Fabrication & Testing of 3m Carbon Blades

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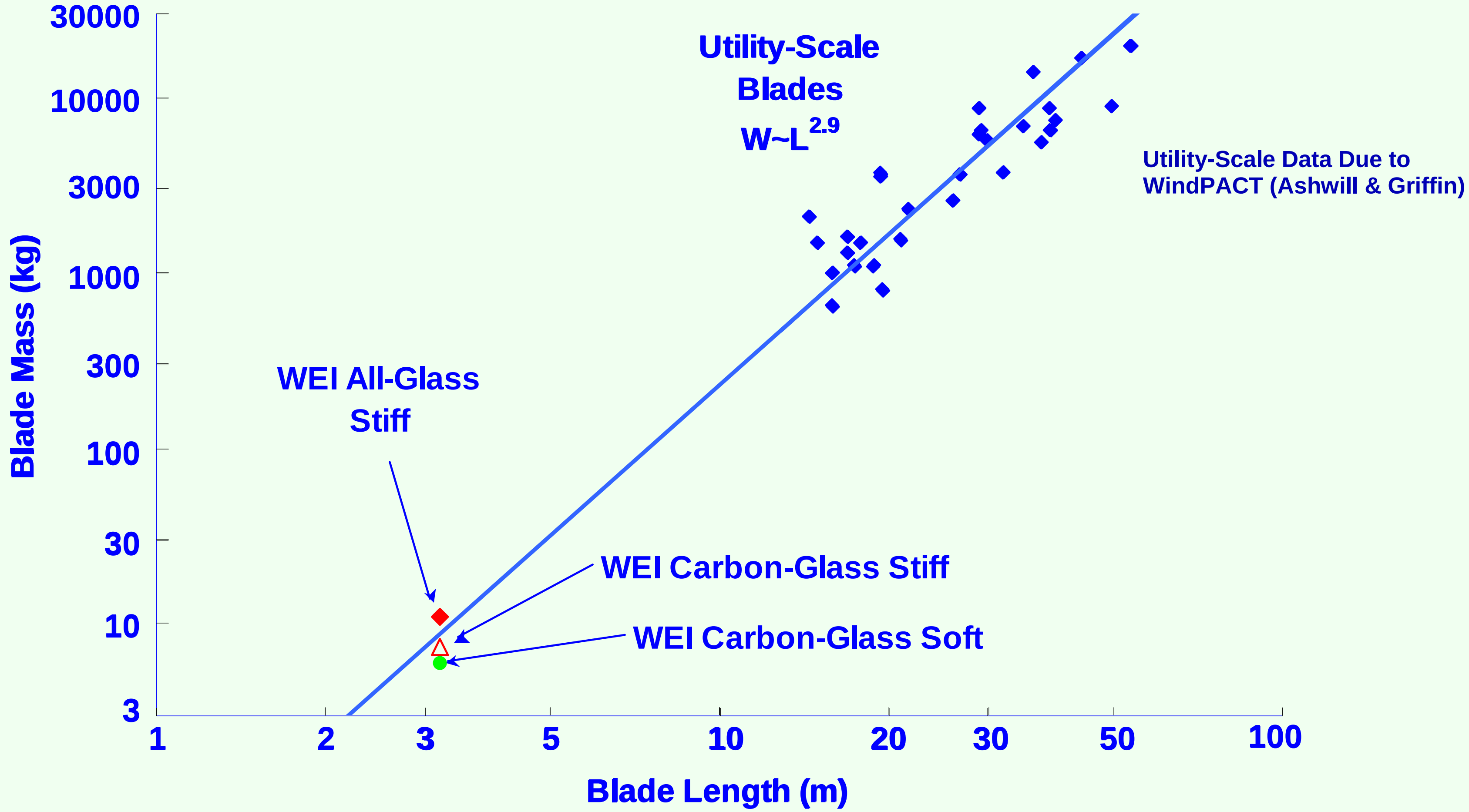
    - Keith Bennett, Administrator

