Blade Manufacturing Requirements & Developments

Presented at:

2010 Sandia National Laboratories Wind Turbine Blade Workshop

By

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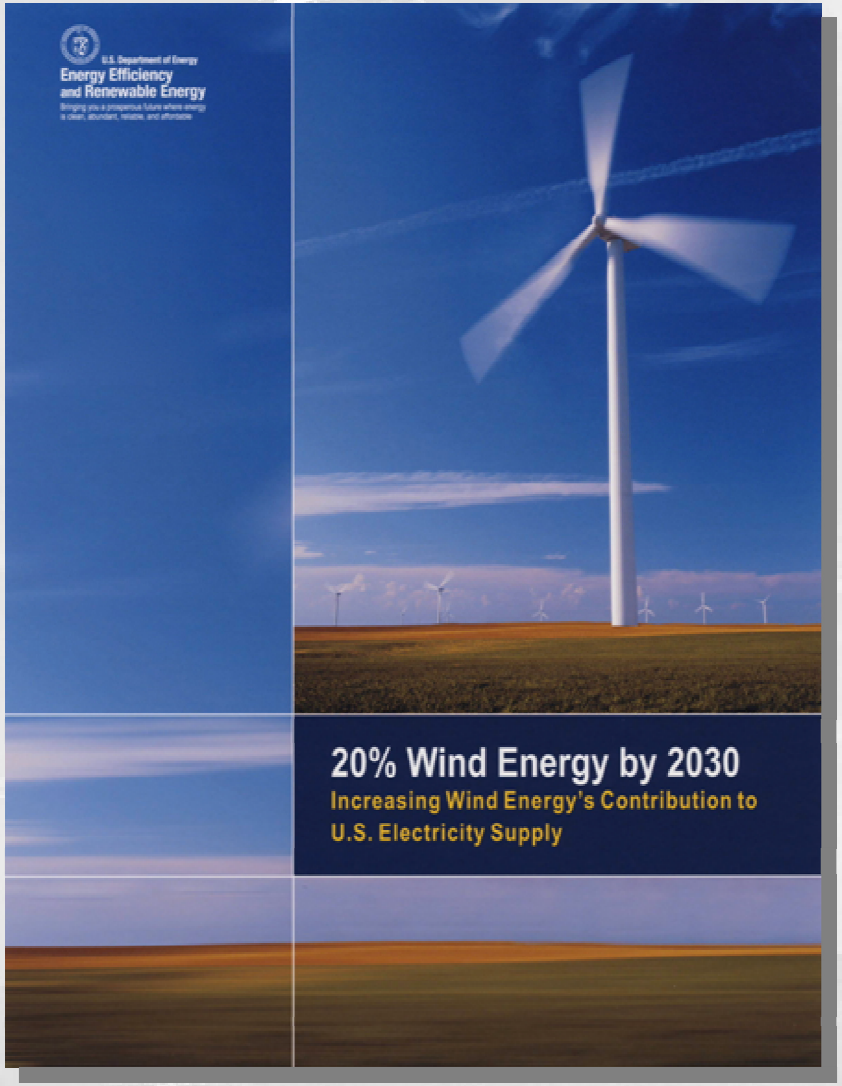
20% Wind Energy by 2030

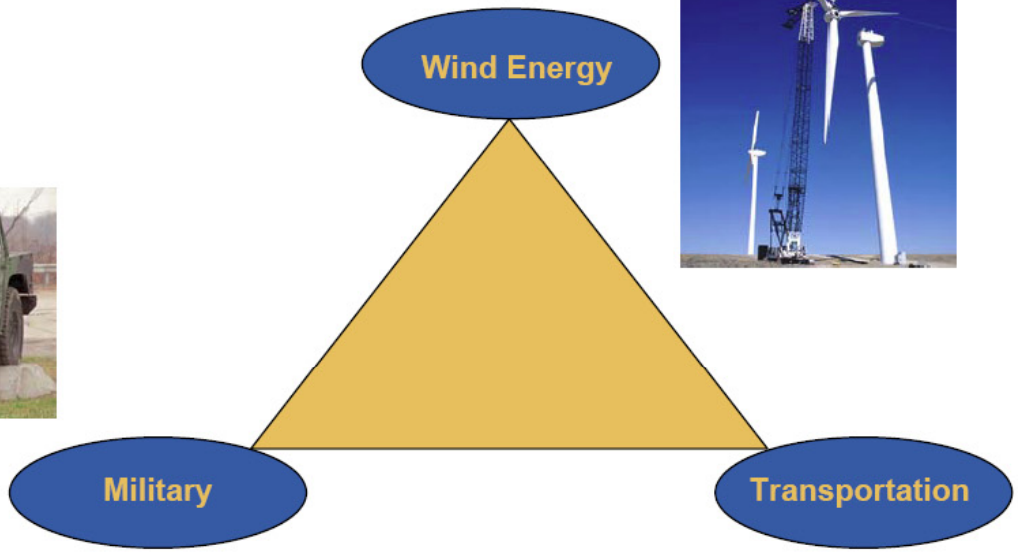


- U.S. Department of Energy (DOE)
- Power Marketing Administrations (PMAs)
- National Renewable Energy Laboratory (NREL)
- Lawrence Berkeley National Laboratory (Berkeley Lab)
- Sandia National Laboratories (SNL)
- Black & Veatch
- American Wind Energy Association (AWEA)
- Leading wind manufacturers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

Check out www.20percentwind.org

TPI Composites, Inc. – Our Misson

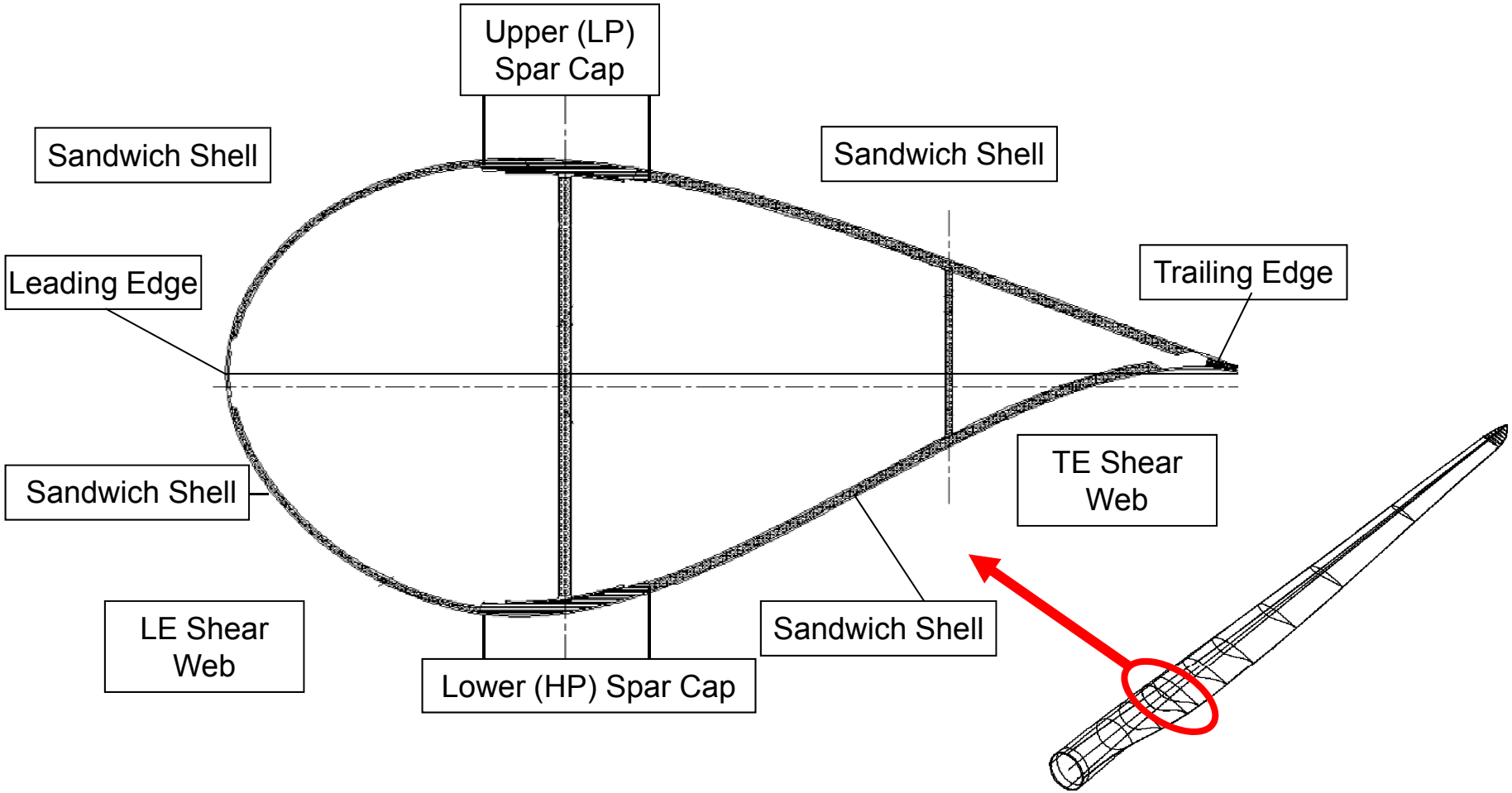
Deliver structural composite solutions in volume to the wind energy, military and transportation markets. Solid growth through long term partnerships with major players in each of these industries.



