate limit state (ULS) - Fatigue

		3		
90	Blechdi-ckenab-hängigkeit für $t > 25$ mm: $k_s=(25/t)^{0.2}$		5) Querstöße von Blechen oder Flachstählen. 6) Vollstöße von Walzprofilen mit Stumpfnähten ohne Freischnitte. 7) Querstöße von Blechen oder Flachstählen, abgeschrägt in Breite oder Dicke mit einer Neigung ≤ ¼. Der Übergang muss kerbfrei ausgeführt werden.	– Die Nahtüberhöhung muss ≤10 % der Nahtbreite und mit verlaufendem Übergang in die Blechoberfläche ausgeführt werden. – Schweißnahtan- und -auslaufstücke sind zu verwenden und anschließend zu entfernen, Blechränder sind blecheben in Lastrichtung zu schleifen. – Beidseitige Schweißung mit ZFP. Kerbfälle 5 und 7: Die Nähte sind in Wannenlage zu schweißen.
90	Blechdi-ckenabh-ängigkeit für $t > 25$ mm: $k_s=(25/t)^{0.2}$		8) Vollstöße von Walzprofilen mit Stumpfnähten mit Freischnitten.	– Alle Nähte blecheben in Lastrichtung geschliffen. – Schweißnahtan- und -auslaufstücke sind zu verwenden und anschließen zu entfernen, Blechränder sind blecheben in Lastrichtung zu schleifen. – Beidseitige Schweißung mit ZFP. – Walzprofile mit denselben Abmessungen ohne Toleranzunterschiede
80	Blechdi-ckenab-hängigkeit für $t > 25$ mm: $k_s=(25/t)^{0.2}$		9) Querstöße in geschweißten Blechträgern ohne Freischnitte. 10) Vollstöße von Walzprofilen mit Stumpfnähten mit Freischnitten. 11) Querstöße in Blechen, Flachstählen, Walzprofilen oder geschweißten Blechträgern.	– Die Nahtüberhöhung muss ≤ 20 % der Nahtbreite und mit verlaufendem Übergang in die Blechoberfläche ausgeführt werden. – keine Schweißnahtnachbehandlung – Schweißnahtan- und -auslaufstücke sind zu verwenden und anschließen zu entfernen, Blechränder sind blecheben in Lastrichtung zu schleifen. – Beidseitige Schweißung mit ZFP. Kerbfall 10: Die Nahtüberhöhung muss ≤10% der Nahtbreite und mit verlaufendem Übergang in die Blechoberfläche ausgeführt werden.
			12) Querstöße in Walzquer-	– Schweißnahtan- und -auslauf-

Steel Towers - Verifications

Ultimate limit state (ULS) – Lateral vibrations, tremors

- Verification of the stability under wind-induced lateral vibrations is to be submitted according to EN 1991-1-4
- Damage from wind-induced lateral vibrations (stage of construction; standstill) and operation is to overlay, if D > 0,1
- Size of the damage depends on the duration of exposure of the vortex shedding
- Duration of exposure is given, for example: 0.5 a (without machines)
1 a (with machines)
- Earthquake according to EN 1998-1 (certification) or DIN4149 (building regulation) if required
- Typically analytical evidence
- Overlap of earthquakes with the associated moments of wind = exceptional combination of actions

Steel Towers - Verifications

Selection of steel according to DIN EN 1993-1-10

- Verification must be provided!
- Selection of steel with regard to…

  Fracture toughness (= resistance to unstable crack propagation) and through-thickness properties (Z-grade) (= lamellar fracture in the sheet plane)

- Fracture toughness: according to table 2.1 (p. 27) quasi-permanent impacts or application of fracture mechanics
- With thick flanges and cold climate it is not possible to perform a verification with the table values.
- Z-grade: according to table 3.2 (p. 28) with consideration of assembly
- Table 3.2 of EN 1993-1-1 should be applied

