4.5 : Vertical Axis Wind Turbine with Thermoplastic Composite Blades

Summer 2019 IACMI Members Meeting July 24, 2019

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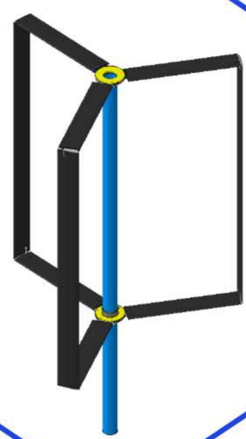
Institute for ADVANCED Composites Manufacturing INNOVATION

IACMI PROGRAM

VAWT design & analysis



Program Management
Techno-economic analysis

Thermoplastic resin

Material testing
Blade fabrication

Acknowledgment: *"The information, data, or work presented herein was funded in part by the Office of Energy Efficiency and Renewable Energy (EERE), U.S. Department of Energy, under Award Number DE-EE0006926."*

PROJECT OVERVIEW

Program Goals

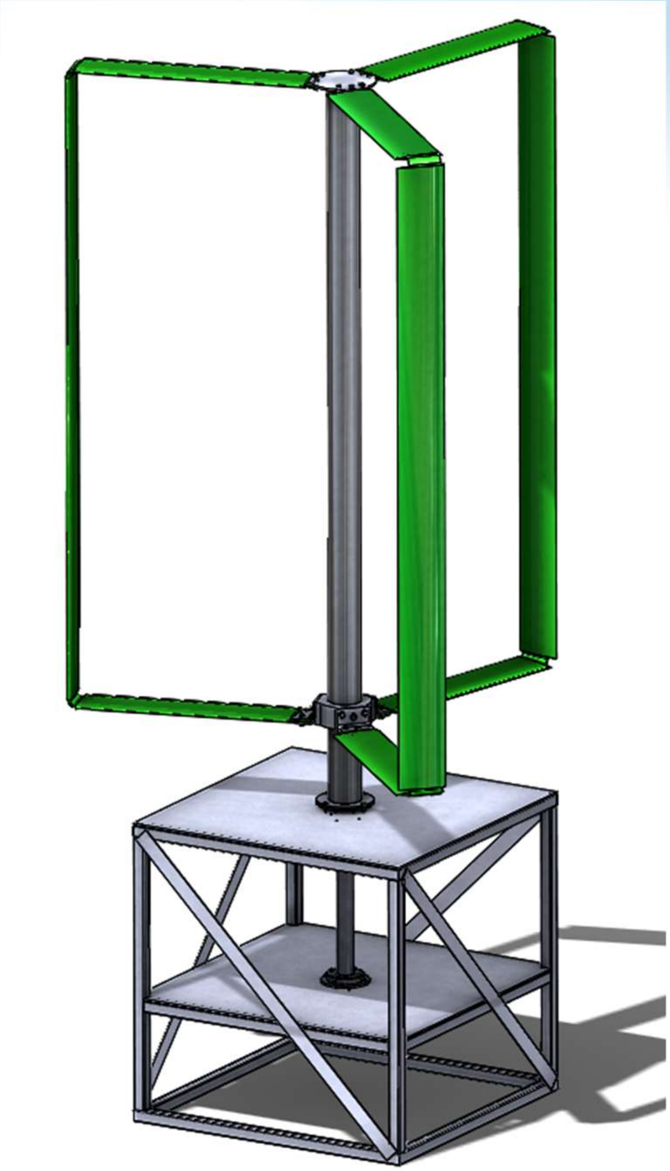
Demonstrate the design and economic feasibility of a small VAWT rotor assembly using reinforced thermoplastic composite.

- Micro vertical axis wind turbine
  - Urban
  - Residential
  - Mobile off grid(e.g., yachts)
  - Rural industrial monitoring
- Design and Analysis
  - Structural FEA
  - Natural frequency response
  - CFD
- 500-1000 Watts rated power output
- Thermoplastic composite features
  - Stiff
  - Durable
  - Recyclable
- Composite characterization
  - Mechanicals
  - Processing
  - Post-processing
- Techno-economic model
  - Levelized cost of energy

DESIGN

Design for Prototype VAWT

- Blades
  - Straight NACA 0015 profile with 6” chord
  - Laminate – [±45(braid)/0_3/±45(braid)]
- Connecting arms, hub-to-blade
  - Use blade cross section for ease of prototyping
- Shaft
  - Diameter and thickness defined by FEA and natural frequency
- Hub and bearings
  - Specified to match shaft diameter
- Balance of Plant
  - Gearbox, generator, etc are not considered

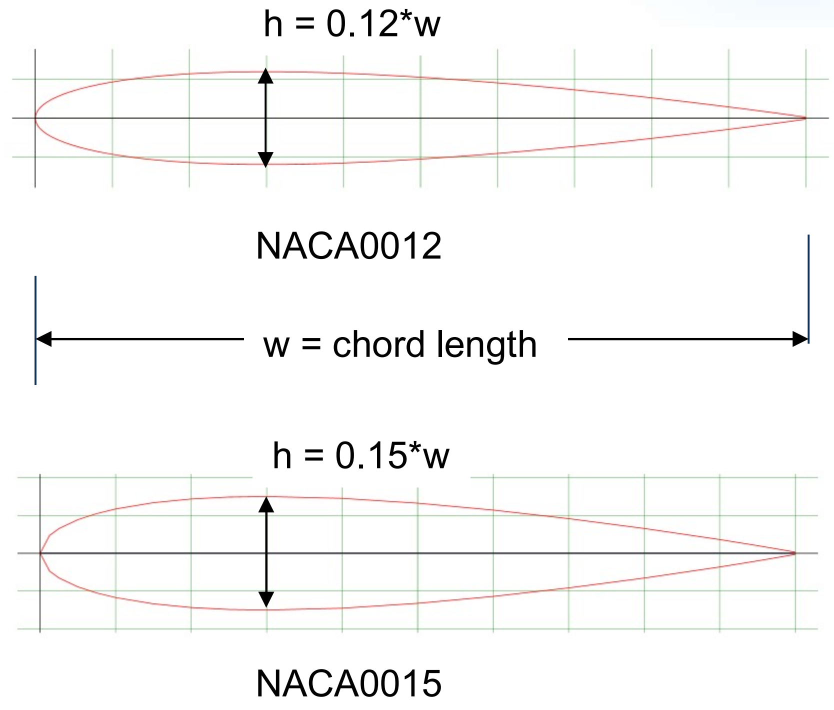


CFD

Blade Profiles

- 2D analysis performed on three (3) different configurations of blade geometry + post
- Symmetric airfoil assumed for blade cross-section
  1. NACA0012 with 4 in. chord length
  2. NACA0012 with 6 in. chord length
  3. NACA0015 with 6 in. chord length

- Analysis performed using OpenFOAM CFD package
  - Incompressible steady state Reynold's Averaged Navier Stokes (RANS) simulations
  - k-ω SST turbulence model



Torque and Power Coefficients

- In CFD simulations the wind speed is kept constant at U_∞ = 10 m/s
- The wind blade assembly is rotated at different rotational speeds (ω)
- The wind pressure acting on the blade surface is computed from Navier-Stokes equation

Navier–Stokes equations *(general)*

$$\rho\left(\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v}\cdot\nabla\mathbf{v}\right) = -\nabla p + \nabla\cdot\mathbf{T} + \mathbf{f}$$

- The resultant load and moment from the pressure is computed over multiple cycles until the torque and power are stabilized

Torque coefficient:

