CHAPTER 1
CONCRETE TECHNOLOGY FUNDAMENTALS

TOWARDS THE DESIGN OF CONCRETE WIND TURBINE TOWERS

A Seminar Presentation by
Panos D. Kiousis, PhD, PE
http://windtowertechnologies.com/

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What is Concrete?

- Concrete is a construction structural material that consists of chemically inert aggregates (sand and gravel) that are bonded together by cement and water.
- Concrete is a viscous fluid at its early stages, and can take any shape through placement into formwork.
- The water in the mix interacts with the cement through a chemical process called hydration that causes the concrete to harden. Hydration is a chemical reaction in which the major compounds in cement form chemical bonds with water molecules and become hydrates or hydration products.

Concrete Composition

- Concrete is a composite material consisting of the following basic ingredients (percentage by volume):
  - Cement and cementitious materials:_____________7% to 15%
  - Water:____14% to 21%
  - Air:____1% to 8%
  - Fine Aggregate (typically sand)__________________24% to 30%
  - Coarse Aggregate (gravel or crushed rock)_31% to 51%
- Chemical admixtures are often used to:
  - Adjust the setting time or initial hardening.
  - Reduce the water demand.
  - Increase workability.
  - Intentionally entrain air.
  - Adjust other fresh or hardened concrete properties.

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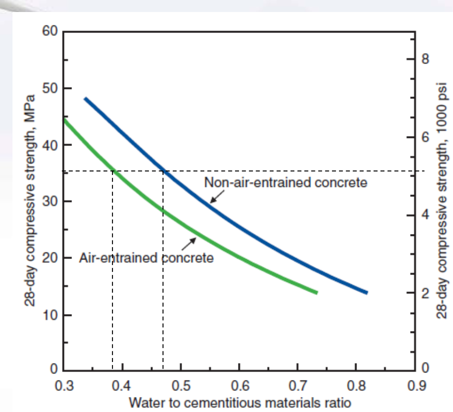
Concrete Composition (Continued)

- Concrete Strength is controlled by the ratio w/cm (water content over cementitious materials by weight).

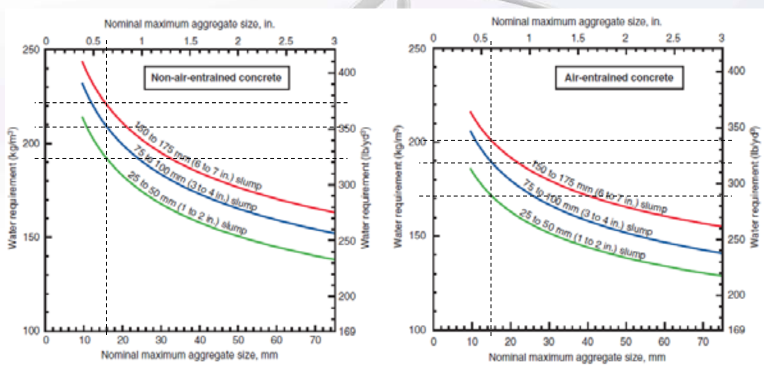
- It is interesting to note here that the concrete business in the United States is almost exclusively based on Traditional USA (imperial) units. However, the wind turbine business is based on metric units.
- Common conversion to remember for concrete applications: 4000 psi = 28 MPa



Note 1: Cementitious materials, other than cement, include other powders that react with water or with the products of hydration of cement, such as fly ash, or slag, or silica fume. Fly Ash : byproduct of coal production; slag cement: granulated blast furnace slag (GGBFS); Silica Fume: Highly reactive pozzolanic material, which is a byproduct from the manufacture of silicon or ferro-silicon metal. A pozzolan is a siliceous or aluminosiliceous material that, in finely divided form and in the presence of moisture, chemically reacts with the calcium hydroxide released by the hydration of portland cement to form calcium silicate hydrate and other cementitious compounds. Pozzolans and slags are generally categorized as supplementary cementitious materials or mineral admixtures.
Note 2: The concrete strength increases as the w/cm decreases. In theory, w/cm of approximately 0.4 is optimal, as this is the amount of water needed for complete hydration of the cement. However, the cement particles are typically hydrated at their surface only, and some cement particles are not reached by the water at all. As a result, hydration is always incomplete. The excess water remains in the paste, forms bubbles, eventually evaporates, generating voids, and tensile cracks due to shrinkage. The outcome is that the more excess water we have, the lower the quality of the concrete, and the lower its strength.
Note 3: Air entrainment generates tiny air bubbles that are diffused into the concrete mass. Thus the final products has a higher porosity. As a result, the same w/cm ratio results in concrete of lower strength.

Concrete Composition (Continued)

- Concrete flowability is typically measured by the slump test, and depends on the water amount used in the mix.



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Note 1: Flowability is a very important issue. High flowability is desired in many projects (more often than not), especially where dense reinforcement is required to secure complete encapsulation of the reinforcement and the avoidance of bugholes. Bugholes are surface voids that result from the migration of entrapped air (and to a lesser extent water) to the fresh concrete-form interface. These surface defects manifest themselves mostly in vertical surfaces, and are commonly the outcome of improper consolidation.
Note 2: High flowability demands higher than average expertise from the concrete manufacturer. Improper concrete mix design of high flowability may lead to segregation with undesirable consequences in strength, cracking, and durability among others.
Note 3: The smaller the size of the aggregate, the larger its surface to volume ratio, and thus the larger the amount of water that it retains on its surface. As a result, we need more water to achieve the same slump when we use smaller aggregates.
Note 4: The air bubbles generated by the air entrainment act as lubricants. As a result, the same slump can be generated with less water in air entrained concrete.

Concrete Composition (Continued)

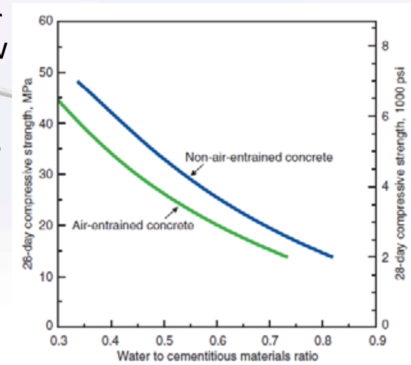
- Why air entrainment?
- It is an issue of durability in cold climates
  - There is always moisture (free water) within concrete.
  - When the water freezes, it expands.
  - As a result, the water that is within the pores of concrete, expands and applies internal pressures to concrete, which in turn causes the development of tensile cracks.
  - The repeated cycles of frost and thaw damage the concrete.
  - The generation of a field of interconnected bubbles allows the water to escape to adjacent unsaturated pores as it expands between 4ºC and 0ºC, and prevent the generation of tensile cracks that damage the concrete.

High Strength Concrete

- Moving (upward) target
  - In the 1950s high strength concrete meant compressive strength $f_c' = 5000\ psi$ or $34\ MPa$
  - In the 1960's, the definition moved to $f_c' = 6000\ to\ 7500\ psi$ or $41\ to\ 52\ MPa.$
  - In the 1970's the limit was pushed to $f_c' = 9000\ psi$ or 62 MPa.
  - Today, we have used concrete in excess of $f_c' = 20000\ psi$ or $138\ MPa$
  - **In the laboratory, we have achieved $\boldsymbol{f_c' = 116000\ psi}$ or $\boldsymbol{800\ MPa}$.**
  - Note that today's upper limits do not define what is high strength concrete.
  - ACI Committee 363 defines high strength concrete with $f_c' \geq 8000\ psi$ or 55 MPa.
  - However, it is also understood that this definition may change from place to place based on what is commercially available.

High Strength Concrete (continued)

- High strength concretes (greater than 6000 psi or 40 MPa in compressive strength) require very low water to cementitious materials ratios.
- At this level, water cannot move freely enough within the cement and aggregates mix to hydrate the cement.
- As a result, the mix can be dry. Cement dough-balls or clumps may be formed, with fairly dry cement in the middle that cannot be hydrated, and the mix is too stiff and unworkable.
- The ability of "wetting" more cement with the same amount of water is improved with the use of surfactants (old days) and superplasticizers (currently).



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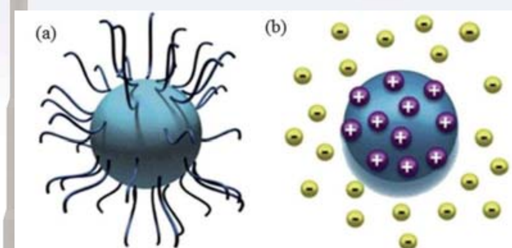
Surfactant: a substance which tends to reduce the surface tension of a liquid in which it is dissolved.

Superplasticizers, also known as high range water reducers, are chemical admixtures used where well-dispersed particle suspension is required

- The issues the produce the demand for surfactants and superplasticizers:
    - Cement particles clump together in water due to dissimilar surface electrical charges.
    - Cement clumps trap mix water.
    - Cement clumps behave like larger rougher particles, that increase the viscosity of the paste.

High Strength Concrete (continued)

- How do we achieve increased “wetting” of the cement particles with the same amount of water?
  - Water reducers neutralize the attractive charge, freeing up trapped water.
  - Stronger superplasticizers cause particles to repel each other electrostatically.
  - Polycarboxylates add a physical barrier (steric repulsion).
  - Link for video below: https://www.youtube.com/watch?v=naRoDinbbdc



N. Ali,J. A. Teixeira,and A. Addali “A Review on Nanofluids: Fabrication, Stability, and Thermophysical Properties, March 2018, Journal of Nanomaterials 2018(3/4)

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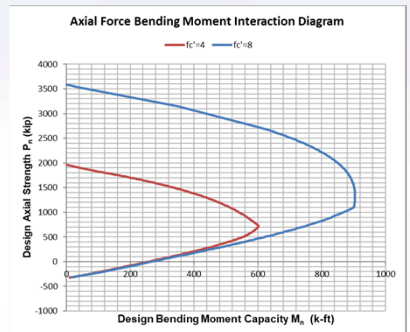
- The dispersion mechanism of electrostatic-based superplasticizers in cement paste can be explained in terms of electrostatic repulsion between the cement particles, which are negatively charged by the adsorption of the polymer molecule onto the cement surface.

