Design and Manufacturing of Modular Wind Turbine Blades

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Wetzel Engineering, Inc.
Austin, Texas USA
Engineering Consultancy
- Clients on 4 continents
- > 50 custom blade designs;
- > 16,000 blades operating

Engineering services to OEMs, Owners and Operators
- Hardware design, fabrication, testing, and certification;
- Forensics engineering and root cause analysis
Wetzel Engineering

- System & Component Optimization
- Mechanical Design & Testing
- Mechanical Testing
- Controls Engineering
- Dynamics, Loads, & Performance Analyses
- Aerodynamics:
  - Airfoil Design
  - CFD
  - Wind Tunnel Model Construction & Testing
- Root Cause Analysis

- Structural Design & Analysis
- Structural Testing (including NDE)
- Manufacturing Process Engineering
- Tooling Design
- Manufacturing Support
- Prototype Manufacturing
- Tailored Composite Materials Development and Engineering
- Certification Support

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Modular Space Frame Blade

Acknowledgements

- USDOE has provided $1.15 million in support for this project through Phase 1 and 2 SBIR Grants DE-SC0009462
  - Thanks to Jose Zayas, Mike Derby, Mark Higgins, et al.
  - Entire team at WEI, especially Amool Raina, Ken Lee, Ryan Barnhart, Alex Tran, Alejandra Escalera, Teeyana Wullenschneider, and James Moore
Modular Space Frame Blade

Three spars connected by ribs
Solid Spars – No trusses
Pultruded Spars
Minimal infused fabric
Non-structural Skins
No core in the shell

Major Sections are Factory Assembled
Open Assembly Fixtures
Ribs & Spars are Bonded
Parts are Sized for Transport
Major Sections are field assembled
Motivation for the Space Frame

Engineering of a 100m blade for a 10MW wind turbine in China motivated major changes in the approach to design and manufacturing

- Elimination of shell panel buckling as a design driver
Motivation for the Space Frame

Engineering of a 100m blade for a 10MW wind turbine in China motivated major changes in the approach to design and manufacturing

• Elimination of shell panel buckling as a design driver
• Reduction in quantity of core in the shell
  • 100m blade would have almost 10,000kg of balsa
Motivation for the Space Frame

Engineering of a 100m blade for a 10MW wind turbine in China motivated major changes in the approach to design and manufacturing:

• Elimination of shell panel buckling as a design driver
• Reduction in quantity of core in the shell
  • 100m blade would have almost 10,000kg of balsa
  • Which would also soak around 6,000kg of epoxy
• Core is Expensive!
Motivation for the Space Frame

Engineering of a 100m blade for a 10MW wind turbine in China motivated major changes in the approach to design and manufacturing:

- Elimination of huge clamshell molds
- Elimination of blind bonds that are difficult to control and inspect
- Lends itself to modularization
- Borrows for aerospace design
Advantages of the Space Frame

- Substantial reductions in weight and cost
  - Buckling is addressed more efficiently
- Reductions in capital expenditures
  - Enables cost-effective production of smaller volumes of a given blade design
- Improvement in Quality
  - Elimination of laminate-related quality problems
  - Elimination of weight tolerance issues associated with infusion of fabric and core
  - Easier inspection of adhesive bonds
- More fault-tolerant design – loads are carried through multiple spars and stringers
- Reduction in labor – more amenable to automation
Motivation for Modularization

- Easier Transportation for land-based machines
- DOE solicitation related to logistics for large land-based machines
- WEI project focused on 6MW land-based machines
- Concepts could benefit blades >50m
- Easier installation for both land-based and off-shore
- Versatility in Manufacturing – Smaller Plants
Motivation for Modularization

• Versatility in Manufacturing
• Smaller Fixturing
• Smaller Parts to Move
• Smaller Manufacturing Plants
• Lends itself to either factory or field assembly
Development Plan

• Structural Component Designs Completed
• 2014-11 Structural Component Tests Completed
• 2015-06 10m Subscale Demonstrator Completed
• 2015-10 34m Subscale Prototype Fabricated
• 2016-02 34m Prototype Test Complete
• 2016-05 83m Detail Design Complete

Commercialization of the concept in large blades would likely occur through Joint Ventures with established turbine or blade OEMs
Design Study