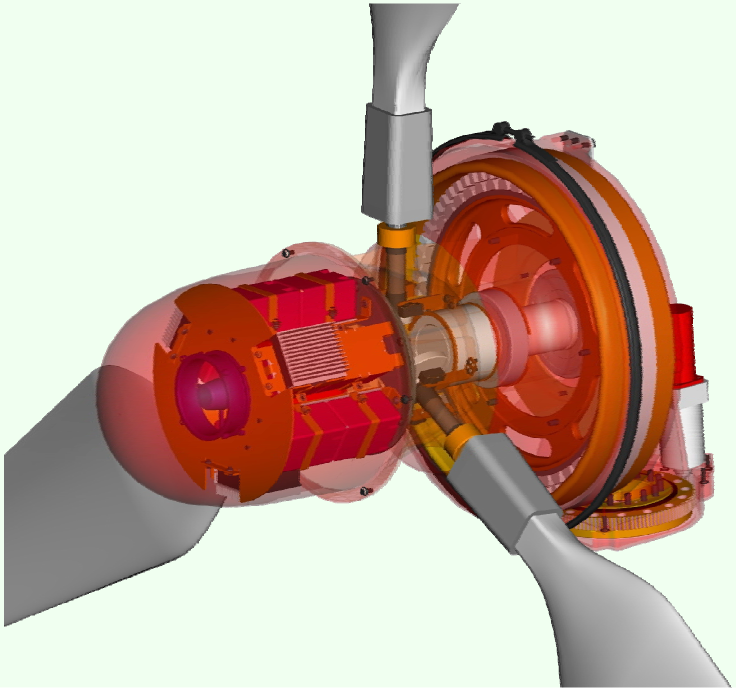
- National Institute for Aviation Research at Wichita State University assisted with fabrication and testing
  - Dr. James Locke was PI at NIAR
  - Dr. Tim Hickey supervised blade testing
  - Sanjay Sharma developed our VARTM process & supervised the shell fabrication
  - Terrence Seet & Michelle Man and others assisted

Blade Weight Trends

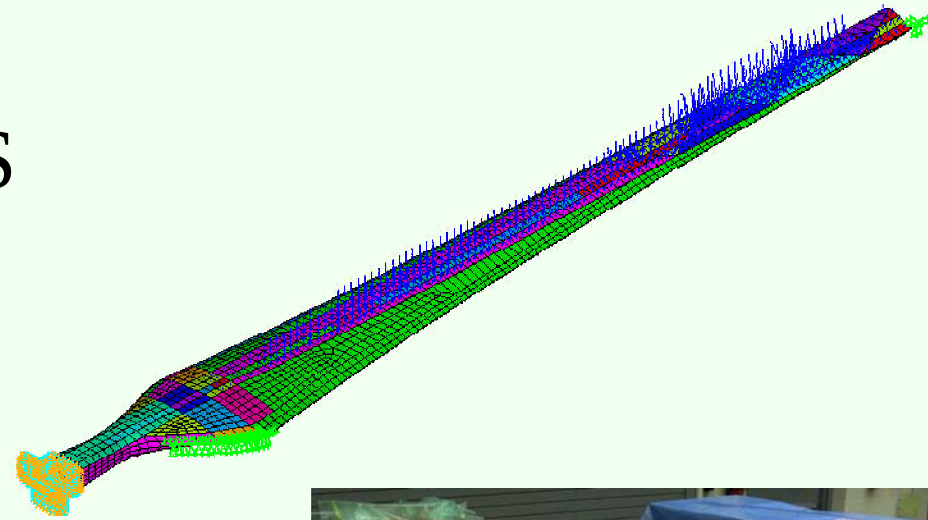


MOTIVATION FOR THE PROJECT

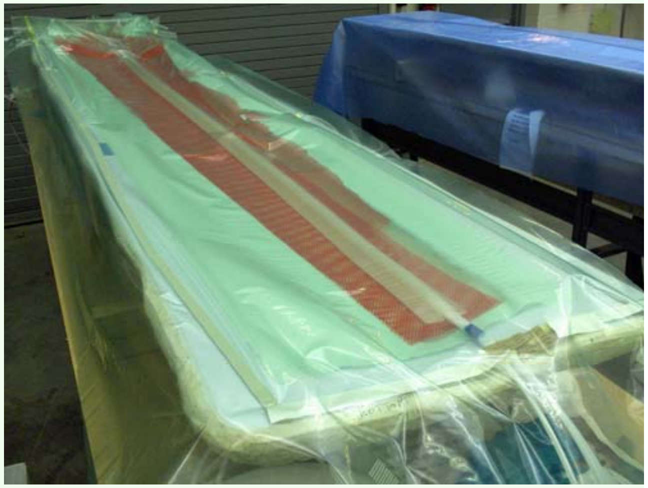
- Aerodynamically Efficient Blades for Small Turbines
  - Optimized twist & taper
  - High-quality manufacturing → VARTM
- Light-weight designs for pitch-control
  - High-quality structural design
  - Carbon-glass hybrid structure
  - High-quality manufacturing
- Twist-flap coupling