Manufacturing Advance Design
Wind Turbine Blades for Major OEM's

- Blades 29-50 meters long, weighing 10-20K pounds
- Cost-efficient, long-term partnership models with key turbine makers
- Factories located in a manner to optimize labor and transportation cost, providing competitive advantage
- Custom designs, tailored to customers machine

Anatomy of a Wind Turbine Blade (near Max Chord)



Modern Wind Turbine Design

Blade Manufacturing – "What's it Take?"

- SPACE! - Physical Plant
  - Factory Space
  - Bridge Cranes/Heavy Lifting
  - Significant Consideration of Layout/Process Flow
    - Large Molding/Assembly Operations
    - Small Parts
    - Finishing Operations
    - Material Flow thru Plant
- Infrastructure
  - Systems
    - Resin Storage/Plumbing for delivery
    - Vacuum Lines/Compressed Air
    - Cure Ovens (if required)
    - Finishing Operations/Dust Control
    - Root Drill/Trim
    - Automation Equipment (if used)
  - Tooling/Assembly Fixtures
    - Heated vs. Ambient Cure Tools
    - Skin Molds
    - Shear Webs
    - Small Parts
      - Spar Caps, Root Preforms, balance boxes, etc.

Blade Production Requires SPACE

Warren, RI, 60K sq ft, Development Center, Manufacturing

Taicang Port, China, 190K sq ft to supply wind blades to GE

Newton ,Iowa, 316K sq ft to supply wind blades to GE

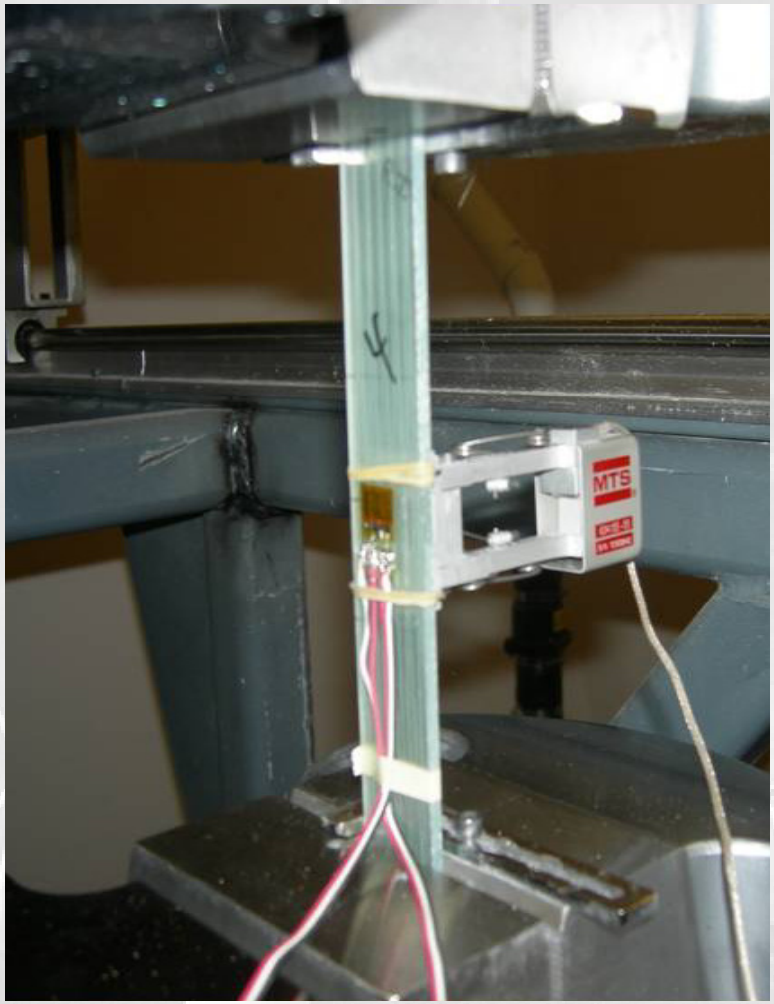
Juarez, Mexico, 2 Plants 477K sq ft, Wind blade JV with Mitsubishi

Springfield, OH - 66K sq ft, Military and Transportation Mfg

Blade Production Requires PEOPLE

- Materials & Materials Engineering
- Structural Design
- Process/Tool Engineering
- Quality Systems/Engineering
- Sensor Development and Technologies to Positively Impact R&M
  - NDI
  - Health Monitoring
  - Control/Load Mitigation
- Transportation/Logistics

Materials and Materials Engineering

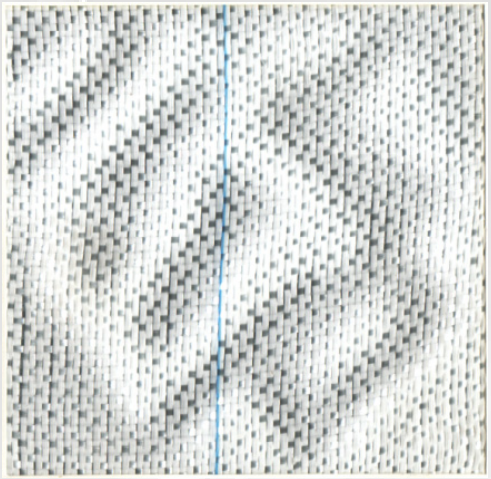


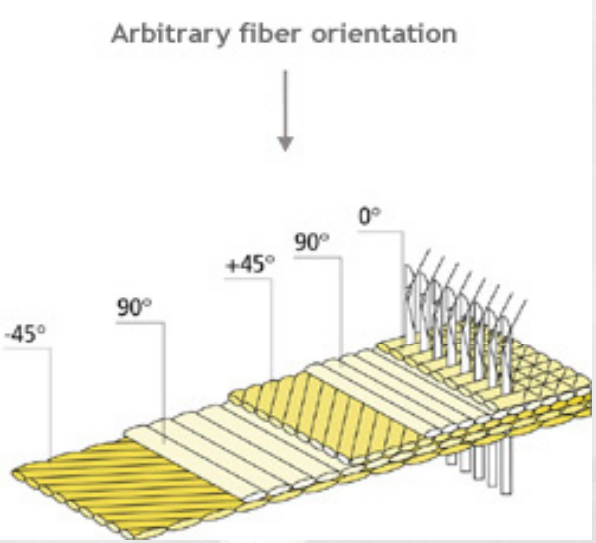
Materials are the primary drivers in system performance and production costs:

