Structural Engineering - Towers

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Wind Turbine Certification
Essen, October 21, 2014
## Agenda

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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)
Introduction

Concrete towers

- Reinforced concrete towers
- Hybrid tower
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**


- Guidelines of the certifying company (eg. GL, DNV)


- 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.
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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
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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

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

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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 $\sigma$
  - Lateral force and torsion: shear stress $\tau$
  - Interaction: equivalent stress $\sigma_v$

- Verification:
  \[
  \frac{\sigma}{\sigma_{R,d}} \leq 1 \\
  \frac{\tau}{\tau_{R,d}} \leq 1 \\
  \frac{\sigma_v}{\sigma_{R,d}} \leq 1
  \]

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

Ultimate limit state (ULS) - Structural Engineering - Towers

Steel Towers - Verifications

Ultimate limit state (ULS) - Fatigue

![Graph showing Fatigue life vs. stress range]
Steel Towers - Verifications

Ultimate limit state (ULS) - Fatigue

http://www.tuv-e3.com/
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
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

<table>
<thead>
<tr>
<th>Stählensorte</th>
<th>Stahllegitgruppe</th>
<th>( J_{\min} )</th>
<th>( T ) °C</th>
<th>( T_{14} ) °C</th>
<th>( \sigma_{sa} = 0,75 \cdot f(t) )</th>
<th>( \sigma_{sa} = 0,50 \cdot f(t) )</th>
<th>( \sigma_{sa} = 0,25 \cdot f(t) )</th>
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<tr>
<td>S235</td>
<td>JR 20 27</td>
<td>60 50 40 35 30 25 20</td>
<td>90 75 65 55 45 40 35 30 25 20</td>
<td>10 0 -10 -20 -30 -40 -50</td>
<td>135 115 100 85 75 65 50 40 35 25</td>
<td>200 200 175 155 135 115 100 85 75 60</td>
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<tr>
<td></td>
<td>J0 27</td>
<td>90 75 60 50 40 35 30 25 20 15</td>
<td>125 105 90 75 65 55 45 40 35 30</td>
<td>10 0 -10 -20 -30 -40 -50</td>
<td>175 155 135 115 100 85 75 60 55 50</td>
<td>200 200 175 155 135 115 100 85 75 60</td>
<td></td>
</tr>
<tr>
<td></td>
<td>J2 -20 27</td>
<td>125 105 90 75 60 50 40 35 30 25</td>
<td>170 145 125 105 90 75 65 40 35 30</td>
<td>10 0 -10 -20 -30 -40 -50</td>
<td>200 200 175 155 135 115 100 85 75 60</td>
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<tr>
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<td>JR 20 27</td>
<td>55 45 35 30 25 20 15</td>
<td>80 70 55 50 40 35 30 25 20 15</td>
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<td>125 110 95 80 70 60 50 45 40 30</td>
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<tr>
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<td>75 65 55 45 35 30 25 20 15</td>
<td>115 95 80 70 65 55 50 40 35 30</td>
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<td>165 145 125 110 95 80 70 55 40 30</td>
<td>200 200 190 165 145 125 110 95 80 70</td>
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<td>110 95 75 65 55 45 35 30 25 20</td>
<td>155 135 110 95 80 70 60 50 45</td>
<td>10 0 -10 -20 -30 -40 -50</td>
<td>200 200 190 165 145 125 110 95 80 70</td>
<td></td>
<td></td>
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<td></td>
<td>M,N -20 40</td>
<td>135 110 95 75 65 55 45</td>
<td>160 155 130 115 95 80 70 55 45 40</td>
<td>10 0 -10 -20 -30 -40 -50</td>
<td>200 200 190 165 145 125 110 95 80 70</td>
<td></td>
<td></td>
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<tr>
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<td>ML,NL -50 27</td>
<td>185 160 135 110 95 75 65</td>
<td>200 200 180 155 130 110 95</td>
<td>10 0 -10 -20 -30 -40 -50</td>
<td>200 200 200 190 165 145 120</td>
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<td>80 60 50 40 30 25 20</td>
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<td></td>
<td>K2,M,N -20 40</td>
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<td>155 135 110 95 80 65 55</td>
<td>200 200 175 150 130 110 95</td>
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<td>ML,NL -50 27</td>
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<td>200 180 155 135 110 95</td>
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<td>S420</td>
<td>M,N -20 40</td>
<td>95 80 65 55 45 35 30</td>
<td>140 120 100 85 70 60 50</td>
<td>200 185 160 140 120 100 85</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Steel Towers - Verifications

