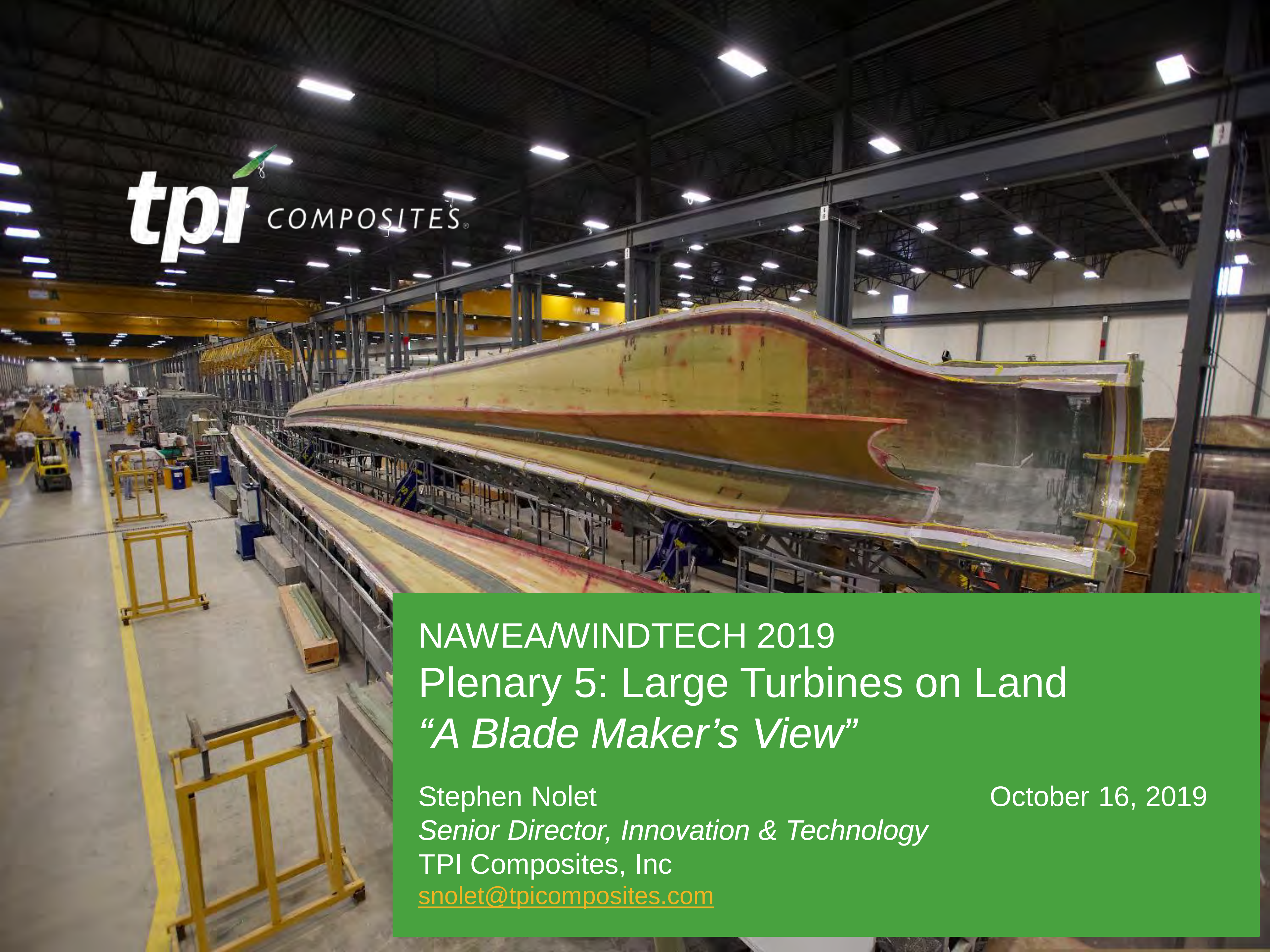


NAWEA/WINDTECH 2019

# Plenary 5: Large Turbines on Land

## *“A Blade Maker’s View”*

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# TPI Builds Wind Turbine Blades

- BIG Wind Turbine Blades!
- And the trend is BIGGER.
  - The goal, as always, is lower Levelized Cost of Energy (LCOE)
  - LCOE = (Costs)/(AEP) and Annual Energy Produced (AEP) scales with rotor size.
  - Blade Swept Area: $\pi * R^2$
    where R ~ Blade Length
- As a manufacturer we see blades designs continuously being extended for a fixed asset

# The Good News: Have not found a blade we can't build

- TPI has migrated through a history of 26.9m 1MW Class 1 blades (approximately 4.5MT) to 70.5m blades @ >18MT.
- One true constant, the cost/kg of finished goods has always trended downward.
  - Labor as a cost/unit kg of product produced trends down.
    - We are good at getting materials into a blade.
    - The larger the area the more productive the labor, kg/hour.
    - Perimeter operations determine labor content Infusion technology scales really well.
    - More area/volume more resin with minimal incremental labor cost
  - No practical limit is seen for infusion and assembly
- 24 Hour cycle times remain the rule
  - Essential for manufacturing economics to continue this trend.