- 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

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



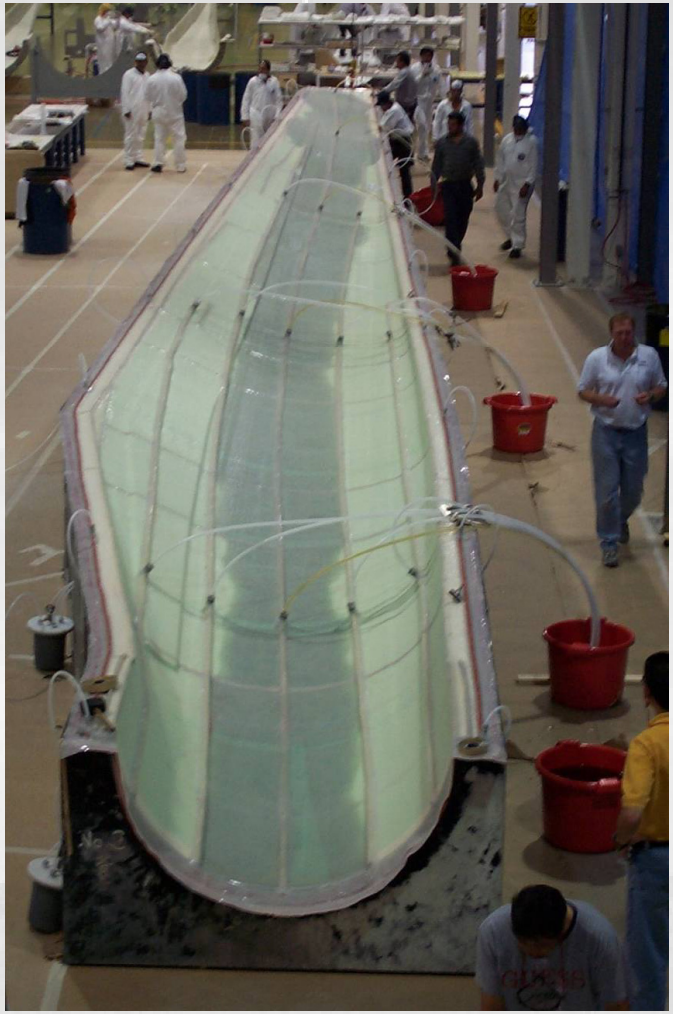


Courtesy of Saertex USA

Resins Matrices and Adhesives

Composite Matrices:

- Epoxies remain a primary resin of use in European based blade designs
  - Excellent fatigue performance.
  - Extended cycle time (cure cycle/elevated temperature curing).
  - Higher cost both for materials and tooling (heated tools).
- Vinyl-esters are attracting much interest by blade designers
  - Good combination of economics and performance.
  - Ambient temperature curing possible or highly reduced cure schedules with heating.
- Polyester resin are still prominent in the industry.
  - Low cost and adequate performance up to at least 46m blade lengths.
  - Room temperature viscosity provides excellent infusion characteristics in modified PE blends.
  - Rapid curing and short cycle times achievable.
  - Some question long term fatigue, environmental, themomechanical properties.
  - Repair requires VE or Epoxy wet layup/infusion materials for adequate bonding.
- Thermoplastics and other matrices
  - Insitu Polymerization
    - Cyclics
    - NyRim
  - 2 Component RIM Polyurethanes

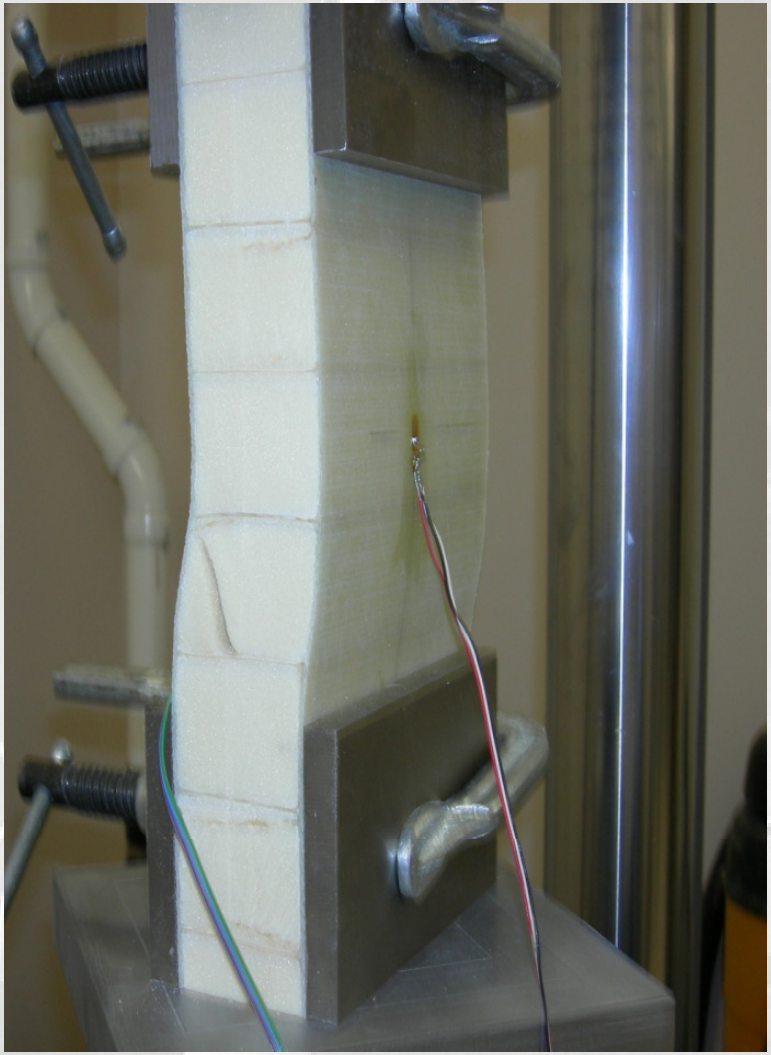


Resins Matrices and Adhesives (continued)

Blade Assembly/Bonding Adhesives:

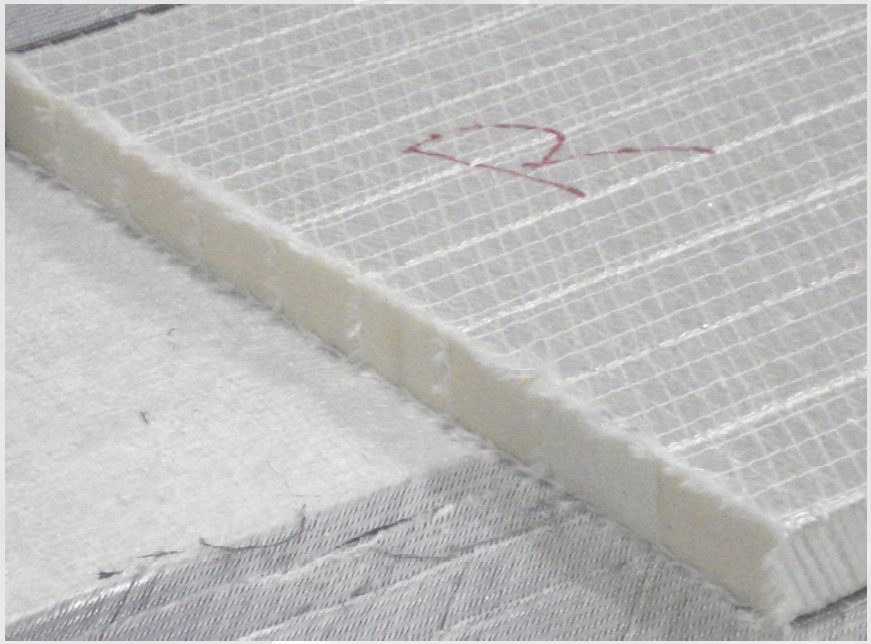
- 2 Part Epoxy Paste Adhesives specifically formulated for their thixotropic properties are the mainstay for bonding and assembly
  - Costly, but result in very good mechanical properties when applied correctly
  - Very sensitive to “off ratio” blending.
  - Elevated temperature cure cycles are required to achieve maximum shear properties.
- Methyl-methacrylates provide excellent adhesion to polyester resin composites
  - Similar (or higher) cost to epoxy adhesives
  - Lower strength and stiffness compared to epoxy but much greater fracture toughness (important for thick bond lines?).
  - Very tolerant of “off ratio” blends (lower cost/risk dispensing equipment)
  - Extremely “tenacious” adhesion with low sensitivity to adherend bond preparation.
  - Ambient temperature curing at rates tailored to process requirements
  - Short cycle time potential (compared to epoxy adhesives)
- Polyurethane bonding agents
  - Similar properties to methyl-methacrylates with lower cost premium
  - Ambient curing possible with accelerated elevated cure schedules possible
  - Less tolerant to large bond gaps seen in mega-watt scale blade assembly
- Others?

