Introduction to Wind Energy: System Design & Delivery

Turbine Tower Design

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Oct 11, 2011

Wind Turbine Tower Design

Topics to be covered

- What is Design?
- Design vs. Construction
- Understanding the Constraints
- Conceptual design
- Material Choices and Status Quo
- <u>Design Approach</u>

Design Approach

- Define loads
- Perform analysis
- Derive dimensions and details
- Example calculations

Design Loads

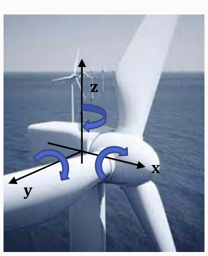
Need to account for the following loads on the tower:

- Dead Load (Self weight)
- Direct Wind Pressure
  - Applied as a static load
- Turbine Load
  - Applied dynamically, or as an amplified static load
- Extreme load (e.g., earthquake load depending on tower location in the country)

Applicable Design Specifications for Loading

- Direct Wind Loading:
  - IEC 61400-1
  - ASCE 7
- Wind Turbine Loading:
  - Typically specified by turbine manufacturers, or simulated
- Earthquake:
  - ASCE 7

Design Loads



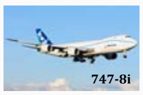
Design Loads

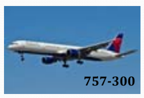
Obtaining Turbine Load Data

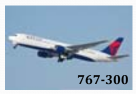
- Companies are reluctant to share much of this information
- The load data found below is from an ACCIONA AW-109/3000 wind turbine

MW	Axial (kip)	V_{Tx} (kip)	V_{Ty} (kip)	M_{Tx} (k-ft)	M_{Ty} (k-ft)	M_z (ft-k)
3	486	144.64	191.93	8124.69	4444.05	3932.81

- These loads represent forces on the head mass of the tower at 100 meters







Operational vs. Ultimate Loads

Operation-Level Loads

- Maximum un-factored loads
- Prestressed concrete is initially designed for these loads, later checked at ultimate
- Should not cause damage to the structure requiring repair

Ultimate Loads

- Maximum factored loads
- Steel and reinforced concrete are initially deigned for these loads, later checked at service-level
- Should not cause failure of the structure
- Structure may require some repair after experiencing these loads

Load Combinations

- Various loads act on a structure simultaneously
- For ultimate loads, design specifications provide factors to which each load type is magnified
- Very unlikely that every load will reach the ultimate level at once
- Various combinations use different factors

Load Combinations

1.4D (Will not govern)
1.2D + **1.6**W + **1.35**TWL
1.2D + 1.0E
*1.0D + 1.0W + 1.0TWL
**1.0D + ΔTWL

*Serviceability
**Fatigue

Perform Analysis

- Apply each load combination
- Determine the governing forces and the corresponding stresses
- This step defines the critical demands

Maximum possible demand $\begin{Bmatrix} > \\ = \\ < \end{Bmatrix}$ Permissible limit state value

Analysis — Design codes

Strength Design

- Design codes provide information on the maximum allowable stresses in materials
- Sections are often reduced so they see a magnitude of stress just below the specified limits
- This provides a more cost effective design
- Both design code stress limits and applied loads use factors to account for possible variations in capacity and demand and to provide a margin of safety.

Limit States

- is used to optimize the design (see Module 1)
- either ultimate or operational limit state criterion may govern a specific feature
- Example:

A wind turbine manufacturer requires that the tower does not exceed 30" of deflection during ultimate loads. The designer finds that by reducing the section size to a point where stresses fall just below the specified limits, deflection at the tower top is 34". The designer must now increase the section size to meet the deflection criteria.

This is an example of the operational limit state governing a design parameter

Applicable Standards for Limit States

No standardized US code for wind turbines

- Strength:
  - ANSI AISC 360-05
  - Eurocode 3
- Fatigue
  - Eurocode
  - Damage Equivalent Load Method

Limit States

Steel Limit States:

- Strength (LRFD or ASD)
  - Buckling (local and global), yielding, shear yielding/buckling, torsional yielding/buckling
  - Interaction
- Fatigue
- Serviceability
  - Deflections - Less defined, guidelines for chimneys exist
  - Frequency- Often based on blade passing frequency

Limit States

Prestressed Concrete Limit States:

- Strength:
  - Cracking/No Tension Service Level Loading
  - Ultimate Capacity – crushing of concrete or fracture of longitudinal steel
  - Shear ultimate capacity – cracking/crushing of concrete, fracture of shear reinforcement (stirrups or fibers)
- Fatigue of concrete, steel
- Operational - Deflections

