Composite Wind Blade Engineering and Manufacturing

Presented to Students and Faculty of :

Massachusetts Institute of Technology

Independent Activities Period Mini-Course

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Overview of TPI Composites

- Transformed into a leading provider of turbine blades to the rapidly expanding wind industry
- Track record of first of their kind innovations in transportation and military vehicle markets
- Solid growth through advanced technology and world class focused factories that enable long term partnerships with major players

WIND BLADES

- 10,000+ blades supplied over 10-years to the strictest quality standards
- Near aerospace quality at industrial cost
- Custom designs, tailored to customer's turbine
- Precision molding and assembly systems
- Patented SCRIMP® vacuum infusion process technology
- Robotic systems improve productivity and quality
- Laser tracking and ultrasonic inspection verify accuracy

OVER 1M FT^2 OF MANUFACTURING SPACE


Newton, IA (316k Ft^2)


Juarez, MX (477k Ft^2)

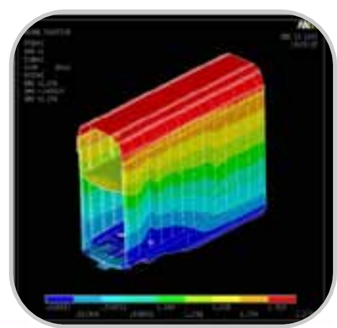

Taicang Port, CH (190k Ft^2)


Warren, RI (91k Ft^2)


Fall River, MA (69 k Ft^2)

TPI INNOVATION DEPLOYMENT TEAM

Mission: Create <u>sustainable competitive advantage</u> for TPI through deployment and protection of advanced technology. <u>Reduce cost of energy</u> - improve performance & reliability while reducing blade cost.



FALL RIVER WIND BLADE INNOVATION CENTER

- 69K sq ft facility with water access
- Enable 45M to 62M+ prototype wind blades
- Conduct blade innovation
- Build initial prototype blades
- Build pilot production blades
- Dial in production tooling
- Create production documents
- Technology transfer
- Phase II expansion opportunity

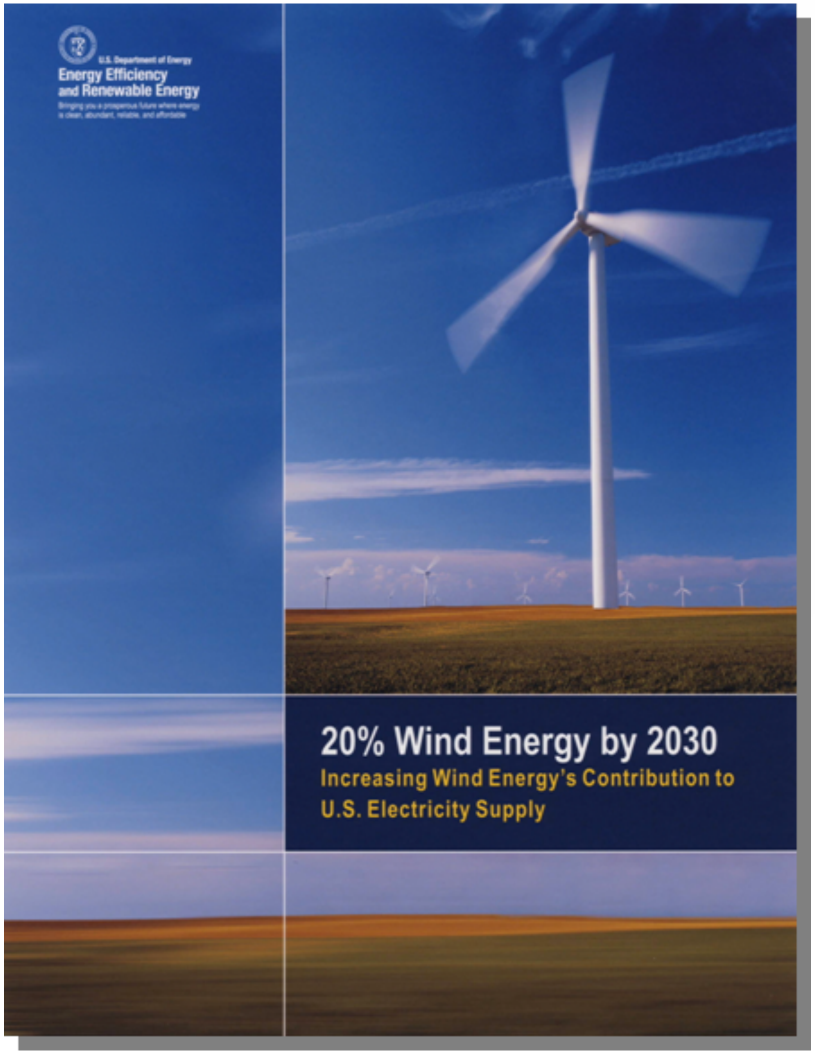
TPI Products

Wind Turbine Blades

TPI Products

Wind Turbine Blades

20% Wind Energy by 2030

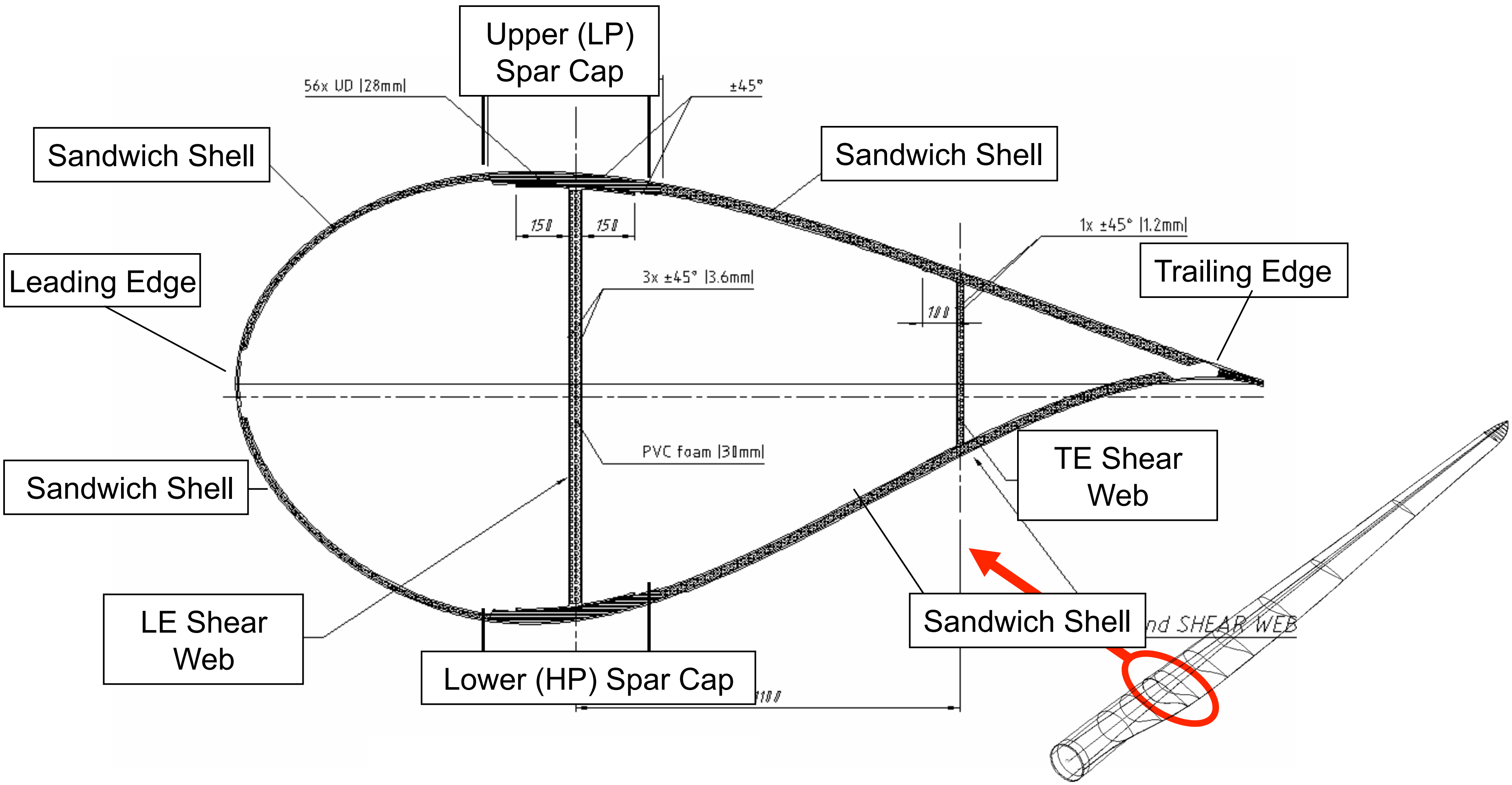


- U.S. Department of Energy (DOE)
- Power Marketing Administrations (PMAs)
- National Renewable Energy Laboratory (NREL)
- Lawrence Berkeley National Laboratory (Berkeley Lab)
- Sandia National Laboratories (SNL)
- Black & Veatch
- Leading wind manufacturers and suppliers
- Developers and electric utilities

Check out www.20percentwind.org

So What does a Modern Wind Turbine Blade Look Like?

Anatomy of a Wind Turbine Blade (near Max Chord)

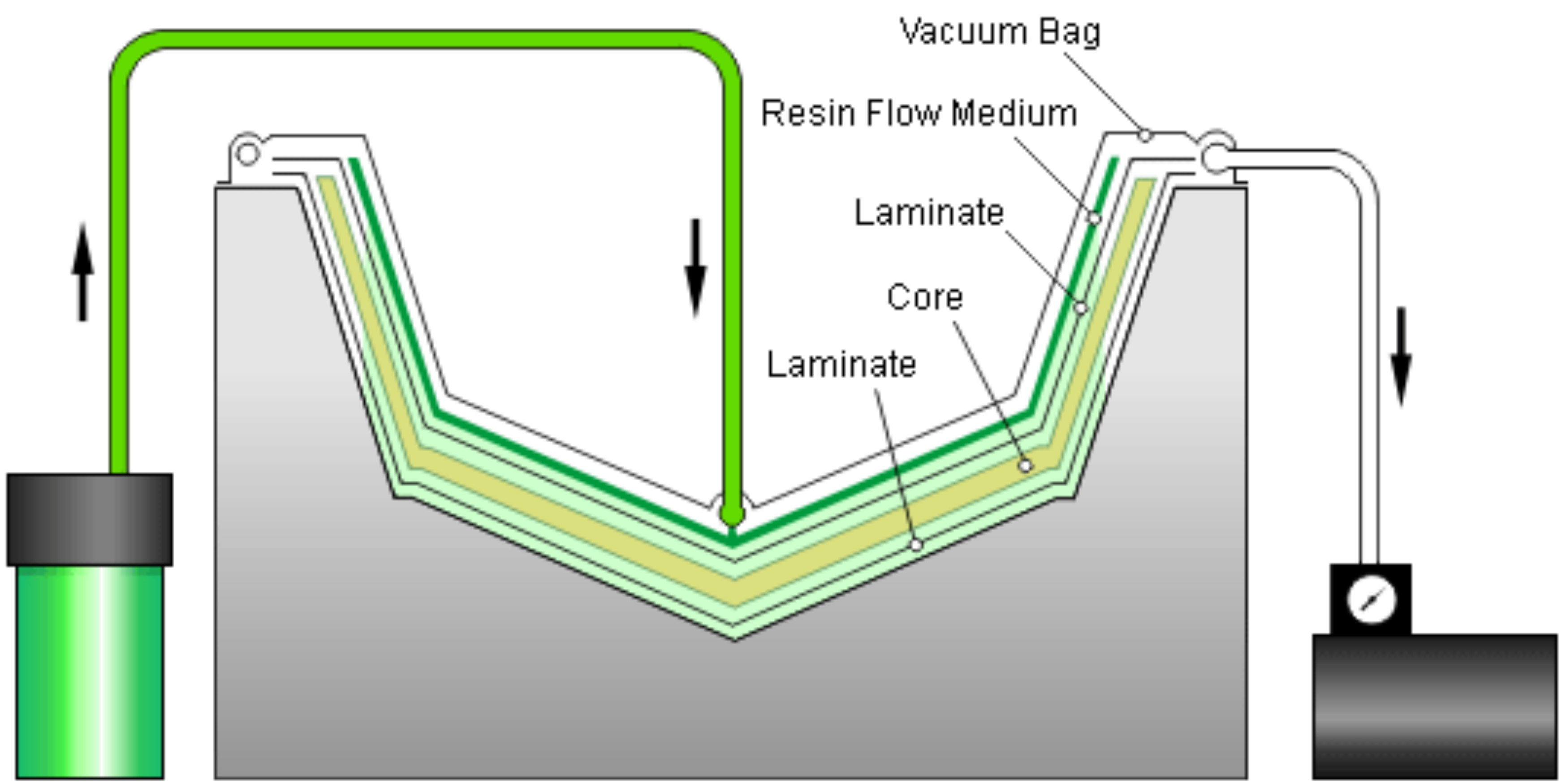


…and just what is a "Composite"?