# Challenges of Current Industry Methods

- Blade Size Trends
  - Max Chord versus Blade span
  - Bolt Circle Diameter
    - T-Bolts and Dinosaurs
    - Bonded, infused, Premanufactured Roots
    - How do we NOT increase BCD
- Blade Mass Trend
  - Square-cubed law debunked (but mass still grows quicker than AEP)
    - Increasing section thickness and aspect ratio retards mass growth
  - Root diameter growth, however is limited,
    - As is root stud density
  - Existing factory infra-structure is quickly becoming obsolete
    - Hook-height of bridge cranes and hinge assembly systems quickly becoming a non-sequitur
    - Crane capacities will be entirely inadequate for blade lift
      - Demolding
      - Factory moves
    - Blade Test Facilities will be challenged

# Additional Challenges that Vex Larger Rotor Fabrication

- Beside blade mass and overall geometry in the factory,
- Large blades suggest:
  - Very large material (laminate) sections for reacting increasing moments (loads)
  - Thick sections frustrate the manufacturing process Extreme exotherms from reactive matrix (resin systems) lead to significant defects in laminates, damage to molds and tooling, risk of fire.
  - Section thickness variation as a function of areal weight and atmospheric conditions challenges overall tolerance in surface profile and adhesive bond gaps.
- Highly loaded blade components, particularly root sections and spar caps are most significantly impacted.
  - Sandwich shells (core and face sheets), tip remain relatively lightweight and thin.
  - Leading and trailing edge reinforcements are most likely to become critical with increased edgewise moments (fully-reversed) driving section thickness here too.

# As Blade Size Increases, so will the Opportunity for Carbon Fiber

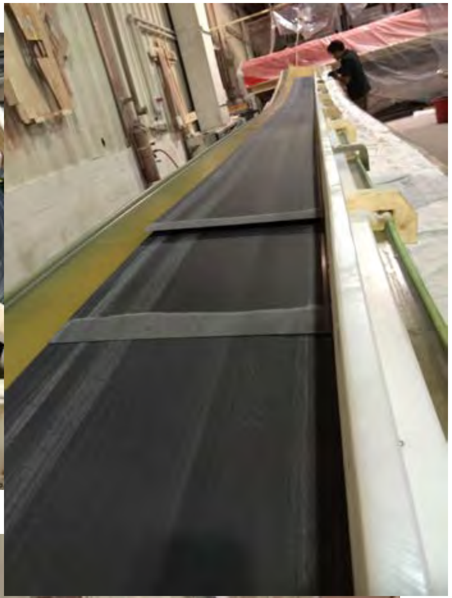
- Larger blades mean greater weight.
- On a fixed turbine, increased weight means higher rotor loads, and at some point higher loading is unacceptable
  - Bearings
  - Gear Box
  - Generator loads
  - Tower dynamics