PROJECT ACTIVITIES

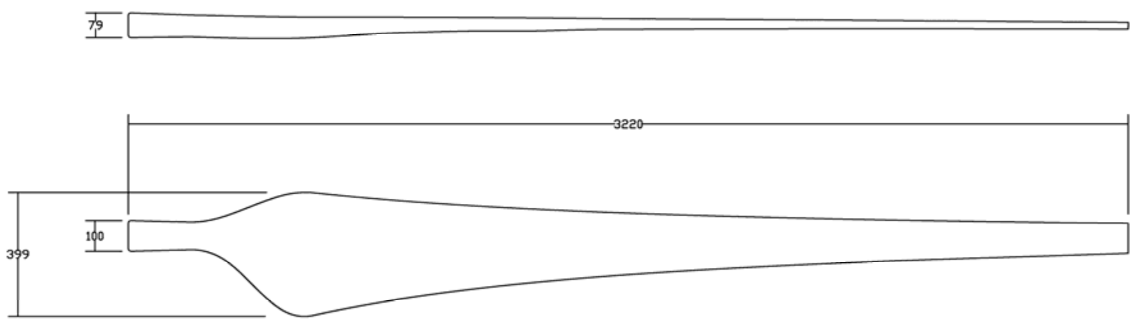


- Blade Design & Analysis
  - Aerodynamic Design
  - Structural Design (ANSYS)
- Blade Fabrication (VARTM)
- Blade Testing
  - Static (to failure)
  - Fatigue (Accelerated Lifetime)

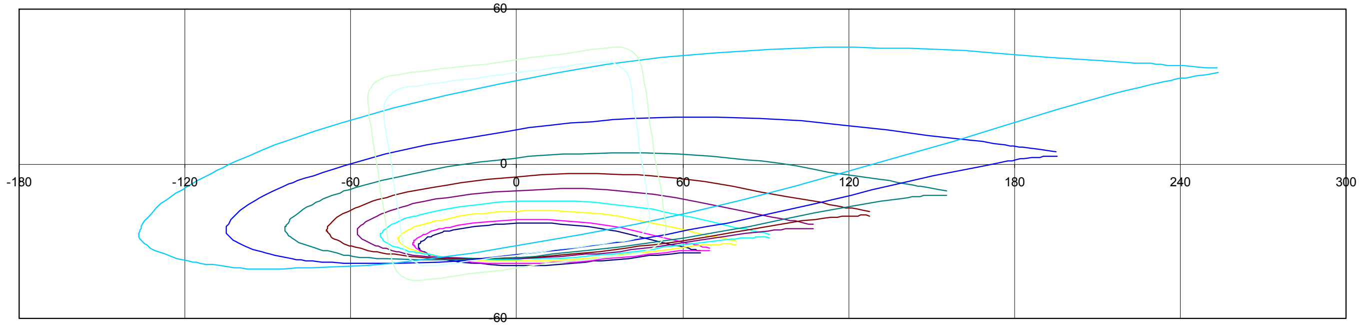


AERODYNAMIC DESIGN

- Maximize energy capture over the entire range of below-rated wind speeds, considering:
  - spanwise distribution of chord length
  - spanwise distribution of twist
  - shaft speed
  - pitch schedule as a function of below-rated wind speed



NREL S822 Airfoil (16%) for All Sections



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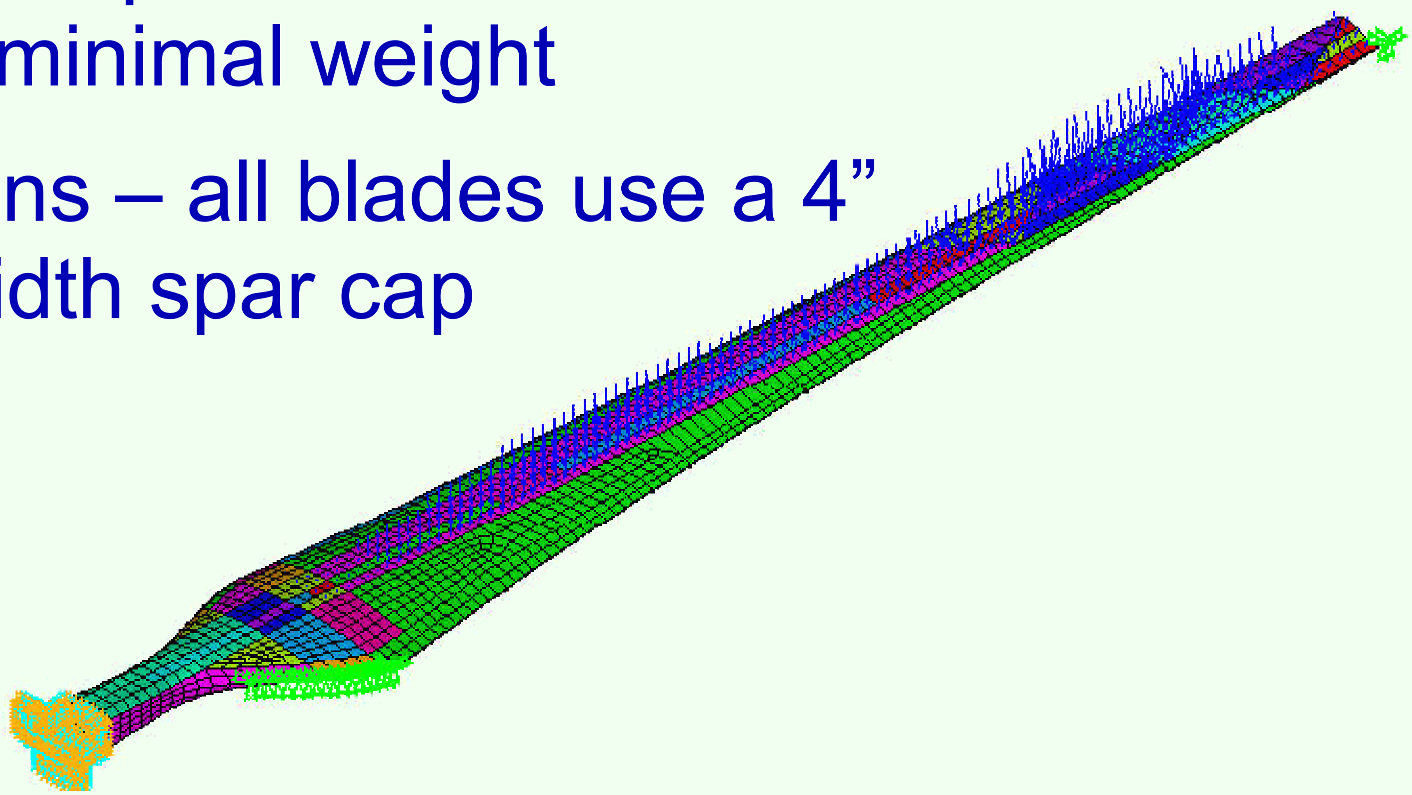
STRUCTURAL DESIGN