$$C_T = \frac{T}{\frac{1}{2}\rho U_\infty^2 R^2 H}$$

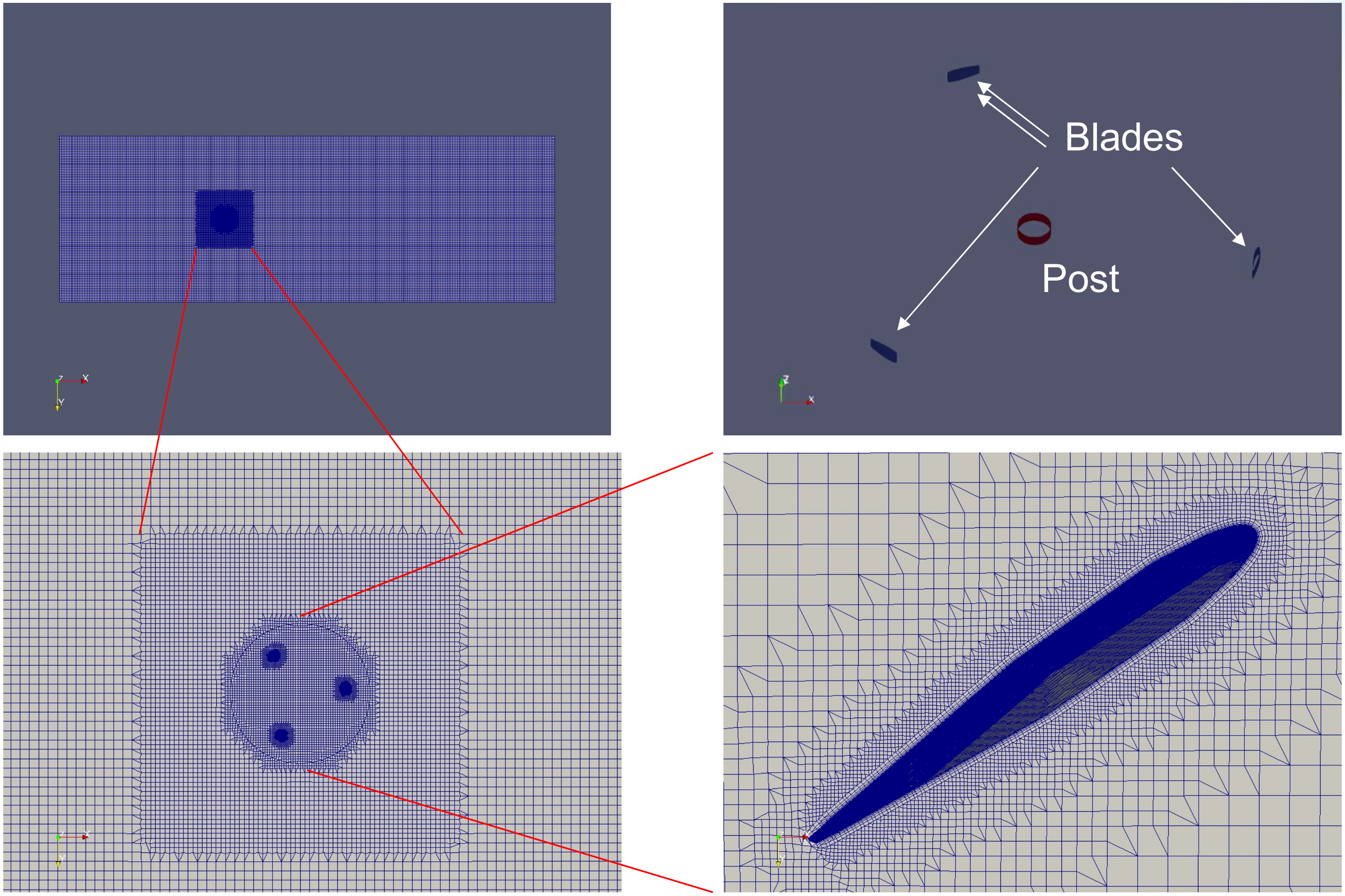
Power coefficient:

$$C_P = \frac{P}{\frac{1}{2}\rho U_\infty^3 R H} = C_T \frac{\omega R}{U_\infty} = C_T \lambda$$

where λ is the tip speed ratio (TSR):

