Wind Turbine Systems – Soils, Foundation and Tower

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Design vs. construction

- Design process
  - Identify loads and limit states
  - Establish critical demands for all elements
  - Ensure capacity is greater than demand in each element
- Design from the top down
  - Roof $\rightarrow$ building $\rightarrow$ foundation
- Construct from the bottom up
  - Foundation $\rightarrow$ building $\rightarrow$ roof
- How do you determine the best design solution?
Shallow vs. Deep Foundations
Poorly designed foundations
Wind Turbine Tower Design

Presentation Topics

- Material Choices
  - Steel
  - Concrete
  - Hybrid
- Design Methods
  - Limit States/Specifications
Status Quo

Most common design:

- Tubular Steel

Source: trinitytowers.com
Typical Steel Towers

- Photos of Zearing Towers
- Typical Dimensions
GE WIND ENERGY

SALZBERGEN, GERMANY-GREENVILLE, SC-PENSACOLA, FL-TEHACHAPI, CA-SCHENECTADY, NY

TURBINE ID: MW-1.5WA247-75

WECS TYPE: WIND TURBINE GENERATOR
TURBINE TYPE: 1.5MW SLE CWE
TOWER TYPE: 79.7 M
ROTOR DIAMETER: 77 M
CUT-IN WIND SPEED: 3.5 M/S
CUT-OUT WIND SPEED: 25 M/S (10 MIN. AVE)
MAXIMUM SURVIVAL WIND SPEED: TC IIS - 52.5 M/S 50 YEAR GUST
LOW SPEED SHAFT: 11.1 TO 20.3 RPM
HIGH SPEED SHAFT: 1200-1440 RPM

MAXIMUM CONTINUOUS POWER OUTPUT: 1.5 MW
OUTPUT VOLTAGE: 575 V, 3 PHASE
OUTPUT FREQUENCY: 60 HZ

PRIMARY OVER-CURRENT PROTECTION RATING:
STATOR CIRCUIT: 2000A
ROTOR CIRCUIT: 840A

SHORT CIRCUIT INTERRUPTING CAPACITY OF PRIMARY OVER-CURRENT PROTECTION:
STATOR CIRCUIT: 500000A
ROTOR CIRCUIT: 500000A

SYSTEM: DOUBLY FED ASYNCHRONOUS GENERATOR WITH POWER CONVERTER ON ROTOR SIDE
UNIT VOLTAGE SWITCH CONTROLLED
Why is steel popular?

- Most prominent design alternative, established manufacturers
- High strength to weight ratio
- Competitive cost in the current market
Tower Mass vs. Power

Moving Forward

- Department of Energy’s 20% Wind Energy by 2030: “Continued reduction in wind capital cost and improvement in turbine performance”
- A call for towers of greater height
  - Faster wind loads
  - Higher power output/more efficient
  - Increase in turbine capacity
MultiMW wind turbines

- Twice as much rated power by applying 5 MW machines
- Relatively lower costs for grid connection, land, road construction and wind farm operation
- Lower Total Costs of Energy when WT-price of 5 MW < 1150 €/kW
Moving Forward

- There is evidence showing economical benefits of increased tower heights
  - E.g., Hybrid tower designed by ATS
    - 100m Steel Tower vs. 133m Steel/Concrete Hybrid Tower
      - 100m: 5090 MWh/yr vs. 133m: 5945 MWh/yr (17%, $110,000 increase in income per year)
      - Additional $450,000 to build 133m tower (~4 year cost recovery time vs. 20+ year typical turbine life)
Moving Forward

- Challenges of steel construction
  - Large sections necessary for taller towers
  - Transportation concerns/increased costs
    - Transportation limits diameters to 14.1 ft (4.3m)
  - Higher site development cost
  - Large crane requirement
  - Potentially long lead time
100m Steel Tower (ISU Design)

For a 100m tower,
- Base Shell Thickness: 1.5 in (38.1 mm)
- **Base Diameter:** 18 ft (5.5m)
- Top Diameter: 10 ft
- Top Shell Thickness: 0.80 in (20.3 mm)
- Increases the volume of steel by 2
- Life span is still limited to 25 years

- Clearly room for innovation in tower design
Bell curve
Design Alternatives

Other emerging options:

- Concrete
- Concrete/Steel Hybrid
- Advanced materials
Concrete

Advantages:

- Potential cost savings
  - Transportation/Development
- No local buckling concerns (thicker sections required for concrete strength)
- More corrosion resistance
- Multiple constructions options (more on this to follow)
Concrete

- Segmental Construction
  - Multiple precast sections would define the cross section
  - Sections are bolted or post-tensioned together
  - Many precasters available who could produce these sections
  - More competition of suppliers could reduce prices
  - Smaller precast modules could be more easily transported
  - Smaller crane required for construction
  - Re-use: 20 year turbine life vs. 50+ year tower life
Design Alternatives

Cast-in-Place Option

- Industrial chimneys similar in scope, construction
- Could prove to be most competitive in price
Design Alternatives

Advantage of the Hybrid:

- Combines the advantage of steel on top, concrete on bottom
- Large diameter steel-tubes not necessary (fewer transportation difficulties)
- Lower seismic weight than concrete tower
- Self-jacking tower could limit crane costs
Design Alternatives

Anatomy Of A Titan

This revolutionary new hybrid tower concept provides a practical and economical tower and foundation system that brings significant performance improvements to the wind power industry.

Comprising the lower 31 m of a 110-m or higher tower, the Atlas CTB is ideal for larger wind turbines. This flared-base, precast concrete lower section accommodates a conventional steel monotower upper section.

The large-footprint base (generally 15 m–18 m) is composed of multiple precast staves that are erected and stabilized by post-tensioning.

A big payoff: the load-distributing, large-footprint base requires a simple ring foundation with a thickness of 1 m or less.

Performance
Economics

Source: www.atlasctb.com/anatomy.html
Wind Turbine Tower Design

Topics:
- Design Loads
  - Sources
  - Specifications
- Steel
  - Limit States
  - Specifications
- Concrete
  - Limit States
  - Specifications
- Dynamic Concerns
Design Loads

Need to account for the following loads on the structure:

- Dead Load
- Direct Wind Pressure
  - Applied as a static load
- Turbine Wind Load
  - Applied dynamically, or as an amplified static load
- Earthquake (depending on tower location)
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
# Load Combinations

<table>
<thead>
<tr>
<th>Combination</th>
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<tbody>
<tr>
<td>1.4D (Will not govern)</td>
</tr>
<tr>
<td>1.2D + 1.6W + 1.35TWL</td>
</tr>
<tr>
<td>1.2D + 1.0E</td>
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<tr>
<td>*1.0D + 1.0W + 1.0TWL</td>
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<td>**1.0D + ΔTWL</td>
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*Serviceability
**Fatigue
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
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

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**

- **Serviceability - 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
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
Questions?