Steel Towers - Verifications

Selection of steel according to 1993-1-10

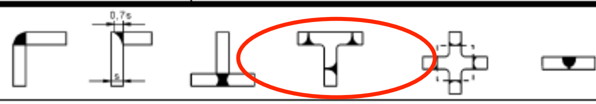
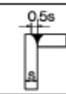
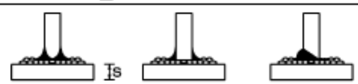
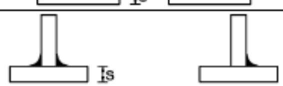
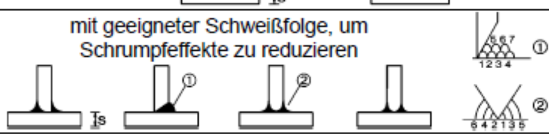
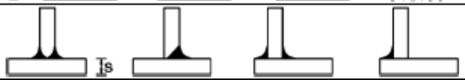
Tabelle 2.1 — Größte zulässige Erzeugnisdicken t in mm

Stahlsorte		KV		Bezugstemperatur T_{Ed} °C																				
Stahlsorte	Stahlgütegruppe	bei T °C	J_{min}	$\sigma_{Ed} = 0,75 f_y(t)$							$\sigma_{Ed} = 0,50 f_y(t)$							$\sigma_{Ed} = 0,25 f_y(t)$						
				10	0	–10	–20	–30	–40	–50	10	0	–10	–20	–30	–40	–50	10	0	–10	–20	–30	–40	–50
S235	JR	20	27	60	50	40	35	30	25	20	90	75	65	55	45	40	35	135	115	100	85	75	65	60
	J0	0	27	90	75	60	50	40	35	30	125	105	90	75	65	55	45	175	155	135	115	100	85	75
	J2	–20	27	125	105	90	75	60	50	40	170	145	125	105	90	75	65	200	200	175	155	135	115	100
S275	JR	20	27	55	45	35	30	25	20	15	80	70	55	50	40	35	30	125	110	95	80	70	60	55
	J0	0	27	75	65	55	45	35	30	25	115	95	80	70	55	50	40	165	145	125	110	95	80	70
	J2	–20	27	110	95	75	65	55	45	35	155	130	115	95	80	70	55	200	190	165	145	125	110	95
	M,N	–20	40	135	110	95	75	65	55	45	180	155	130	115	95	80	70	200	200	190	165	145	125	110
	ML,NL	–50	27	185	160	135	110	95	75	65	200	200	180	155	130	115	95	230	200	200	200	190	165	145
S355	JR	20	27	40	35	25	20	15	15	10	65	55	45	40	30	25	25	110	95	80	70	60	55	45
	J0	0	27	60	50	40	35	25	20	15	95	80	65	55	45	40	30	150	130	110	95	80	70	60
	J2	–20	27	90	75	60	50	40	35	25	135	110	95	80	65	55	45	200	175	150	130	110	95	80
	K2,M,N	–20	40	110	90	75	60	50	40	35	155	135	110	95	80	65	55	200	200	175	150	130	110	95
	ML,NL	–50	27	155	130	110	90	75	60	50	200	180	155	135	110	95	80	210	200	200	200	175	150	130
S420	M,N	–20	40	95	80	65	55	45	35	30	140	120	100	85	70	60	50	200	185	160	140	120	100	85

Steel Towers - Verifications

Selection of steel according to 1993-1-10

Tabelle 3.2 — Einflüsse auf die Anforderung Z_{Ed}

a)	Schweißnahtdicke, die für die Dehnungsbeanspruchung durch Schweißschrumpfung verantwortlich ist	Effektive Schweißnahtdicke a_{eff}, siehe Bild 3.2	Nahtdicke bei Kehlnähten	Z_i
		$a_{eff} \leq 17$ mm	$a = 5$ mm	$Z_a = 0$
		$17 < a_{eff} \leq 10$ mm	$a = 7$ mm	$Z_a = 3$
		$10 < a_{eff} \leq 20$ mm	$a = 14$ mm	$Z_a = 6$
		$20 < a_{eff} \leq 30$ mm	$a = 21$ mm	$Z_a = 9$
		$30 < a_{eff} \leq 40$ mm	$a = 28$ mm	$Z_a = 12$
		$40 < a_{eff} \leq 50$ mm	$a = 35$ mm	$Z_a = 15$
		$50 < a_{eff}$	$a > 35$ mm	$Z_a = 15$
b)	Nahtform und Anordnung der Naht in T-, Kreuz- und Eckverbindungen			$Z_b = -25$
		Eckverbindungen		$Z_b = -10$
		Einlagige Kehlnahtdicke mit $Z_a = 0$ oder Kehlnähte mit $Z_a > 1$ mit Buttern mit niedrigfestem Schweißgut		$Z_b = -5$
		Mehrlagige Kehlnähte		$Z_b = 0$
		Voll durchgeschweißte und nicht voll durchgeschweißte Nähte	mit geeigneter Schweißfolge, um Schrumpfeffekte zu reduzieren 	$Z_b = 3$
		Voll durchgeschweißte und nicht voll durchgeschweißte Nähte		$Z_b = 5$