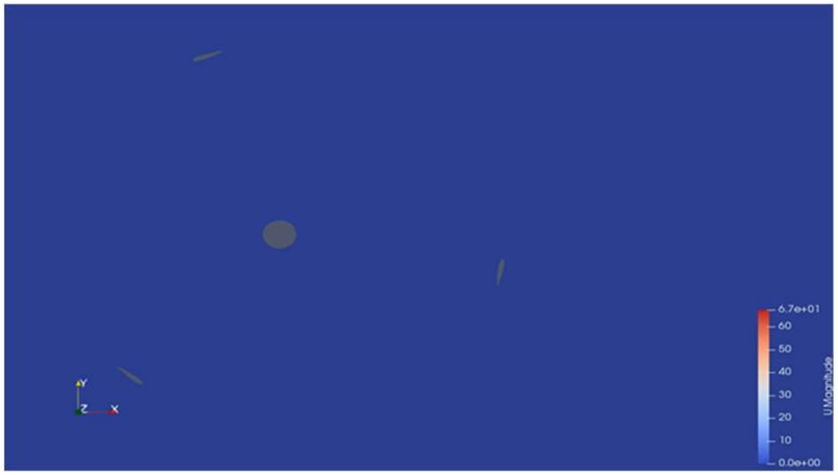
$$\lambda = \frac{\omega R}{U_\infty}$$

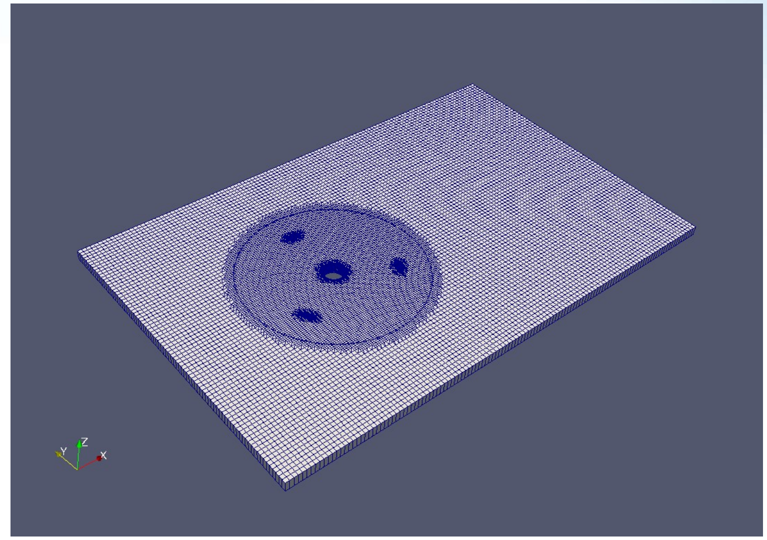
CFD Model



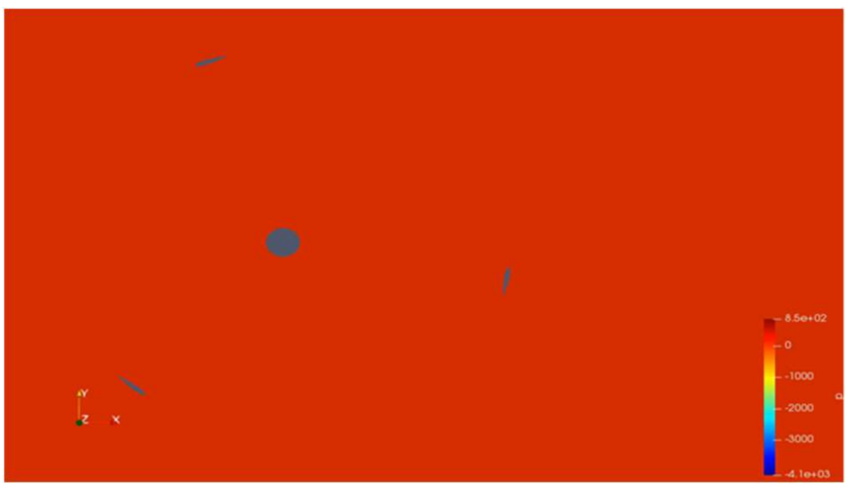
CFD

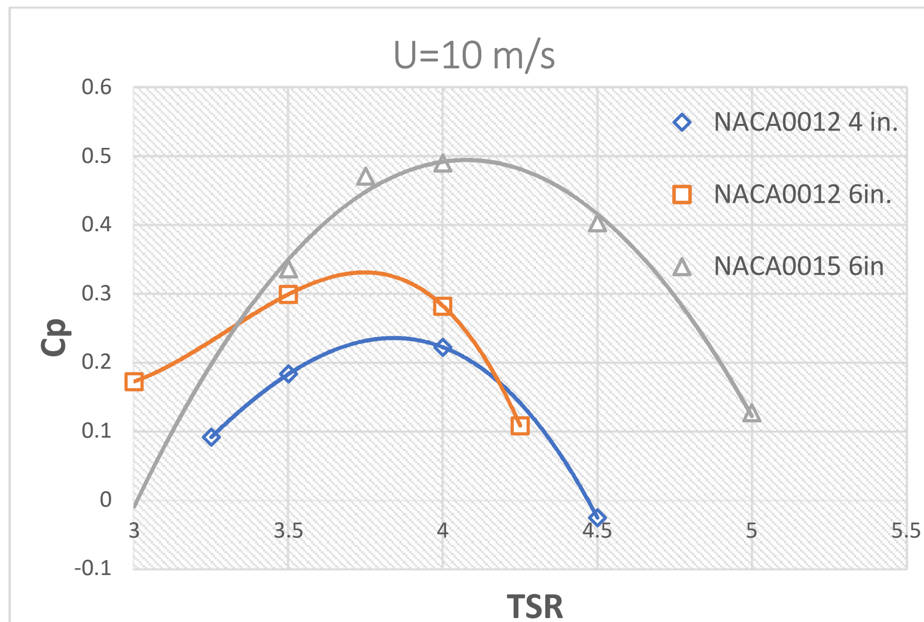
velocity





pressure

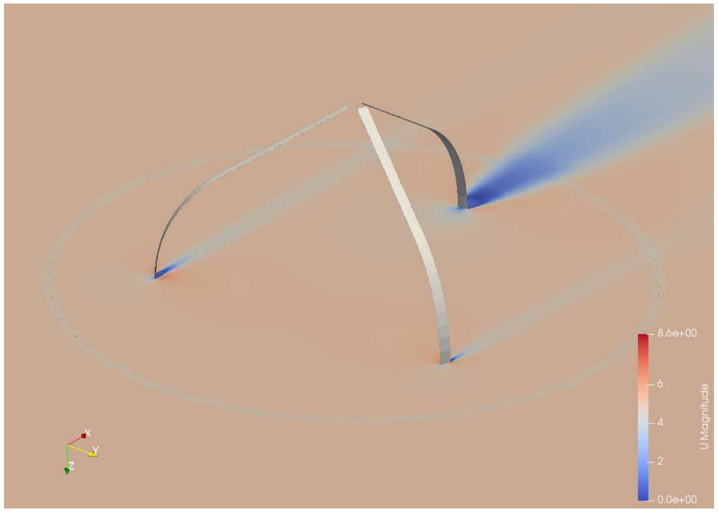


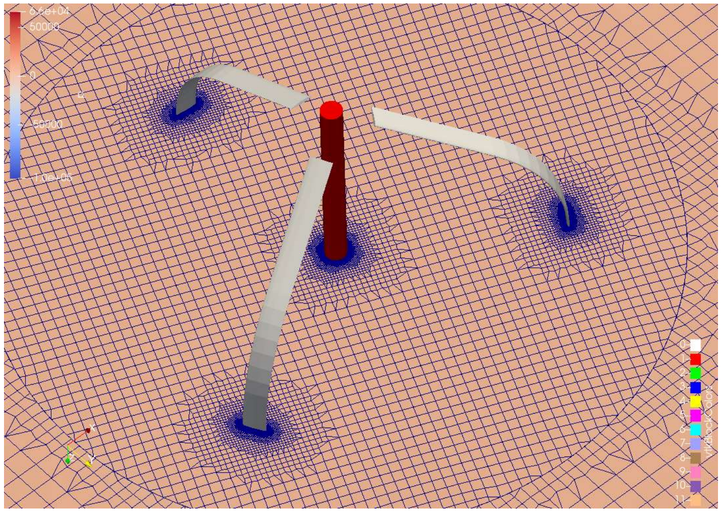


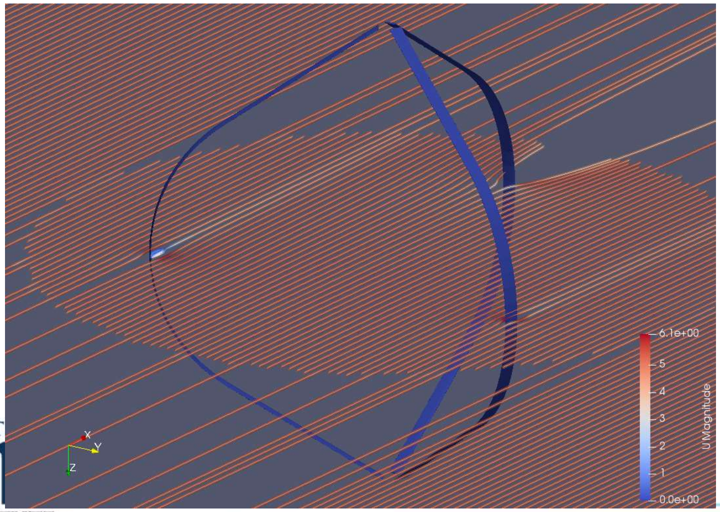
THE COMPOSITES iacmi INSTITUTE

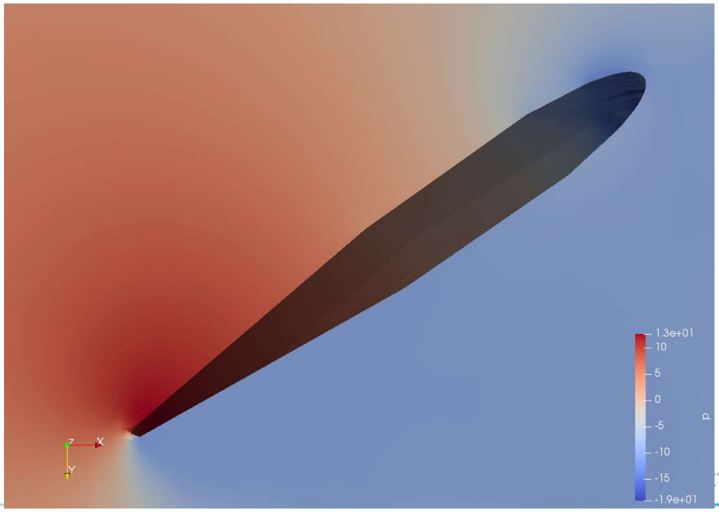
3D CFD Simulation of Darrieus Wind Turbine

3D Simulations were attempted. However, they were found to be too time intensive and hence abandoned



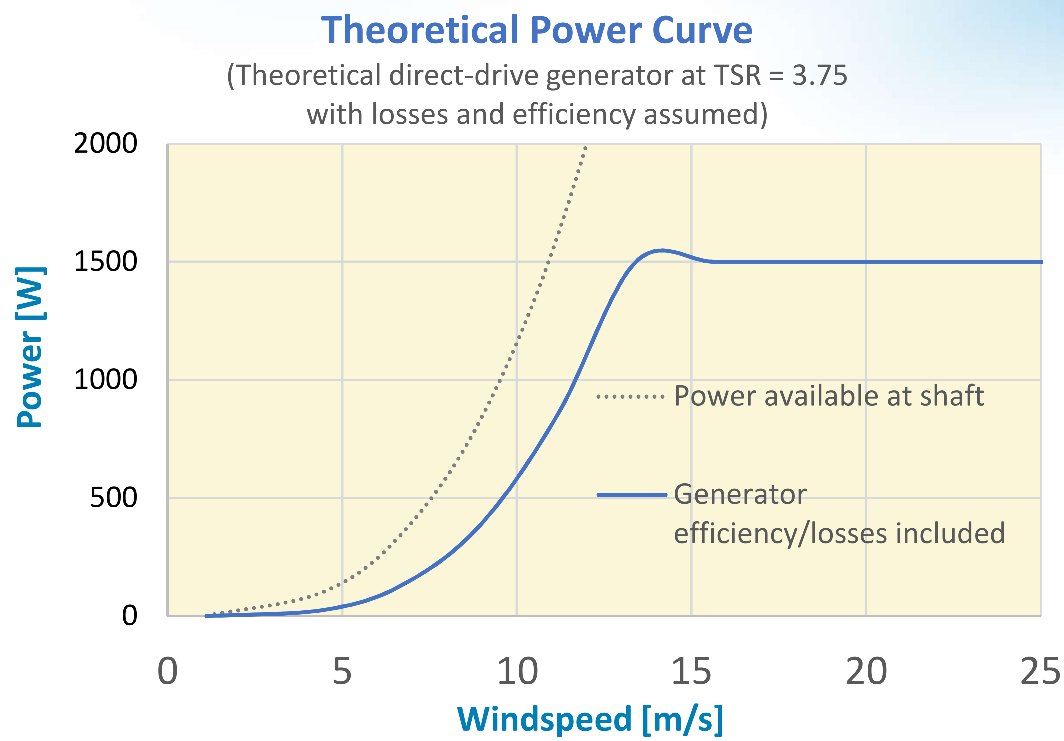


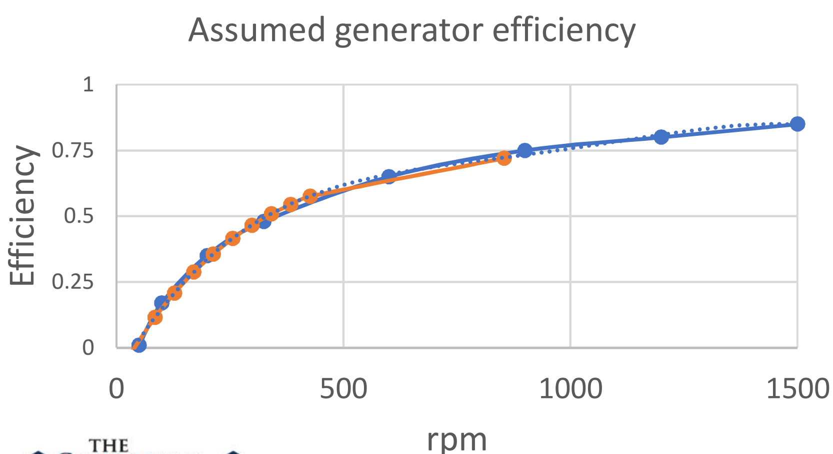




Estimated power output

Wind speed [mph]	[m/s]	Power available [W]	Power output (est.) [W]
2.5	1	3	0
10	4	220	26
15	7	742	131
20	9	1758	383
25	11	3434	854
30	13	5934	1500
35	16	9423	1500
40	18	14065	1500
45	20	20027	1500
50	22	27472	1500