Selection of steel according to 1993-1-10

![Diagram showing the selection of steel according to 1993-1-10](http://www.tuv-e3.com/wind.html)
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

Spannung im Blech

Segment mit max. Belastung

Schraubenkraft $F_S$ nach Schmidt-Neuper

Zugkraft $Z$

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

### Door opening

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

<table>
<thead>
<tr>
<th>Kerbfall</th>
<th>Konstruktionsdetail</th>
<th>Beschreibung</th>
<th>Anforderungen</th>
</tr>
</thead>
<tbody>
<tr>
<td>112</td>
<td>1</td>
<td>1) Voll durchgeschweißter Stumpfkontakt.</td>
<td>1) Alle Nähte blechbe in Lastrichtung geschlossen.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- Schweißnähte- und -auslaufstücke sind zu verwenden und anschließen zu entfernen.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- Booster sind blechbe in Lastrichtung zu schließen.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- Beidseitige Schweißung mit ZFP</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- Für Exzentrizitäten siehe Anmerkung 1 unten.</td>
</tr>
<tr>
<td>100</td>
<td>2</td>
<td>2) Voll durchgeschweißter Stumpfkontakt.</td>
<td>2) Nähte nicht blechbe geschlossen</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- Schweißnähte- und -auslaufstücke sind zu verwenden und anschließen zu entfernen.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- Booster sind blechbe in Lastrichtung zu schließen.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- Beidseitige Schweißung</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- Für Exzentrizitäten siehe Anmerkung 1 unten.</td>
</tr>
<tr>
<td>100</td>
<td>3</td>
<td>3) Kreuzdübel mit voll durchgeschweißten K-Nähten.</td>
<td>3) Anstellwinkel ≤90°</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- Für Exzentrizitäten siehe Anmerkung 1 unten.</td>
</tr>
<tr>
<td>100</td>
<td>4</td>
<td>4) Unbolzende Kohinhäle.</td>
<td>4) Anstellwinkel ≤100°, siehe auch Anmerkung 2.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>5</td>
<td>5) Enden von Anschlussblechen oder Längsstößen.</td>
<td>5) Anstellwinkel ≤100°, siehe auch Anmerkung 2.</td>
</tr>
<tr>
<td>100</td>
<td>6</td>
<td>6) Enden von Gurtschienen und ähnliche Anschluss.</td>
<td>6) Anstellwinkel ≤80°, siehe auch Anmerkung 2.</td>
</tr>
<tr>
<td>90</td>
<td>7</td>
<td>7) Kreuzdübel mit belasteten Kohinhäften.</td>
<td>7) Anstellwinkel ≤90°</td>
</tr>
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<td></td>
<td></td>
<td>- Für Exzentrizitäten siehe Anmerkung 1 unten.</td>
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</table>

**ANMERKUNG 1:** In Tabelle B.1 sind keine Exzentrizitäten enthalten, diese müssen bei der Spannungsermittlung berücksichtigt werden.
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!
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 (e.g., after the design evaluation of the foundation).
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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 $0,60 \times f_{ck}$
- Limiting the concrete compressive stress under quasi-continuous loads to $0,45 \times f_{ck}$

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

- 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

\[ S_{cd,\text{min}} = \frac{S_d \cdot \sigma_{c,\text{min}} \cdot \eta_c}{f_{cd,\text{fat}}} \]
\[ S_{cd,\text{max}} = \frac{S_d \cdot \sigma_{c,\text{max}} \cdot \eta_c}{f_{cd,\text{fat}}} \]
\[ \Delta S_{cd} = S_{cd,\text{max}} - S_{cd,\text{min}} \]

Bild 7: Wöhlerlinien des Betons unter Druckbeanspruchung
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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