- Polycarboxylates introduce electrostatic repulsion, but also add steric repulsion, where short range physical barriers are created between the cement particles. One side of the polymer chain gets absorbed on the surface of the cement grain, while the long unabsorbed side creates the steric repulsion. The physical barrier generated, prevents the cement particles to come close enough, in which case the van der Waal’s force of attraction would become effective.

High Strength Concrete (continued)

- HSC is not very effective in increasing the capacity in bending.
- The performance of HSC improves in shear, based on the square root of $f_c{}'$. For example, doubling the strength of concrete results in approximately 1.4x increase in shear capacity.
- The performance of HSC improves practically proportionately (1 to 1) in axial load capacity. As a result, HSC is the preferred material for columns in high rise structures, and in prestressed structures, which are designed to take a combination of axial forces (from the prestressing) and bending.

f_c'	M_n	% inc f_c'	% inc M_n
ksi	k-in	%	%
4	6009.412		
6	6166.275	50%	2.6%
8	6244.706	100%	3.9%
10	6291.765	150%	4.7%
12	6323.137	200%	5.2%



Note 1: The table above the figure describes the effect of compressive strength increase (f_c') to the bending moment capacity. All comparisons are with respect to the common structural concrete with $f_c' = 4000\ psi$.

Note 2: The increase in bending capacity was based on a beam with a cross-section of 30”x18” and reinforced with 4#9 bars at an effective depth of 27”. The performance improves a bit for a shallower beam and becomes worse for a deeper beam.

Note 3: The column interaction diagram is based on a column that is 22”x22” and is reinforced by 3#8 (60 ksi capacity) bars on each side. The effects on increased concrete strength (from 4 ksi to 8 ksi) are very obvious and 1 to 1 proportional for the cases of large axial loads, and diminish in cases of pure bending, which was expected based on the previous discussion regarding the ineffectiveness of HSC in bending.

High Strength Concrete (continued)

- HSC requires higher quality control, expert personnel, more cement and other cementitious materials, and more expensive chemical admixtures. Thus, as a delivered material, it is more expensive.
- The typical cementitious materials content ranges from 650 to 1000 lbs/cy^3 (386 to 593 kg/m^3). Common cement substitutes (typically in the order of 5 to 20%) are fly ash, slag, and silica fume.
- Here are concerns:
  - Hydration is an exothermic reaction. The curing process is accompanied by heat generation, which is non-uniform, and heat dissipation, which definitely has a gradient within the structure. As a result, thermal stresses are generated that may produce tension cracks and diminish the quality of the concrete.
  - The products of hydration have a smaller volume than the original materials. Thus the cured concrete has smaller volume that then original materials. Outcome: Concrete shrinkage, tension stresses, and diminished quality of concrete.
  - HSC demands small w/cm ratios. As a result, the hydration process exhausts the water in the mix, which results in fine capillaries, shrinkage, internal tensile stresses, and concrete cracking.

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High Strength Concrete (continued)

- Chemicals and other cementitious materials become important in preventing the advantages of HSC from becoming disadvantages due to poor quality
  - Internal curing using saturated porous aggregates that do not contribute their water during curing, but make it available later, prevent *autogenous shrinkage*. Lightweight aggregates have been used for this purpose. Recycled concrete, which can be quite porous, is another alternative.
  - Wet curing has similar effects. However, such an approach is more practical in slabs.
  - Use of shrinkage and crack-reducing admixtures can reduce, or sometimes completely eliminate drying shrinkage.
  - Fibers used in the mix result in crack control and an extended service life of the concrete.

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AUTOGENOUS SHRINKAGE: At low water/cement ratios, less than about 0.42, all the water is rapidly drawn into the hydration process and the demand for more water creates very fine capillaries. The surface tension within the capillaries causes autogenous shrinkage (sometimes called chemical shrinkage or self-desiccation) which can lead to cracking. This can be largely avoided by keeping the surface of the concrete continuously wet; conventional curing by sealing the surface to prevent evaporation is not enough and water curing is essential. With wet curing, water is drawn into the capillaries and the shrinkage does not occur. Note that autogenous shrinkage is separate from and additional to conventional drying shrinkage, which will start when water curing ceases.

High Strength Concrete (continued)

- Fly ash type F, and other pozzolanic materials, can be effective in reducing thermal cracks. Fly ash type F (as opposed to type C) is not cementitious (does not hydrate). When it replaces cement (for example 30% by weight), then only the remaining cement, (70%), reacts with water (hydration). As a result, less heat is generated. Fly ash type F reacts with the products of hydration. Because this is a delayed exothermic reaction, the resulting heat from this reaction occurs later, when some of the heat from the primary hydration has already dissipated.
  - **The advantage:** The resulting concrete is at least equally strong, with less cracks, and less permeability (i.e. higher durability).
  - **The price we pay:** Lower early strength, since the early strength is generated from the cement part only, which is less than 100% of the cementitious materials.
  - **Other advantages of this fly ash:** The fly ash particles are tiny little spheres that act as lubricants to the mix, and improve its workability.

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Self Consolidating Concrete (SCC)

- Very high flowability
- No need to vibrate. As the name implies, it consolidates under its own weight.
- Also known as self-compacting (mostly in Europe), and self-leveling concrete (self-leveling is not exactly an accurate property description).
- It was first developed in Japan as the solution of achieving good flow around very densely placed reinforcing steel, demanded by strict seismic requirements.

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SCC (continued)

Link to the video below: https://www.youtube.com/watch?v=gJqEGMWHHsk

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Observe the ease with which the SCC flows around the foundation, resulting in full encapsulation without the need to vibrate.
It is noted however, that long flows from the point of dispatch may result in segregation and should be avoided.
Typically, flow of about 10’ from the point of dispatch is a good limit.

SCC (continued)

- How do we achieve SCC?
- We should keep in mind that making concrete very flowable is easy.
- Making it **flowable** AND **stable** (resisting segregation) is challenging.
  - Use sufficient amounts of super-plasticizers to develop high flowability without adding excessive amounts of water.
  - Potentially add viscosity modifying agents (VMAs), to increase the viscosity of the mix and help stabilize against segregation.
  - Design the mix such that the density of the mortar (cement, sand, and water) is similar to the density of the coarse aggregate. This allows neutral floating of the coarse aggregate within the mortar, and thus increases the stability of the mix.

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Concrete Durability

- Durability is the ability to last many years (possibly its entire design life) without significant deterioration.
- A properly constituted, placed, and cured concrete is capable to resist weathering actions, most chemical attacks, and abrasion while maintaining its desired engineering properties.
- The theoretical design service life of most buildings is in the order of 30 years, although buildings often last 50 to 100 years or longer.
- Clearly, the environment in which a concrete structure operates influences the vulnerabilities that must be addressed to resist deterioration and potential loss of ability to perform as designed.

Concrete Durability (continued)

- Water, which is the “nectar of life” of concrete, can also be its poison.
- Concrete performs much better in a wet environment than a dry environment.
- Yet, water is generally involved in practically every form of deterioration. As such, the ease of penetration of water into concrete, determines the rate of its deterioration.
- Physical effects that adversely influence the durability of concrete include surface wear, cracking due to crystallization of salts in pores, and exposure to temperature extremes such as during frost action or fire.
- Deleterious chemical effects include leaching of the cement paste by acidic solutions, and expansive reactions involving sulfate attack, alkali-aggregate reaction, and corrosion of the embedded steel in concrete.

http://www.cep-sintra.ca/photos/bull_degrad_beton1.jpg

https://www.cement.org/images/default-source/contech/aar_asr_1.jpg?sfvrsn=ea1733bf_2