AEP estimates

40% of Rayleigh-Betz: 1200 kWh/yr

"Small Wind Guidebook": 1000 kWh/yr

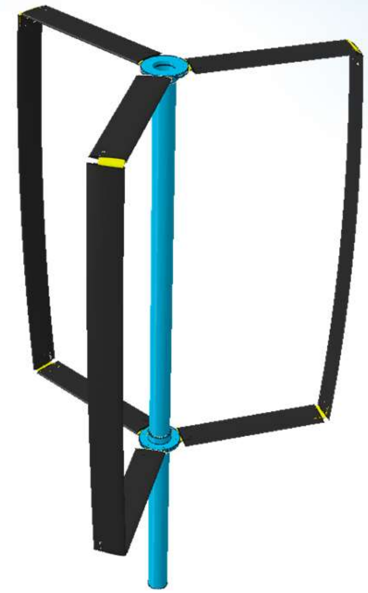
Hugh Piggott: 1100 kWh/yr

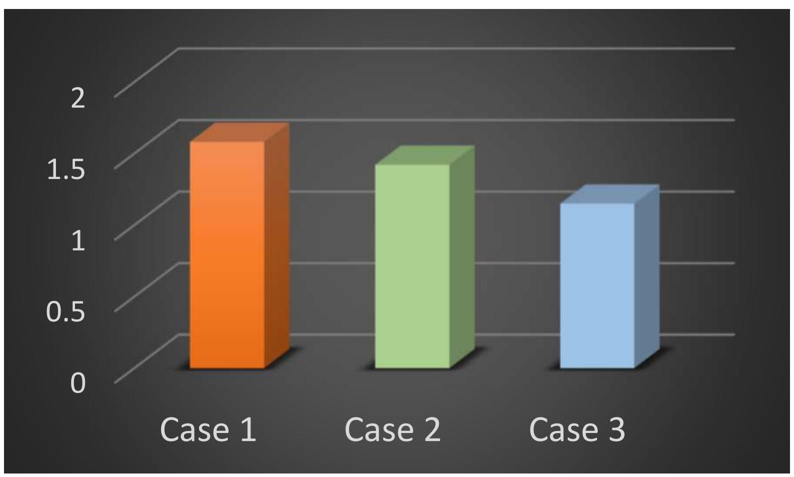
Wind-works.org: 1300 kWh/yr

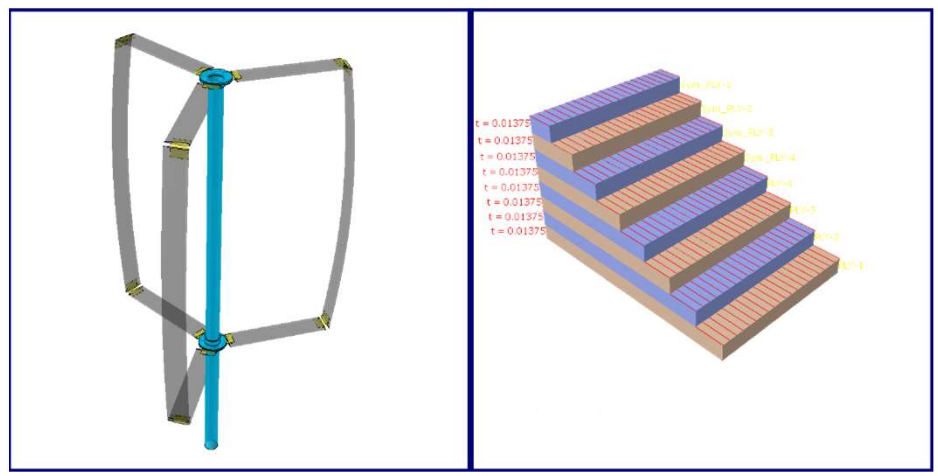
FEA

Finite Element Analysis of Blade Deflection

- Analysis trade studies:
  1. Straight blade vs curved blades
  2. Laminate architectures
- Carbon fiber + Arkema Elium Composite
- Static pressure resulting from 60 mph wind load
- Analysis were performed using ABAQUS commercial FEA software
- FE model incorporated orthotropic composite properties and nonlinear geometry







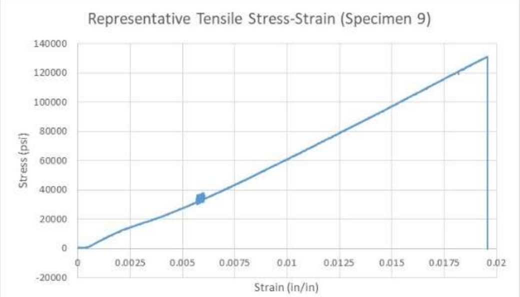
Materials Study – Carbon Fiber/Elium 150

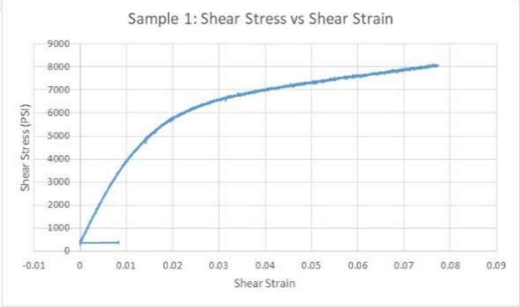
- Tensile Tests (Material Allowables)
  - Non-woven bias fabric
    - T700SC w/F0E sizing, ~300gsm
    - Tensile (0/90) vs. Shear (±45)

Test setup

Specimens after testing:
8-ply shear, left vs. 4-ply tensile, right

	# Plies	Thk (in)	V_f (%)	V_v (%)	Strength (ksi)	Modulus (Msi)	Strain (%)	Poisson's Ratio
Tensile	4	0.055	49	1.0	114 ± 12.3	7.74	1.9	0.07
Shear	8	0.11	49	1.7	7.1 ± 0.13	0.56	7.5	

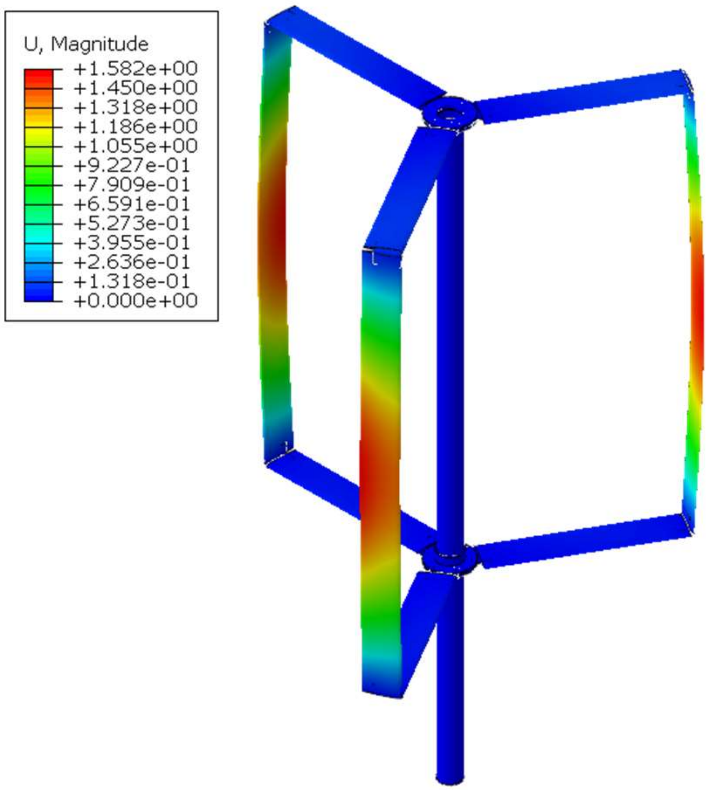




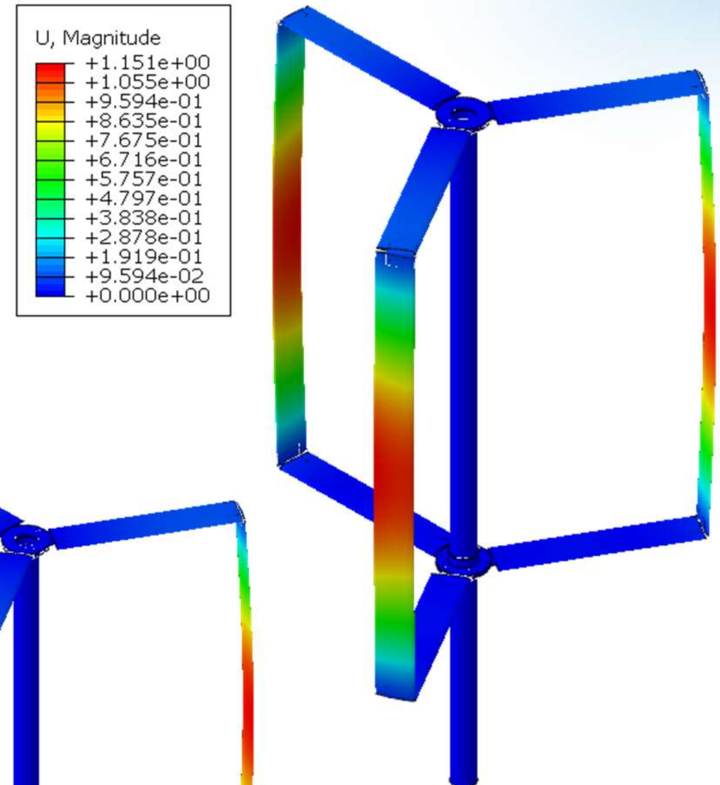
- Tensile Tests (Laminate Configuration)
  - Laminate evaluated $[\pm45/0]_S$
    - T700SC/F0E size, T300/GP sized (0.072" thickness, 45% V_f)
    - Load curve – linear to failure
    - Modulus ~ 5.4 Msi; Strength ~ 84 ksi