- Let's keep it simple:
  - A composite material is one, that on a macro-scale, is "composed" of multiple non-homogeneous materials.
  - The composites that "TPI Composites" concerns itself with is continuous fiber reinforced polymers.

"STRING and GLUE"!

Seemann Composite Resin Infusion Molding Process (SCRIMP®)



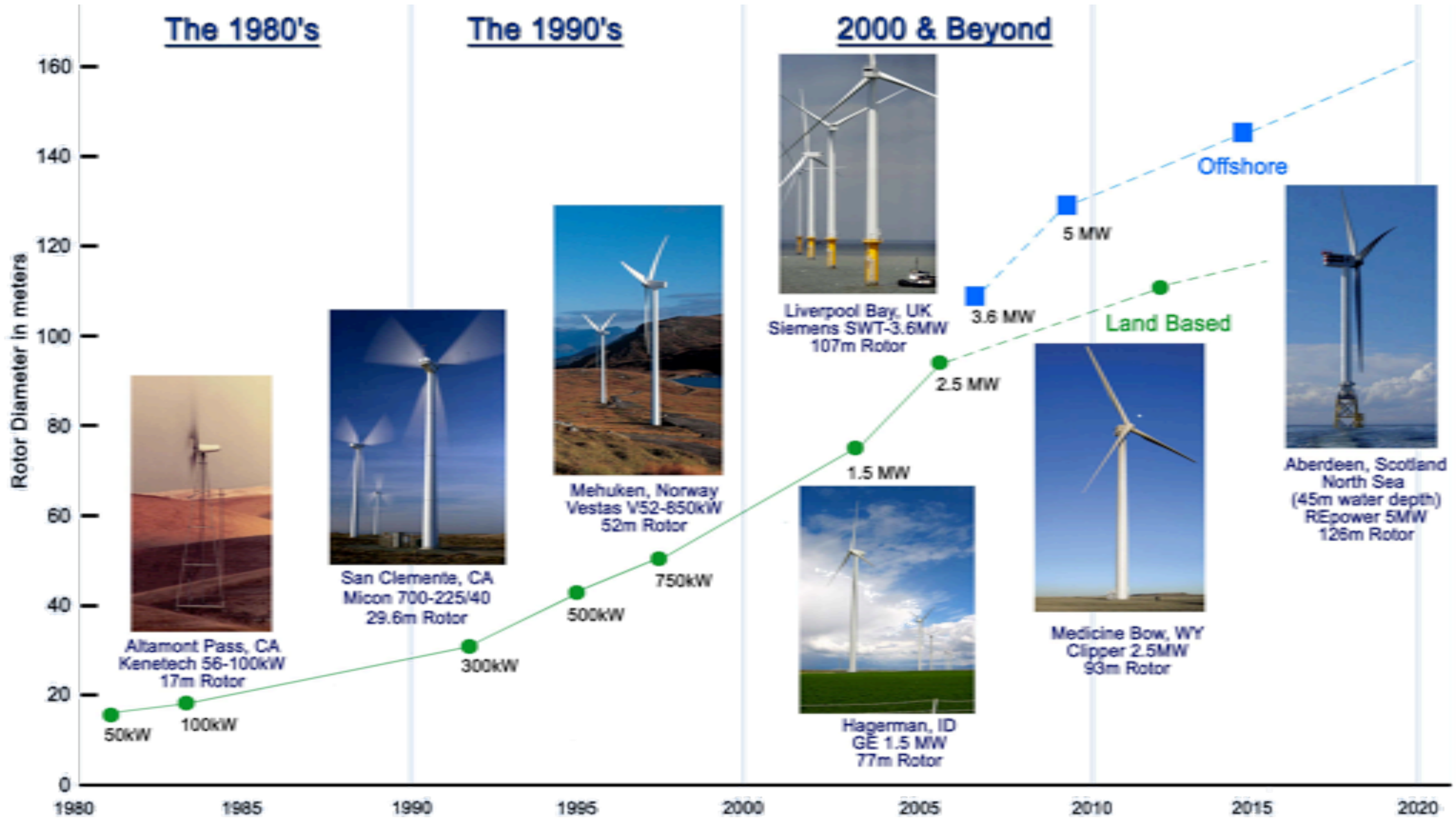
Catalyzed Resin

Typical SCRIMP™ Schematic

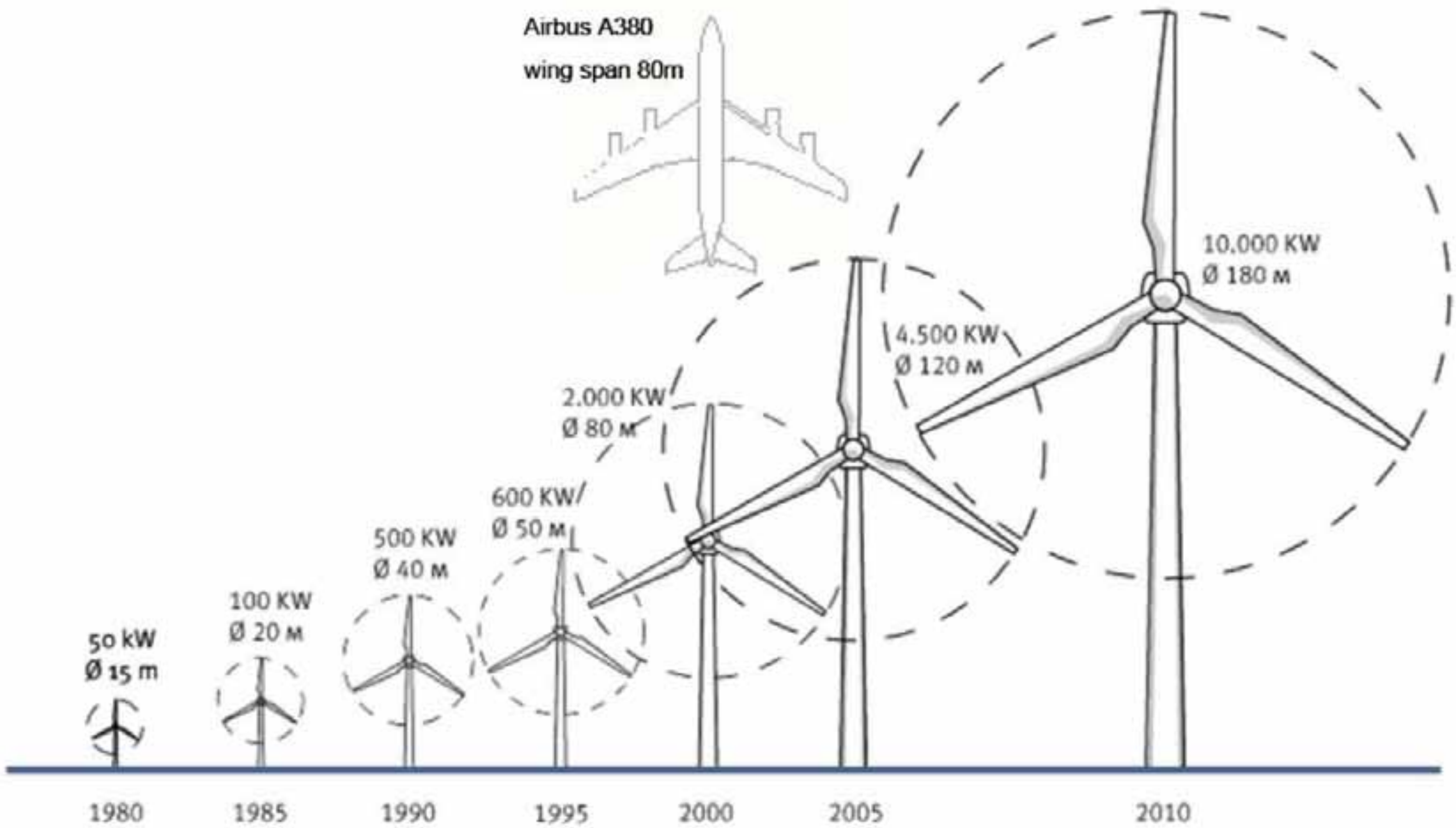
Vacuum Pump

Manufacturing of Wind Turbine Blades

Evolution of Commercial Wind Technology



Growth of Rotor Diameter



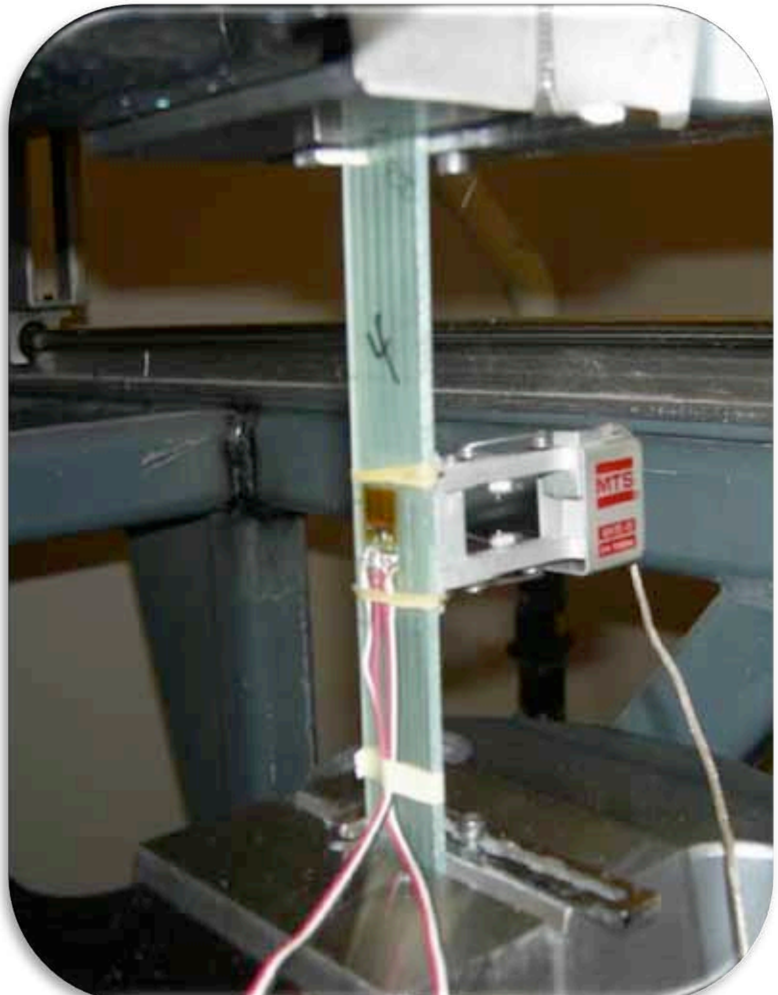
Trend toward bigger turbine sizes

Blade Engineering with Expertise in MANY Disciplines

- Materials Engineering
- Structural Design
- Embedded Sensor Technologies
- Tooling/Process Engineering
- Metrology and NDE
- Structural Testing/Certification
- Transportation/Logistics

Materials Engineering

Materials Engineering



Materials are the primary drivers in system performance and production costs:

- Structural Composite Materials
  - Reinforcements
    - Glass: Low-cost high specific strength, modest specific stiffness
    - Carbon: High cost but with high specific strength AND stiffness
    - Others : Aramids, Basalt etc.
  - Resins
    - Epoxies
    - Vinyl/Poly-ester
    - "Toughened" Resins
      - ETBN/CTBN Reactive Liquid Polymers
      - Core Shell Rubber
      - Nano-technologies
    - Thermoplastics

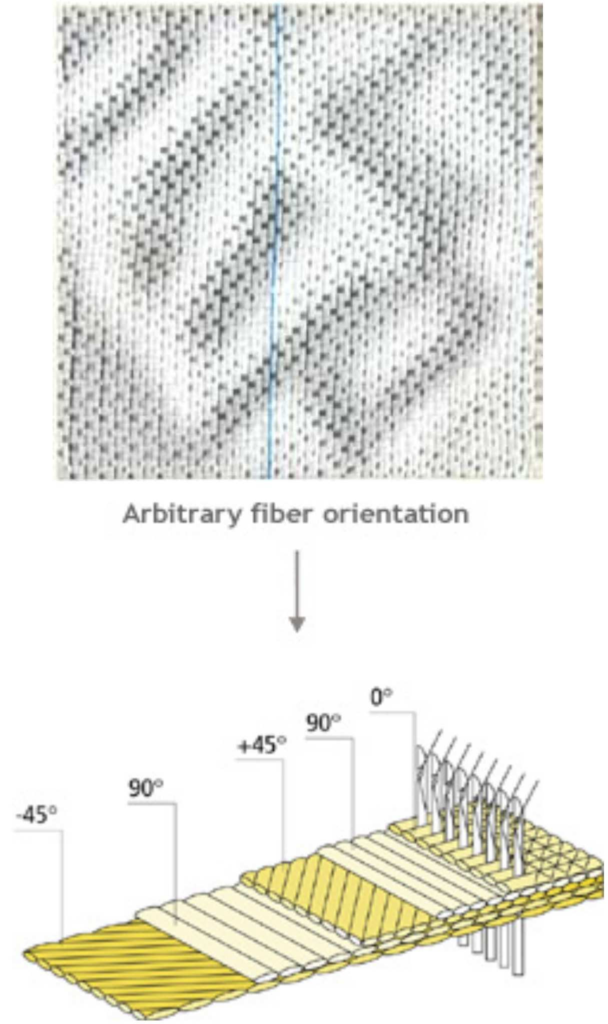
MTS 810 Servo-Hydraulic Universal Testing Machines at TPI Composites Engineering/Development Center