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

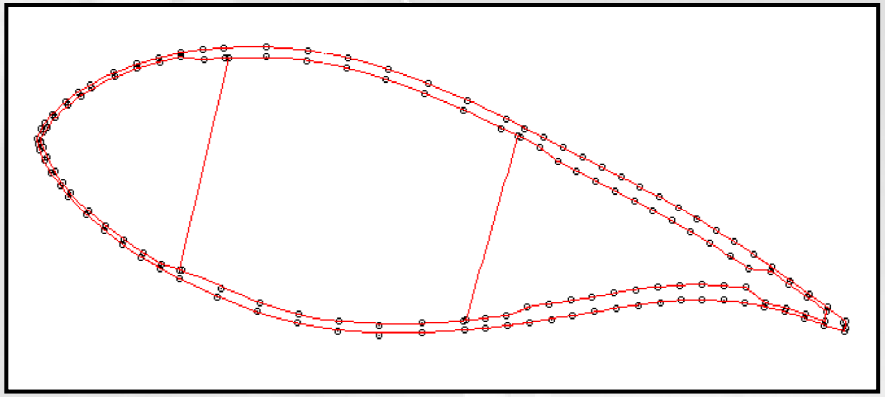
Webcore Technologies, TYCOR Sandwich Core Materials

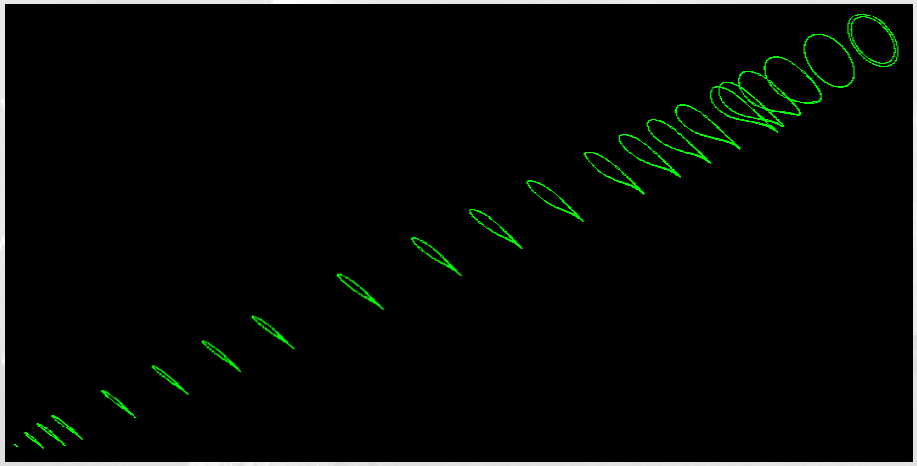


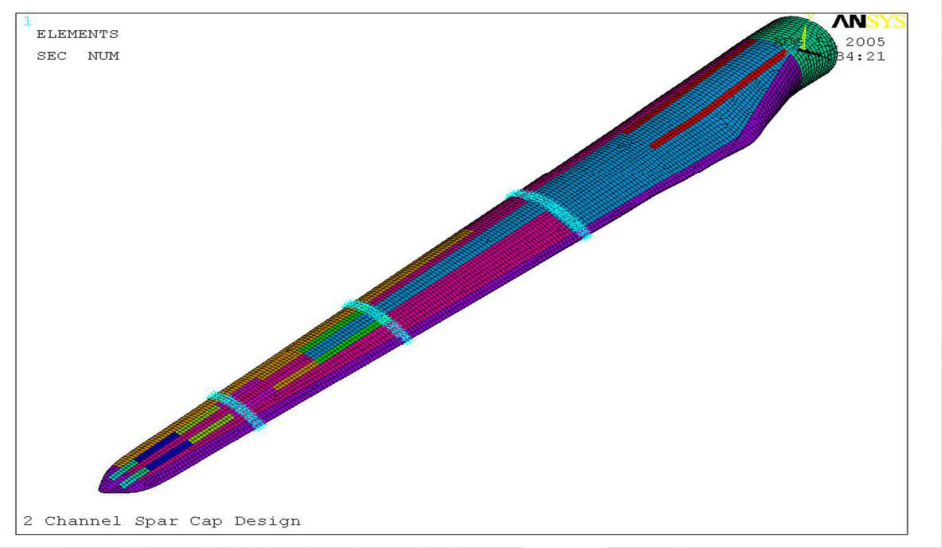
- TYCOR material applied to shear webs in production blades for multi-megawatt scale turbine. Reduced cost of materials by over 20% and component weight by nearly 25% (compared to end grain balsa).
- Very low weight, high performance core at a highly competitive price.
- Kitting and assembly in mold has proven to be faster and more accurate than balsa and foam materials.

Structural Design

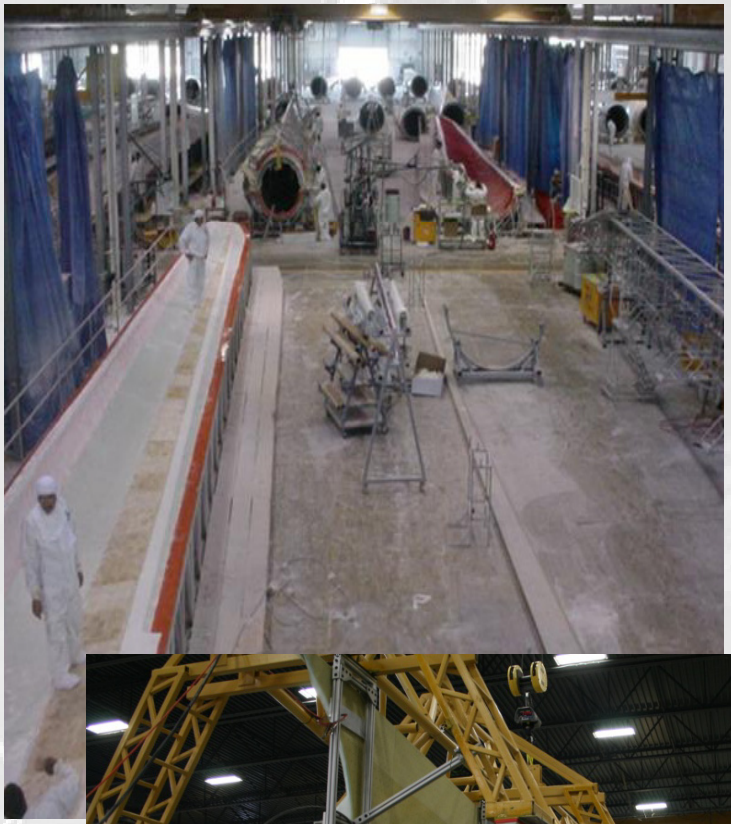
- Opportunities to innovate abound.
- From materials selection and fundamental layout of components to functional performance; the choices are endless.
- A multidisciplinary exercise requiring close coordination between systems and aero engineers, materials and structures groups as well as manufacturing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