Performance values suggest good fiber/matrix load transfer

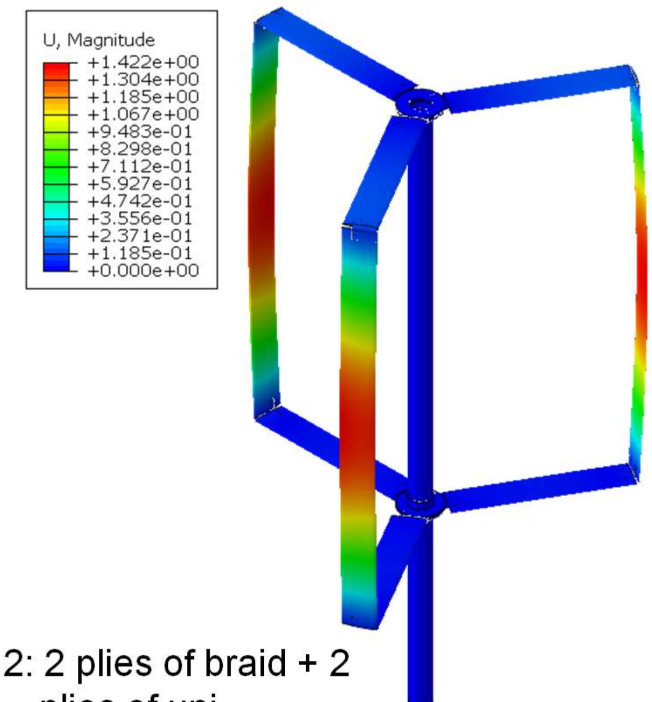
Blade deflections



Case 1: 2 plies of bias + 2 plies of uni



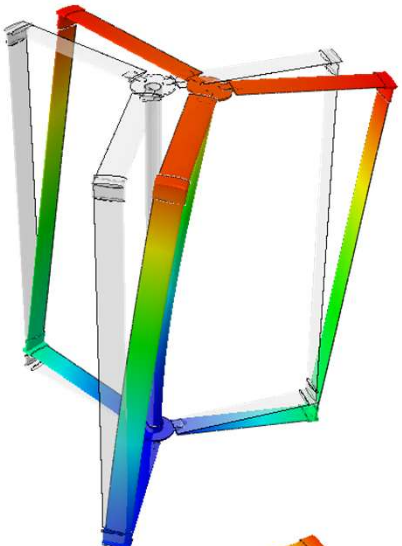
Case 3: 2 plies of braid + 6 plies of ORNL uni



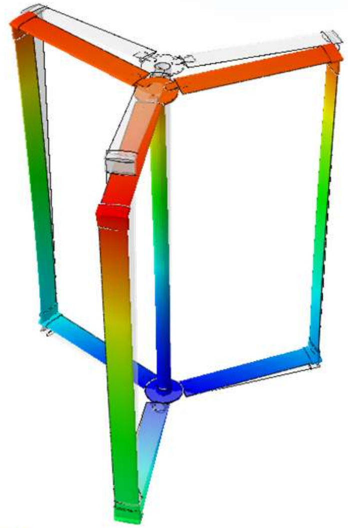
Case 2: 2 plies of braid + 2 plies of uni

Natural Frequency Analysis

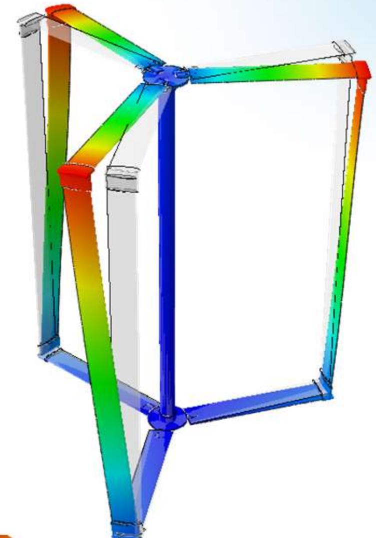
Mode 1



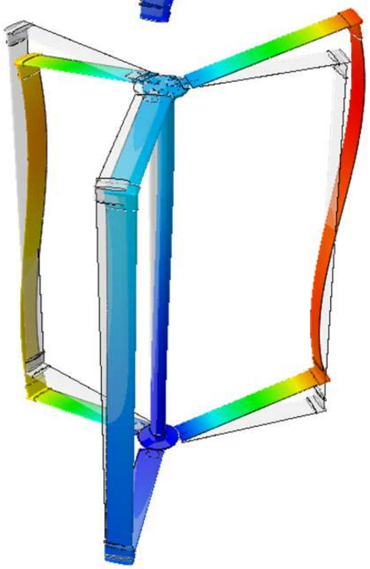
Mode 2



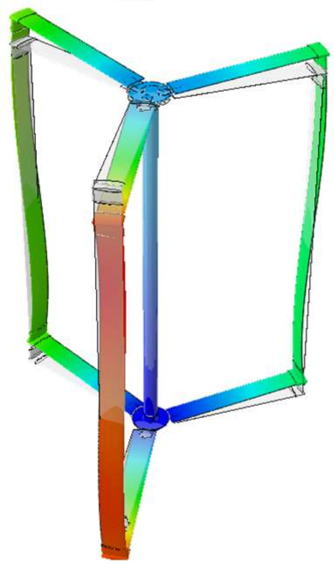
Mode 3



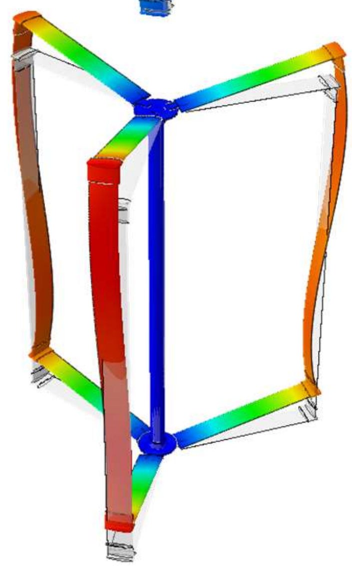
Mode 4



Mode 5



Mode 6



Stiffness of the central post was determined to have the biggest influence on the first few mode shapes

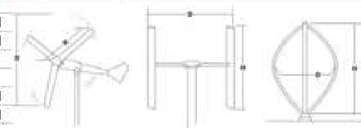
TECHNO-ECONOMIC ANALYSIS

Techno Economic Analysis

Scott Carron (NREL)
Techno-Economic Model for IACMI 4.5 Project
Rev 0 - Prelminary-2016.10.31

Yellow needs to be inputed
Red could use some more attention with time

			Comments
Peak Power	1500	W	
Rated Power (AWEA Standard at 11m/s or 24.6 mph)	750	W	
OEM Rated RPM	1500	RPM	
Tip Velocity at Rated	157.1	m/s	
TSR at Rated	14.3		
Cut In			
Cut Out			
Air Density	1.225	kg/m3	
Weibull k (shape factor equal to 2 for Rayliegh Distribution)	2		
Average Wind Speed (to calculate AEP)	5	m/s	
Rated Power Wind Speed	11	m/s	
Number of Turbines Manufactured per year	1000	turbines/yr	
Number of Blades	3		
Number of Blade Support Arms per Blade	2		
Blade Chord (assuming constant Chord)	0.125	m	
Blade Thickness (assuming constant Thickness)	0.015	m	
Solidity			
Rotor Height (H-Rotor VAWT)	2	m	<------Enter "0" for turbine configurations not used
Rotor Diameter (H-Rotor VAWT)	2	m	<------Enter "0" for turbine configurations not used
Swept Area (H-Rotor VAWT)	4	m2	
Equivalent Rotor Diameter (H-Rotor VAWT)	2.256758	m	
Rotor Height (Darrieus VAWT)	0	m	<------Enter "0" for turbine configurations not used
Rotor Diameter (Darrieus VAWT)	0	m	<------Enter "0" for turbine configurations not used
Swept Area (Darrieus VAWT)	0	m2	
Equivalent Rotor Diameter (Darrieus VAWT)	0	m	
Maximum Possible AEP (Rayleigh-Betz)	3036	kWh/yr	
Cp (Rayleigh-Betz)	0.2300		
Gross AEP Approximation (40% of Rayleigh-Betz)	1214.5008		The AEP calculation needs some more attention. I can do a higher fidelity later. For now I have estimated by taking an average of 3 quick methods. We need to get power curves or use power curve
Gross AEP Approximation (from "Small Wind Guidebook")	1018.6311	kWh/yr	
Gross AEP Approximation (from Hugh Piggott)	1119.8661	kWh/yr	
Gross AEP	1117.6660	kWh/yr	<------SteelHead needs to calculate Power Curve to get AEP (for now approximating)
Availability	100	%	<------Enter
Soiling Losses	1	%	<------Enter
Controls Losses	1	%	<------Enter
Collection Losses	3	%	<------Enter
VAWT H-Rotor Losses	20	%	<------Enter (suggest 50% loss for H-Rotor Config for now as can be seen from the reducti
Net AEP	838	kWh/yr	
CAPEX-Wind Turbine System Equipment	26019.6	$	<------Comes from Turbine System Equipment Tab
CAPEX-Balance of Station (BOS)	450	$	(assuming $0.30 per Watt(peak power))
OPEX	292.20	$	(ideally want this zero, but for unfortunate owner that needs service, assuming 2 days at $400 per day and 25% of Turbine Equipment Cost averaged over 25 years)
AEP	838	kWh/yr	
FCR	5	%	(5% is assuming a 25-year loan at 1.3% interest and a 35% tax rate)
LCOE	**1.93**	**$/kWh**	