http://www.concrete-experts.com/pages/ft.htm

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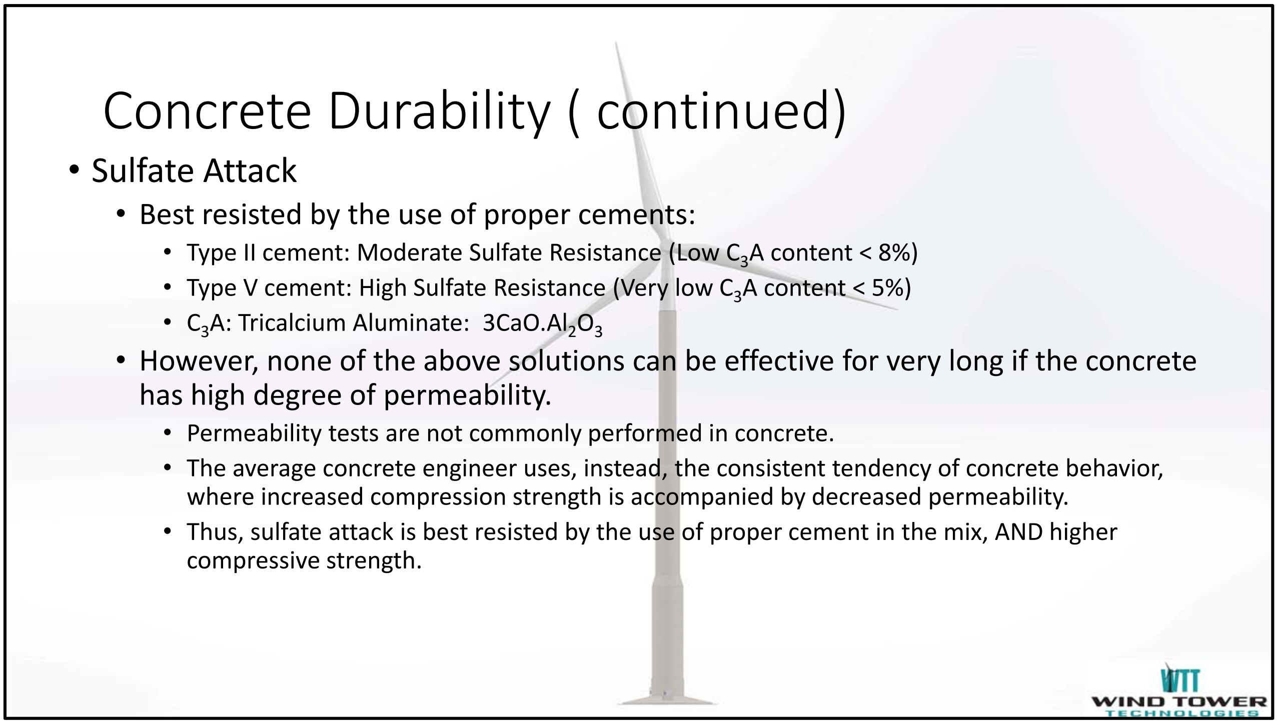
External sulfate attack – Left picture: Typically occurs where water containing dissolved sulfate penetrates the concrete. A fairly well-defined reaction front can often be seen in polished sections; ahead of the front, the concrete is normal, or near normal. Behind the reaction front, the composition and microstructure of the concrete will have changed. These changes may vary in type or severity but commonly include: Extensive cracking, Expansion, Loss of bond between the cement paste and aggregate. IN ESSENSE, THE CEMENT PASTE BREAKS DOWN, WHICH RESULTS IN AN OVERALL LOSS OF CONCRETE STRENGTH.
Alkali-Aggregate Reaction – Central picture: In most concrete, aggregates are more or less chemically inert. However, some aggregates react with the alkali hydroxides in concrete, causing expansion and cracking over a period of many years. The most significant form of alkali-aggregate reaction is alkali-silica reaction (ASR). In ASR, aggregates containing certain forms of silica will react with alkali hydroxide in concrete to form a gel that swells as it adsorbs water from the surrounding cement paste or the environment. These gels can induce enough expansive pressure to damage concrete.
Freeze-Thaw Resistance – Right picture: When water freezes, it expands about 9 percent. As the water in moist concrete freezes, it produces pressure in the pores of the concrete. If the pressure that is developed exceeds the tensile strength of the

concrete, the cavity will dilate and rupture.



- In hardened concrete, C_3A can react with sulfate salts from outside the concrete to produce calcium sulfoaluminate. This results in volume increase of the solid phase by 227 percent and causes a gradual disintegration of concrete.

Concrete Durability (continued)

- Alkali Silica Reaction
  - Good source of information: Concrete in Practice document #43 – Alkali Aggregate Reactions (AAR).
  - https://www.nrmca.org/aboutconcrete/cips/43pr.pdf
  - For deleterious ASR expansion to occur, three factors are required: alkalis, reactive silica, and exposure to moisture. Concrete that remains dry inside buildings and not in contact with soil will typically not need preventive measures. In other situations various strategies can be used to avoid damage due to ASR.
    - Avoid the use of aggregate sources that are determined to be reactive. This may not always be feasible because alternative non-reactive aggregates may not be economically available or data may not exist as to their potential performance.
    - Use a low alkali cement, typically characterized as one with Na_2O, less than 0.60%. Low alkali cement, however, is not available in many regions.
    - The more accepted option to mitigate deleterious ASR is to incorporate a supplementary cementitious materials (SCM) in concrete. SCM include fly ash (type F), natural pozzolan, slag cement, or silica fume. SCMs bind alkalis in the hydration products and prevents the deleterious expansion from occurring.

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Concrete Durability (continued)

- Freeze-Thaw
  - When water freezes, it expands about 9 percent. As the water in moist concrete freezes it produces pressure in the pores of the concrete. If the developed pressure exceeds the tensile strength of the concrete, the cavity will dilate and rupture
  - The cumulative effect of successive freeze-thaw cycles and disruption of paste and aggregate can eventually cause expansion and cracking, scaling, and crumbling of the concrete.
  - **Air entrainment -** The resistance of concrete to freezing and thawing cycles is significantly improved by the use of intentionally entrained air. The tiny entrained air voids act as empty chambers in the paste for the freezing and migrating water to enter, thus relieving the pressure in the pores and preventing damage to the concrete.
  - Concrete with a low permeability (that is, a low water-cement ratio and adequate curing) is better able to resist freeze-thaw cycles.

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Concrete Durability (continued)

- Chlorides
  - Chlorides (Calcium Chloride, Magnesium Chloride, Sodium Chloride, etc.) are often used as deicers. They also exist naturally in the ground water and in the air in areas that are close to the sea.
  - Chlorides typically have some very adverse effects in concrete.
  - Concrete, in its natural state, provides a very alkaline environment (pH between 12 and 13 is commonly measured).
  - In such an environment steel cannot oxidize.
  - However, when chloride salts are in a water solution, and dissipate into the concrete, the chloride ions (Cl^-) can lower significantly the alkalinity of the concrete. When pH drops below 9, the conditions favor the oxidization of the reinforcing steel.
    - Oxidized steel loses effective area, and has reduced interface strength properties, resulting in reduced strength of the reinforced concrete elements.
    - When steel is oxidized, it expands. This results in “popping” of the concrete cover, thus exposing the reinforcing steel, resulting in accelerated oxidization and deterioration.

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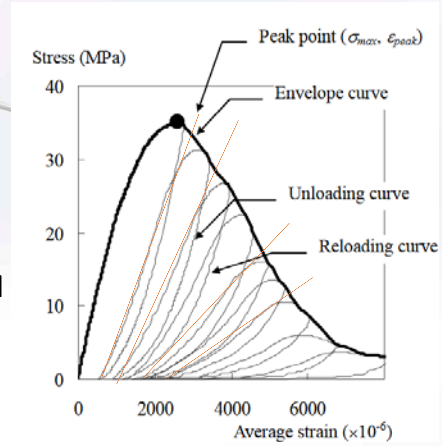
CHAPTER 2
CONCRETE MECHANICS FUNDAMENTALS

Towards the Design of Concrete Wind Turbine Towers

A Seminar Presentation by
Panos D. Kiousis, Ph.D.
http://windtowertechnologies.com/

Mechanical Characteristics of Concrete

- Concrete has much higher strength in compression than in tension.
- Concrete is typically reinforced with steel on its tensile side to counter its very low tensile strength.
- Non-linear stress-strain behavior, characterized by softening after the development of the peak stress.
- Notice the elastic modulus degradation in the softening side, as demonstrated by the unload-reload cycles.
- Good bonding characteristics with reinforcing steel.
- Compatible thermal characteristics with reinforcing steel.



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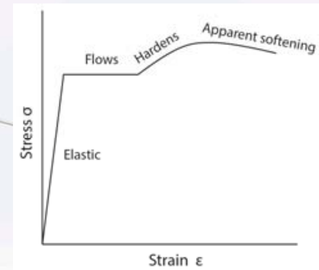
The need for ductility

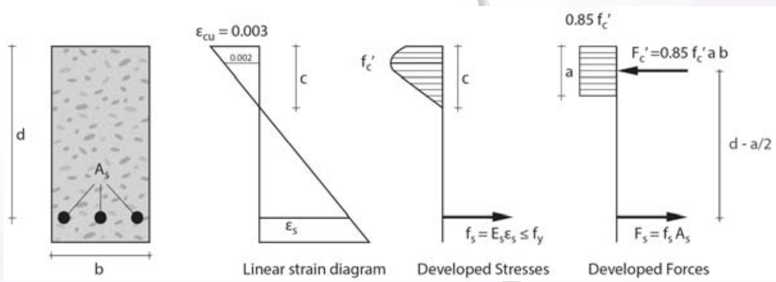
- Concrete is a brittle material (it fails without much warning).
- Steel is a ductile material (able to deform and carry load past its yield).
- The design of reinforced concrete is based on the principle that a structural element must have some ductility. The less ductility, the larger the imposed reduction (i.e. penalty) of its calculated nominal capacity.
- In general, concrete design, on the resistance side is calculated as follows:
  - The nominal capacity is calculated. For example M_n
  - Based on its calculated ductility, a reduction factor ϕ is calculated. $\phi \leq 1$. The smaller the ductility the smaller the value of ϕ (the larger the strength reduction).
  - The resistance (accepted strength) is $M_r = \phi M_n$



Why is ductility important?

- Brittle structures provide no warning of failure. Ductile structures exhibit significant deformations (warning) before failure.
- Ductile structures absorb energy (area under the stress-strain curve) when subjected to seismic loads, thus decreasing the risk of collapse when overloaded.