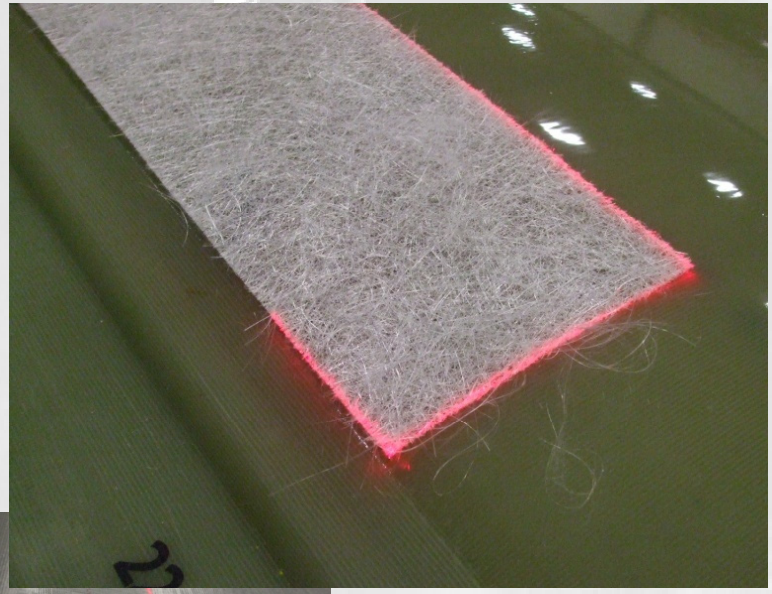


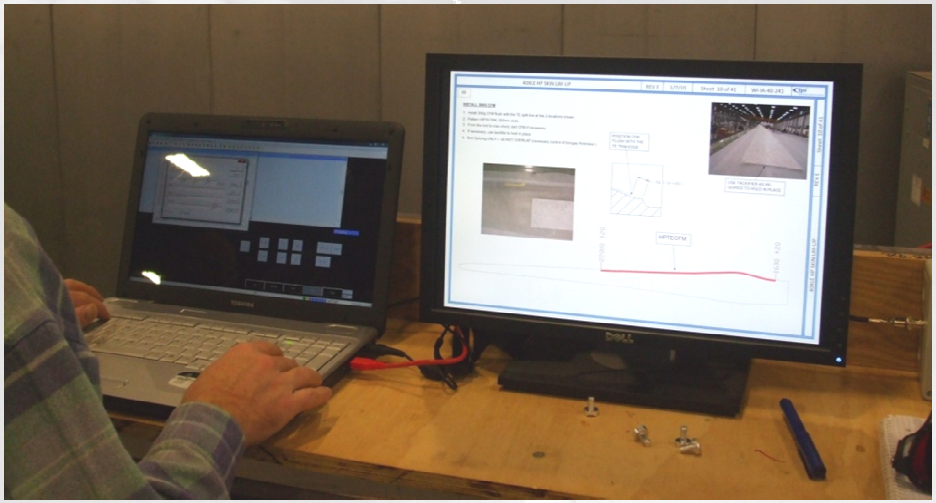
Process and Tool Engineering

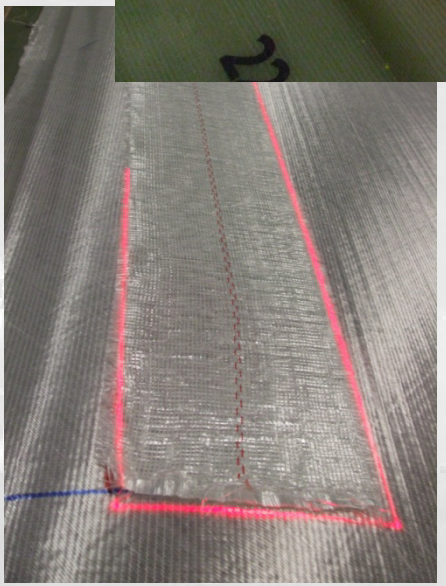


- Materials Processing
  - Infusion (both VARTM and/or RTM)
  - Preimpregnated Mat'ls
  - Wet Layup
  - Automated Tape Layup
- BoM
  - Performance
    - Carbon vs. glass
    - Prepreg vs. Infusion vs. Wet Layup
- Cycle Time
  - Drives factory output
    - Floor plan
    - Tool count/CAPEX
    - Labor content
  - Highly Dependent On:
    - Blade size
    - Complexity
    - Parallel Processes (e.g., premanufactured spar caps)
    - Process/Material types employed
    - Typical Cycle Times of 5 to 7 metric tonnes of material per mold per 24 hours
- CAPEX
  - Number of Tools/Fixtures
  - Root Trim/Drill
  - Other Automation
  - Heated vs. Non-heated tools
  - Paint Booths/Finishing Booths/etc.

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

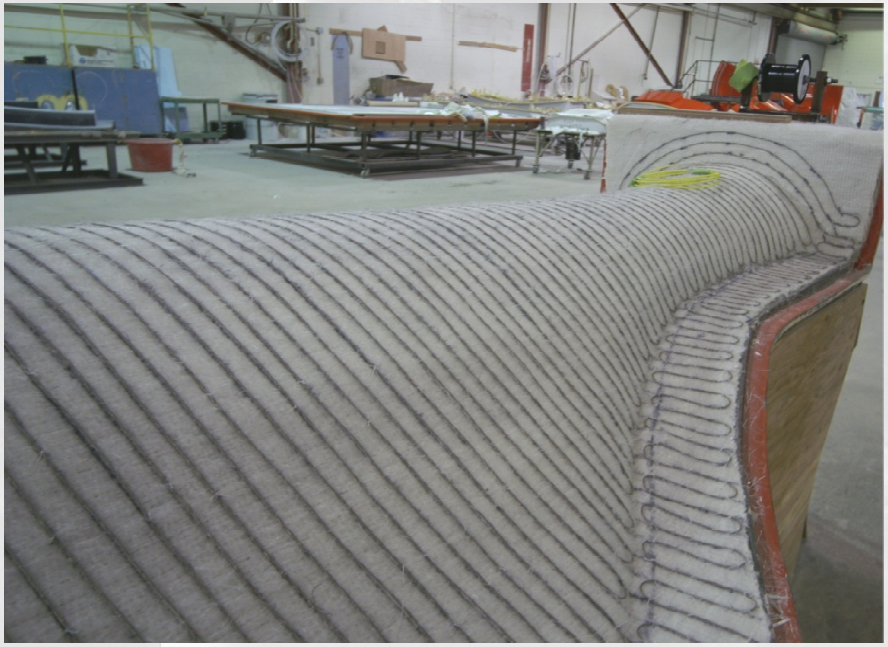
Reusable Silicon Bag Technology for SCRIMP®

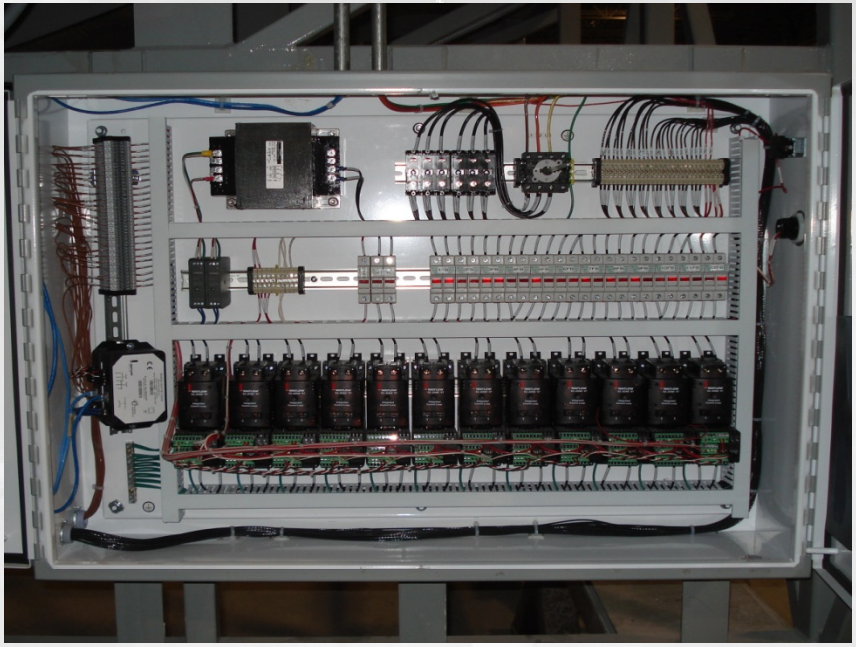
- Silicone bags are rapidly fitted to the infusion tool
- Feed lines, vacuum lines and embossed distribution channels are integrated into the bag improving the repeatability of the process
- Setup time and process robustness greatly improved

Hydraulic "Power Hinges" for Blade Assembly

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

Electro-Resistive Heating for Epoxy Matrix Molded Blades





- In-house fabrication with proprietary ER 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.