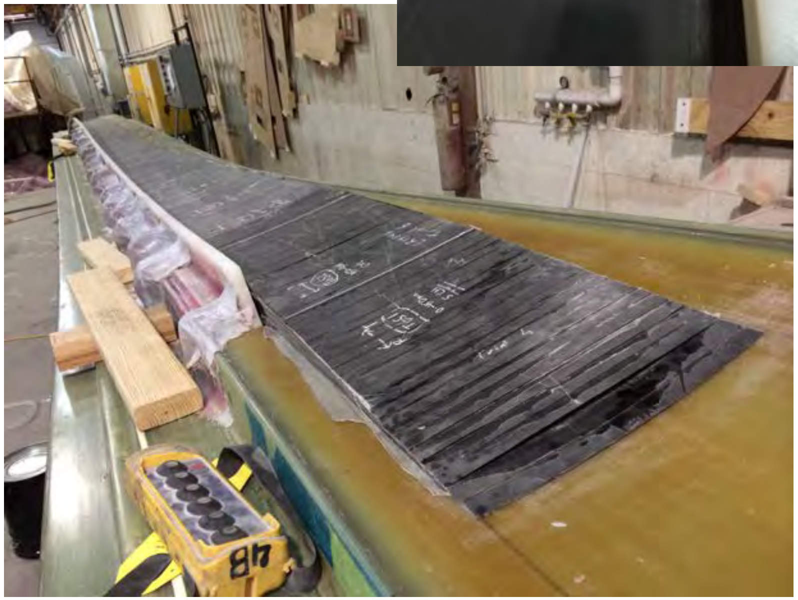
…..all adversely affected

- Just as important higher mass affects edgewise blade loading
  - Rotation of blade implies fully reversed (tension/compression) on leading and trailing edges.
- Cyclic fatigue loading will necessitate weight reduction and more fatigue resistant structure in both the LE and TE.
- Don't forget Bend-Twist Coupling!
- Carbon Fiber provides a path to enable these larger blade applications.

# Pultrusion as a Feed Stock for Carbon Fiber Spars

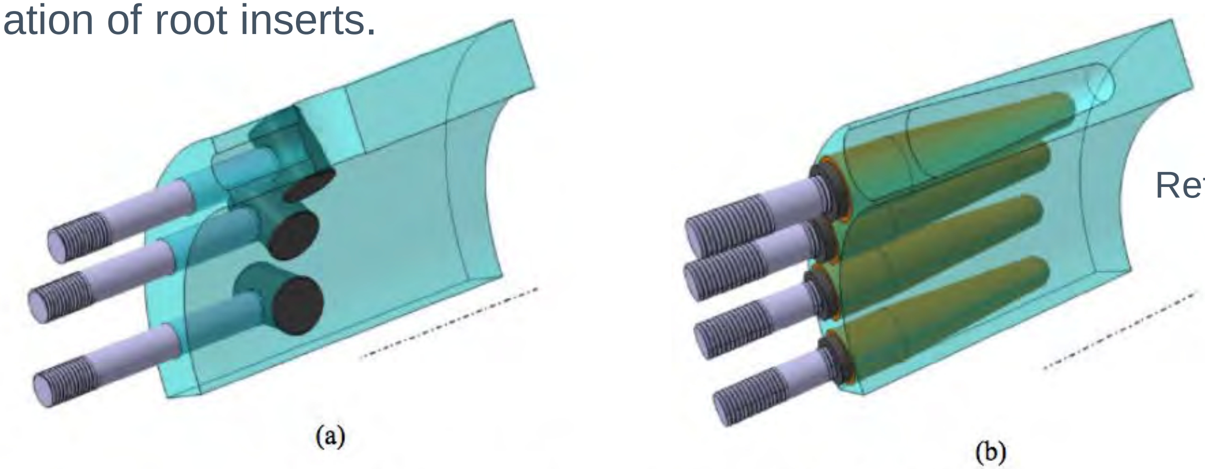
- Uni-directional Pultruded Plate spooled and delivered is finding its way into more blade designs.
  - Laminate properties determined a priori.
  - When laminated as part of a bonding or infusion process, variance in laminate thickness is small.
  - Competitive costs minimizes impact on BoM.
- Not a drop in replacement for NCF's and infusion
  - 3mm - 5mm thick plates will not shear, so compound surfaces, non-linear paths and twist create molding headaches
- But if incorporated as part of the design process, pultrusion creates opportunities
  - Build very thick parts
  - No elevated temperatures and problems associated with exotherms in thick parts.
  - High compressive strain capability and lower variance in strength properties.
  - Cycle time improvements whether molded as a component OR incorporated and laminated directly in the shell mold.





# Root Insert Technology – T-Bolts versus Inserts

- Increasing length means increasing root moment for a given BCD
  - Composite root section may be increased but load transfer via mechanical connections (bolts) must also increase and BCD limits number of connections
  - T-bolt connection butts up against limit sooner than root-insert technology
  - Industry trend driving root insert innovation.
    - Patent literature ripe with innovative solutions for design, fabrication and installation of root inserts.