500kN Load Capacity with Environmental Chamber

100kN Load Capacity for Resin testing and Cross-Plied Laminates

Reinforcement Forms for Wind Blade Manufacturing

- Preimpregnated versus "Dry" reinforcement forms
  - Processing
    - Consolidation of Prepregs
    - Vacuum Resin Infusion (VARTM, SCRIMP, etc)
    - Hand Layup/Vacuum Assisted Hand Layup
    - Automation (Prepreg tape and "Tow-pregs")
- Woven Fabrics
  - Most often used in tooling applications and preimpregnated forms
  - Higher cost, less applicable as structural components for blades
  - Specialized use in areas of high 3D stress fields (resist peel)
- Non-woven Multiaxials
  - Most widely used in VARTM processes
  - Low-cost, non-crimp form results in superior performance
  - High areal weights possible reduce labor cost in layup
  - "Uni-directional", Biaxial, Double Bias, Triaxial and Quadraxial material forms available.
  - Glass/Carbon/Aramid Hybrids



Courtesy of Saertex USA

Resins Matrices and Adhesives

Composite Matrices:

- Epoxies remain a primary resin of use in European based blade designs
- Vinyl-esters are attracting much interest by blade designers
- Polyester resin are still prominent in the industry.
- Thermoplastics and other "toughened" matrices

Resins Matrices and Adhesives (continued)

Blade Assembly/Bonding Adhesives:

- Two-Part Epoxy Paste Adhesives specifically formulated for their thixotropic properties are the mainstay for bonding and assembly
- Methyl-methacrylates provide excellent adhesion to polyester resin composites
- Polyurethane bonding agents

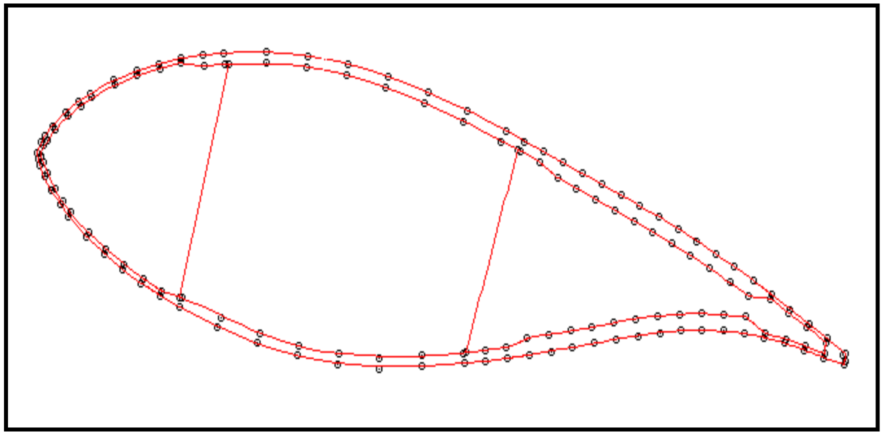
Core Materials in Blade Manufacturing

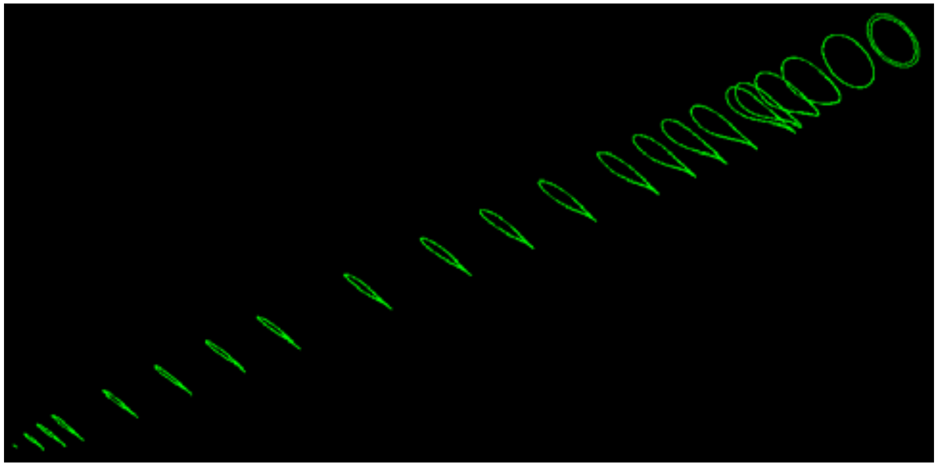
- Core Materials, used primarily for large area unsupported stability in leading/trailing edge panels and shear webs.
  - End Grain Balsa
    - Low Cost, High Shear Properties, Higher Weight
  - Foam Cores
    - PVC
    - SAN
    - Urethane
    - PET (extruded forms look cost effective)
  - Engineered Core Materials
    - Webcore TYCOR
    - NexCore

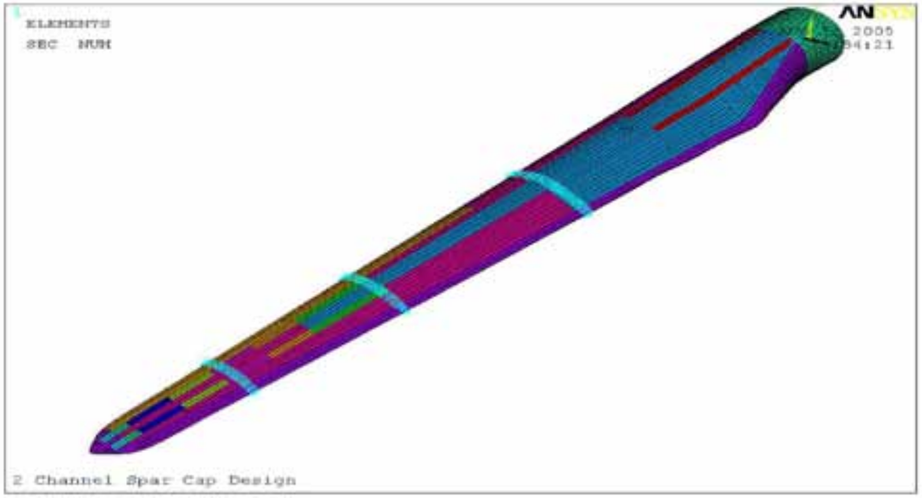
Structural Design

Structural Design

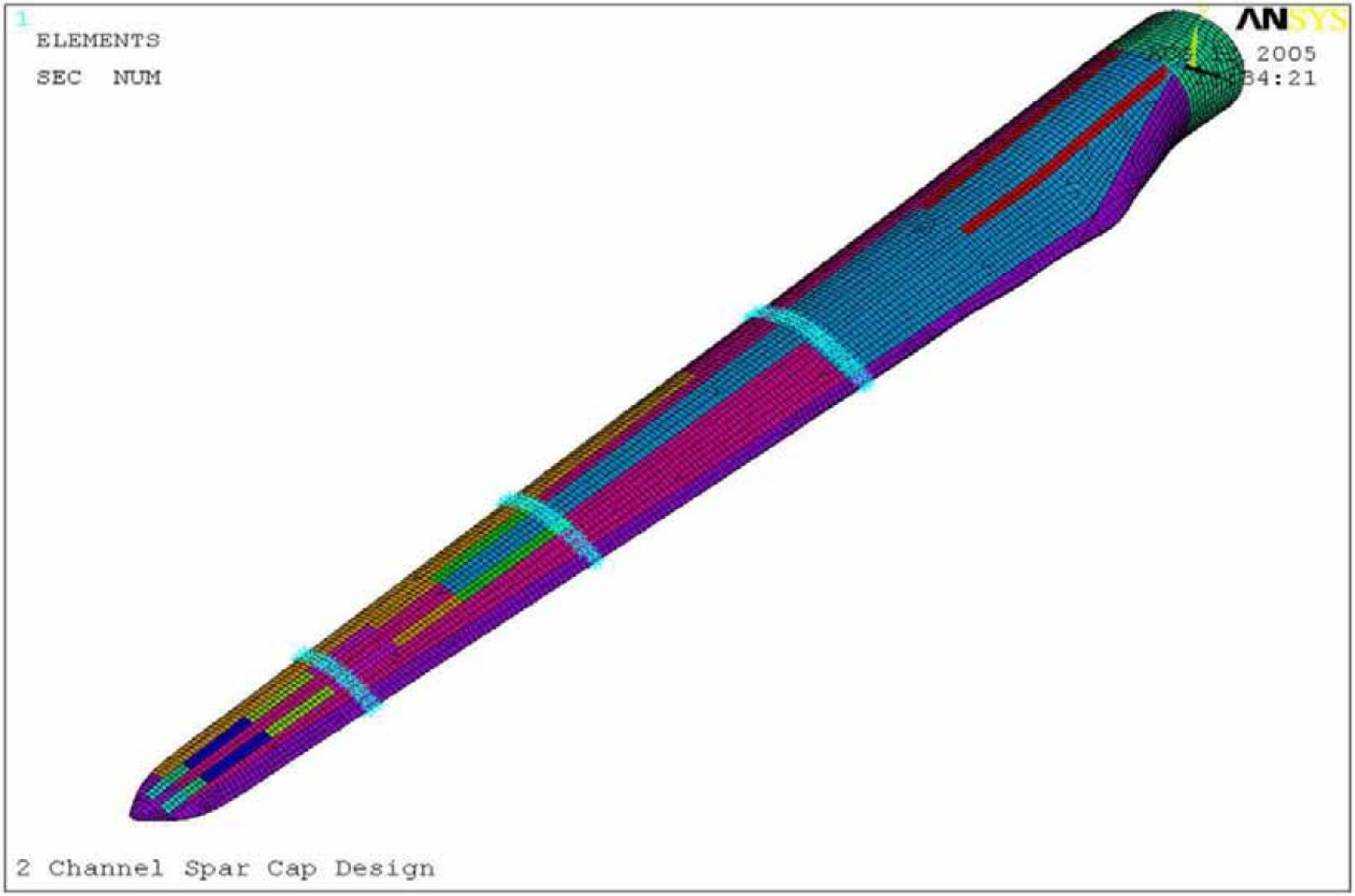
- Opportunities for innovative design still exist
- From materials selection and fundamental layout of components to functional performance; the choices are endless.
- A multidisciplinary exercise requiring close coordination between systems and aero engineers, materials and structures groups as well as manufacturing engineers.
- Detailed analysis of components and dynamic analysis of entire turbine system required for completing product design.



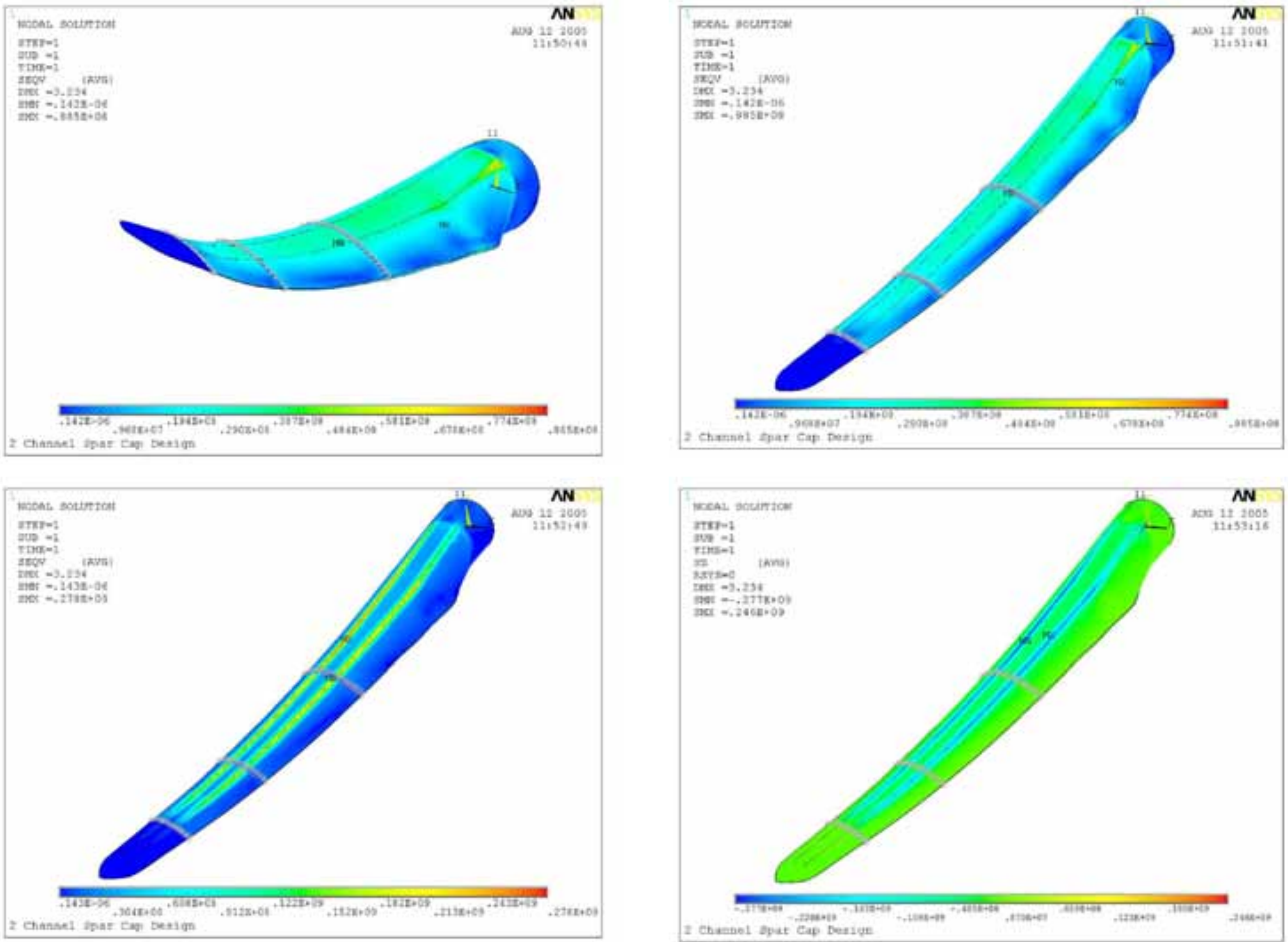




Full-scale Finite Element Analysis Using Plates and Shells



Static Results Provide Deflection and Stress Information to Guide Design



Design Development Work for US Department of Energy

- Nine Meter (9M) Blade Program
  - NPS 100 Blade: a Baseline
  - CX-100 Blade: Carbon Spar Cap Epoxy Blade
  - TX-100 Blade: Bend-Twist Coupling Epoxy Blade
  - BSDS Blade: Thick Airfoil / Carbon Spar Cap Epoxy Blade