Blade	Spar Cap Construction	Skin Fiber Construction	Design Tip Deflection	Designed	Fabricated	Tested
A	100% Glass 0°	100% Glass ±45°	420 mm	Yes	Yes	No
B	**100% Carbon 0°**	**100% Glass ±45°**	**420 mm**	**Yes**	**Yes**	**Static & Fatigue**
C1	**92% Carbon off-axis 8% Glass 0/90°**	**100% Glass ±45°**	**420 mm**	**Yes**	**Yes**	**Static**
C2	Improvement on C1			Yes	In-Progress	Pending
D	92% Carbon of-axis 8% Glass 0/90°	100% Glass off-axis	420 mm	Yes	In-Progress	Pending
E	Carbon/glass hybrid off-axis		420 mm	Yes	In-Progress	Pending
F/H/I1	**100% Carbon 0°**	**100% Glass ±45°**	**150 mm**	**Yes**	**Yes**	**I1 Static**
I2	Improvement on I1			Yes	Yes	Static
G	100% Carbon 0°	100% Carbon ±45°	420 mm	Yes	Yes	Pending

- Clamshell Design with Spar Caps Integrated into the Shells
- C- or O-channel shear web bonded between shells in a secondary process

STRUCTURAL DESIGN

- Structural Optimization Pointed to a Spar Cap Tapered in Width & Thickness
- Fabricating Tapered Width was a Nuisance and saved minimal weight
- Final Designs – all blades use a 4” constant-width spar cap