Ref (1)

**Figure 1.** Common root connectors (a) T-Bolts (b) Bonded inserts

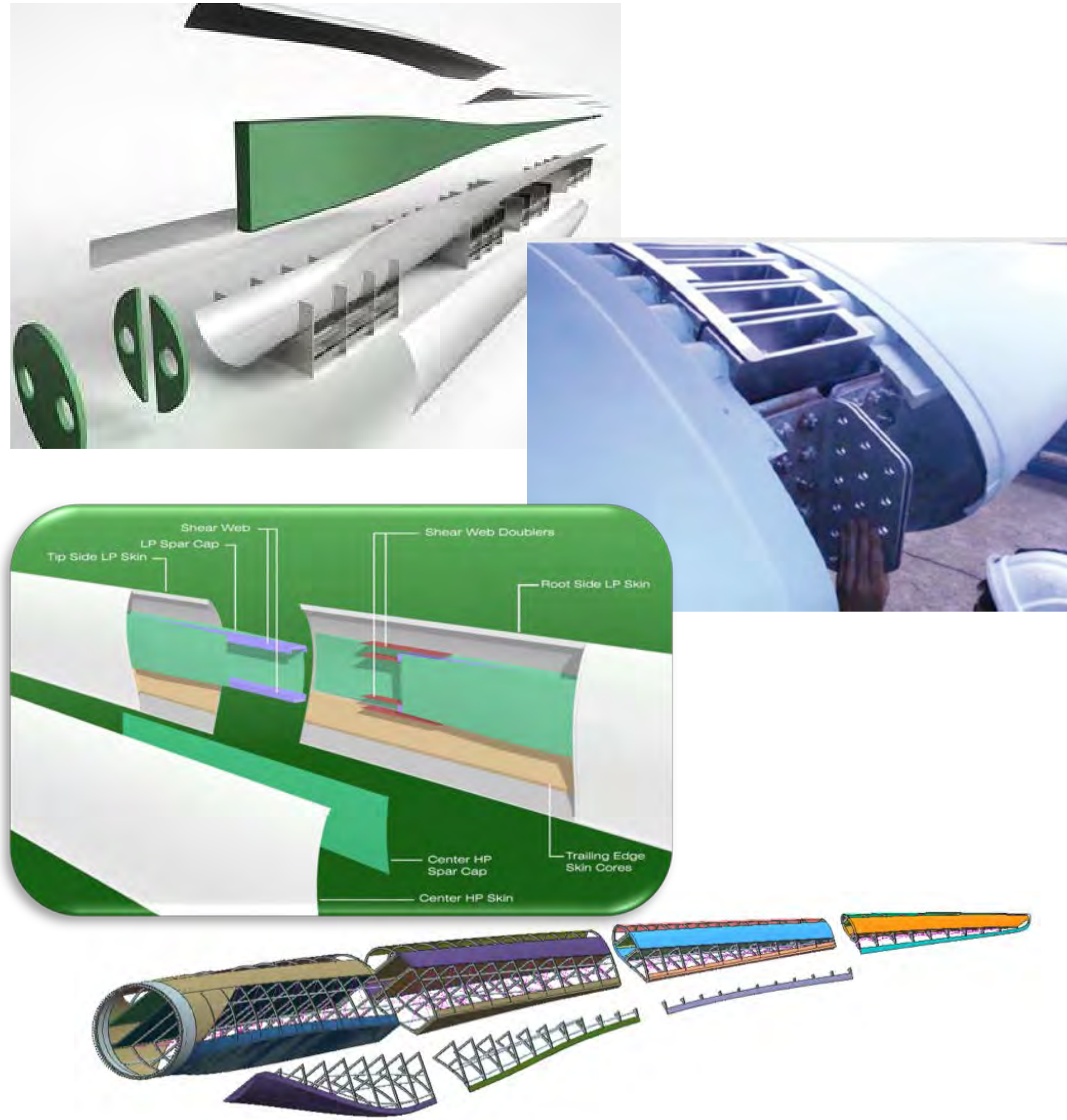
[1]T-Bolt Bearing Strengths in Composite Blade Applications ECCM15 - 15TH EUROPEAN CONFERENCE ON COMPOSITE EUROPEAN CONFERENCE ON COMPOSITE MATERIALS, Venice, Italy, 24-28 June 2012

# Transportation – Does Length Matter?

- There may not be a practical limit in blade length for onshore installations
- But there is most certainly a limit on root diameter and maximum chord length
- Bridge clearance maximum of 14’ 3” or about 4.3 meters will prevent a load from moving.