Mechanics of Bending



- Presumed crushing strain of concrete $\varepsilon_{cu} = 0.003$
- Presumed peak strain of concrete $\varepsilon_{co} = 0.002$
- Compression zone $a = \frac{F_s}{0.85 f_c' \, b}$
- Bending moment capacity $M_n = F_s \cdot \left(d - \frac{a}{2}\right)$
- By code, steel area must be designed such that $\varepsilon_s \geq 0.005$ for the case of bending
- ACI 318 demands that $M_u \leq \phi M_n$, where M_u is calculated based on $1.2DL + 1.6LL$, while $\phi = 0.9$ for most practical applications

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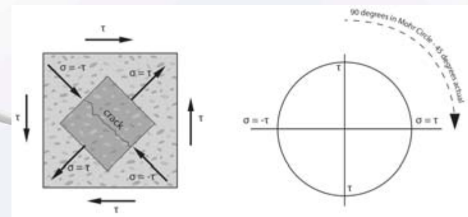
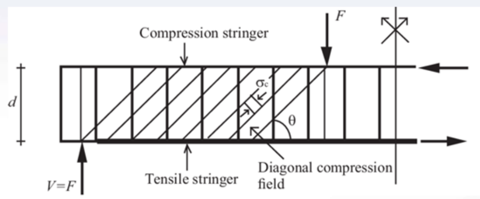
- Bending is based on the assumption that plane sections before deformation remain plane after deformation. This means that the strains are linear, even if the material stress-strain relation is not.
- The state depicted here is a state of failure. This means that the concrete has crushed. The crushing strain is presumed to be 0.003 based on ACI-318
- The non-linear strain is not convenient to calculate its area (i.e. its resultant force), and it's not convenient to find its centroid (i.e. the location of its resultant).
- It is replaced by an equivalent uniform stress block, which has a pressure magnitude of $0.85 f_c{}'$ and a depth $a = \beta_1 c$, where $\beta_1 = 0.85$ for concretes with $f_c' \leq 4000\, psi$. β_1 decreases by 0.05 for every increase of $f_c{}'$ of 1000 psi down to $\beta_1 = 0.65$. β_1 does not change after that.
- More precise values for the intensity of the stress in the concrete block and the coefficient β_1 have been evaluated, but are not commonly used.
- As ε_s increases, the neutral axis moves up. Thus the compression force decreases. For equilibrium, the tensile force must decrease. Since the steel has yielded, this means that A_s must be smaller.

Mechanics of Shear

- Shear strength is really tensile strength in the case of concrete.
- Thus, concrete beams are analyzed for shear based on a truss analogy.
- ACI code specifies θ to be 45°.
- AASHTO considers θ to be variable based on the size of the beam and the amount of bending.

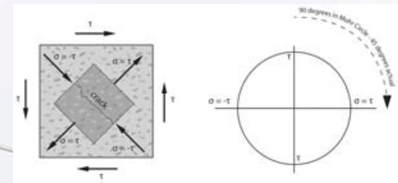


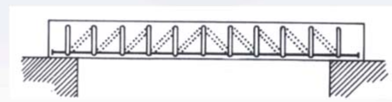


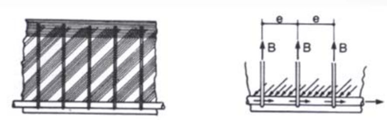
- In the truss equivalency, diagonal elements of concrete take the compression as shown. The compression has a vertical and a horizontal component.
- The vertical component is taken by a tensile force of the stirrups or ties (vertical steel reinforcement).
- The horizontal component is carried on the top side by the compression of the top fibers of the concrete mass.
- The horizontal component is carried at the bottom side by the tension of the horizontal reinforcement.
- ACI: American Concrete Institute.
- AASHTO: American Association of State Highway and Transportation Officials

Mechanics of Shear

- Shear strength is really tensile strength in the case of concrete.
- As such, and due to lack of continuity caused by cracking, concrete beams are analyzed for shear based on a truss analogy.
- ACI 318 provides the design equations for the shear capacity.
- $V_n = V_c + V_s$
  - V_c = Shear strength provided by concrete
  - V_s = Shear capacity provided by the stirrups or ties
- Design requirement: $V_u \leq \phi V_n$, where where V_u is calculated based on load combinations such as: $1.2DL + 1.6LL$, while $\phi = 0.75$.
- Shear failure is not as ductile as pure bending. As a result, it has a smaller ϕ.







(a) Truss model (b) Stirrup forces

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- In the truss equivalency, diagonal elements of concrete take the compression as shown. The compression has a vertical and a horizontal component.
- The vertical component is taken by a tensile force of the stirrups or ties (vertical steel reinforcement).
- The horizontal component is carried on the top side by the compression of the top fibers of the concrete mass.
- The horizontal component is carried at the bottom side by the tension of the horizontal reinforcement.

Mechanics of Shear (continued)

- $V_c = 2\left(1 + \frac{N_u}{2000A_g}\right)\lambda\sqrt{f_c'}b_w d$ for non-prestressed elements with compression. N_u is positive for compression. Units MUST be lbs and inches.
- $V_c = 0.17\left(1 + \frac{N_u}{14A_g}\right)\lambda\sqrt{f_c'}b_w d$ for non-prestressed elements with compression. N_u is positive for compression. Units MUST be N and mm.
- $V_c = 2\left(1 + \frac{N_u}{500A_g}\right)\lambda\sqrt{f_c'}\, b_w d$ for non-prestressed elements with significant axial tension. N_u is negative in tension. V_u shall not be negative. Units MUST be lbs and inches.
- $V_c = 0.17\left(1 + \frac{N_u}{3.5A_g}\right)\lambda\sqrt{f_c'}\, b_w d$ for non-prestressed elements with significant axial tension. N_u is negative in tension. V_u shall not be negative. Units MUST be N and mm.
- λ is a tensile strength reduction factor for light-weight concrete. $\lambda = 1$ for normal weight concrete.
- $V_s = \frac{A_v f_{yt} d}{s}$, where A_v is the total vertical cross-sectional of the stirrups or ties, f_{yt} is the yield strength of the stirrups or ties, and s is the horizontal spacing of the stirrups or ties.
- Shear capacity for prestressed structures is more complicated and outside the scope of this presentation. ACI 318-14 covers this subject in section 22.5.8.

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- It is noted that ALL equations of the code that include $\sqrt{f_c'}$ are unit dependent.

Mechanics of Axial-Bending Interaction

- Columns subjected to axial compression have a capacity equal to:
- $P_n = 0.85 f_c' A_c + f_y A_{st} = 0.85 f_c' (A_g - A_{st}) + f_y A_{st}$
- This becomes possible because concrete and steel peak in strength at approximately the same strain of 0.002.
- The concrete brittle behavior (softens after it peaks) would not allow such combination if the concrete strength peaked earlier than steel.
- The code applies a reduction factor to the above equation as follows:
- $P_n = 0.8\ (0.85 f_c' A_c + f_y A_{st})$ for tied columns
- $P_n = 0.85\ (0.85 f_c' A_c + f_y A_{st})$ for columns with spirals

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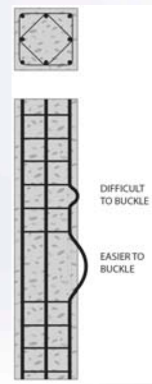
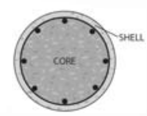
- The axial capacity consists of the independent contribution of the concrete area A_c and the axial reinforcement area A_{st}
- As can be seen from the column equations, there is a reduction in the theoretical capacity. This reduction is because the code demands that a minimum accidental eccentricity be accounted for, even if the analysis indicates that there is no eccentricity.
- The columns with spiral reinforcement have a smaller reduction. This will be discussed in the following slides.

Axial-Bending Interaction (continued)

- Columns typically carry axial reinforcement, even if they remain strictly in compression, to avoid creep effects (concrete creeps, steel does not).
- The axial reinforcement must have lateral support to prevent buckling.
- Lateral support is provided by ties (typical for rectangular cross-sections), by hoops (common for circular cross-sections) or by spirals (also common for circular cross-sections).
- Spiral-shaped reinforcement can only be considered to be *structurally* spiral if it meets specific restrictions on the volumetric content (volume of steel compared to gross volume of the column), and if it meets spacing (pitch) restrictions.
- A column consists of a core (inside the spirals) and a shell (outside the spirals). The confinement provided by the spirals makes the core stronger than the shell.
- The idea of a spiral is that after the shell fails (and part of the column strength is gone), the core increases in strength enough to recover the loss of the shell.





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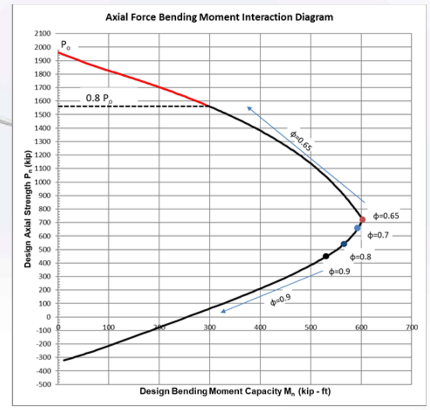
Axial-Bending Interaction (continued)

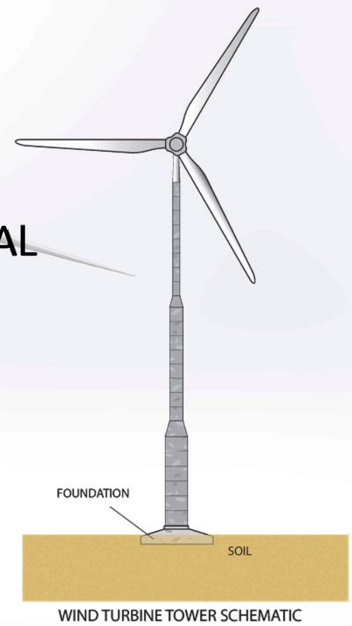
- Concrete columns are typically subjected to a combination of axial compression and bending.
- Bending and axial forces interact with each other and produce a locus of points that describe all the failure combinations (M_n, P_n) as shown here.
- It is seen that for relatively small axial loads (problems that are dominated by bending), the bending moment capacity increases with the increase of axial load. This is the natural outcome of the fact that axial compression delays the development of tensile stresses due to bending.
- However, for large axial compression, the bending moment capacity decreases with axial load. This is the outcome of the fact that a large axial load brings the compression side close enough to crushing, that failure occurs before the benefits of reduced tensile stresses take effect.
- As the axial load increases, the ability of a column to fail in a ductile way becomes smaller.
- This is expressed by the values of ϕ shown in the adjacent figure.