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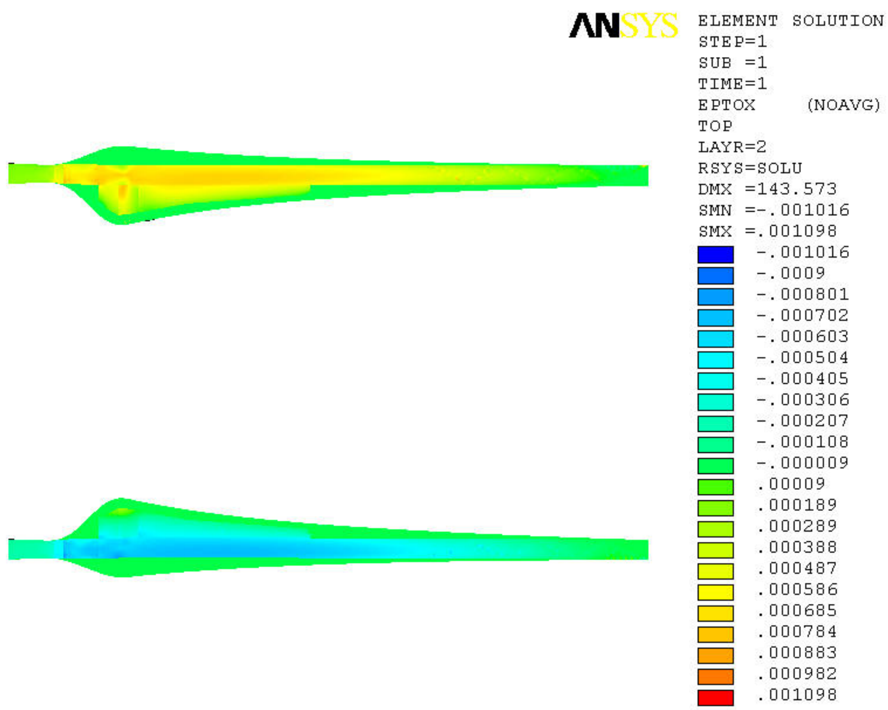
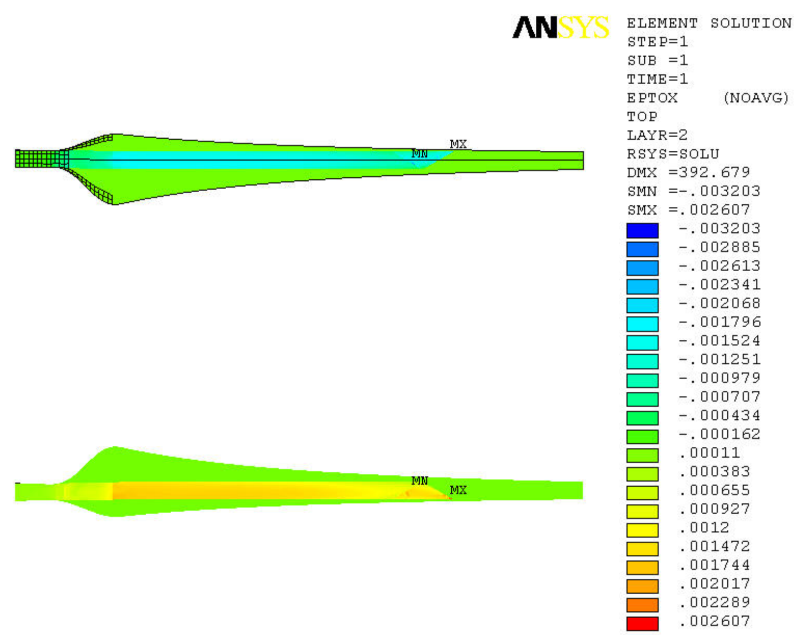
Structural Design

- Design Requirements:
  - Carbon fiber strain < 0.3%
    - Soft Blades at margin, stiff blades extra margin
  - 20-year fatigue life → all blades ~ infinite life
  - Buckling LF > 2.1 → uncoupled blades OK





Blade I, Axial Strain < 0.11%

Blade B, Axial Strain < 0.32%

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BLADE FABRICATION

- VARTM shells in Clamshell Tools
- Tools from CNC routed mandrels
- 13 osy Carbon Uni
  - 68k tow Fortafil fiber
  - High fiber volume fraction
  - Low permeability!
- 12 and 17 osy Glass ±45°
  - PPG Hybon 2022 fibers
- We had no choice in carbon material at the time we purchased!!

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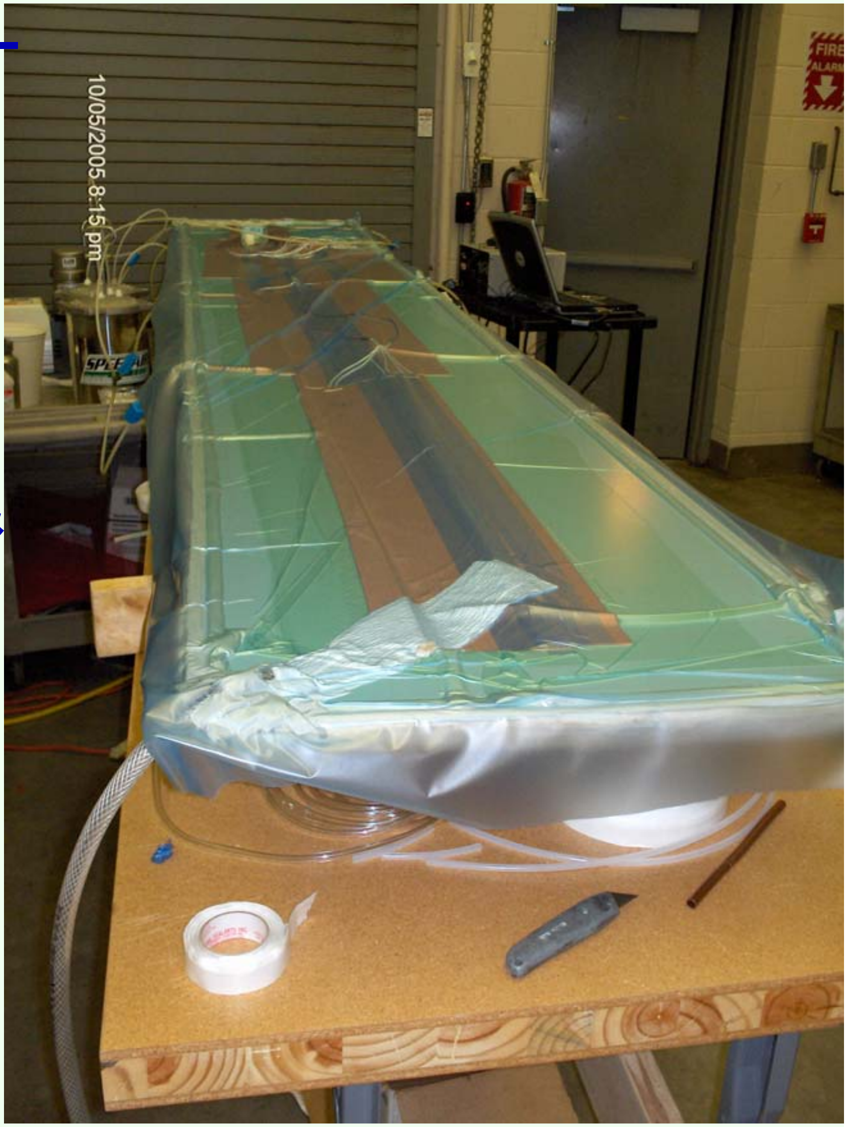
BLADE FABRICATION