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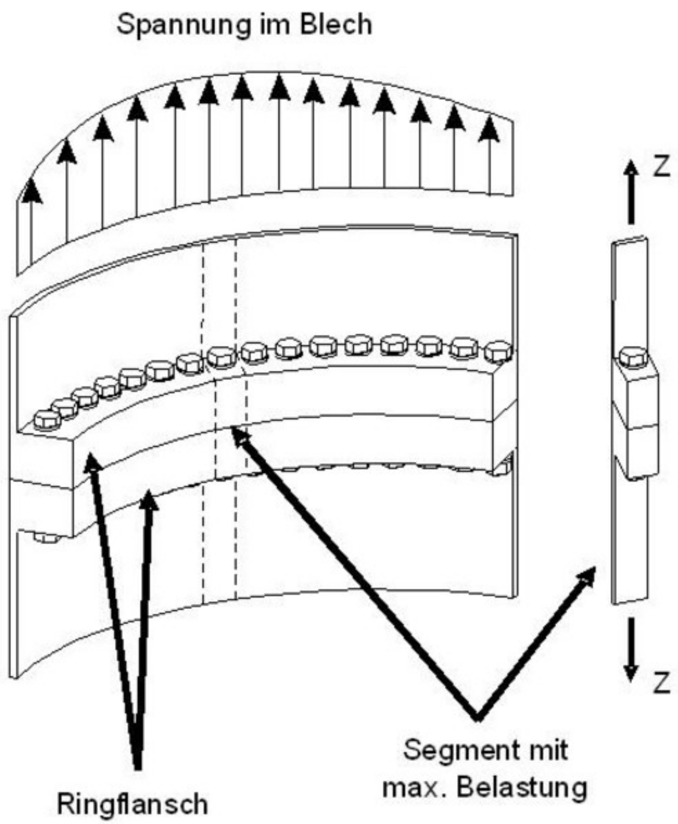
Steel Towers - Verifications