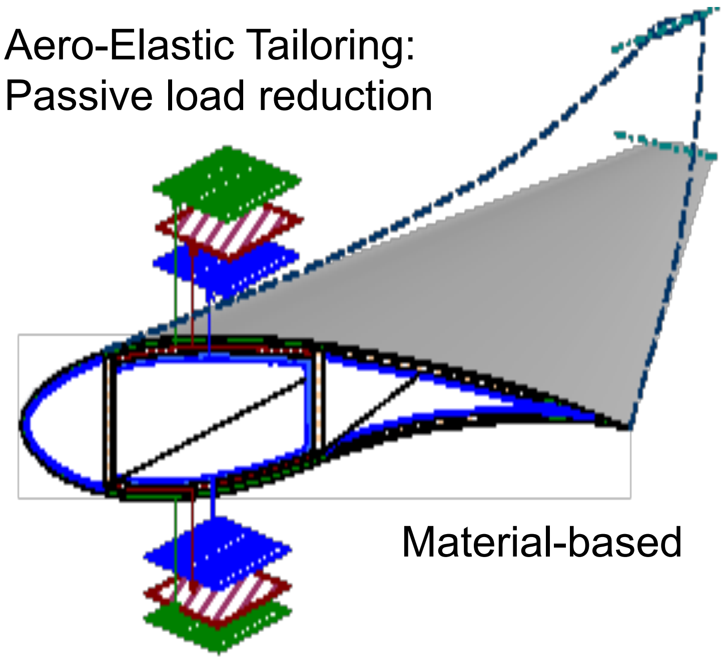
9M CX-100 Carbon Fiber Spar Cap Blade

- Triaxial stitched fabric carbon fiber "Uni-directional".
- Spar cap plies interleaved with root plies.
- Epoxy infusion for highest compression design strain.

9M TX-100 Bend-Twist Coupled Blade w/Carbon Fiber Skin

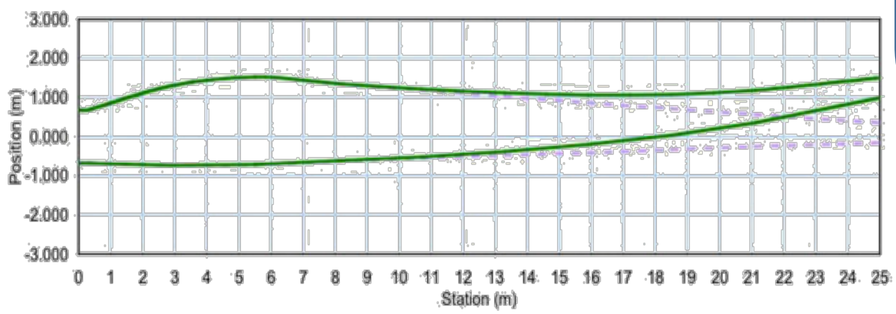
Bend-Twist Coupled Behavior: ***2 ways to Skin that Cat for Load Mitigation***

Aero-Elastic Tailoring:
Passive load reduction

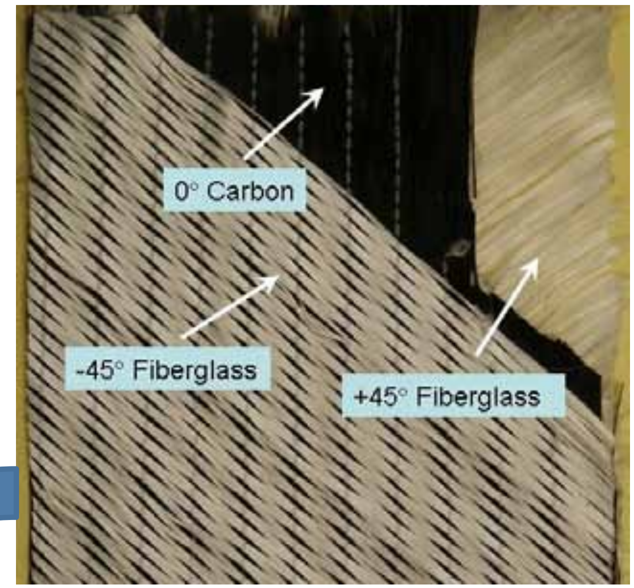


Material-based

Geometry-based



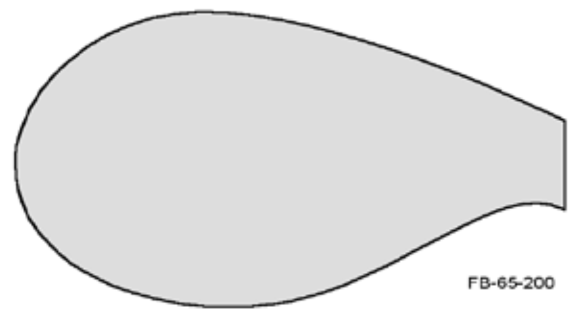
New Materials – Carbon/Glass Hybrid



9m Blade with Advanced Airfoil Design: Blade System Design Studies (BSDS)

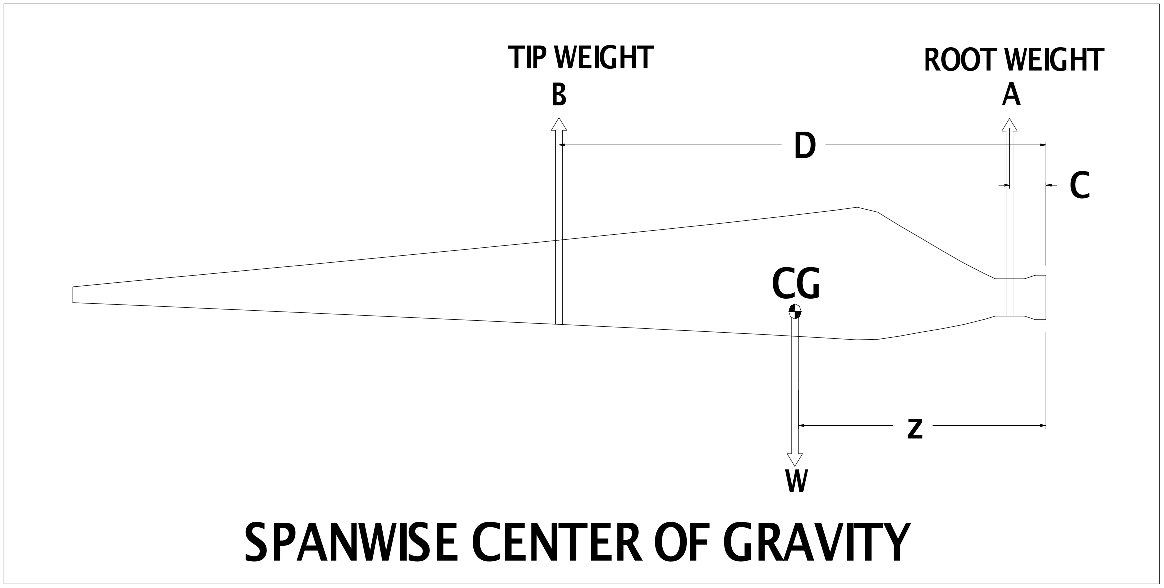
- Used on inboard sections of blade (5% - 45% Radius)
- Increased thickness (t/c) airfoils provide more flapwise section (I), **AND** Blunt TE on flatback airfoil provides more edgewise section (I)
  - Can reduce material usage to achieve same EI
- Airfoil thickness (t/c) and flatback thickness (tfb/c) can be tailored for optimum structural design efficiency
  - Can allow for constant width / constant thickness spar cap for most of the blade
  - Cuts down on material scrap and labor (cutting and material placement) hours

… Resulting in Lighter/Longer Blades



- **Flatback Airfoil (FB-65-200)**
  - Thickness to Chord Ratio (t/c): 0.65
  - Flatback Thickness to Chord Ratio (t_{fb}/c): 0.20
  - Approximate Span Location: 15% Radius

9m Blade Design/Manufacturing Study Results



	Blade Length (mm)	Blade Weight (kg)	Spanwise CG (mm)	Static Balance (kg-m)	Wt Reduction From Baseline (%)
NPS 100 (Base line)	8,997	221.4	2,450	542.4	--
CX -100 (Carbon Fiber Spar Cap)	9,000	173.7	2,287	397.0	22%
TX-100 (Bend-Twist Coupled)	9,000	163.7	2,339	382.8	26%
BSDS ("Flat-back" Airfoil Design)	9,000	129.1	n/a	n/a	42%**

***Note: Total weight savings achieved from a combination of reduced root thickness resulting from incorporation of molded in studs and increased net section diameter. Normalized weight savings due to airfoilshape is approximately 24%.*

Using Geometry for Load Mitigation

- Structural Test of Knight and Carver STAR Blade
  - Test preparation of a swept 27.5m turbine blade.
  - Swept design provides bend-twist coupling for gust load reduction.
  - STAR = Swept Twist Adaptive Rotor.
- Replaces cost of building carbon fiber skins with cost/ challenge of form curvilinear spar caps.

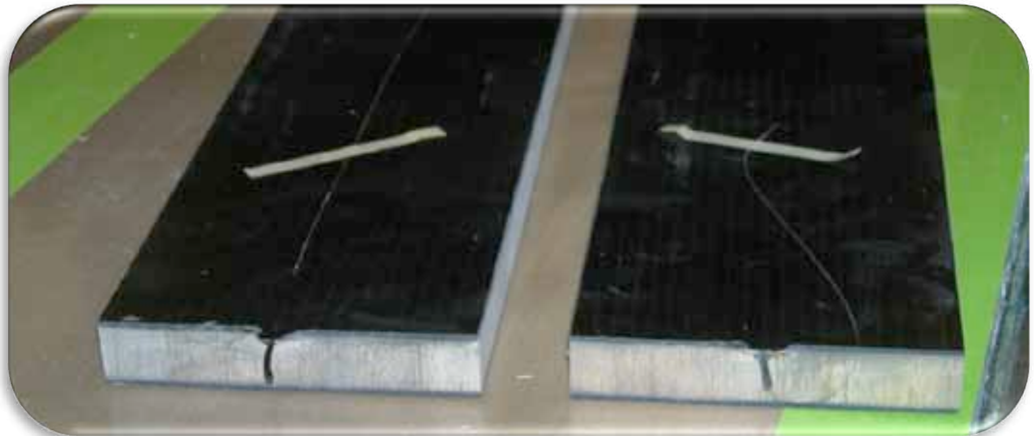
Courtesy of Knight and Carver

Embedded Sensor Technologies

Sensor Technologies

- Designs migrating toward larger and lighter weight rotors
  - Offshore and improved Cp
  - Reduced Margin Designs
- The cost of failure is unacceptably high, but the cost of O&M may also be prohibitive
- Health monitoring systems in a variety of forms where innovation rules, may be the answer.