- Shells are infused using vacuum-assisted resin transfer molding
  - Full vacuum
  - 0-25 psi back pressure
  - JeffCo 1401-21(18) resin
  - Experimented with number, type, & placement of infusion ports & channels and vacuum ports.
  - Heated with Si rubber heaters during infusion and cure cycle
  - 4-10 minutes to infuse one shell



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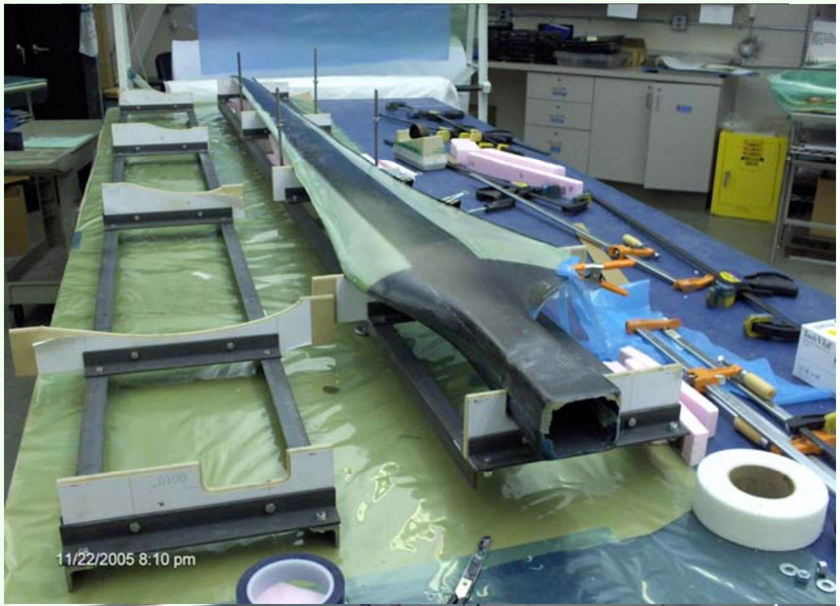
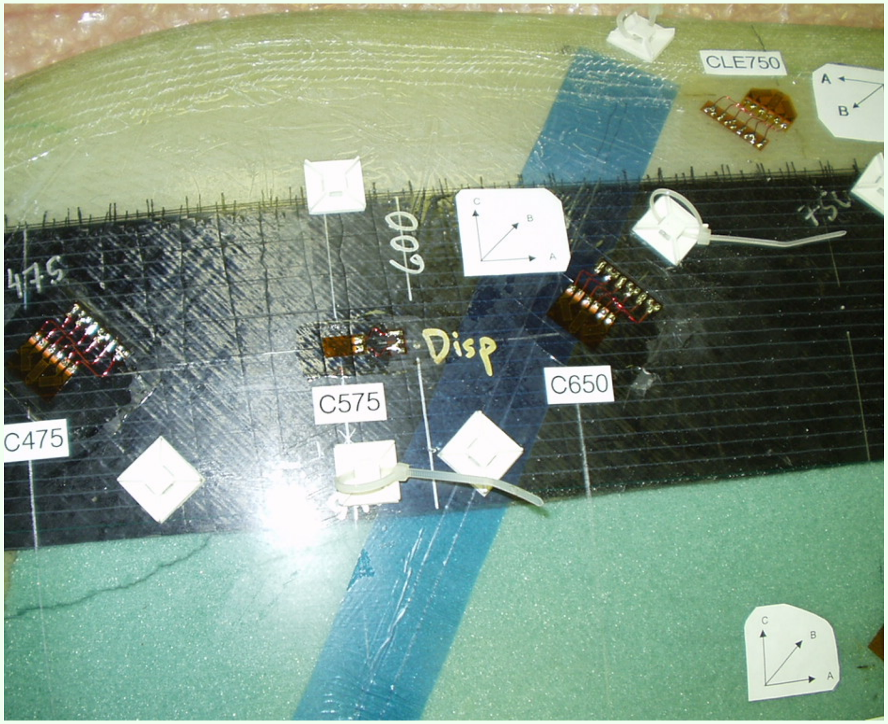
BLADE FABRICATION