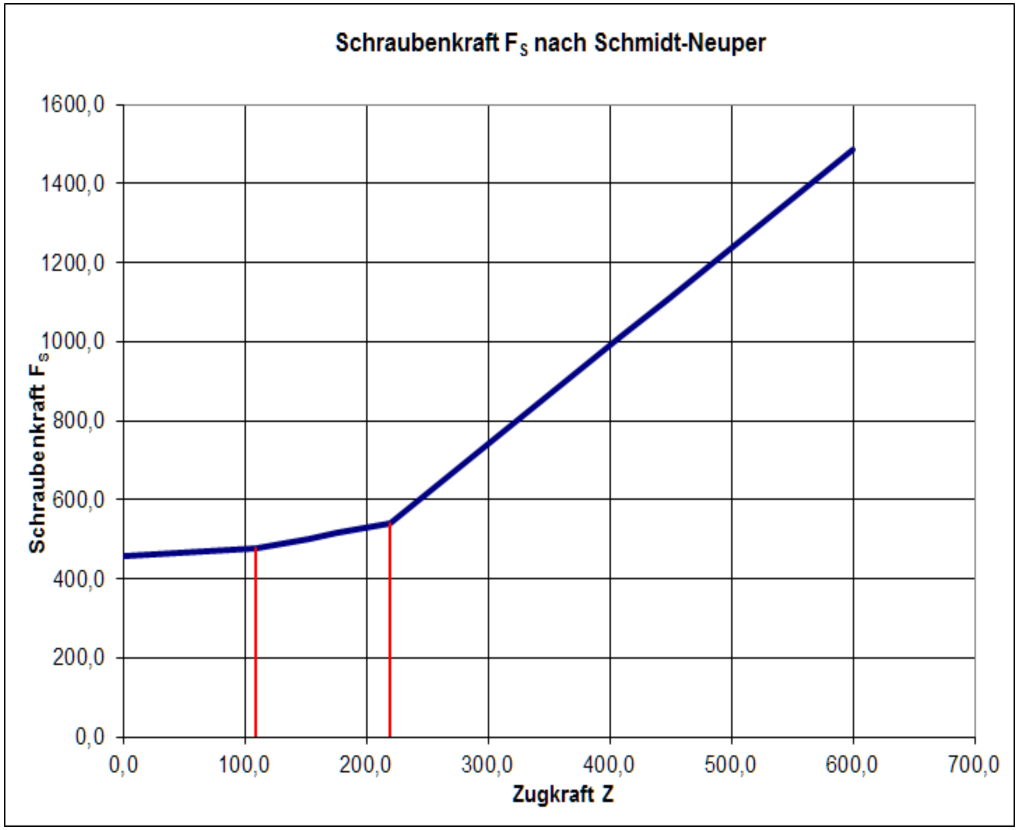
Connection flanges

- Bolted ring flange connections (L flange) = friction couplings; face joints theoretically possible with lattice towers
- Generally verification of the segment = flat, analytical model
- Stress on the connection through normal and shear force
- Proof of the load-bearing capacity: types of plastic failure according to Petersen and Seidel
- Proof of fatigue: bolt force function according to Schmidt/Neuper subject to allowable gaps in the flanges and taking into account the mean value of the strain
- Evidence of fragmentation of bolt joints: shearing, hole bearing, limit slideby force (no sliding = no fatigue!)
- Explanations shall apply correspondingly to the base flange

Steel Towers - Verifications

Connection flanges





ENERGY EXPERTISE EVERYWHERE

Steel Towers - Verifications

Door opening

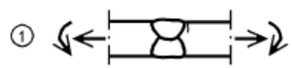
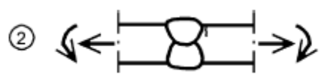
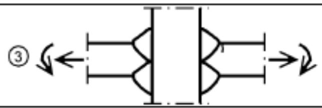
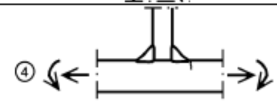
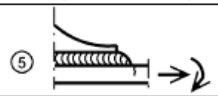
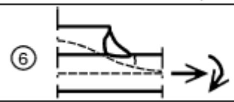
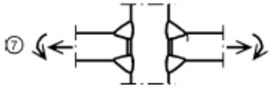
- Generally calculation of stresses based on the FE model

- Strength (ULS): Stress analysis
- Stability (ULS): Analytical method (DIBt-Ril) with given boundary conditions or numerically-based method (ideal buckling stress; LBA)
- Fatigue (ULS): Structural stress with detail category table Annex B, principal stresses or stress components based on the welding seam

Steel Towers - Verifications

Door opening

Tabelle B.1 — Kerbfälle bei Verwendung von Strukturspannungen (Kerbspannungen)

Kerbfall	Konstruktionsdetail	Beschreibung	Anforderungen
112		1) Voll durchgeschweißte Stumpfnaht.	1) – Alle Nähte blecheben in Lastrichtung geschliffen. – Schweißnahtan- und -auslaufstücke sind zu verwenden und anschließen zu entfernen, Blechränder sind blecheben in Lastrichtung zu schleifen. – Beidseitige Schweißung mit ZFP. – Für Exzentrizitäten siehe Anmerkung 1 unten.
100		2) Voll durchgeschweißte Stumpfnaht.	2) – Nähte nicht blecheben geschliffen – Schweißnahtan- und -auslaufstücke sind zu verwenden und anschließen zu entfernen, Blechränder sind blecheben in Lastrichtung zu schleifen. – Beidseitige Schweißung. – Für Exzentrizitäten siehe Anmerkung 1 unten.
100		3) Kreuzstoß mit voll durchgeschweißten K-Nähten.	3) – Anstellwinkel ≤60°. – Für Exzentrizitäten siehe Anmerkung 1 unten.
100		4) Unbelastete Kehlnähte.	4) Anstellwinkel ≤60°, siehe auch Anmerkung 2.
100		5) Enden von Anschlussblechen und Längssteifen.	5) Anstellwinkel ≤60°, siehe auch Anmerkung 2
100		6) Enden von Gurtlamellen und ähnliche Anschlüsse.	6) Anstellwinkel ≤60°, siehe auch Anmerkung 2
90		7) Kreuzstöße mit belasteten Kehlnähten.	7) – Anstellwinkel ≤60°. – Für Exzentrizitäten siehe Anmerkung 1 unten. – siehe auch Anmerkung 2