WIND TOWER TECHNOLOGIES

CHAPTER 3
STRUCTURAL AND GEOTECHNICAL MECHANICS OF CONCRETE TOWERS

A Seminar Presentation by
Panos D. Kiousis, Ph.D.
http://windtowertechnologies.com/
303-219-4981



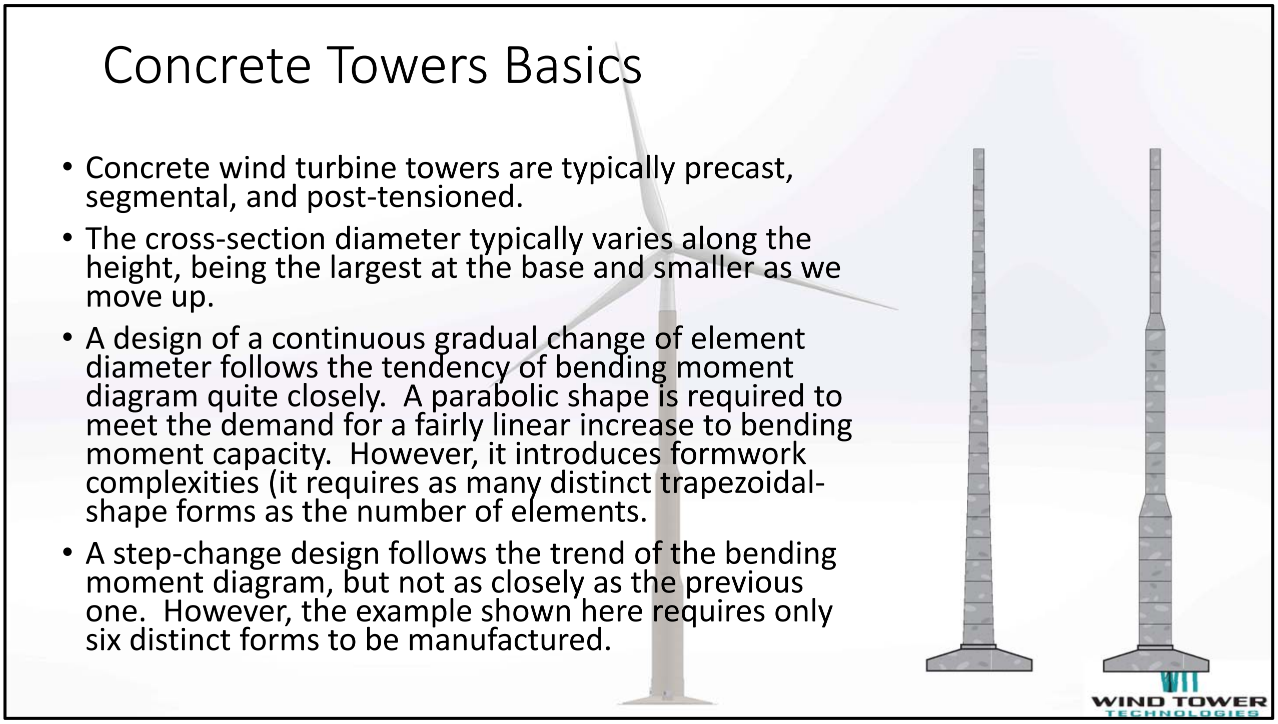
Why Concrete Towers

- The majority of wind turbines are mounted on steel towers. There are certainly reasons for that, including consistent manufacturing, reasonably easy transport, quick erection, etc.
- So, what issues may exist that encourage the consideration of concrete towers?
  - A wind turbine tower is typically a segmental cantilever structure (commonly consisting of three pieces), with a large concentrated force at its free end. As we go higher and higher, to catch better and more consistent wind, and to be able to use larger blades, we need a larger diameters at the lower end of the cantilever to support the loads. Larger diameters become too heavy and cannot fit under bridges. Thus, transportation becomes an issue.
  - To address this issue, some manufacturers create steel towers, which are segmental not only along their length, but also in their cross-section. However, connections of steel structures are notoriously sensitive to fatigue.
  - The natural period of cantilever structures increases super-linearly with the length of the cantilever. Thus, longer compliant steel structures, with their thin wall construction, can become very flexible with unacceptable natural periods that may be too close to the operational rotational period of the blades (danger of resonance).

Why Concrete Towers (continued)

- Concrete wind turbine towers are typically manufactured using on-site pre-cast sections, which require only local transportation. As a result, the sectional sizes become less of an issue.
- This allows tower heights that are mostly limited by crane capacities.
- Fatigue is typically not critical in concrete.
- Structural stiffness is less of an issue, given the large cross-sectional dimensions.
- The assembly of the pre-cast sections is quick.
- The main concern: Is there always a reliable concrete producer to provide the high quality, high strength concrete that is required?

WIND TOWER TECHNOLOGIES



1. We use the term “prestress” to indicate that we put a structural element in compression BEFORE it experiences the actual loads.
    - There are two approaches to prestressing: Pre-tension and Post-tension.
    - Pre and Post tension indicate whether the stretching of the tendons occurs before or after the concrete has cured.
    - Pre-tensioned describes a case where the tendons are stretched using two opposing anchors. Concrete is placed in between them, it cures, and then the tendons are released, which results in concrete prestressing.
    - Post-tensioned describes a case where the concrete is formed with open round channels within it (typically steel or plastic pipes). The tendons are within the channels and they are loose. After the concrete is cured, the tendons are anchored at the one end, and are stretched with a jack at the other end. This applies prestressing to the concrete.
2.
3. The formwork is bulky, difficult to design and quite expensive. There exist problems of stiffness and strength. They are not easy to store and transport. And there are numerous logistics associated with where each one is, in a construction site that is designed to produce multiple towers, commonly 100 or more.

Concrete Towers Basics (continued)

- As stated earlier, concrete wind turbine towers are typically precast, segmental, and post tensioned.
- The segmental technology can be based on “match-casting” or interface-matched using different approaches.
- In match-casting, each section is cast against the section immediately below it. Thus, there is an almost perfect match of their interface. This allows a dry-joint construction, where one section is placed directly above the other, without treatment.
- If the sections are cast independent of each other, then their interface is not a close match for them to be assembled together without additional treatment.
  - In this case the interface surfaces can be matched by grinding or by added grout.
  - The difficulty with grinding is the need for expensive, specialized equipment, which are capable of grinding flat an annulus of 7 m diameter or so.
  - The difficulty with interface grout is that the upper section must apply sufficient pressure to the grout to make certain that it will spread out evenly over the entire interface. This pressure is typically significantly larger than the overburden weight of the upper section. Thus, partial prestressing is typically needed every time a new section is added.

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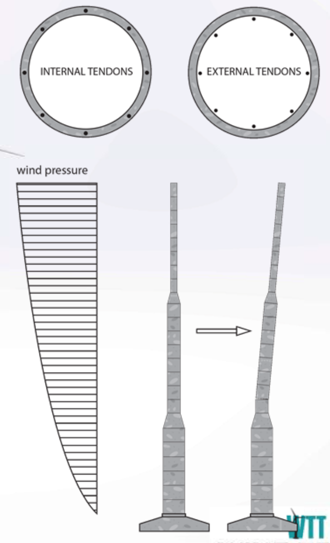
Concrete Towers Basics
(continued)

- The stability of these segmental structures is secured by post-tensioning (internal or external).
- During construction, issues of stability, mainly due to wind loads must be addressed.
- The tower is erected without prestressing. Thus, it is feasible that wind may overtop it.
- IF overtopping is possible, the critical elevation must be identified, and prestressing (post-tensioning) must be applied from the base to that elevation.
- Whereas this issue is important, one must remember that the main wind thrust (that of the turbine blades) does not apply here.



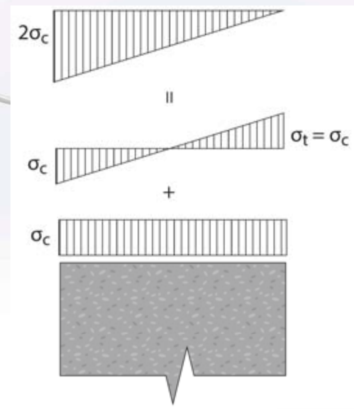
1. Internal or external is not referenced to the shape
2.
3. During construction, prestressing is preferably NOT applied. As a result, wind overturning can be prevented only by the gravity of the sections.

Concrete Towers Basics – Post-tensioning

- Post-tensioning is the important component that makes segmental construction work.
- Post-tensioning is commonly applied with high strength strands or wires (270 ksi or 1860 MPa).
- The strands are anchored into the foundation and the top element, and are subsequently stretched to a stress approximately equal to 189 ksi or 1300 MPa (70% of the strand capacity). For a 0.6 in. diameter strand, this corresponds to a load of 41 kips or 182 kN.
- Strands are typically grouped into tendons. For example, a tendon of 22 strands carries a load of 902 kips or 4012 kN.
- A 120 m tower carrying a 3 MW nacelle with 145 m diameter blades, probably needs 9 such tendons, or a prestressing force of 8120 kips (4060 tons) or 36120 kN (3683 metric tonnes)

Post-tensioning (continued)

- So, *how does post-tensioning work?*
  - It applies a large axial compression to all cross-sections between the top and bottom anchor points, which is combined with the applied flexure stresses.
  - As can be seen from the example sketches, the intent of pre-stressing is to eliminate tension under service load.
  - This prevents the interface from cycles of separation and compression.
  - Zero decompression is desired (even required) for the service loads, but does not have to occur at ultimate loads.
  - It is reminded here, that the ultimate load IS NOT an anticipated load. It is the service load, magnified to incorporate a factor of safety.