Quality Systems/Engineering

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!

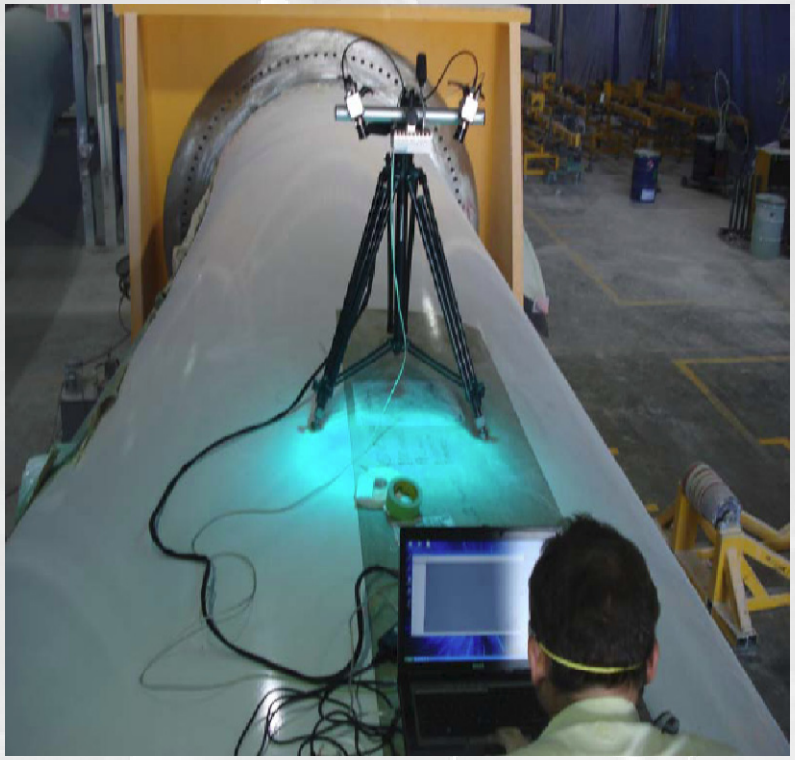
Quality Systems

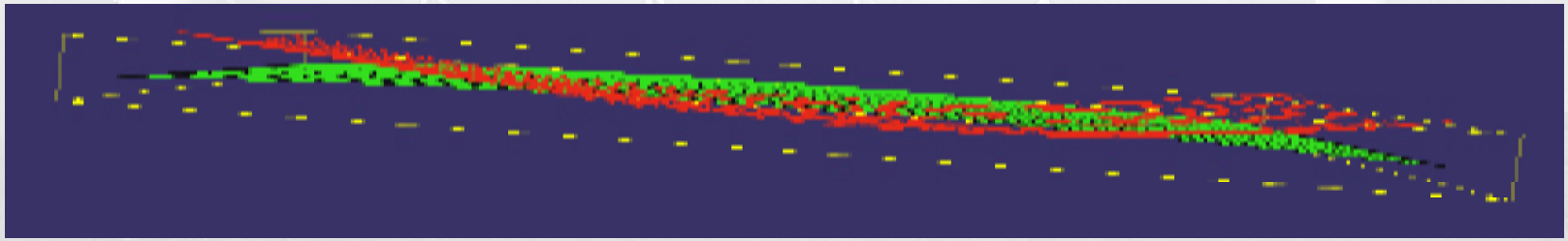
- High performance, technically complex product.
- High skill level with multiplicity of operations required by each manufacturing technician.
- Detailed documentation and constantly revised work instructions, training and certification.
- Tight material specifications with adequate in-coming/receiving testing.
- Physical sciences lab with minimal level of wet chemistry, test and inspection services.
- High level capability for metrology; laser tracking CMM are a must
- Documentation, documentation, documentation.

Quality Systems: Physical Sciences/Wet Chemistry

- Perkin-Elmer DSC-7
  - Differential Scanning Calorimeter
  - 0.1mg Adams Analytic Balance
    - Density of Composites/Resins via displacement method
- Brookfield DV-II+ Pro Viscometer
  - Rheometry w/computer data acquisition
  - Temperature controlled circulating bath for rhelogical measurements as a function of temperature
- Gardner Gel Tester
- Large Blue-M Oven for specimen post cure
  - Programmable PID controller
- Muffle furnace for resin burn-off
  - Fiber volume fraction of fiberglass composites
- Barcol Hardness Tester

Digital Image Correlation for Wide Area Strain Measurement and NDI



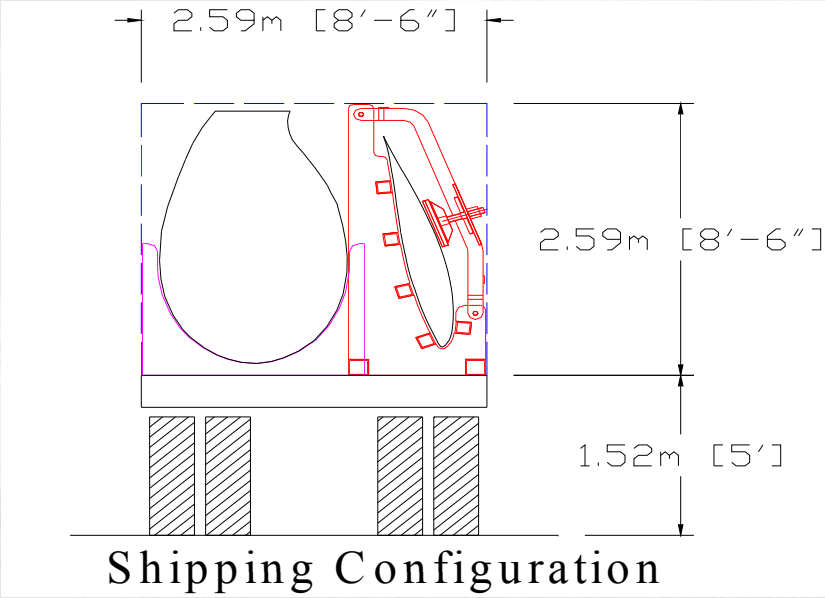


Blade Transportation

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.

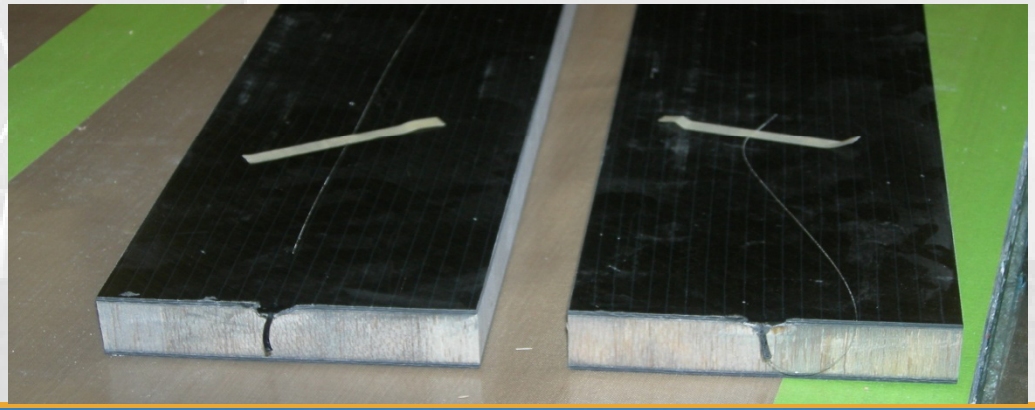
Current shipping configuration of 2.4MW 46.2m wind blade



Sensor Technologies

- Designs migrating toward larger and lighter weight rotors (Offshore and improved Cp)
- The cost of failure is unacceptably high, but the cost of O&M may well be prohibitive and require the use of technology to ensure long term reliable operation.
- Health monitoring systems in a variety of forms where innovation rules, may be the answer.