• 83m Blade for 6MW (WEI) machine
• Design Class
  • Class I Parked
  • Class II Operating
  • Class III Fatigue
• Variable speed, full-span pitch-regulated
## Cost Benefits – 83m, 6MW

<table>
<thead>
<tr>
<th></th>
<th>Conventional Structure</th>
<th>Space Frame Structure</th>
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<tbody>
<tr>
<td>Total Material Weights (kg)</td>
<td>31,493</td>
<td>23,862</td>
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<tr>
<td>Total Labor (Hours)</td>
<td>1,650</td>
<td>1,350</td>
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<td>Total Material $</td>
<td>292,022</td>
<td>221,895</td>
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<td>Labor (hours; $/hr)</td>
<td>40,425</td>
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<td>Total Direct $</td>
<td>332,447</td>
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<td>G&amp;A (20%)</td>
<td>66,489</td>
<td>66,489</td>
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<td>Facilities</td>
<td>22,455</td>
<td>9,855</td>
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<td>Tooling Amortization</td>
<td>17,386</td>
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<td>Total Indirect $</td>
<td>106,330</td>
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<td>COGS</td>
<td>438,777</td>
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<tr>
<td>% Reduction</td>
<td>-22.5%</td>
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</table>
Cost Benefits – 83m, 6MW

Transportation Costs

• Conventional 83m – Cannot presently be moved long distances in the US
• If it could, $115,000-$150,000 to move 1,000 miles -- 3-5% of total installed cost of turbine
• Modularized into 4 primary sections and 3 smaller sections, $24,000 to move 1,000 miles
• Modularized further can reduce the cost to $15,000
## Cost Benefits – 83m, 6MW

### COE Reduction due to Space frame Technology

<table>
<thead>
<tr>
<th>Reduction in COE</th>
<th>Description</th>
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<tr>
<td>7.0%</td>
<td>Increased Annual Energy Production from larger rotor enabled by weight reduction</td>
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<tr>
<td>3.0%</td>
<td>Extended design life</td>
</tr>
<tr>
<td>3.0%</td>
<td>Reduced transportation cost</td>
</tr>
<tr>
<td>3.0%</td>
<td>Reduced materials cost from structural efficiency and more stringent quality control</td>
</tr>
<tr>
<td>1.0%</td>
<td>Reduced warranty and maintenance costs</td>
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<tr>
<td>17.0%</td>
<td>Total Savings</td>
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# Development Plan

34m Prototype Preliminary Design is Complete

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>GE34m Baseline</th>
<th>WEI 34m Conventional</th>
<th>WEI 35m Conventional</th>
<th>WEI 36m Conventional</th>
<th>WEI 34m Space Frame</th>
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<tr>
<td>AEP</td>
<td>MWhr</td>
<td>6026</td>
<td>6086</td>
<td>6252</td>
<td>6415</td>
<td>6086</td>
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<tr>
<td>Blade Root Mxy</td>
<td>kNm</td>
<td>4435</td>
<td>3871</td>
<td>4341</td>
<td>4384</td>
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<tr>
<td>Blade Mass*</td>
<td>kg</td>
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<td>5159</td>
<td>5439</td>
<td>5740</td>
<td>&lt;4400kg</td>
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</table>
Development Plan

34m Prototype Preliminary Design is Complete
Development Plan

34m Prototype Preliminary Design is Complete
Design refinement is required to resolve buckling issues

Shear Web Stress

Spar Stress
Development Plan

10m Demonstrator in Progress

Composite Ribs
Pultruded Spars
Composite Shear Webs
10m Test Article
Finite Element Modeling

- ANSYS 15.0
- Shell elements for modeling spars & ribs
- Beam elements for modeling ribs
- Solid elements for modeling adhesive bonds
- Test Loads equivalent to 34m blade
10m Test Article
Adhesive Bond Results

- Lap Shear stresses maintained below 3.1MPa
Hollow Pultrusions for Spar Caps

Patent Pending
Hollow Pultrusions for Spar Caps

- Can a hollow channel be used to improve buckling resistance of a thin carbon spar cap with no increase in mass?
- Can this be modeled using an equivalent solid channel with adjusted modulus while capturing both deflection & buckling
Hollow Pultrusion Design Study