- Cured shells were demolded & trimmed
- Shear webs were fabricated using wet layup
- Shells and webs were bonded in a secondary process
- Finished blades were post-cured at 200F for 8 hours in an oven
- Blades were instrumented for testing



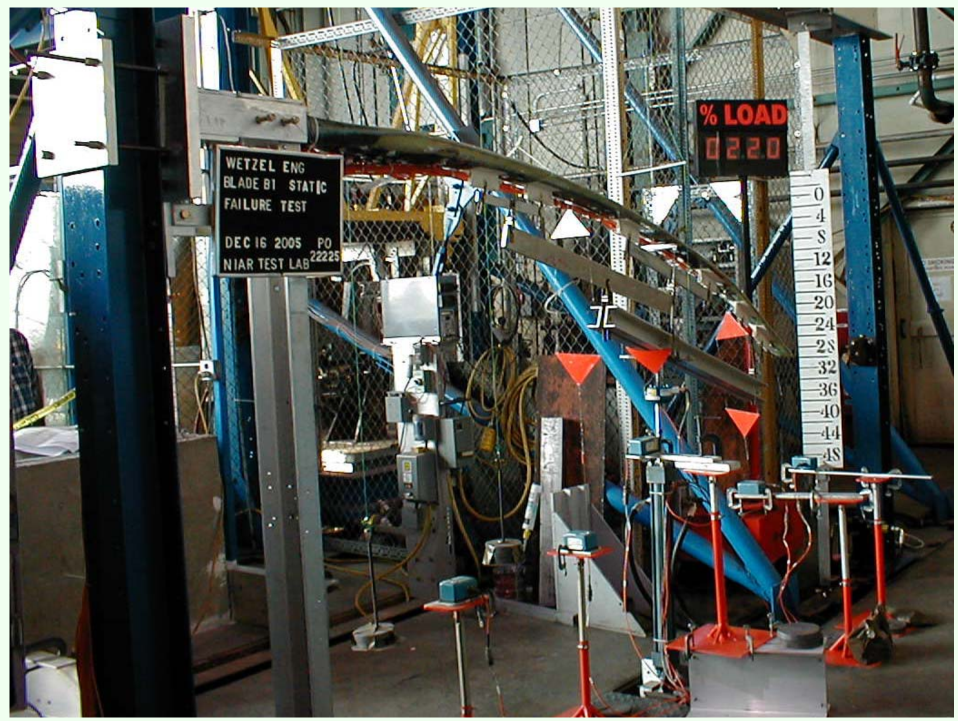
STRUCTURAL TESTING

- NIAR/Raytheon 46000-sf Test Center
- 30-36 channels of strain per blade
- Axial gauges and 3-element rosettes
- 6-point Whiffle Tree Static Load
- Displacement at 6 Spanwise Stations



STRUCTURAL TESTING

Blade	Peak Carbon Fiber Strain at 100% Proof Load		Tip Deflection at 100% Proof Load		Buckling LF		Tip Twist at 100% Proof Load	
	Design	Test	Design	Test	Design (Linear)	Test	Design	Test
I1	0.11%	0.10%	147	191	2.56	2.30	-	-
I2	0.11%	0.10%	147	162	3.10	2.90	-	-
B1	0.32%	0.27%	414	373	2.53	2.26	-	-
C1	0.33%	0.33%	375	318	2.20	1.65	7°	1.5°