ANMERKUNG 1 In Tabelle B.1 sind keine Exzentrizitäten enthalten; diese müssen bei der Spannungsermittlung

Steel Towers - Verifications

Openings, boreholes, welding components

- Weakening of the tower metal or welded joints on the tower metal
- Vents, connection of platforms and internal components (screw bushings, flags sheets)
- Design of these components and the nature of the welding connection has an impact on the load capacity of the tower tubing, in particular in the fatigue limit state (FLS)!
- Typically a notch type is determined in the stability verification of the tower:
  → compliance with connections planned at a later time (= interface)
- Therefore, specification as early as possible of these detailed points!

Steel Towers - Verifications

Platforms and internal components

- Generally platforms and internal components are not part of the certification of the component "tower" but separate components. This also applies correspondingly to the type inspection!

- This is indicated in the certification report or in the type inspection report.

- Prior to the conclusion of the type certification and especially before obtaining a building permit, the verifications of platforms and internal components must be submitted for examination according to German building regulations.

Steel Towers - Verifications

Foundation interface

- Connection of the tower to the foundation with embedded steel can or anchor cage

- Clarification of the interfaces:
  Part of the tower = calculation within the tower assessment
  Custom component = separate assessment
  Part of the foundation = foundation assessment

- Example: Where is the verification of the concrete compressive stress in the joint performed?

  → At the conclusion of the design evaluation of the tower after clarification of interfaces (eg, after the design evaluation of the foundation).

Agenda

Concrete Towers & Hybrid Towers - Verifications

Natural frequencies, prestressing

- Examination of the natural frequencies (see „Steel towers“)
- Taking into account the loss of pretension force through chock slippage, friction, creep and shrinkage for the planned life of the wind turbine
- Dispersion of prestressing must be considered

Concrete Towers & Hybrid Towers - Verifications

Ultimate limit state

- Assessment according to EN 1992
- Bending + longitudinal force: verification of the concrete strains $\varepsilon \leq \varepsilon_{c2}$
  gaping joints e < k
  cross-section resistance (temperature)
- Lateral force + torsion : cross-section resistance
- Minimum reinforcement for ensuring ductile component behavior; failure of tendons
- Thrust transmission in the segment joints (over compressed or gaping)
- Verification of the vertical joints

Concrete Towers & Hybrid Towers - Verifications

Serviceability limit state

- Limiting the concrete compressive stress under unusual loads to 0,60 x f_{ck}
- Limiting the concrete compressive stress under quasi-continuous loads to 0,45 x f_{ck}

- Limiting the prestressing steel stress under unusual loads of 0,90 x $f_{p0,1k}$ or 0,80 x f_{pk}
- Limiting the prestressing steel stress under quasi-continuous loads to 0,65 x f_{pk}

- Limiting the crack width for internal constraint and loads

Concrete Towers & Hybrid Towers - Verifications

Ultimate limit state - Fatigue

- Assessment according to EN 1992, DIBt-Ril, DAfStb 439 (Model Code 1990)

- Concrete: Damage with the compressive stress of concrete and Woehler (SN) curves according to DIBt Ril (MC 90)
  Basically detection of model inaccuracies in the joint area with $\gamma_{Sd} = 1{,}1$

- Prestressing steel: Damage with Woehler (SN) curves or in conformity with approval