The fixed parameters are as follows (based on 65m blade for 3MW turbine):
- Sparcap Width, $w = 600\text{mm}$
- Total Sectional Thickness, $h=1006\text{mm}$
- Web Thickness, $t_w = 150\text{mm}$
- Bond Thickness, $t_b = 6\text{mm}$
- Web Core Material = PVC Foam
- Web Face Sheet Material: Double bias ($\pm45^\circ$) fiberglass-reinforced plastic

The variables are then confined to:
- Sparcap thickness, $t_{\text{cap}}$ (or $t_{\text{pul}}$)
- Sparcap material
- Pultrusion shape and porosity
  - Flat plates (negligible porosity)
  - Rectangular gaps in laminate stack (variable porosity)
Hollow Pultrusion Design Study

- Conventional – Solid laminate with negligible porosity
- Pultruded Channels – Laminate with porosity as defined by the geometry of each pultruded tube
- Equivalent Conventional – Solid laminate with negligible porosity as in (1), except that the modulus of the material is altered such that the buckling resistance is equal to that of (2) when the spar cap thickness is remains constant between (2) and (3), i.e. $t_{cap} = t_{pul}$.

$$E_{11,\text{Step10}} = \frac{A_{pul,\text{Step4}}}{A_{pul,\text{Step10}}} E_{11,\text{Step4}}$$
# Hollow Pultrusion FEM Model Configuration

<table>
<thead>
<tr>
<th>Step</th>
<th>Configuration</th>
<th>Material Type</th>
<th>Modulus of Carbon, $E_{11}$</th>
<th>Sparcap Thickness, $t_{cap}$</th>
<th>Pultrusion Height, $t_{pul}$</th>
<th>$t_{pul,top}$</th>
<th>$t_{pul,bot}$</th>
<th>$t_{web}$</th>
<th>Cross Sectional Area, $A_{tot}$</th>
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<td>2</td>
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<td>Pultruded Tube</td>
<td>131.5</td>
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<td>11.3</td>
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<td>N/A</td>
<td>N/A</td>
<td>21000</td>
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</table>
Hollow Pultrusion FEM Model Design

- ANSYS 15.0
- Sparcap elements are 20 node SOLID186 brick elements
  - Material moduli are dependent on the configuration
- Adhesive elements are 20 node SOLID186 brick elements
- Web core elements are 20 node SOLID186 brick elements
- Web face sheet elements are 8 node SHELL181 elements
### Hollow Pultrusion FEA Results – 1st Iteration

<table>
<thead>
<tr>
<th>Step</th>
<th>$t_{cap}$ ($t_{pul}$)</th>
<th>$t_{pul,top}$</th>
<th>$t_{pul,bot}$</th>
<th>$t_{web}$</th>
<th>Modulus of Carbon, $E_{11,pul}$</th>
<th>Out-of-Plane Deflection, $\Delta x$</th>
<th>Cross-Sectional Area, $A_{pul}$</th>
<th>Out-of-Plane Stiffness, $EA_{pul}$</th>
<th>First Flange Buckling LF</th>
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Hollow Pultrusion FEA
Results – 2\textsuperscript{nd} Iteration

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<tr>
<th>Step</th>
<th>$t_{cap}$</th>
<th>Modulus of Carbon, $E_{11,pre}$</th>
<th>Out-of-Plane Deflection, $\Delta x$</th>
<th>Cross-Sectional Area, $A_{pre}$</th>
<th>Out-of-Plane Stiffness, $E_{A,pre}$</th>
<th>First Flange Buckling LF</th>
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## Hollow Pultrusion FEA Results – 3rd Iteration

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<th>Cross-Sectional Area, $A_{pre}$</th>
<th>Out-of-Plane Stiffness, $EA_{pre}$</th>
<th>First Flange Buckling LF</th>
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<td>2.790</td>
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Hollow Pultrusion FEA
Results – Trends

• >3X Increase of buckling resistance of the spar cap achieved hollow pultrusion geometry studied
• Cannot collapse various hollow geometries to a single equivalent solid geometry
• Cannot simultaneously capture stiffness & buckling with a single set of characteristics
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Conclusions

- No show-stoppers are identified with respect to achieving the space frame concept
- Challenge remains resolving buckling in a relatively lightly reinforced structure
- Solutions have been identified
Thank you!

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