Embedded Sensors and Applied Instrumentation



- TPI, Aither Engineering and Purdue University with support from Sandia labs have built a new CX-100 with fully integrated FBG (Fiber-optic Bragg Gratings) strain instrumentation and accelerometers for real time measurement on a NWTC test turbine at Bushland, Texas.
- Test panels with embedded fibers as well as mechanical testing for characterization of material systems completed to provide analytical predictive capability and demonstrate survivability through processing.

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

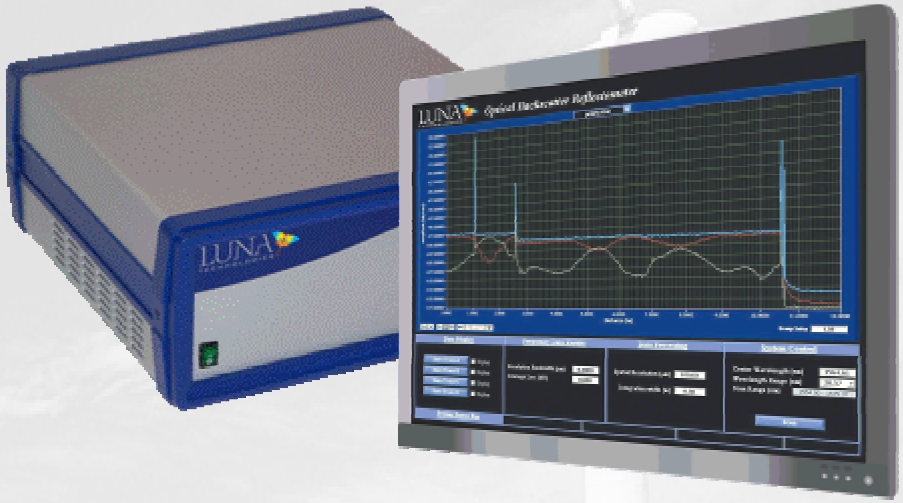
Number of blades	3
Number of sensors per blade	6
Range	±4500 microstrain
Measurement resolution	1 microstrain
Measurement frequency	25 Hz/sensor
Power supply	24 V DC
Power consumption	<3 W
PLC interface	RS232, RS422, RS485,CANbus
Weight	2 kg
Dimensions L x D x W	240 x 97 x 120 mm
Operating temperature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

Luna Technologies

High Resolution OTDR

- High resolution fiber-optic component manufacturing, installation and maintenance testing
  - *Component/fiber/module manufacturing*
  - *Avionics*
  - *Ship-board*
  - *Mobile Platforms*
  - *Secure Networks*

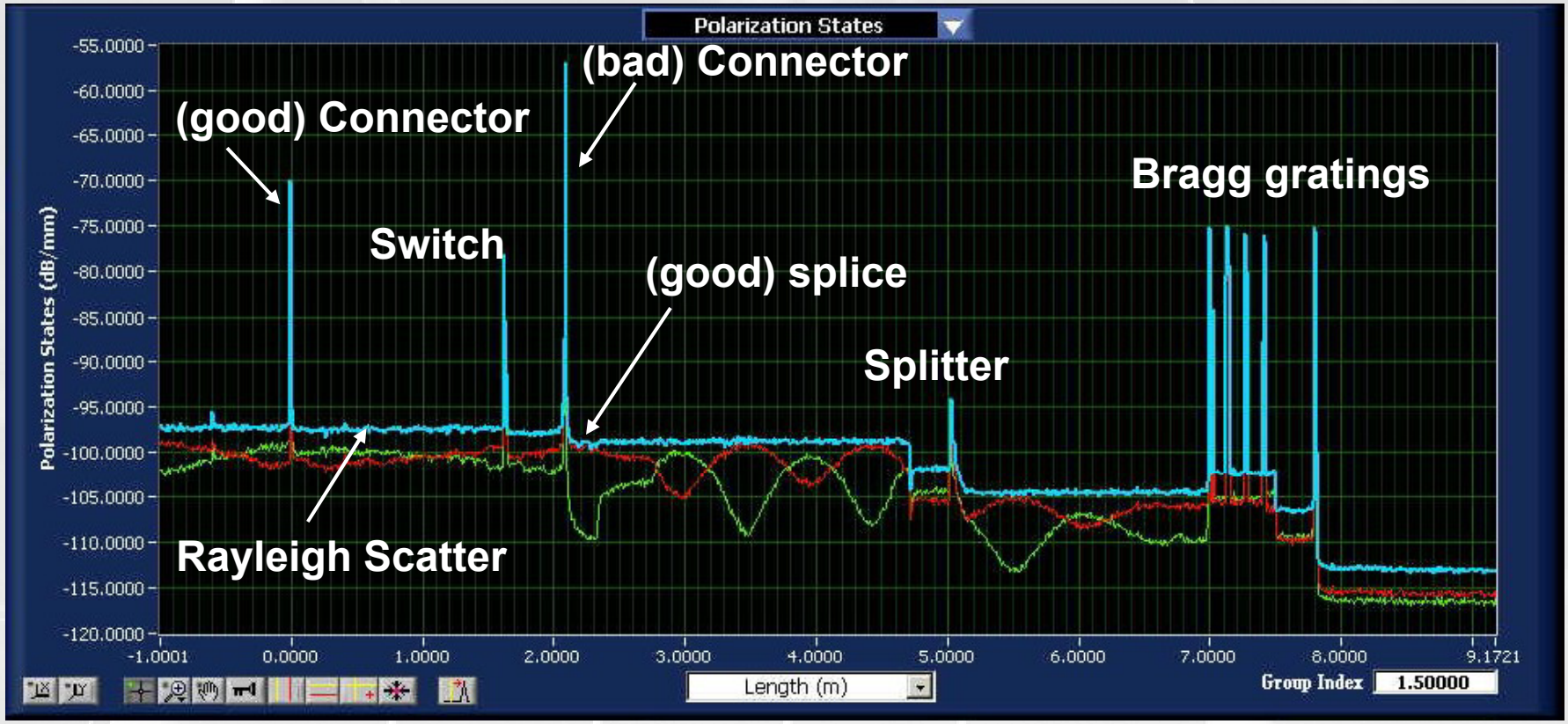
Optical Backscatter Reflectometer



- Unprecedented inspection and diagnostic capabilities for the fiber-optic industry
- Industries' *only* micrometer resolution OTDR designed for testing components, modules and assemblies
- More comprehensive testing and inspection in less time