Concrete Towers & Hybrid Towers - Verifications

Ultimate limit state - Fatigue

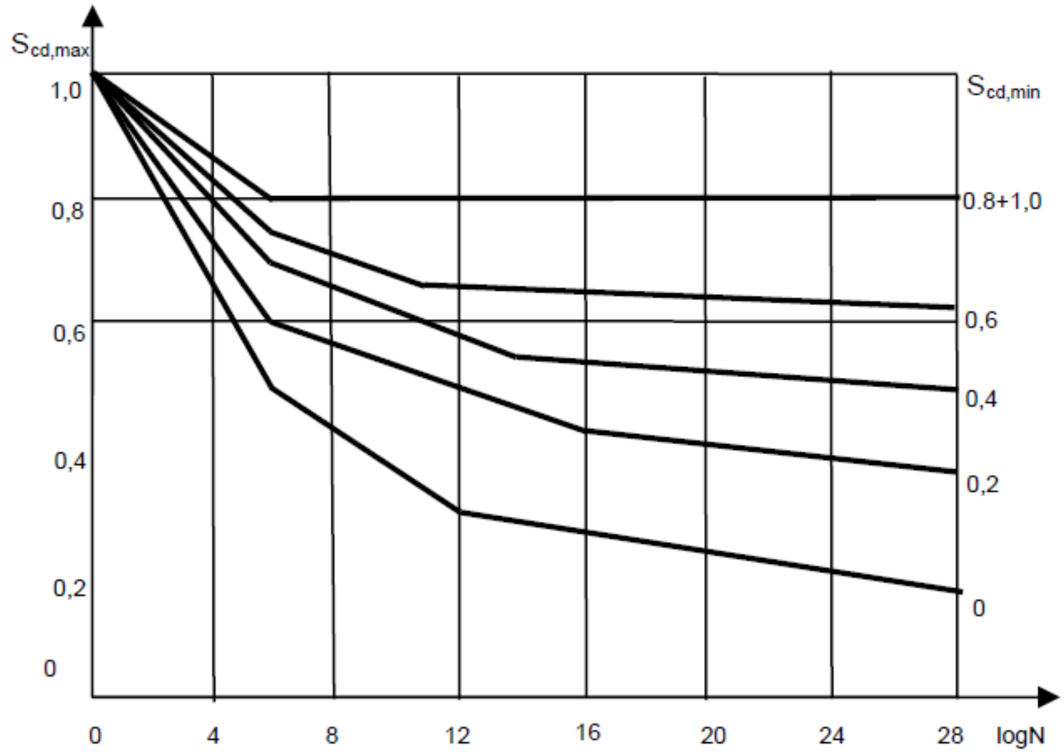


Bild 7: Wöhlerlinien des Betons unter Druckbeanspruchung

$$S_{cd,min} = \gamma_{Sd} \cdot \sigma_{c,min} \cdot \eta_c / f_{cd,fat}$$

$$S_{cd.max} = \gamma_{Sd} \cdot \sigma_{c,max} \cdot \eta_c / f_{cd,fat}$$

$$\Delta S_{cd} = S_{cd,max} - S_{cd,min}$$

Concrete Towers & Hybrid Towers - Verifications

Openings in the tower wall

- Critical situation in bending pressure zone: use small opening widths
- Assessment of the horizontal reinforcement (lintel) according to DAfStb 240
- Assessment of the vertical reinforcement as column
- Verification of the fatigue for concrete and reinforcement
- Crack width analysis under load and internal constraint (SLS)
- Verification of the concrete stress (SLS)

Concrete Towers & Hybrid Towers - Verifications

Saddle region, connection flange

- Saddle region: tensioning wire passes the active deflection force outward to the tower shell
- Assessment of the internal forces of the shells analytically (short cylindrical shells) or from the complete model
- Cross-section assessment (ULS) of the tower wall
- Reducing flange: problem detection of fracture toughness due to the greater sheet metal thicknesses

Concrete Towers & Hybrid Towers - Verifications

Lateral vibrations, tremors, building conditions

- Verification for lateral vibrations from vortex shedding must be provided (see. Steel Tower)
- Earthquake verification must be provided as required
- Verification of the building condition with wind loads prior to the clamping must be provided according to EN 1991-1-4 with consideration to the wind direction of the gust reaction factor
- Verification of the tipping stability $e < k$
- Examination of the prestressing procedure

Thank you for your attention!

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