9m CX-100 Based TPI "Sensor Blade" and Next Generation "Smart Blade"



- Development using the 9m platform continues:
  - TPI, Sandia , Purdue University and Aither Engineering collaborated to build the "Sensor Blade"
  - Fully embedded Fiber Optic Bragg Grating (FBG), Full 3D accelerometers and foil strain gages applied within the assembled blade
  - Real-time measurement up tower to support better understanding of actual blade loading to aero models.
- Next Generation "Smart" Blade being fabricated in Warren, Rhode Island this this week!
  - Similar instrumentation as Sensor Blade
  - Feedback to control actuated tabs outboard

Insensys (Moog) – Independent Pitch Control Load Measurement System

Insensys IPC Load Measurement System IPC

Proven technology for advanced turbine control applications

Key benefits of the Insensys system for IPC applications

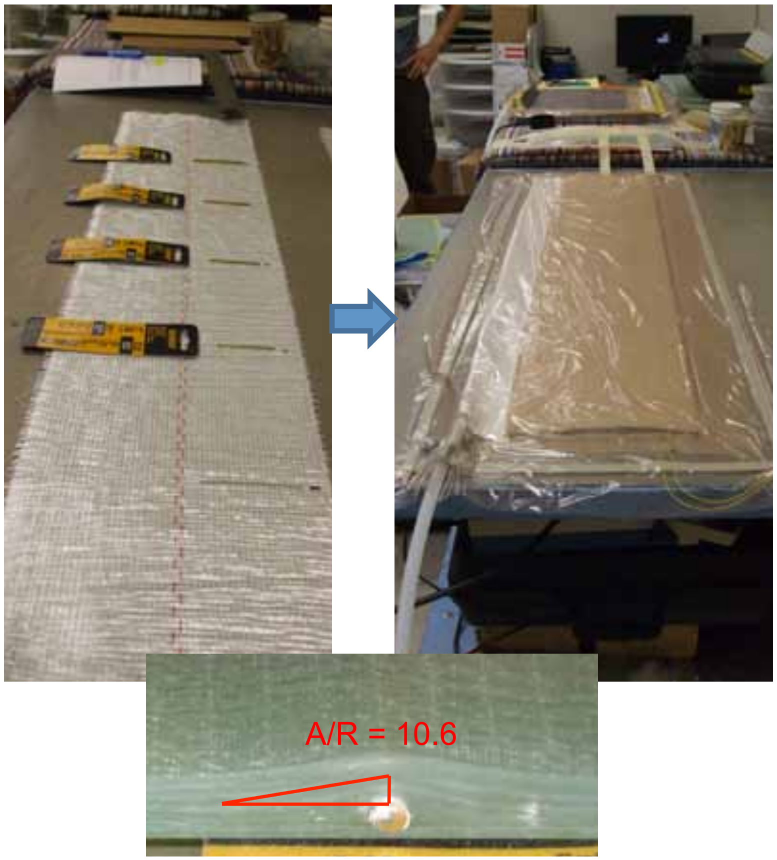
The Insensys IPC load measurement system has been specifically designed for wind turbine operation and is based on a mature fibre optic sensing platform that provides an accurate, reliable and cost effective load signal input.

- Proven, reliable, technology for wind turbine deployment
- OEM-specific design for simple system integration
- Cost effective for series deployment
- Simple interfacing with existing control systems
- Fast, simple, sensor integration into the blade production process
- Excellent long term sensor fatigue performance
- Non-conductive system eliminates EMI and lightning issues in the blade and hub

Typical system specification

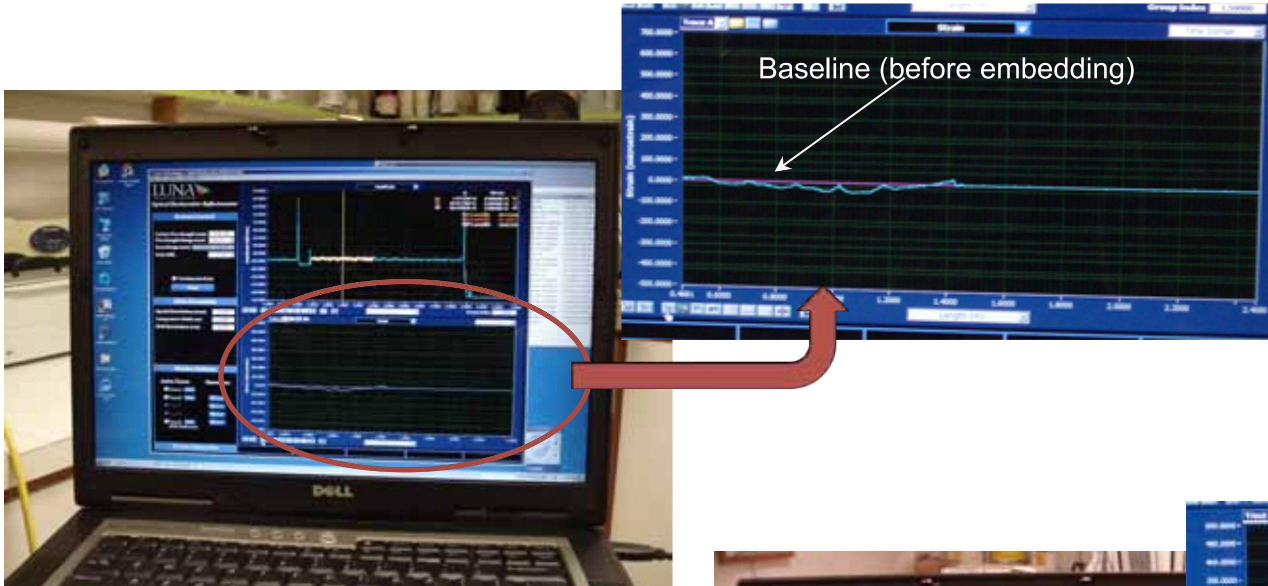
Number of blades	3
Number of sensors per blade	6
Range	±4500 microstrain
Measurement resolution	1 microstrain
Measurement frequency	25 Hz/sensor
Power supply	24 V DC
Power consumption	<3 W
PLC interface	RS232, RS422, RS485,CANbus
Weight	2 kg
Dimensions L x D x W	240 x 97 x 120 mm
Operating temperature	-40°C to +60°C
Protection Class	IP40

Use of Continuous Fiber Optic Sensing for In-situ Measurement of Laminate Strains

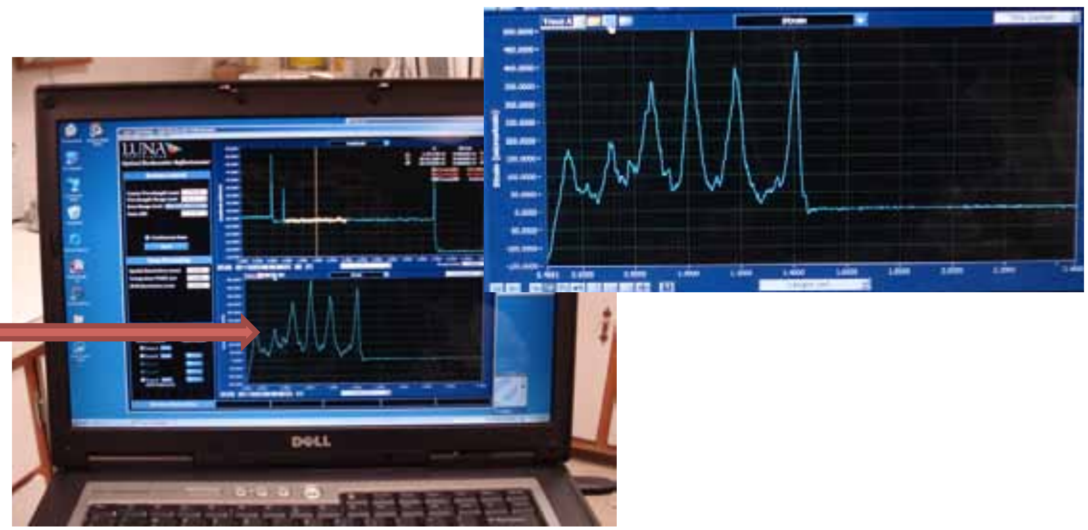


- Use of Optical Backscatter Reflectometry
  - "Near real-time" continuous strain measurement of over 40M long fiber optic with <0.5cm resolution
  - Can be used for both measurement of strains in process/fabrication and for up tower health-monitoring applications.

Fiber Optic Signal: Before and After Vacuum Application

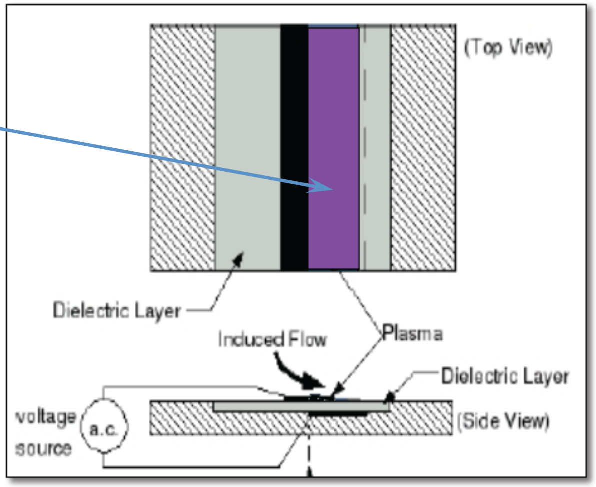


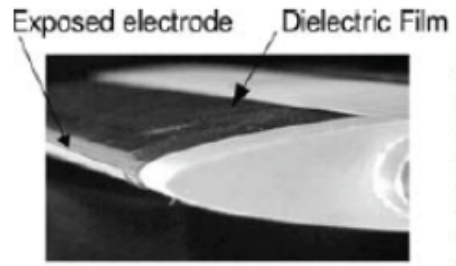
Embedded fiber "defects" become readily visible!



Ion-Plasma Actuators

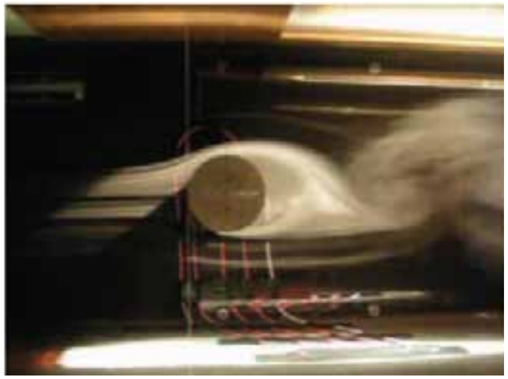
- Electrical current causes air to ionize and create plasma field (purple).
- Electrical field manipulates plasma to inject thrust into airflow (reshaping).
- Trailing edge actuators can perform identically to trailing edge flaps.
- Leading edge actuators can prevent airflow separation and curtail stall.





NACA 0015

- **Leading Edge Actuator**
- **Nominal Stall Angle ~14 deg.**



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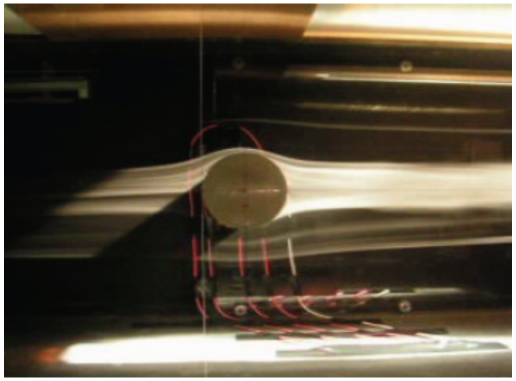

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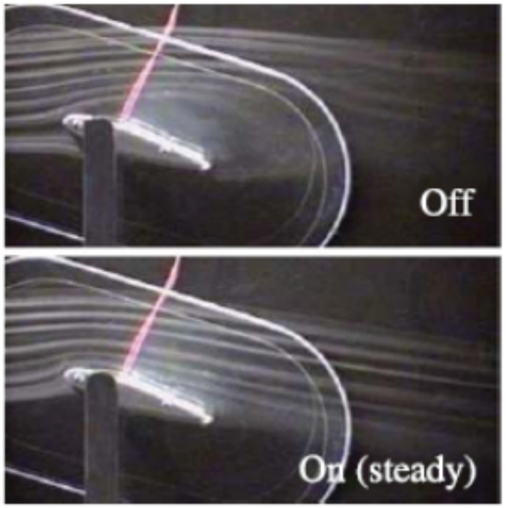


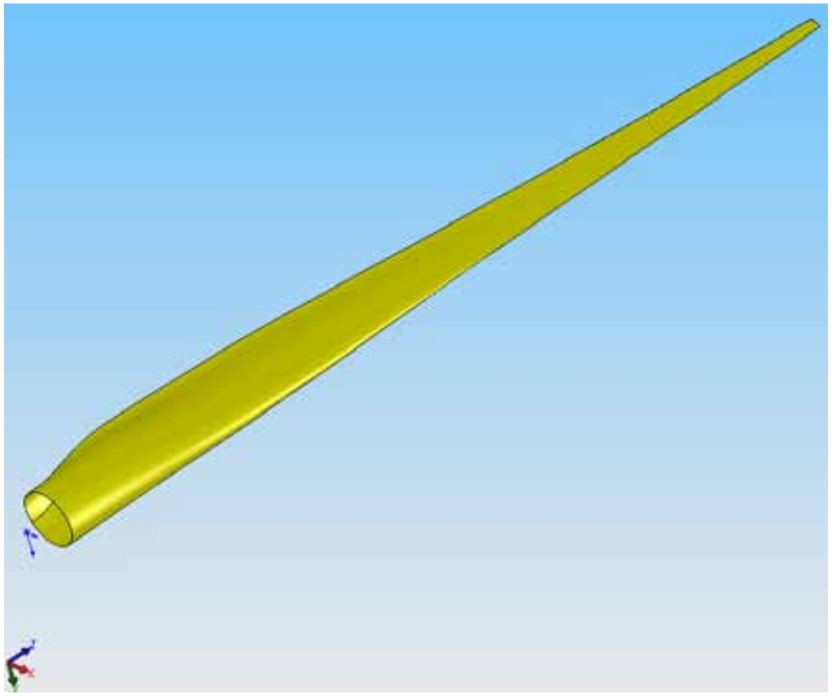
NACA 0015 with LE actuators at 16 deg. angle of attack