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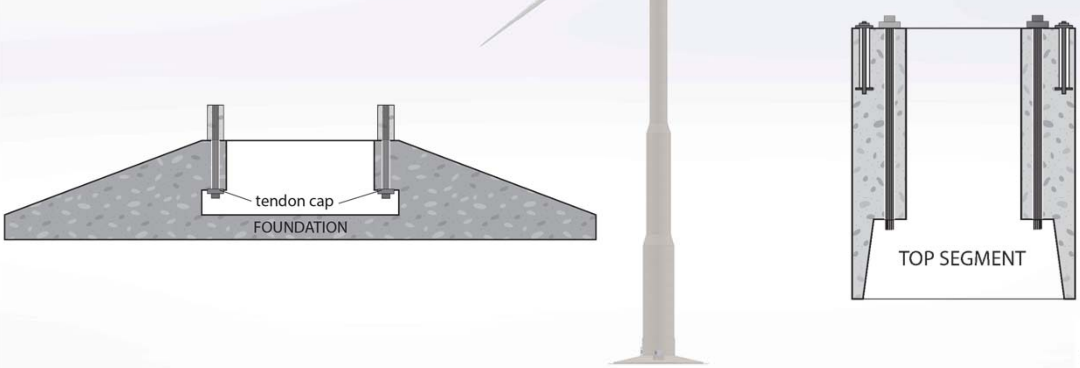
Post-tensioning (continued)

- Post tensioning tendons need to be anchored
  - at the foundation
  - and at the top element.



Concerns with Post-Tensioning

- In time, concrete becomes shorter (loses length)
  - Partly because of shrinkage
    - Shrinkage due to the hydration process
    - Shrinkage due to drying
    - Other causes.
  - Partly because of creep
    - The continuous subjection of a concrete element to the fairly large prestressing compression forces results in axial shortening.
  - Given that the prestressing tendons are anchored at the two ends of the concrete element, this shortening is equivalent to partial unstretching of the tendons, and thus, loss of prestressing with time.
  - Losses can be quite significant. In the order of 10% or more, depending on the concrete strength, the environmental conditions (low humidity is not good for concrete), and other issues.
  - Unless these losses are taken into consideration, the intent of applying sufficient compression to prevent tension under bending, can be violated.

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Concerns with Post-Tensioning (continued)

- The losses must be predicted with reasonable accuracy.
- Addressing the issue of prestress losses in concrete wind turbine towers may be an act of fine balance between two unwanted extremes.
- The structure must remain in compression AFTER all anticipated losses.
- This means that the initial forces must be larger than what is needed to prevent decompression.
- However, if the initial prestressing is excessive:
  - Concrete may be crushed in the short term.
  - Concrete may fatigue in the long term.
  - The reinforcement and the tendons may fatigue as well.

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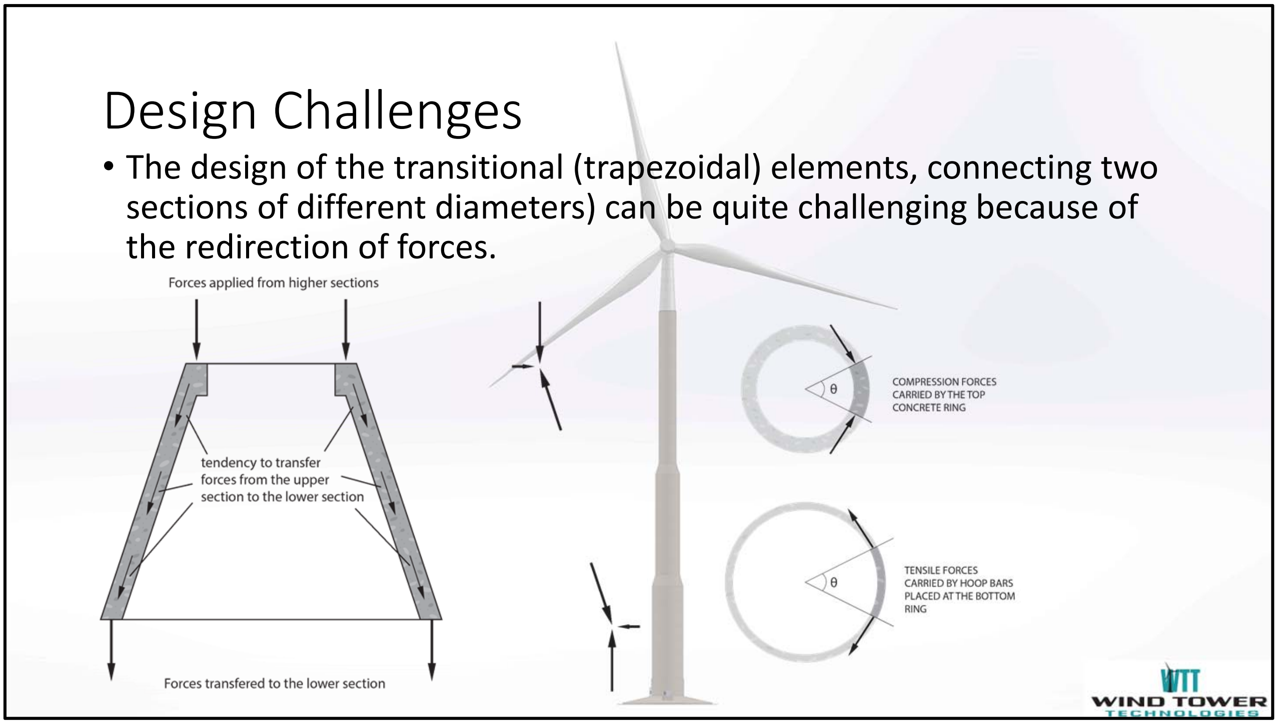
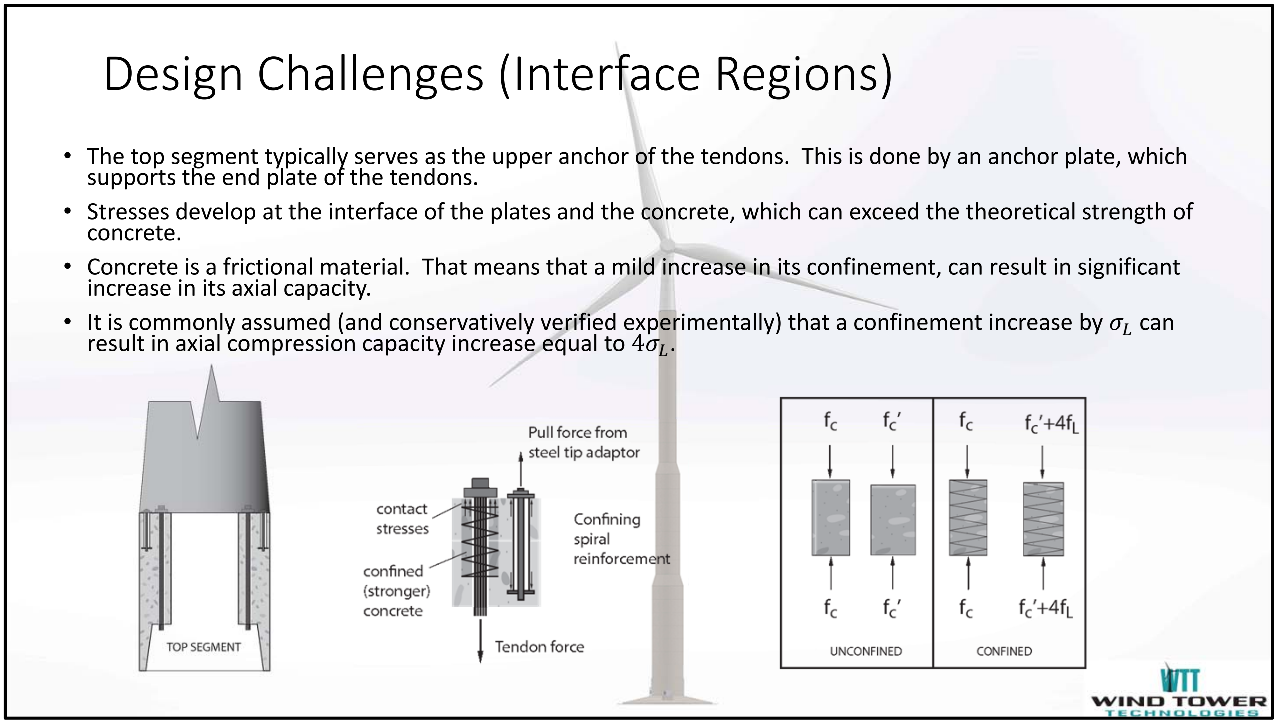
- Concrete is much less sensitive to fatigue than steel.
- However, high initial prestressing, when its strength is not sufficiently develop, may result in unwanted fatigue sensitivities.



- The left figure presents the flow of forces through a transitional element surrounded by cylindrical elements
- The central figure indicates NODAL force equilibrium at the top and bottom interfaces of the transitional element.
- The right figure presents the necessary hoop force development at the top and bottom rings of the transitional element to satisfy the nodal force equilibrium.
- It is noted that top and bottom membranes cannot be introduced to accommodate these forces, because continuous access along the height of the tower is required.

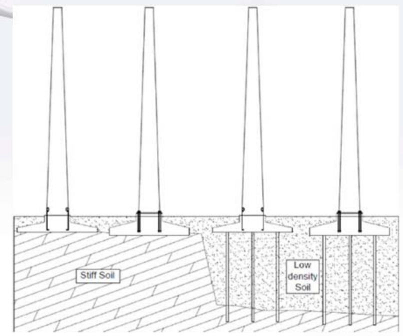


- The top segment typically serves as the upper anchor of the tendons. This is done by an anchor plate, which supports the end plate of the tendons.
- Stresses develop at the interface of the plates and the concrete, which can be quite in excess of the theoretical strength of concrete are possible.
- Concrete is a frictional material. That means that a mild increase in its confinement, can result in significant increase in its axial capacity.
- It is commonly assumed that a confinement increase by σ_L can result in axial compression capacity increase equal to $4\sigma_L$.