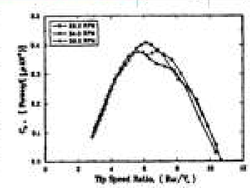


Figure 10. Measured Turbine Performance Coefficient

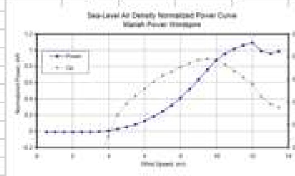


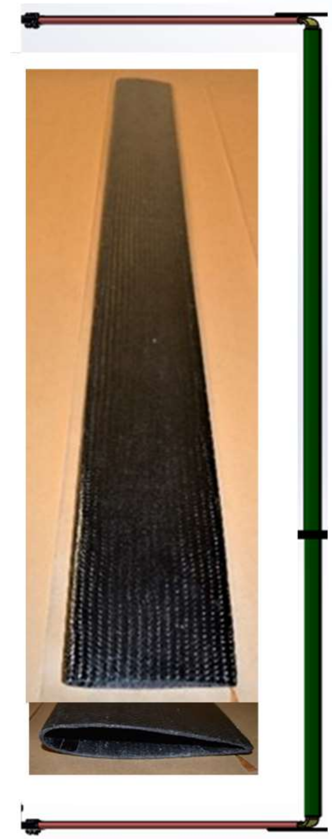
Figure 1. Power curve summary for the normal configuration

The Institute for Advanced Composites Manufacturing Innovation

BLADE PROCESS DEVELOPMENT

Blade Manufacturing Concept

- Demonstrate resin infusion of a hollow carbon fiber/Elium airfoil
  - Section geometry - 6” chord, 0.9” thickness
  - High quality outer surface required
    - Infusion inside a closed mold set
- Demonstrate “fusion bonding”
  - Add carbon fiber reinforced Elium mounting tabs to each end of each blade
    - Use post deformation heat to reform airfoil geometry, locally, and join to flat mounting tab plates
- Demonstrate post-process deformation
  - 1 piece blade of complex profile
  - Create overall blade profile by heating and bending infused fiber reinforced thermoplastic airfoils



Blade Infusion Process – preliminary trials – glass fiber fabrics

- *Primarily Triax fabrics*
- *Evaluated flow media, bagging process, etc*
- *Translucence enable simplified evaluation*

Expendables: Trial 1

<u>Materials</u>

- DAHLPAC outlet
- Spiral tubing inlet
- Mesh flow media
- Peel ply
- Poly tube-bag

<u>Results</u>

- Moderate repeatability
- Difficult expendables positioning
- Difficult expendables removal

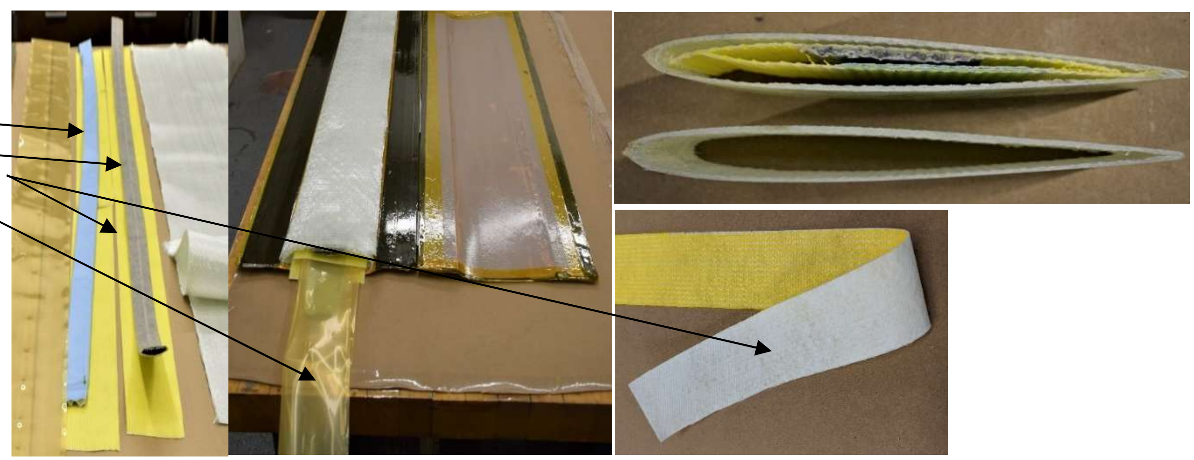
Expendables: Trial 2

<u>Materials</u>

- DAHLPAC outlet
- EnkaFusion inlet
- Compoflex ® (flow media + peel ply)
- Nylon tube-bag (higher T capable)

<u>Results</u>

- Good repeatability
- Simplified expendables positioning
- Consistent expendables removal



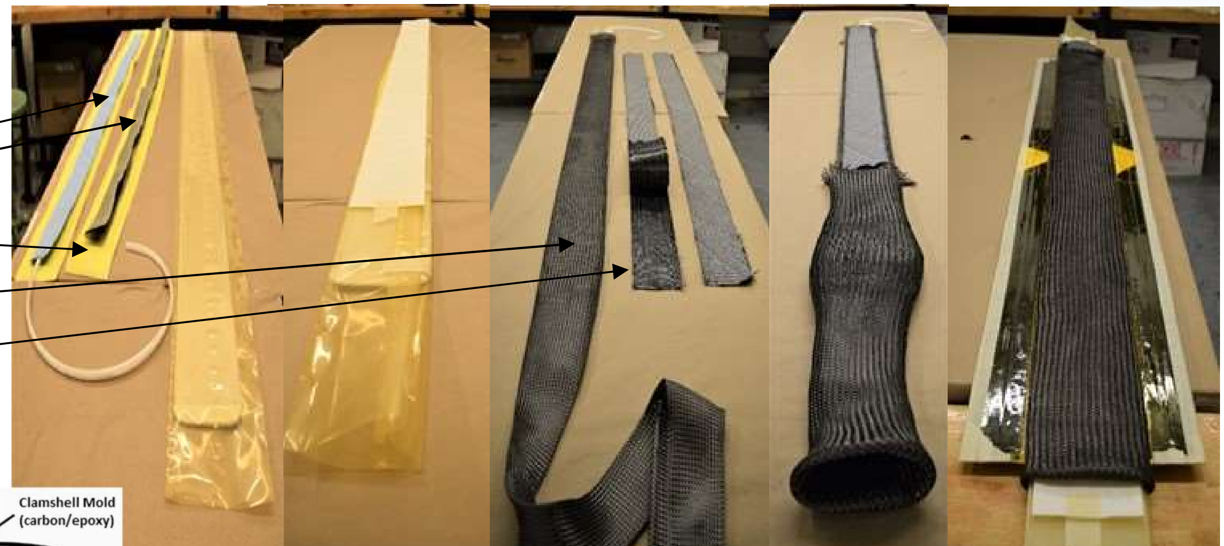
Infusion – preliminary trials (64”) - carbon fiber reinforcement

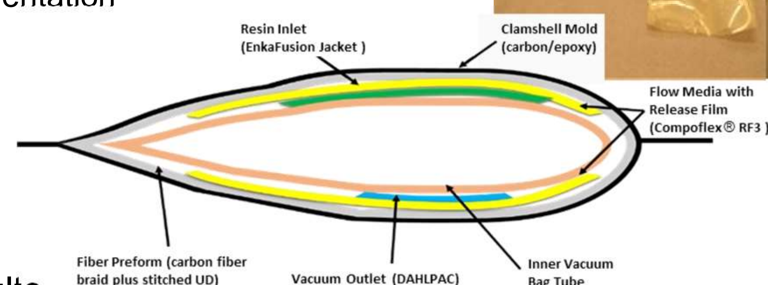
- *Non-Woven bias and 4” braid evaluated as shear/torsion plies*
- *UD stitched carbon with veil backing (353 gsm)*

Trial Set 3

Materials

- DALHPAC MC79 outlet
- EnkaFusion inlet
- Compoflex ® (flow media + peel ply)
- Nylon tube-bag (higher T capable)
- Carbon braid
- UD Carbon with veil backing
- Braid is “rolled” back on itself, over the UD to trap it in position and orientation