Tooling and Process Engineering

Tool and Tool Manufacturing

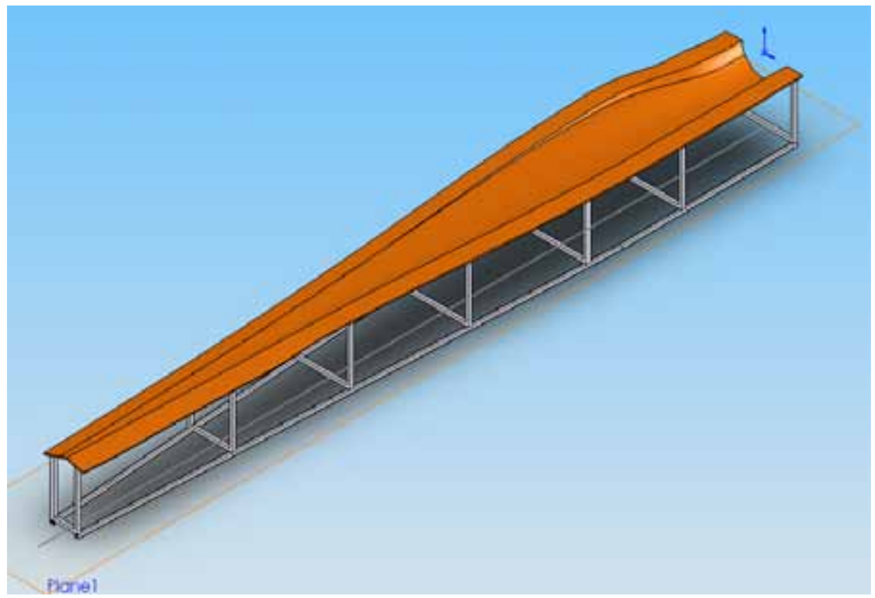
- TPI Composites maintains an comprehensive set of capabilities to address all aspects of tool and mold fabrication.
  - 3-D Cad Design tied to engineering data of design.
  - Design of Master Models (Plugs) for mold fabrication.
  - Deployment of Plugs within TPI facility with full metrology reporting prior to mold build.
  - Fully infused molds with integrated process control (heating) and process software (CyberTherm) as required.
  - Complete metrology and thermal tolerance reports provided to customer.

Solid Modeling – Blade Geometry and Tool Development

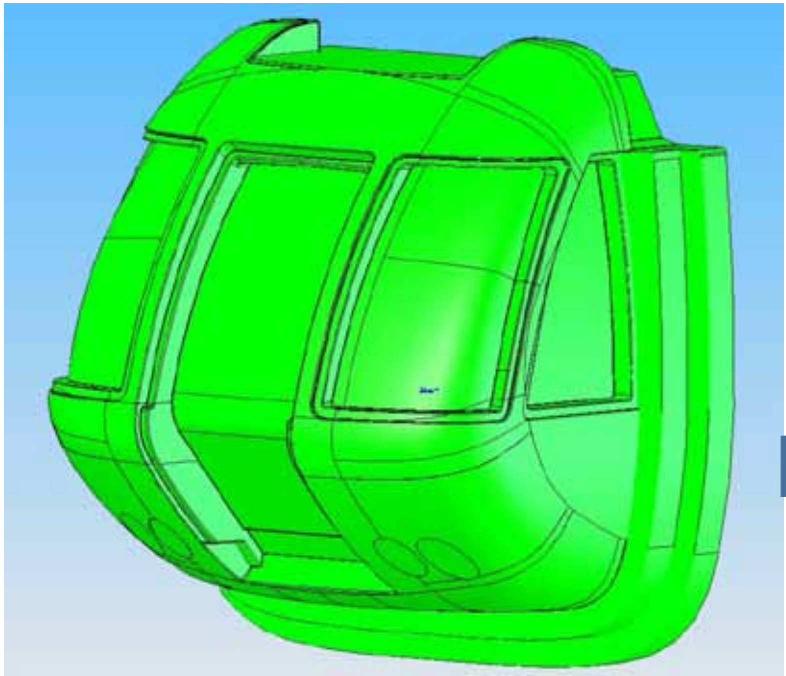


- Blade OML Geometry generated from advanced airfoil design.
- Geometry feeds FEA model development and BoM

- Engineering data feeds tool and fixture design.
- Single source of engineering data ensures fidelity of finished tools to the model.



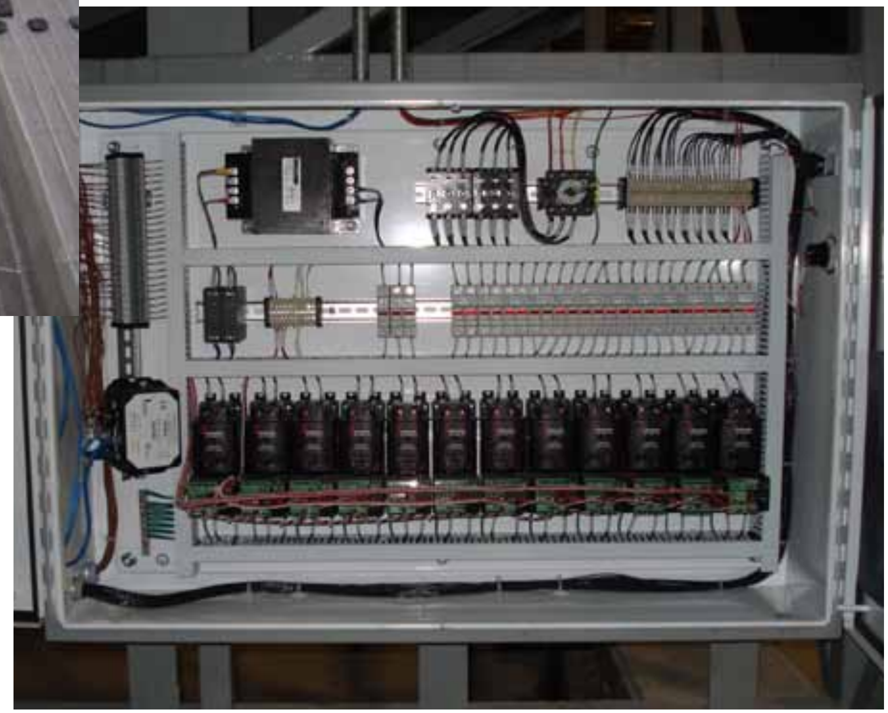
3D Solid Modeling From CAD to Master to Molded Part



- CATIA V5 solid modeling is now applied for design of all geometric surfaces.
- Applied to both structural analysis and surface generation for tooling.

- CAD models uploaded to 3 and 5 axis machine centers for plug fabrication.
- Multiple mold sets pulled from machined plugs to build final product structure.

Electro-Resistive Heating for Epoxy Matrix Molded Blades

- In-house fabrication with proprietary electro-resistive cables and fit for purpose laminate design.
- Dedicated multi-zone PID temperature control with supervisory control via TCP/IP based remote SCADA for set point control, production monitoring and logging.

Assembly Fixtures

- Accurate assembly of blades with consistent bond line thickness depends not only on accurate molding but locating fixtures to properly place major assemblies.
- Here a TPI designed and fabricated shear web bonding fixture locates the 40m Shear web for bonding to the Low Pressure skin.

TPI Shear web fixture uses tooling points and vacuum assisted handling for shear web placement.

Hydraulic "Power Hinges" for Blade Assembly

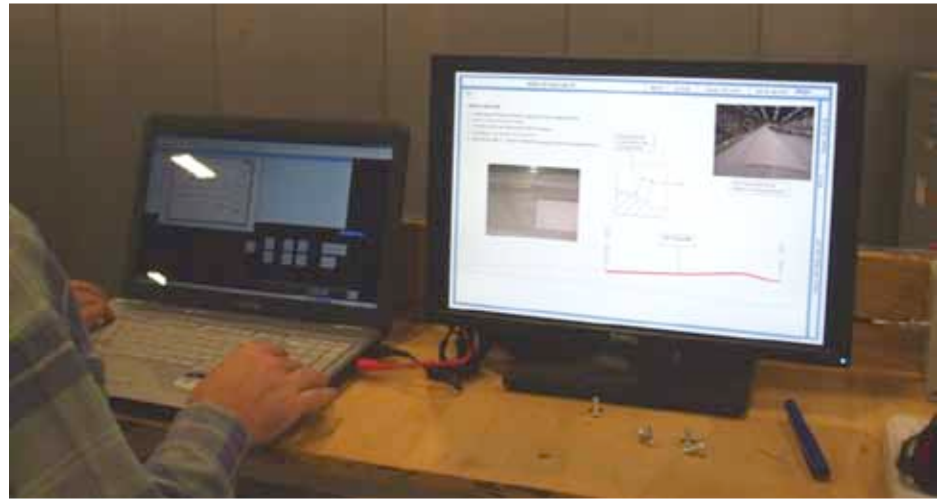
- Hinges eliminate flip fixtures and HP or LP Skin de-molding prior to bonded assembly
- Greatly reduces assembly time
- Improves accuracy
- Eliminates risk of damage to either skin as a result of handling

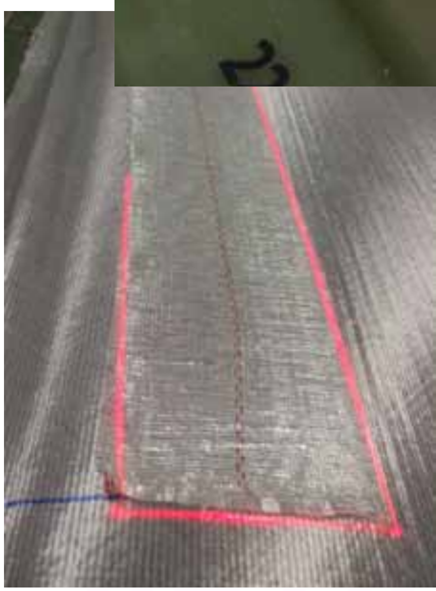
NEW
Hydraulic Clamps around perimeter of shell molds for consistent and uniform clamping forces

Reusable Silicon Bag Technology for SCRIMP®

- Silicone bags are rapidly fitted to the infusion tool.
- Feed lines, vacuum lines and embossed distribution channels are integrated into the bag improving the repeatability of the process.
- Setup time and process robustness greatly improved with reduced disposable material cost/waste.

3D Laser Projection Systems





- Laser Projection Systems for real time tool based projection of ply locations, bonding adhesive outlines and shear web location.
- Ceiling mounted laser projectors. Up to five “ganged” together to provide full coverage across a single pair of 47.2m molds.
- Technology is now applied to all 2.4MW blade production

Automation of Blade Fabrication

- Automation of aerospace composite manufacturing is virtually routine with hundreds of prepreg tape machines operating across the globe.

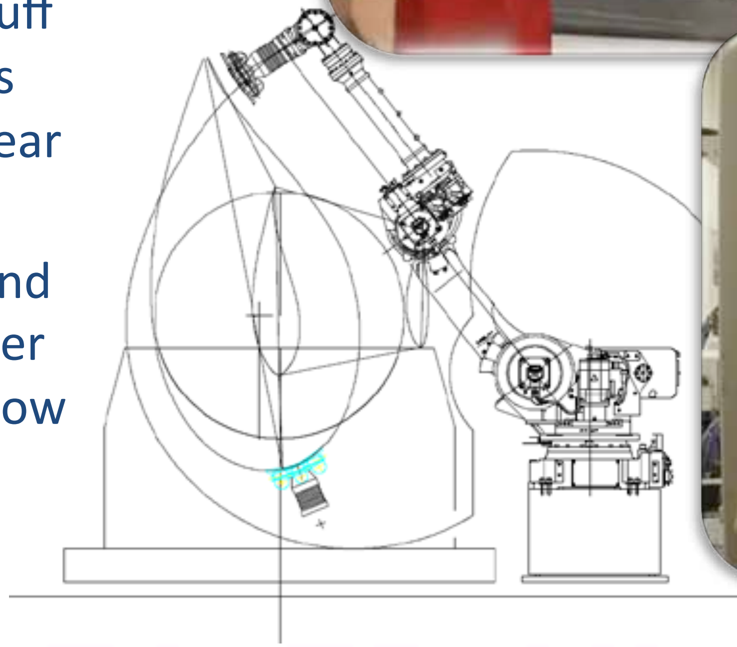
- Turbine blade manufacturing consists of a labor intensive set of highly distributed manual operations.
- From pattern cutting for material kits to layup to infusion and demolding of a multiplicity of sub assemblies over a vast area and distance, automation is a challenging and expensive endeavor.
- Return on CAPEX is rapid for structures with cost of finished goods from $200 to $700/lb as opposed to $5.00 to $10.00/lb required for the energy markets.