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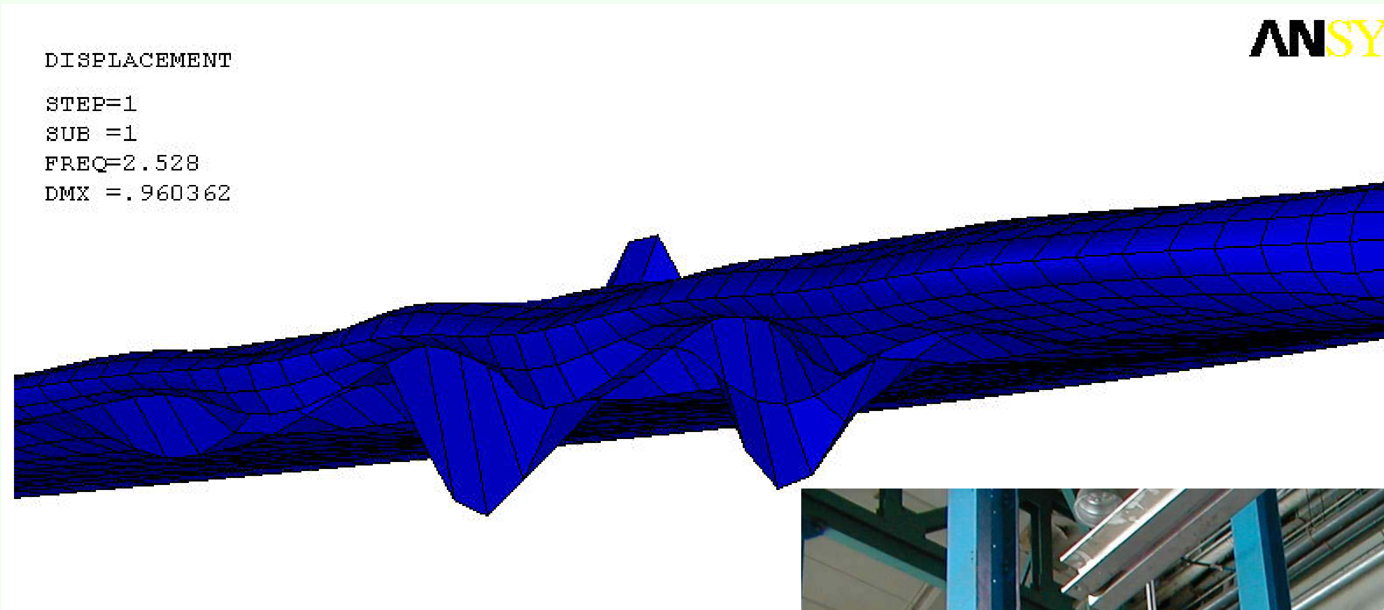
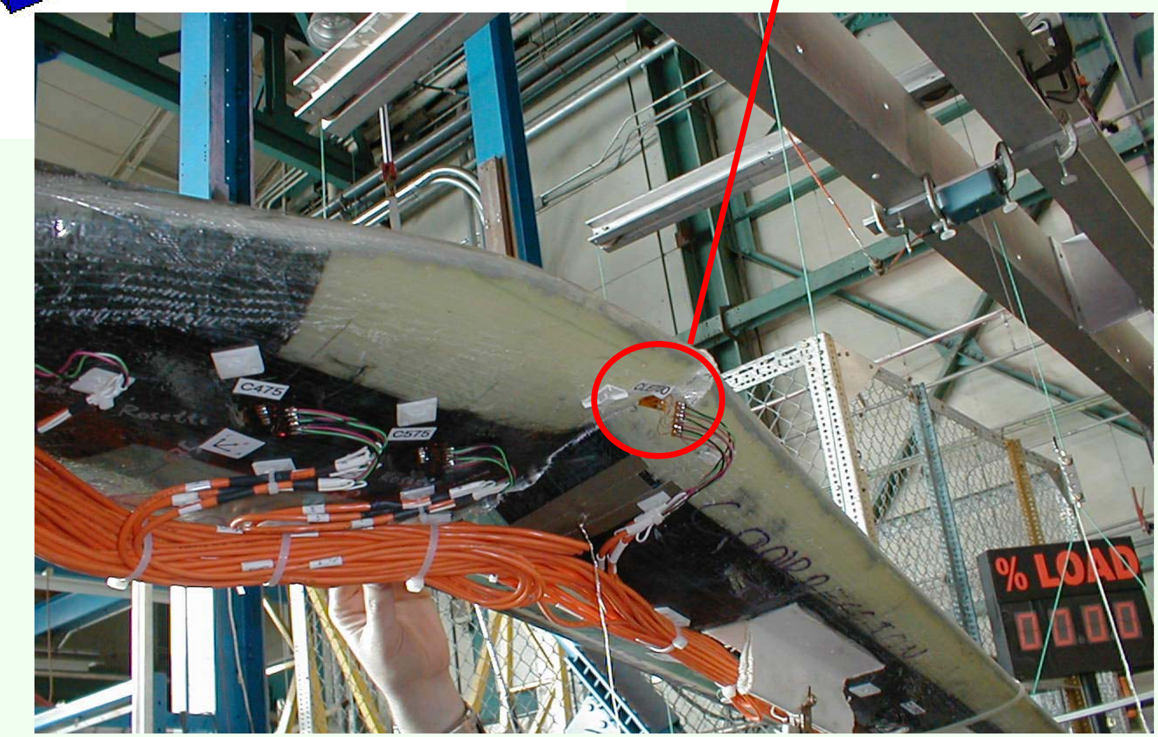
Structural Testing



Rosette Placed to Capture Buckling



- Buckling Initiated Exactly where predicted in all static tests
- Test Load Factors were close to linear prediction in uncoupled blades

FUTURE PLANS

- Remodeling Blades B, C, & I “as fabricated” to verify against test results
- Completing designs of Blades D & E (twist-bend coupled designs)
- Fabricating & Testing Blades D & E to demonstrate significant twist-bend coupling
- Working with warm vacuum prepreg products that do not require autoclaves