Results

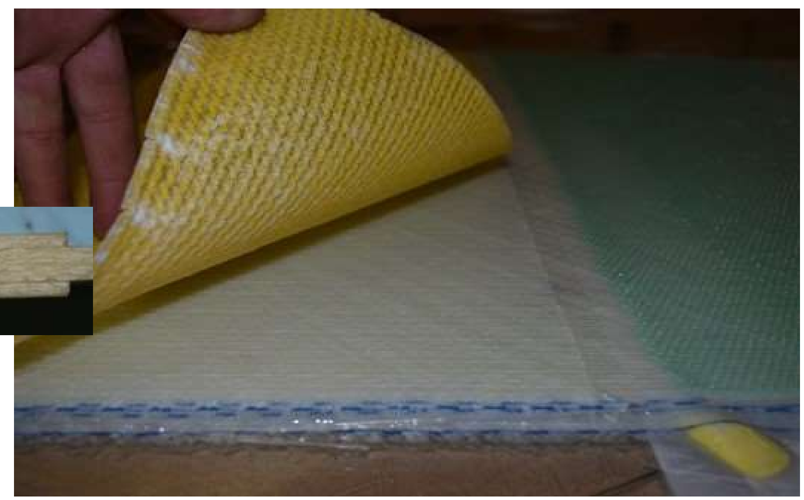
- Improved repeatability w/ braid
- Simplified expendables positioning
- Simplified/consistent expendables removal
- Improved leading and trailing edge quality
- Blade weight ~ 950g/m

2 layers of UD within 2 layers of braid
(~ 2.4mm wall thickness)

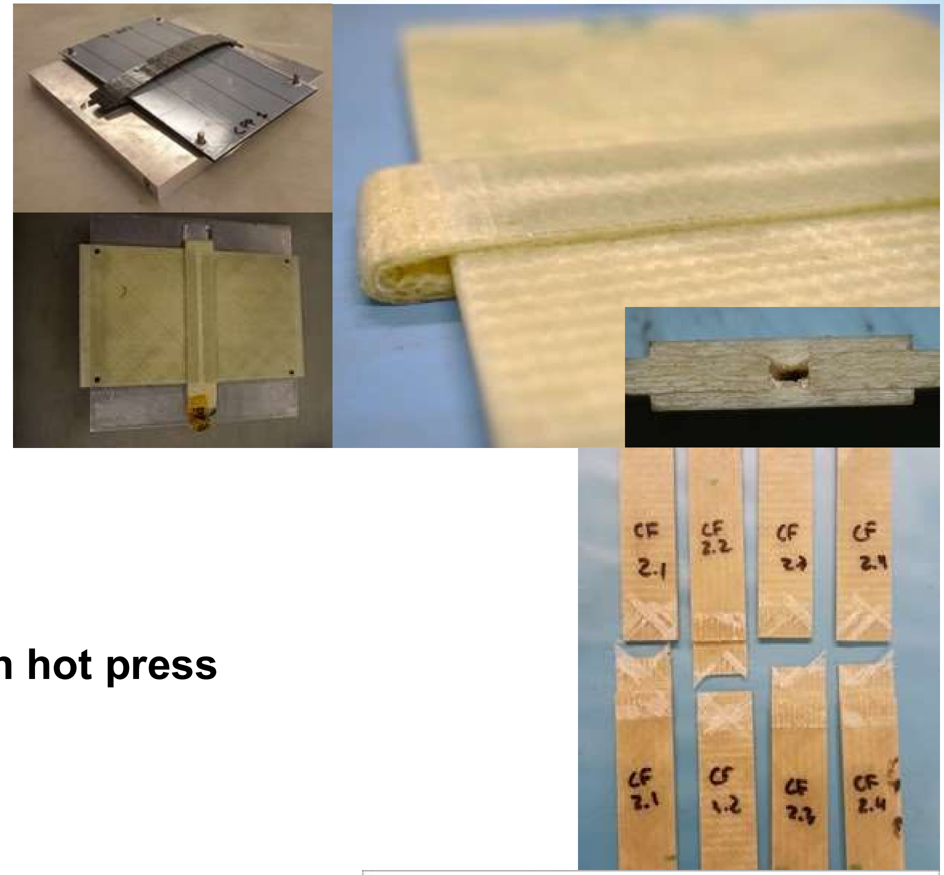
Heat Fusion Bond Testing

- Experimental Setup (ASTM 3528)
  - Compression tooling
    - Center channel positions airfoil to obtain exactly ½” bond area
    - Dowel pins space plates
  - Fiberglass & Carbon Fiber Tested
    - Goal is no secondary processing (such as surface modification)
    - Compare 3 plate surface textures
      - Peel Ply, Compoflex RF3, G-Flow
    - Test geometry – double lap shear
      - 1” wide specimens
      - Minimum 5 repetitions
  - Blade section – texture
    - Compoflex RF3

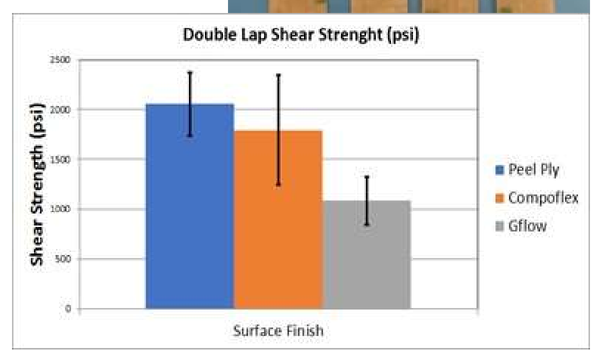



Heat Fusion Bond Testing



- Processing Variables include:
  - Molding temperature (T_m)
    - 180°C vs **200 °C**
  - Consolidation pressure
    - **250 psi** vs 500 psi
  - Hold time at (T_m)
    - 5 min vs **10 min**
  - Cooling Method
    - In hot press vs. **active cooling in hot press**
- Preliminary Results
  - Peel ply surface performed best
    - High average strength 2328 psi (16.1 MPa)
      - 1” wide, double-lap shear joint specimens with 0.5” overlap resisted loads >4,000 lbs
      - 1.75” x 4” joint area should resist a load of 28,000 lbs
    - Bond is approaching interlaminar shear strength of laminate



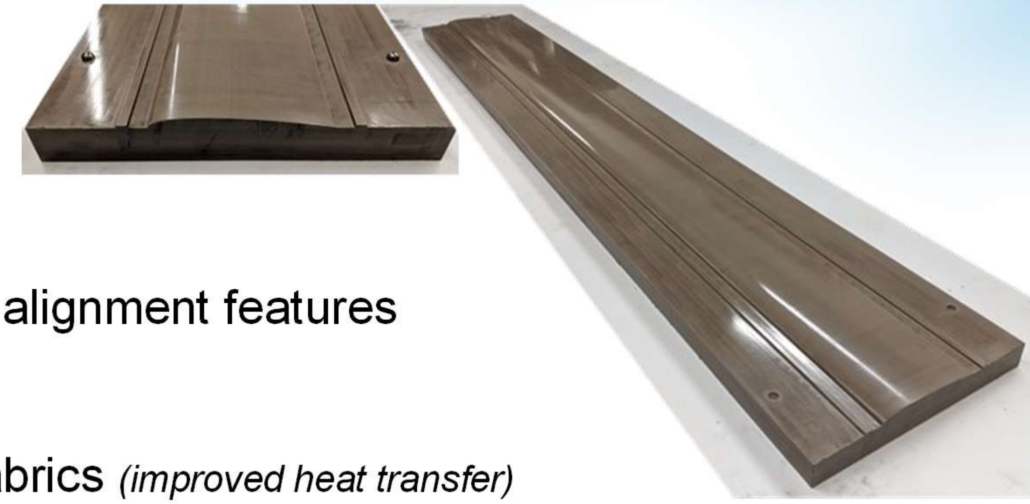
Post-Process Deformation

- Blade to spreader 90° bend
  - Materials
    - Preliminary Trials
      - Glass fiber reinforced blade segments
      - Glass fabric reinforced stiffener plate inserts
    - Fully Fixtured Trials
      - Carbon braid (2 layers) and 2 UD layers
  - Tooling/fixturing
    - Preliminary Trials
      - Standard aluminum and steel shapes – cold
      - Custom matched geometries in MDF
    - Fully Fixtured Trials
      - Uses an alignment fixture and a wiping process
  - Approach
    - Preheat reinforced area of blade and crush to bond airfoil surfaces in hot press
    - Remove hot blade and insert into fixture to bend

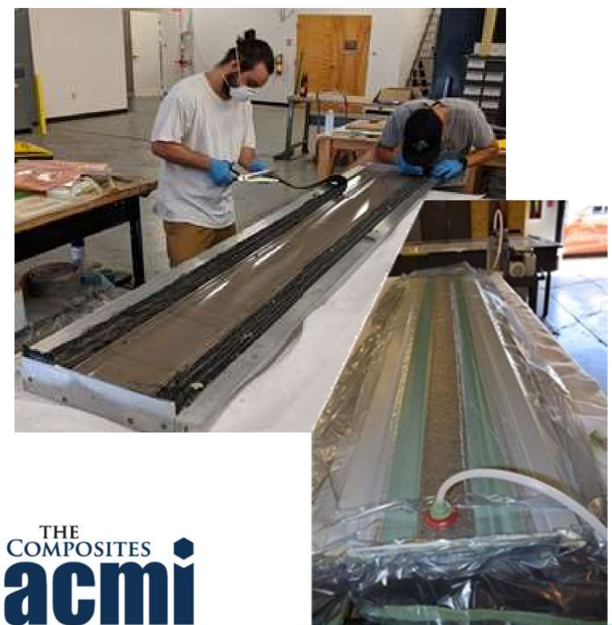
Challenge: retaining quality in transition region