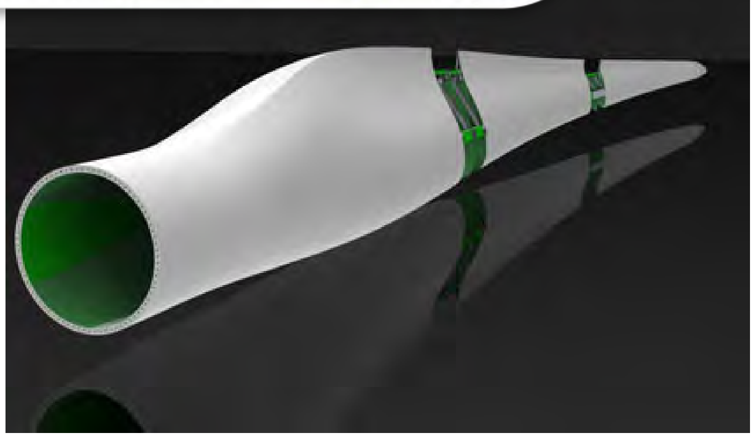
# Segmented or Modular Blades, Lots of Activity

- Blade Dynamics acquired by General Electric Renewables
  - Non-field level bonded joint construction for global sourcing of major components
    - D49 and D78 blades
- ”Innoblade” from SGRE
  - has demonstrated a field installed bolted joint.
- TPI studied and proposed a detailed design to MHI in January 2004 for segmented blades



# Modular Wind… before it's time

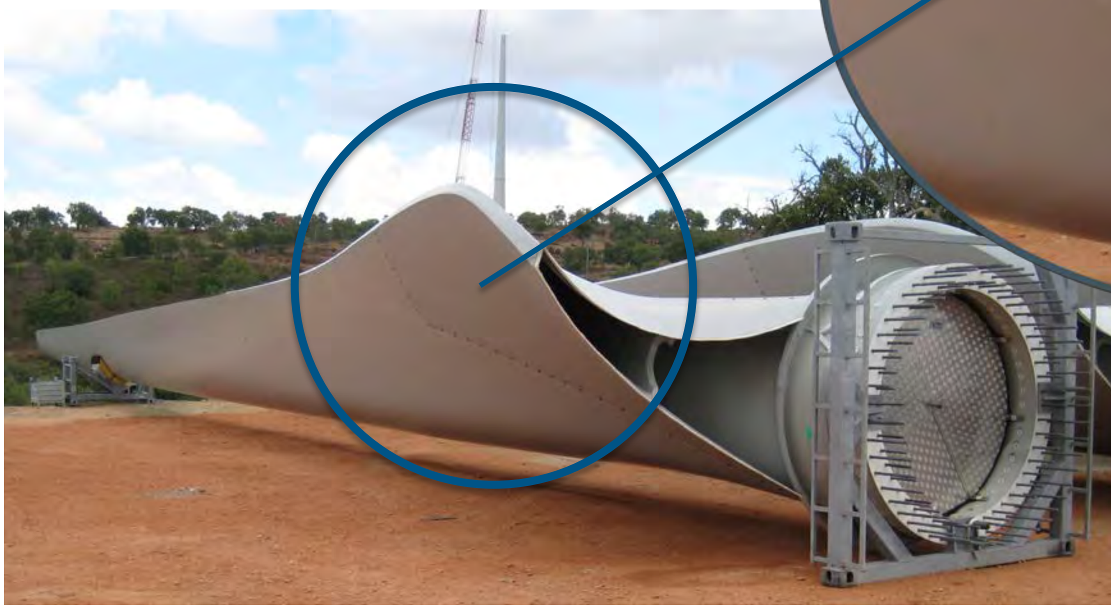
- Modular Wind (Huntington Beach, CA) produced and certified a 45m segmented blade design in 2011.
- By 2013 the blade maker was on the sales block and ceased operations. (Vestas acquired ModWind IP)
- Field applied joint with interleaved 'finger joint' of pultruded spar cap laminates.

For a comprehensive review of modular design considerations, see: *"The Concept of Segmented Wind Turbine Blades: A Review",* energies, MDPI, Basel, Switzerland, July 2017
http://www.mdpi.com/1996-1073/10/8/1112

# Why Not Chord-wise Assembly?

- We often think of modularity as span-wise segments.
  - What about Chord-wise sections?
    - Center-line spar section full-length
    - Bolt/bond-on leading and trailing edge
    - Split line of root for larger BCD's



Enercon E-115 wind turbine blade

# Closing Thoughts…

- Economics of wind favor rotor extension
  - Current manufacturing methods, materials and effective use of labor suggest “supersized rotors” (always keep in mind 24 hr cycle) are within manufacturing capabilities
  - Material and design opportunities have offset increase in span to reduce impact of “square-cubed law”.
- However, growth in mass will demand significant investment in current infrastructure for blade handling and movement.
  - Blade fabrication facilities today will not support 40MT blade fabrication with lengths exceeding 100m (hook height, bridge-crane capacities)
- Transportation considerations will limit maximum root diameter and chord width.
  - Modularity is likely an enabling feature for supporting transportation and erection
  - Economics and reliability of field level fabrication/assembly not well established