Automation of Blade Fabrication

- Automation is at work in blade factories today:
  - Use of x-y ply cutting for material kits, automated ply nesting software, pick and place automation.
  - Limited use of material transfer systems into open molds, primarily with semi-automated or driven A-frames and gantries
  - Automated trimming and limited machine assisted surface grinding/ finishing
  - Automated root trim, machine, and drill for T-Bolt installation.
  - Robotic application of coatings.

Automation in Blade Finishing

- Blade molding operations account for less than 50% of total labor content.
- Finishing operations offer a brilliant opportunity for cost-effective CAPEX spending.
- Compliant grinding/finishing, scuff sanding and coating applications will become ubiquitous in the near term.
- The advance in vision systems and on the floor computational power coupled with the availability of low cost multi-axis robots makes automation of many tedious processes possible.

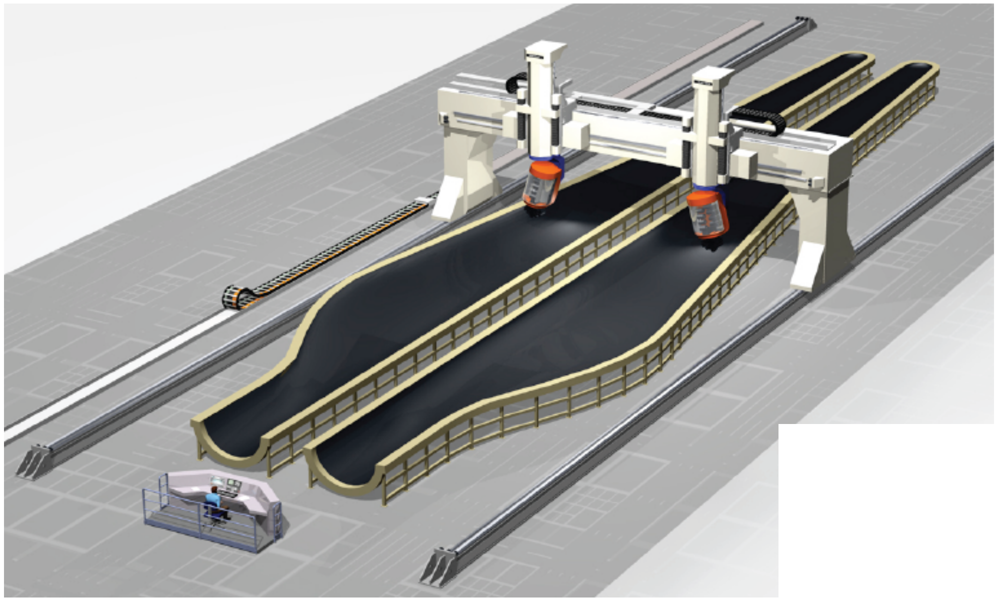


Automation of Blade Components a First Step

High Volume Machine for Spar Caps

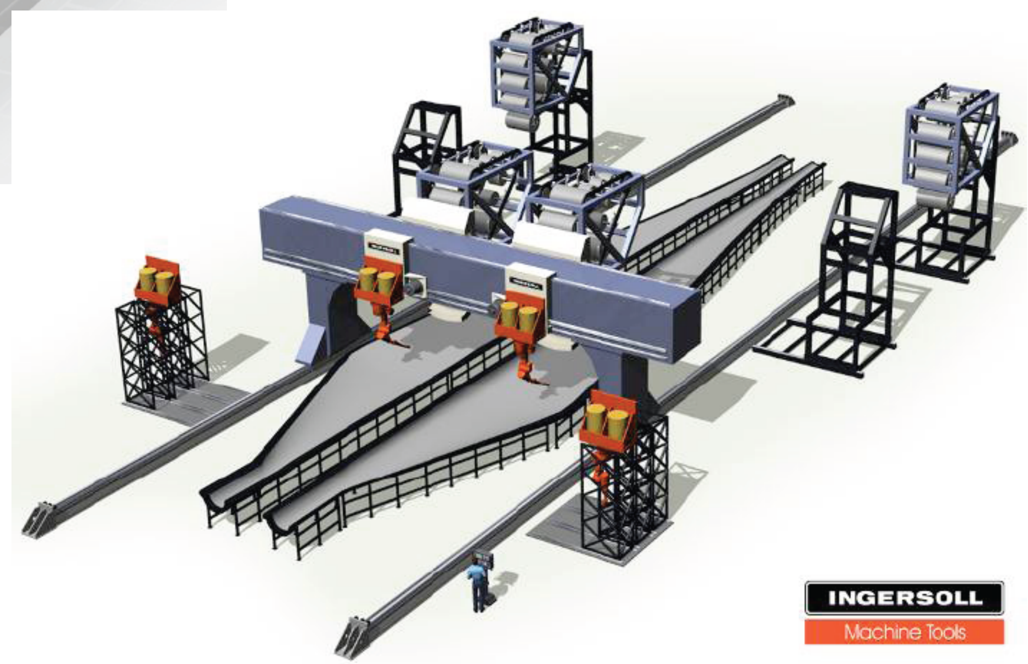
- Spar Cap components are the logical first step with root preform parts a natural extension of capability.
  - Simple Geometry.
  - Uni-directional materials for lowest possible cost of prepreg/tow preg materials.
  - "Steerable" for curvilinear spar caps in swept blade design.
  - Performance critical.
- Assurance by major machine manufacturers that layup rates approach 1,200 kg/hr in straight run spar caps possible!

Automation of Blade Manufacturing to Come



- The jury is still out regarding the shape and form of future blade automation, but it is sure to come.
- Longer blades, use of carbon fiber and the need to ensure lower partial safety factors for manufacturing and material variance will expedite the drive for more automation in blade layup.

- Whether future automation is in the form of fiber/tow placement, prepreg or dry fabric robotic application, there are designs waiting in the wings.
- TPI is intimately involved in this process and helping to shape this future.

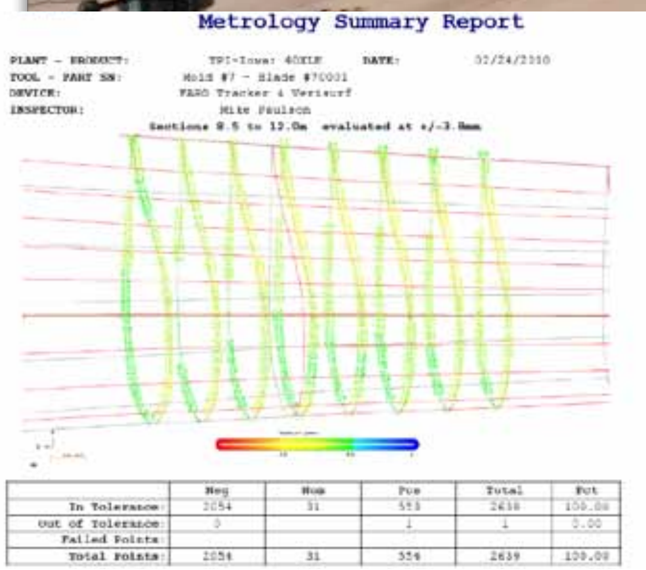


Metrology and Non-Destructive Evaluation (NDE)

Metrology and NDE

- High performance, technically complex product.
- High skill level with multiplicity of operations required by each manufacturing technician.
- Detailed documentation and constantly revised work instructions drive training and certification of D/L.
- In-coming/receiving inspection and testing
- Physical sciences lab with wet chemistry, test and inspection services.
- High level capability for metrology through laser tracking CMM.

Surface Metrology for Both Tools and Fabricated Parts



Metrology Summary Report

PLANT – PRODUCT: TPI-Iowa: 40XLE DATE: 02/24/2010
TOOL – PART SN: Mold #7 – Blade #70001
DEVICE: FARO Tracker & Verisurf
INSPECTOR: Mike Paulson
Sections 8.5 to 12.0m evaluated at +/-3.0mm

	Neg	Nom	Pos	Total	Pct
In Tolerance:	2054	31	553	2638	100.00
Out of Tolerance:	0		1	1	0.00
Failed Points:					
Total Points:	2054	31	554	2639	100.00

- Combined use of FARO 3D Laser Tracking and VeriSurf Computer Metrology Package yields full suite of measurement capability for both Tool and Mold Fabrication and Finished Part verification.
- FARO tracker provides 3D Point measurement with accuracy to 0.1mm
- VeriSurf integrates measurement data with "as designed 3D part geometry" to provide real time metrology reporting and formatted Quality Assurance documentation.

Quality Systems/Engineering: Static Proof Testing

Full-Scale Blade Proof Testing:

›46.2m Blade at 90% Max Operating load during proof testing at Vientek

›Tip deflections exceed 8 meters at max load.

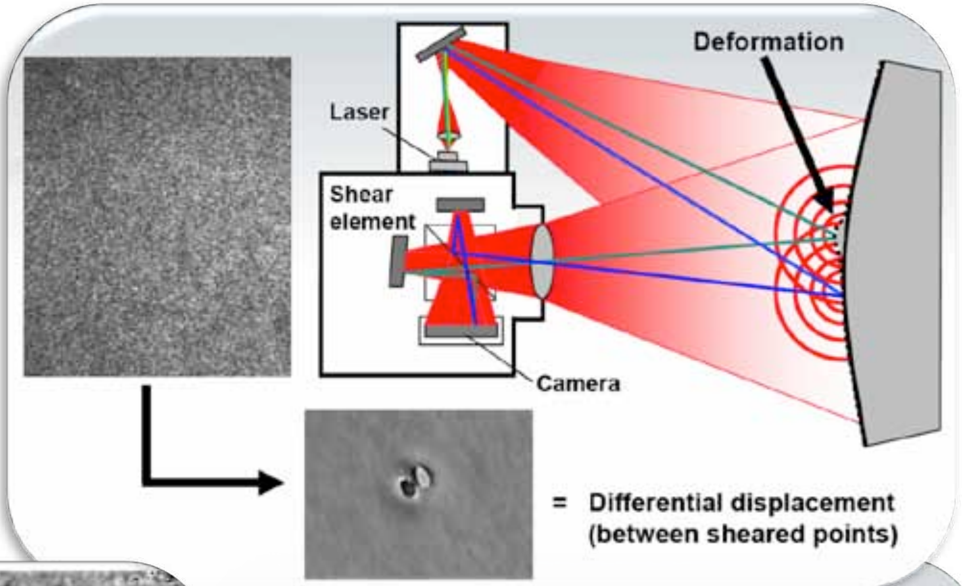
›Root test stand designed to react over 30 million N-m of bending load!

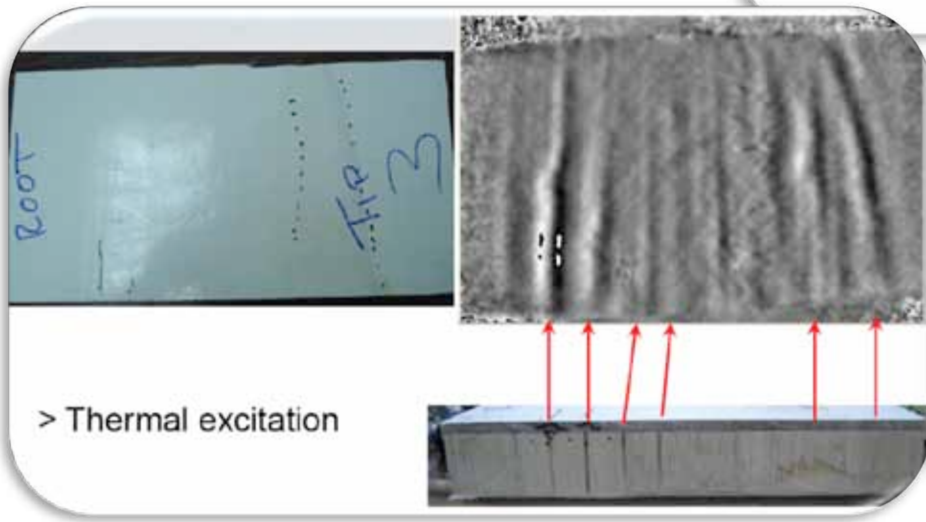
Non-Destructive Evaluation - Ultrasonic

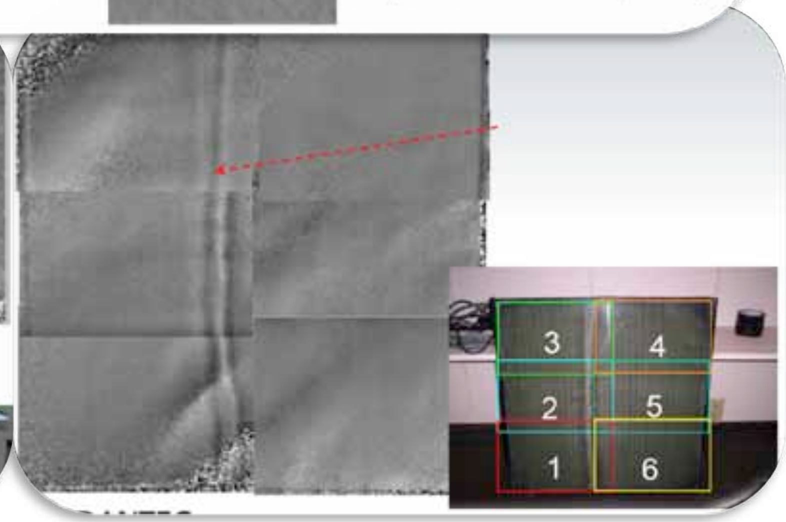
- TPI has applied ultrasonic pulse echo bond testers for over ten years to interrogate adhesive bond lines in wind blades.
- More recently the use of C-Scan and A-Scan has become prevalent in laminate inspection as well.
- Latest work includes portable systems providing field service inspection capability up-tower!