Foundations

- Foundations can be:
  - Shallow (also known as gravity foundations) with or without the assistance of drilled shafts or piles (typically a large circular or octagonal footing – approximately 20 m in diameter, and 2 m thick in the middle.)

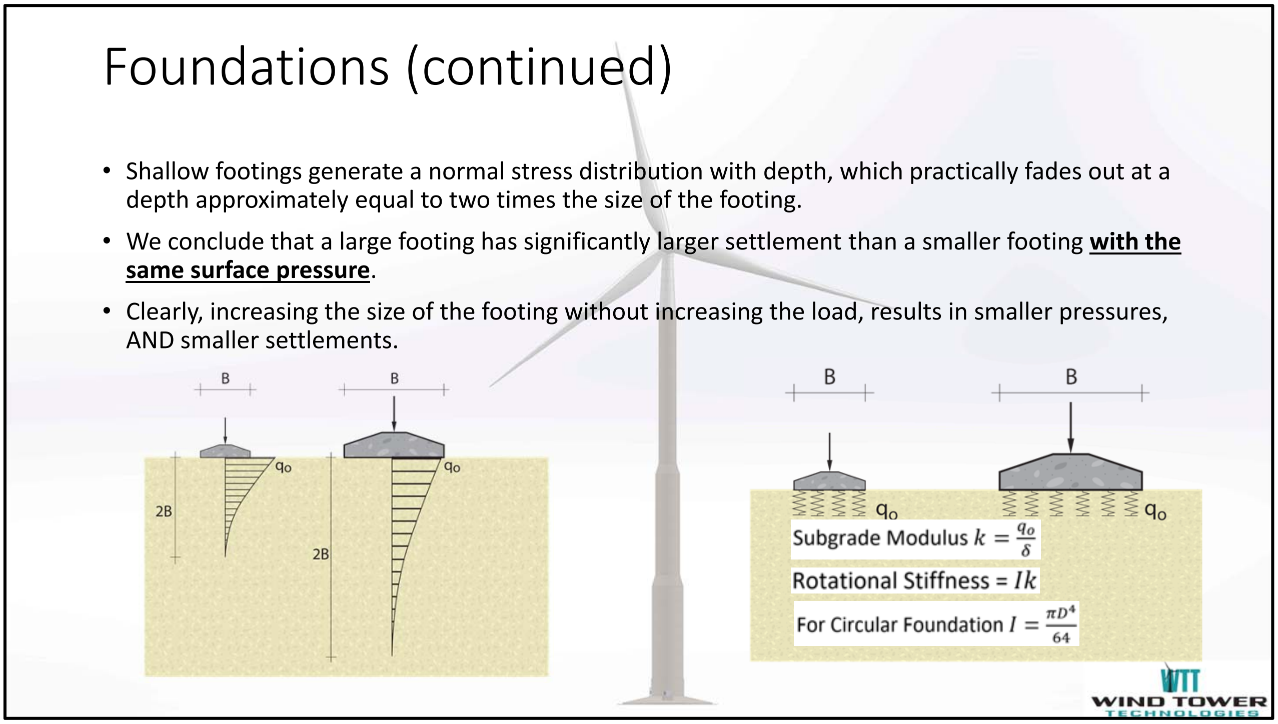
http://www.steelwindtower.com/wp-content/uploads/2018/05/wind_turbine_foundation-800x451.jpg



https://www.researchgate.net/profile/Charalampos_Baniotopoulos/publication/286479574/figure/fig1/AS:323247624212480@1454079653805/Wind-turbine-tower-foundation-configurations.png

WIND TOWER TECHNOLOGIES

- This type of foundation serves two purposes:
  1. It provides a large mass at the base to help reduce the eccentricity applied to the foundation soil caused by the overturning moment from the wind.
  2. The lateral extent of the foundation provides a sufficiently large resisting moment arm to prevent overturning.
- Whereas a shallow foundation can be sufficient to support a wind turbine tower, it may need the assistance of piles or drilled shafts when the foundation is placed o a weaker foundation soil.



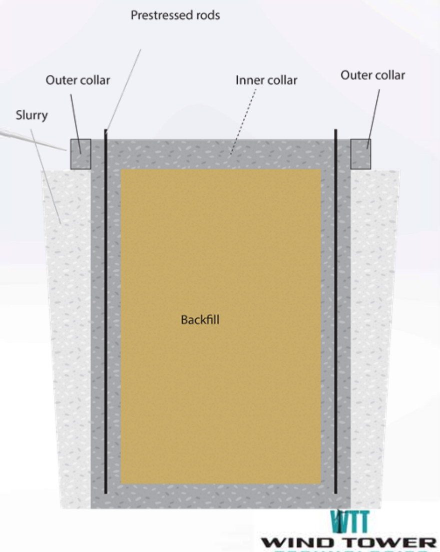
Comments on the left figure:

1. A wider footing extends its influence deeper. As can be seen in this figure, the vertical normal stresses σ_v extends deeper. This means that the strains ($\varepsilon_v = \sigma_v / E_{soil}$) extend deeper. As a result, the settlement, which is the integral of strain along the depth, becomes larger, **if the stress is kept constant**.
2. Thus the compression stiffness, known as the subgrade modulus **decreases with increasing size of the foundation**, for the same footing pressure.
3. It is important to make the distinction here.
    1. As the foundation size increases, the settlement *decreases* for a constant foundation *load*.
    2. As the foundation size increases, the settlement *increases* for a constant foundation *pressure*.
4. The rotational stiffness, based on a Winkler spring model, is equal to $S_R = I \cdot k$. We can see that as the foundation size increases, the moment of inertial I increases, and the subgrade modulus decreases. A design, which does not take into account the fact that k decreases with foundation size, may result in significant over-estimation of the rotational stiffness.

Foundations (Continued)

- Foundation can be:
  - Deep (often a Patrick and Henderson – P&H tensionless foundation)

https://www.conteches.com/Portals/0/Images/gallery/wind/Tensionless-Pier-PH.jpg?ver=2018-07-16-134740-253



- This is in essence a double-wall "can" constructed by corrugated metal. The space between the two walls gets filled with reinforced concrete and long bolts that provide prestressing to keep the foundation in compression. The bottom of the foundation structure is typically constructed as a concrete slab The inside open space is filled with soil. The outside space between the soil opening and the foundation is filled with flowable fill (very low quality concrete) to make certain that the interface is not loose.
- The tower is connected to the same bolts that prestress the P&H foundation.

Foundations (Continued)

- Whereas P&H foundations are relatively inexpensive and popular, they often suffer from inadequate stiffness
- In the past, GE required rotational stiffness of 873 MNm/degree
- Instrumentation and tests, performed in the past, revealed that some P&H foundations failed to provide the necessary stiffnesses.
- There is not much complexity in the structural design of the P&H foundations, and is not discussed further here.

Foundations (Continued)

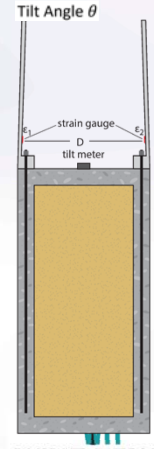
- The rotational stiffness of a P&H foundation, as well as of any other foundation, can be experimentally verified by field measurements under operations, as follows:
- The tower and its foundation are instrumented by tilt meters on the foundation and strain gauges on the tower wall.
- The curvature at the base of the wall is evaluated based on the strain gauge measurements.
- The bending moment at the base of the wall is evaluated based on elastic equations.
- The foundation tilt θ is evaluated.
- The rotational stiffness is finally calculated.

Rotational Stiffness $=\frac{\Delta M}{\Delta \theta}$

Curvature $\kappa = \frac{\varepsilon_2 - \varepsilon_1}{D}$

Moment $M = EI\kappa$

Tilt Angle θ



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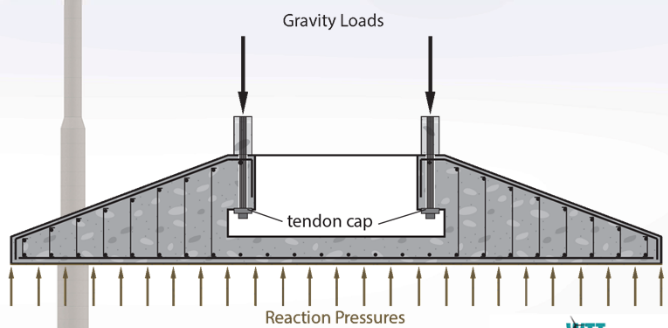
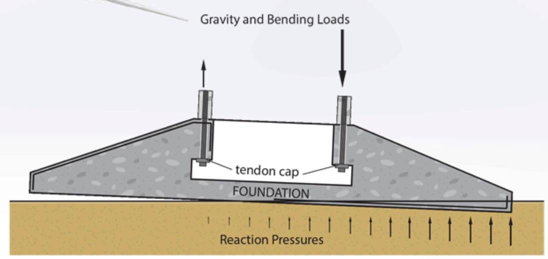
Foundations (Continued)

- Spread footings present challenges in their analysis and design because of their circular or octagonal shapes
- A typical spread footing with its reinforcement is shown here.
- It should be noted that a profile picture, such as the one shown here, can be misleading, because it hides the 3-D effects.
- Any section is actually a cord of a circle (or octagon). The closer we come to the center, the wider (and deeper) becomes the cross-section.
- As shown, reinforcement is required both at the top and the bottom side, along with hoop and shear reinforcement.