Applicable Standards for Limit States

- Strength:
  - ACI 318
  - Eurocode 2
- Fatigue
  - CEB-FIP Model Code 1990 (U.S. codes do not currently address high-cycle fatigue)
- Serviceability
  - ACI 307 (Design and Construction of Reinforced Concrete Chimneys)

Dynamic Concerns

Natural Frequency of Tower

- Rotor operation produces time varying loads
- Want to avoid excessive dynamic amplification
  - For small damping, resonance condition occurs approx. when driving freq. = natural freq. of structure
  - 1P and 3P
    - For a 3MW turbine,
      - 1P = 0.22 Hz
      - 3P = 0.66 Hz

Source: NREL/SR-500-36777

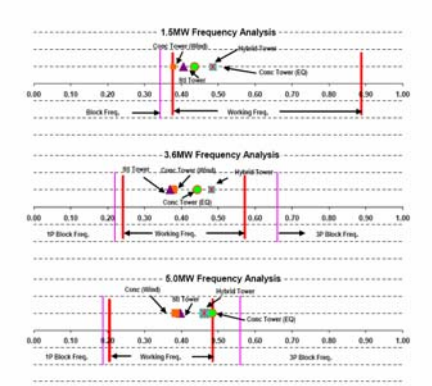


Figure 4.4. Operational frequency ranges for 1.5-, 3.6-, and 5.0-MW turbines

Expected Controlling Limit State

Hybrid:

- Steel fatigue controls the ultimate limit state

Prestressed Concrete:

- In a seismic region, strength controls
- In a wind-controlled region, concrete fatigue and tension strength control

Steel:

- Steel fatigue controls the ultimate limit state

Material Strength

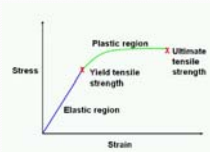
Steel

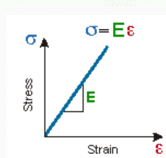
- Strength given in terms of maximum tensile stress

Concrete

- Strength given in terms of maximum compressive stress

Typically work in linear-elastic region



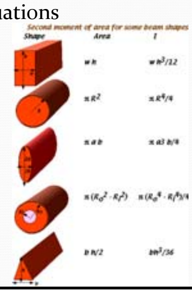


Stress Equations

While working in the linear-elastic portion of the curves we can make use of the following equations

σ=F/A (1)

σ=(M*y)/I (2)



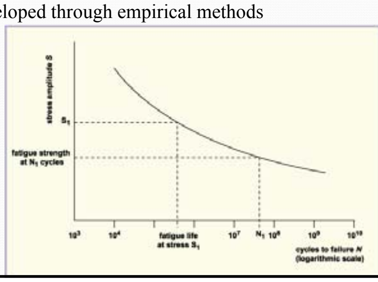
F=axial force on a cross section
A=cross-sectional area
M=moment applied to a section
y=distance from centroid to area of interest
I=second moment of area of the cross section

Fatigue

- Caused by multiple load cycles over an extended period of time
- Result of micro-crack propagation that may have been created during manufacturing
- Loads do not have to exceed the yield strength of the material to cause failure

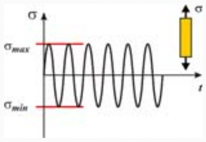
Fatigue

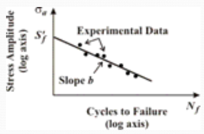
- S-N curves are commonly used to determine the fatigue life of a material
- Developed through empirical methods



Fatigue Life

For a material experiencing a cyclic load of magnitude σ_{max} over time, t





we are able to determine the fatigue life using the equation

$$N_f := \sqrt[b]{\frac{\sigma_{max}}{S_f}}$$

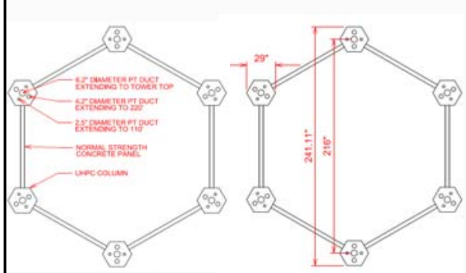
100m Concrete Design (ISU)

- Utilizes Ultra-High Performance Concrete to reduce material requirements
- Compressive strengths of 28,000 psi
- Sections transported in 30-ft segments
- Post-tensioning used to secure precast segments and increase load capacity
- Panels provide an enclosed section to reduce corrosion and protect internal components

Courtesy of ATS Inc.

A UHPC Design

Tower Base Cross Section



Foundation Design

Once the tower is designed, make sure we have a good foundation and that the tower is securely attached to the foundation.