Laser Shearography – Wide Area Inspection

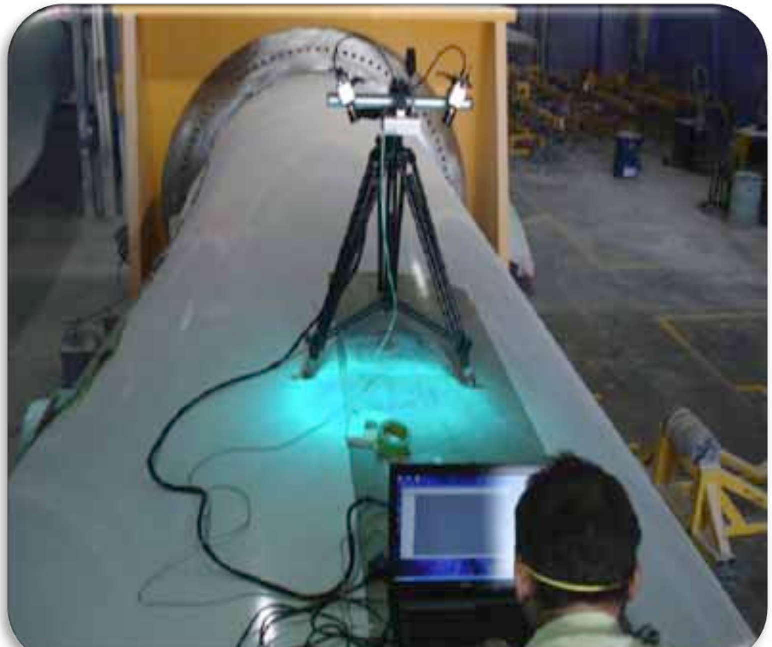
- Technique readily identifies defects in laminated sandwich composites.
- Slightest surface excitation (thermal loading) leads to surface deformations resulting from internal flaws.
- Full-field, non-contact technology.

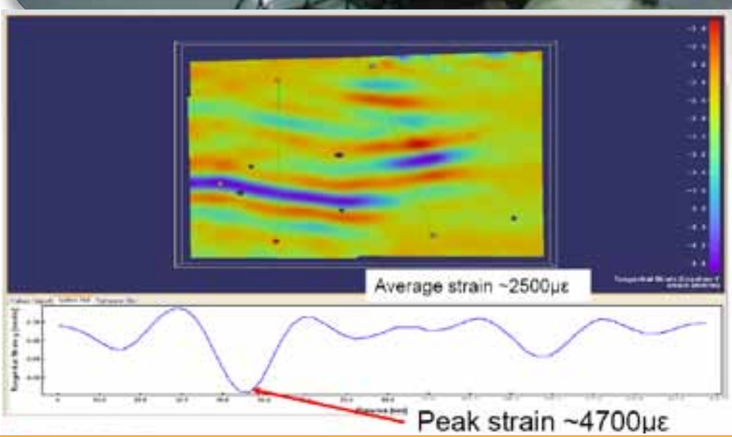


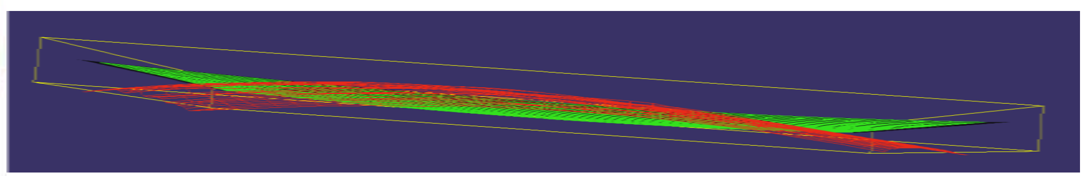




Digital Image Correlation for Wide Area Strain Measurement and NDE

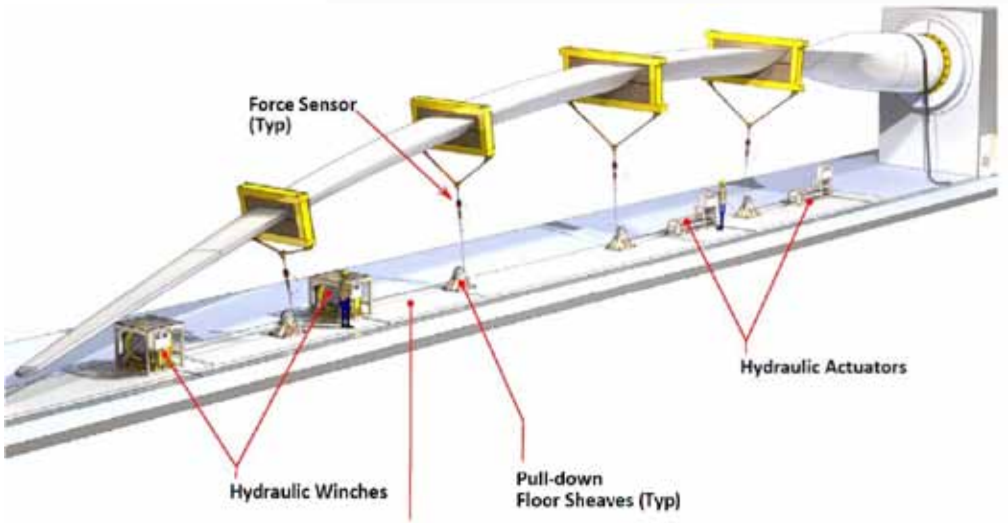






Structural Testing/Certification

Static Testing of Megawatt Scale Turbine Blades



- Static testing to simulate maximum operational loading is a critical element of design certification and is required by ALL certifying agencies (GL, IEC, DNV, etc.)
- Testing has formally been accomplished with makeshift operations:
  - Deadweight loading
  - Use of overhead cranes
- New facilities are coming online domestically that utilize fully computer operated dedicated loading systems.

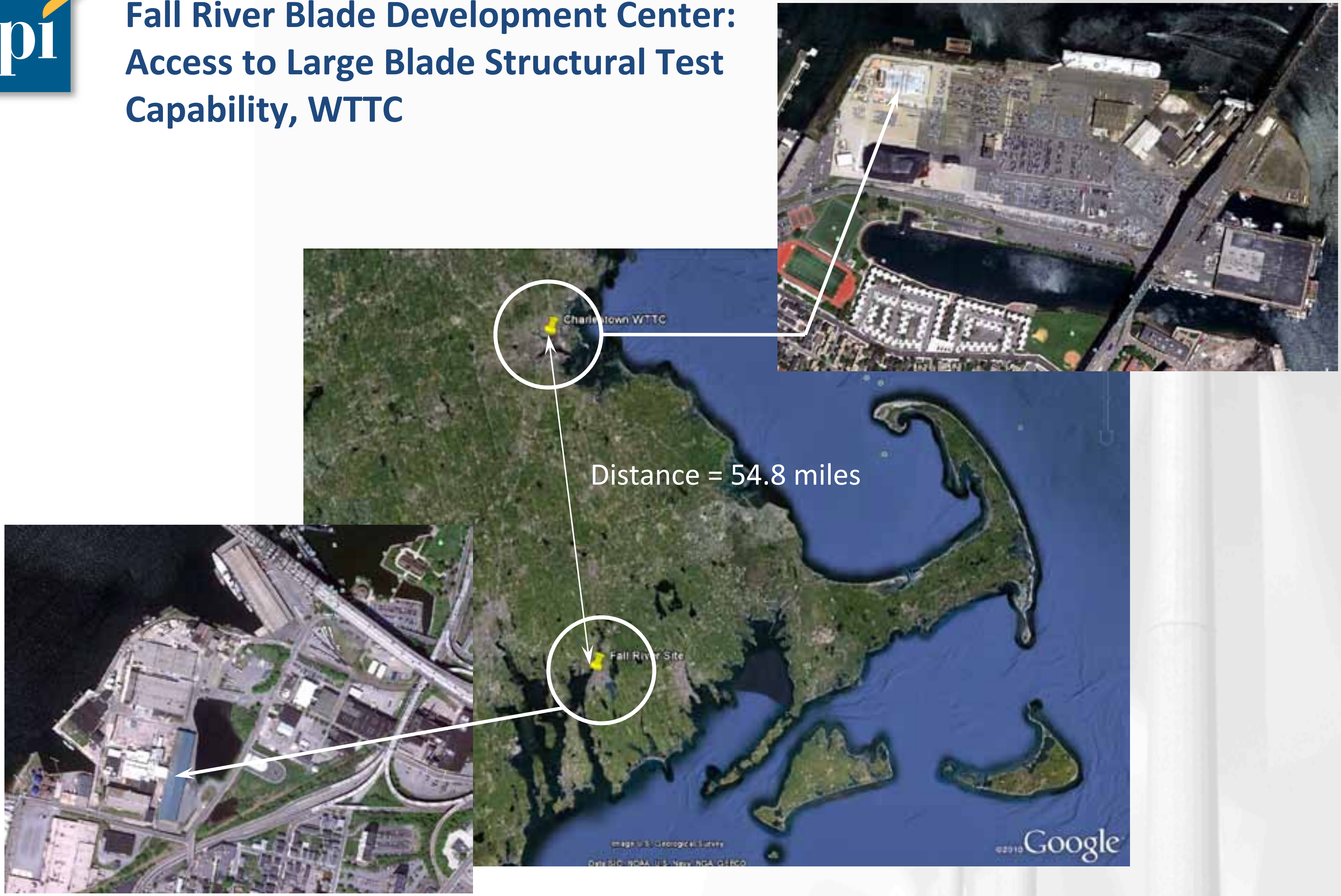
Fatigue Testing of Megawatt Scale Turbine Blades

- Cyclic load testing has previously been accomplished through forced displacement using distributed hydraulic actuators.
- This has been replaced with the development of resonant frequency cyclic load testing.
- Distributed mass can be used to develop arbitrary moment profiles to simulate operational aerodynamic pressure loading.

Large Blade Test Centers North America

- National Renewable Energy Laboratory
  - Boulder Colorado: Testing up to 50m
- Wind Technology Test Center
  - Charlestown Massachusetts: Testing up to 90m (open January 2011)
- AEWC (Advance Structures and Composites Center) at the University of Maine
  - Orono Maine: Testing up to 70m (open March 2011)

Fall River Blade Development Center: Access to Large Blade Structural Test Capability, WTTC



Transportation/Logistics

Blade Transportation

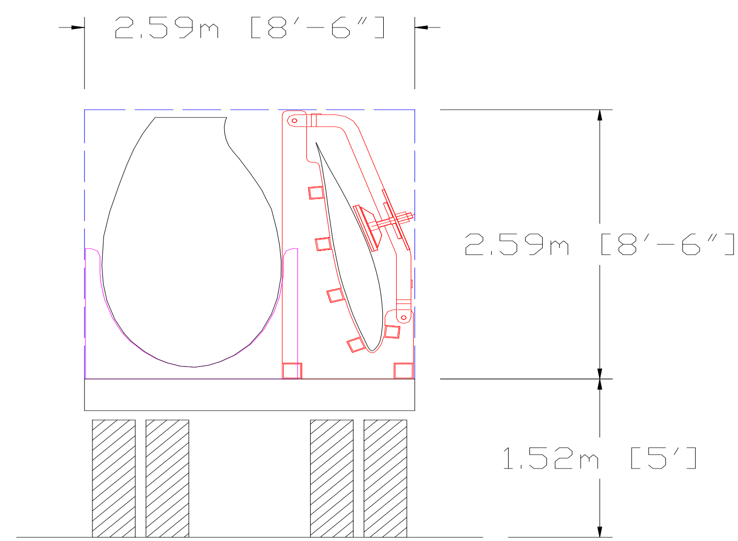
Multi-Megawatt Blades Ship in Single Units Per Truck

- MHI's 2.4 MW wind turbine
  - MWT92/2.4 and MWT 95/2.4
- 44.7m WTB Class II Service
- 46.2m WTB Class III service

44.7M Blade: Working to Reduce Transportation Cost

- TPI Engineers are looking for designs to minimize transportation costs.
  - Shortened Maximum Chord reduces shipping package height.
  - Increased root thickness translates to structural weight reduction.
    - Will ship TWO blades per truck without exceeding weight restrictions.

Current shipping configuration of 2.4MW 46.2m wind blade



Shipping Configuration
Preliminary 40m Flatback Blade


tpi