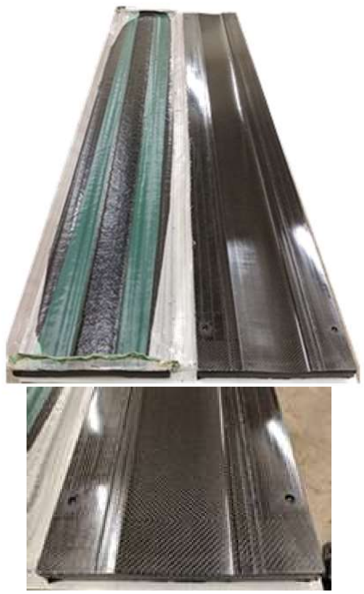
FINAL BLADE MANUFACTURE

Blade Master & Mold Preparation



- Master
  - Nominally 2.34m (92”) long
  - Coated 40 lb/ft^3 tooling board
  - ‘O’-ring sealing channels and alignment features
- Molds
  - Epoxy resin infused carbon fabrics *(improved heat transfer)*
  - 3 – 2.34m molds segments manufactured
    - 1 + ½ segments bonded together to yield a 3.5m (138”) mold set



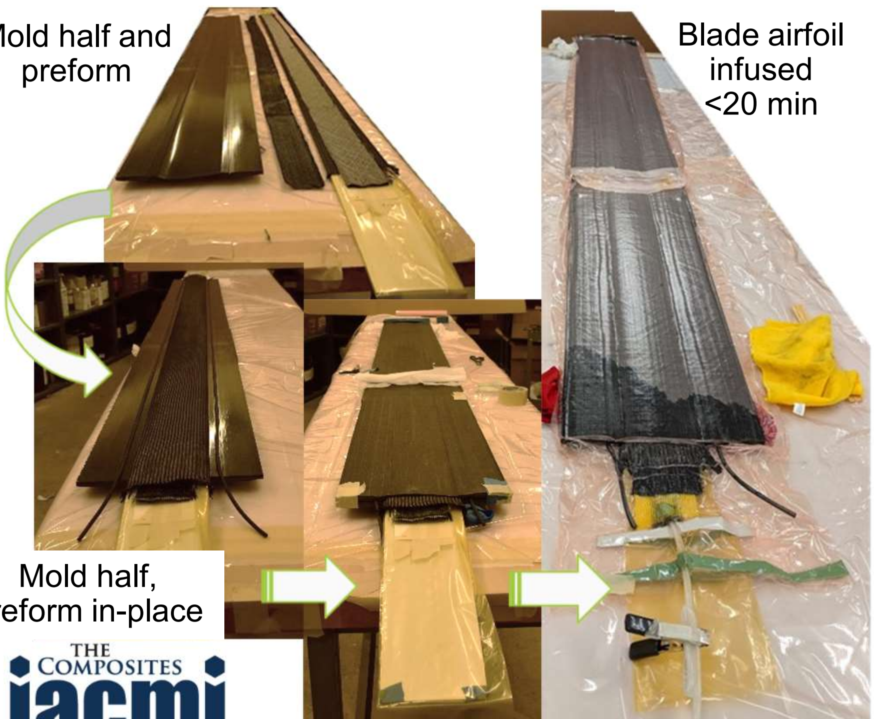


2.34 m

3.5 m

Blade Airfoil Manufacture

- Hollow airfoil infusion inside closed molds
  - Process and expendables as developed in preliminary trials
  - 3.5 m length is sufficient for 1-piece blade airfoil and spreaders
  - Materials as determined during modeling and testing
    - Carbon fiber preform of 2 - 4” braided sleeves, capturing 3 layers of stitched UD w/veil. Arkema Elium 150 matrix. Total thickness ~ 3 mm (0.125”)
      - Braid from Highland Composites and A&P Technology; stitched UD from VectorPly



Mold half and preform

Mold half, preform in-place

Molds closed

Blade airfoil infused <20 min

3 – 3.4m airfoils awaiting trimming and expendables extraction

3 – 3.4m airfoils awaiting end fitting and bending

Blade Completion

- Blade airfoils are trimmed to length (~3.28 m / 129”)
- Mouting tabs (carbon fiber/Elium) are inserted and fused
  - Custom fixture
  - Hot press temperature: 200C
- Blades are bent at a specified distance from each mounting tab

3 – 3.4m airfoils, tabs trimmed and ready to bend

1st bend completed at a specified distance from the end

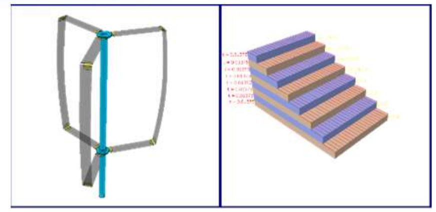
2nd bend completed. Both bends at same distance from associated end.

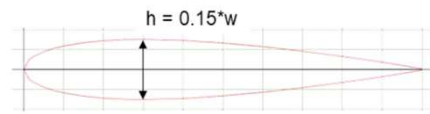
Ready for installation on the tower!

SUMMARY

Summary

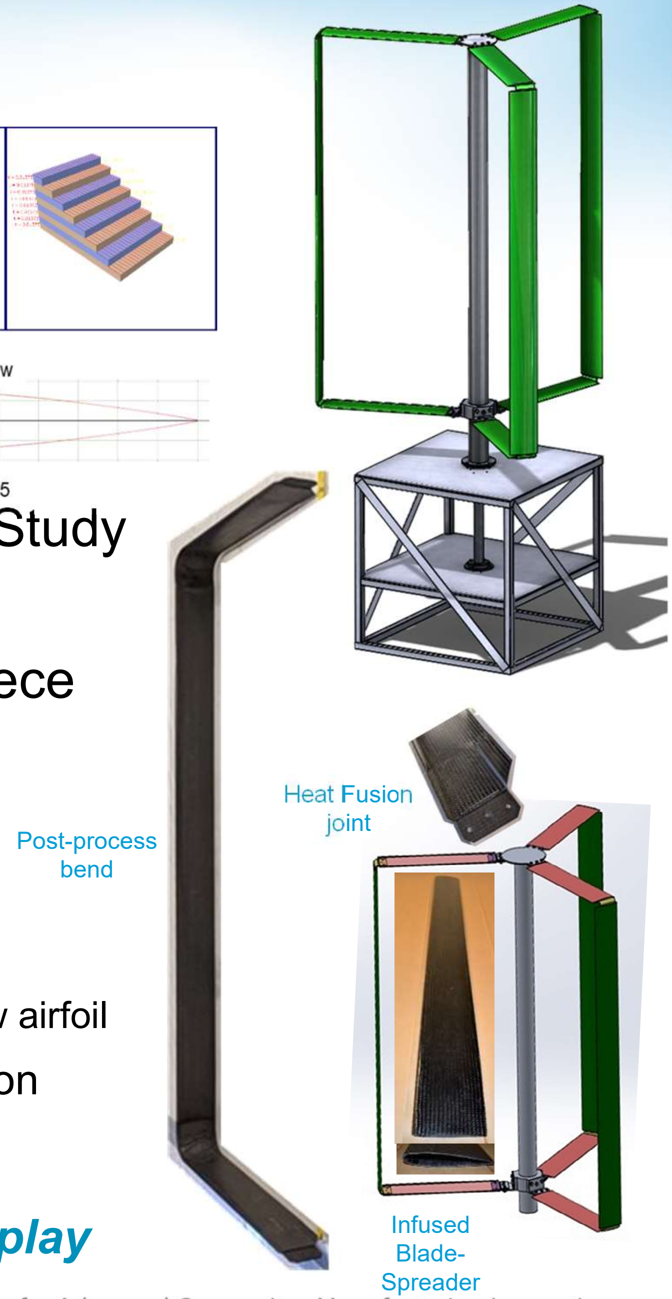
- Completed Preliminary Design Study
  - Finite element analysis of structure
    - Static
    - Dynamic
  - 2D CFD to confirm blade airfoil section
    - NACA 0015 – 6” chord





NACA0015

- Completed Preliminary Carbon/Elium Materials Study
  - Informed analysis to determine appropriate laminate
- Completed demonstration of Thermoplastic 1-piece Blade Manufacture
  - Demonstrated infusion of hollow 3.4m airfoils
    - Carbon fiber/Elium process repeatability
    - Tailorable preform
  - Demonstrated fusion joining
    - Blade-to-tower mounting tab plates fused into ends of hollow airfoil
  - Demonstrated ability to perform post-process deformation
    - 1-piece airfoil bent to form blade-spreader set



Completed VAWT hardware on display