Foundations (Continued)

- A short discussion on the needs for reinforcement follows.
- When the foundation is subjected to eccentric load (combination of gravity and wind loads), it rotates.
- For the typical design loads, part of the foundation is lifted up in the air.
- This is more pronounced in the case of steel towers because the tower gravity loads are smaller, and thus the eccentricity is larger.
- We can see that one side of the foundation is in tension at the top.
- At the same time, the other side is in tension at the bottom.
- The circular (or octagonal) shape of the foundation results in bending both in the direction shown here, but also in the transverse direction. Thus, bending reinforcement in both directions is required.
- Finally, the tendency for punch demands the need for shear (vertical) reinforcement.



CHAPTER 4
OTHER SUBJECTS OF INTEREST

A Seminar Presentation by
Panos D. Kiousis, Ph.D.
http://windtowertechnologies.com/

Initial Quality and Deterioration in Time

- The condition of the tower and its foundation must be inspected
  - For construction defects
  - For environmental damage with time.
    - Chemical effects
    - Wind abrasion effects
    - Water damage
    - Frost-thaw action
  - Ware signs due to fatigue

Inspection and Monitoring

- Global visual inspection
  - Detection of obvious or extensive damage (honeycombing, large cracks, chipped edges, etc.
  - Overall Structure is inspected at distance (e.g. Binoculars)
  - Documented with photographs.
- Close visual inspection
  - Sections are inspected at pre-casting yard.
  - Overall Structure is examined on surface areas of concern (e.g. Drones)
- Testing
  - Areas of concern may be tested using
    - Non-destructive testing
    - Destructive testing
- Select towers are instrumented and monitored for performance.

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Common Sources of Errors

- Workmanship Quality
  - Structural failures may occur due to low quality concrete.
    - Insufficient strength.
    - Slow strength development (Expected life is reduced when prestressing is applied too early).
    - Low quality grout at interfaces.
  - Structural failures may occur due to construction/assembly defects.
    - Lack of simplicity often leads to errors.
    - Inexperienced personnel is often prone to mistakes.
- Deficiencies in design
  - Real loads, or load paths that have not been accounted for.
  - Insufficient geotechnical reports
    - Insufficient testing that results to unconservative strength and/or stiffness estimations.
    - Insufficient testing that does not discover existing deleterious substances in the earth.
  - Incorrect dynamic analysis resulting in near resonance.

Where to Inspect

- Structural deficiencies (immediate or in time) can occur at any section of a wind turbine concrete tower.
- More often than not, the most significant issues are associated with the foundation, because:
  - Visual inspection is typically incomplete.
  - Deleterious substances in the soil may deteriorate the foundation in areas that cannot be visually inspected.
  - Soil conditions are often different than assumed.
    - It is common that ONE borehole is drilled per tower.
    - A simple calculation of the volume tested, makes clear that much less than 0.01% of the soil that is influenced by the loads of the structure is tested. Considering that soils are natural (not man-made), the geotechnical component is often the highest risk component of the design.
    - A soft patch of soil that has not been accounted for may have significant and unwanted influence both to the overall performance of the structure, AND the foundation itself.

How to Inspect

- Both non-destructive, and destructive tests are available to the engineer.
- Non-destructive evaluation typically implies the use of wave propagation techniques to inspect the health of the material that cannot be conclusively inspected visually.
  - Short ultrasonic pulses are transmitted to concrete.
  - Changes in stiffness or density, voids, cracking, honeycombing, etc. all result in reflection of the waves.
  - Sensitive equipment capture the reflected waves, and evaluate the distance traveled, which allows the location of such flaws.
- Destructive testing, commonly involves collection of concrete specimens, in the form of small cylinders (≤ 2 in. or 50 mm), that can be visually inspected for continuity and tested for strength.

WIND TOWER TECHNOLOGIES

Potential Signs of Fatigue

- Fatigue occurs when material is subjected to repeated loading and unloading.
- Cracks begin to form.
- Cracks reach a critical size, and further damage occurs.
  - Fracture, water ingress, failure, etc..
- Interfaces between concrete sections, or between concrete and steel plates are often formed with the help of grout.
  - A non match-cast concrete interface is typically too rough and uneven. It is commonly enhanced with the use of grout, which can create a flat and smooth surface.
  - This interface grout is formed in thin layers, and may be subjected to large cyclic loads, making it quite susceptible to fatigue.
  - Not all cracks are equally dangerous. However, cracks in tension zones are best treated by the introduction of specialty epoxy grouts, which fill the gaps and reduce stress concentrations, and prevent the development of larger cracks.

WIND TOWER TECHNOLOGIES

Applicable Codes

- The issue of codes is complex, and occasionally confusing.
- It is preferable NOT to mix codes, as they are often based on assumptions that are not fully compatible with each other.
- The design of a building in the United States is typically based on the International Building Code (IBC).
- Depending on the municipality, it could be that IBC 2018, or 2015, or even 2012 may be applicable.
- The IBC draws from a number of COMPATIBLE codes.
  - Loads in IBC are based on ASCE-7.   The version is typically the latest available for the specific version of IBC. For example IBC 2018 uses ASCE 7-16, while IBC 2015 uses ASCE 7-10.
  - All concrete design is based on ACI 318. Again the same logic applies on the applicable version of ACI 318.
  - All steel design is based on the proper version of AISC Steel Construction Manual.
  - Etc.

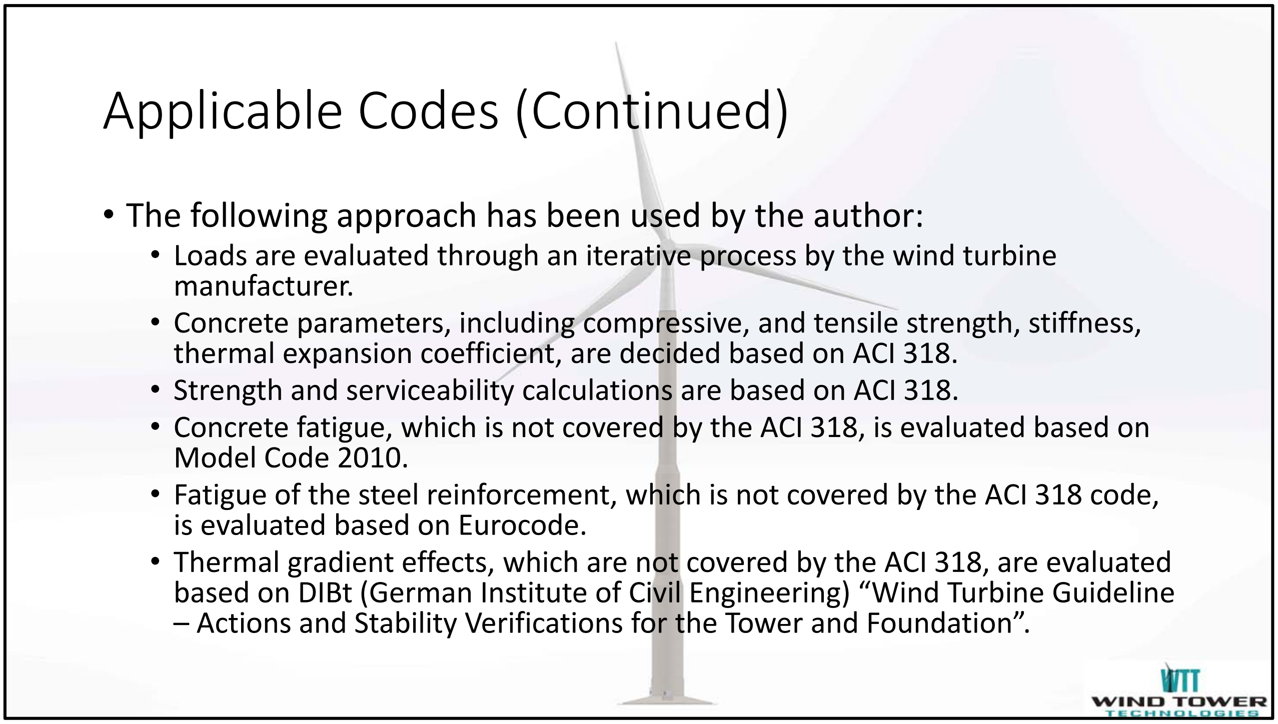
ASCE : American Society of Civil Engineers.

Applicable Codes (Continued)

- Wind turbine towers can be designed based on the principles outlined by IEC 61400.
  - For example IEC 61400-1:Design Requirements
- ASCE along with AWEA have published RP2011: "*Recommended Practice for Compliance of Large Lang-based Wind Turbine Support Structures*", which for all practical purposes duplicates the IEC 61400 recommendations.
- None of these codes is a concrete design code.
- In the United States, a concrete structure MUST be designed base on ACI 318.
- However, it is clear that IEC 61400 and ACI 318 are not fully compatible, despite the recommendation in ASCE/AWEA RP2011 that ACI 318 be used for the design of concrete wind turbine towers.
  - The load factors are not fully compatible.
  - There are no significant provisions to address fatigue in ACI 318.
  - There are no specific thermal load requirements in ACI 318 or ASCE 7 to address the needs of wind turbine towers.

WIND TOWER TECHNOLOGIES

AWEA: American wind energy association



- The iterative load design is based on the following steps:
  - The designer provides the geometric design.
  - The wind turbine manufacturer calculates the loads.
  - The designer adjusts the geometry and sends it back to the wind turbine manufacturer.
  - The wind turbine manufacturer reevaluates the loads, and so on.

Applicable Codes (Continued)

- The plurality of the code mixing is NOT ideal.
- However, the author has made selections based on engineering judgment, and with the best effort to bring as much compatibility as possible.
- In an ideal code, all decisions, all load and strength factors of safety are selected in such a way as to NOT generate a “weak link”. In stead, the risk of failure is the same for all possible modes of failure.
- It is understood that due to code mixing, this is no longer possible.
- However, it is also understood that in most cases, the approach that we have selected results in outcomes that are at least as conservative as the approach taken by ACI on the issues that it covers.

WIND TOWER TECHNOLOGIES