Rayleigh Scatter Measurement

- OFDR offers unprecedented sensitivity

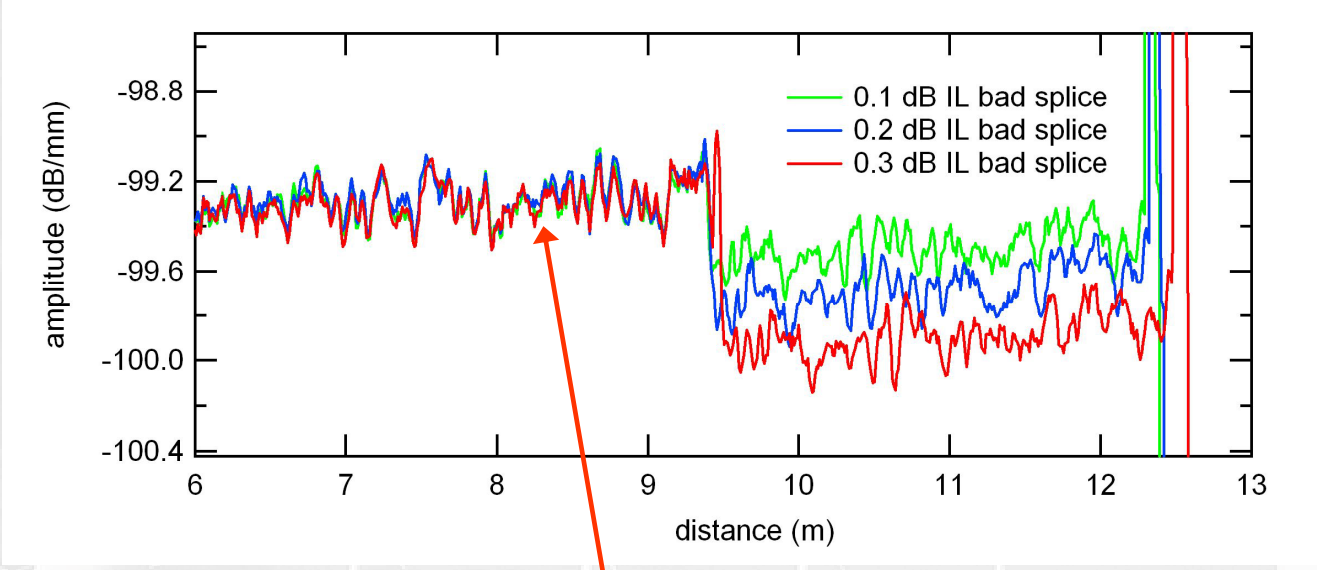


The fiber itself can be used as the sensor

- Rayleigh Sensing
- Standard telecom grade SMF becomes the sensor

A Closer Look at the RBS

- Three consecutive scans of the same fiber length

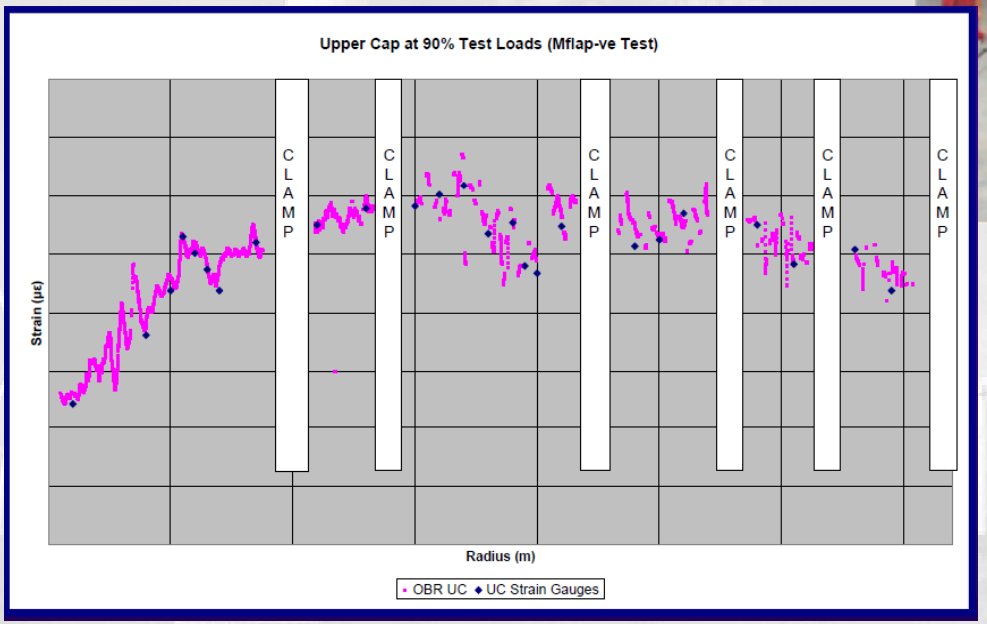


Note the repeatability of the “noise”

Strain on Composite Structure*

Advantages

- Strain measured along full length of blade ***at every point***
- No sensor placement issues
- Fully distributed measurement along entire length of sensor

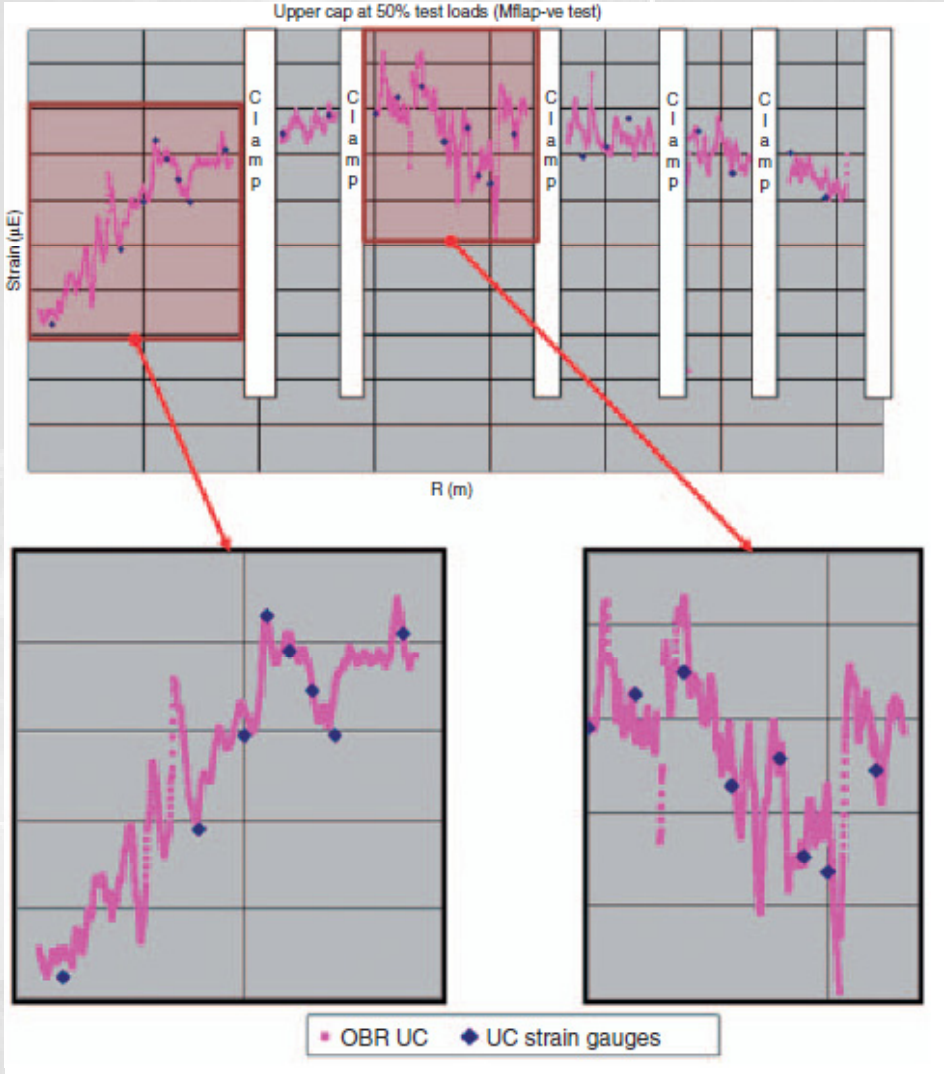


- Software adjustable strain sampling between 1 and 1000 pts/meter
- No specialty fiber

*Optical Fiber Distributed Sensing – Physical Principles and Applications, Alfredo Guemes, Antonio Fernandez-Lopez, and Brian Soller, Structural Health Monitoring Vol 9(3): 233–245.

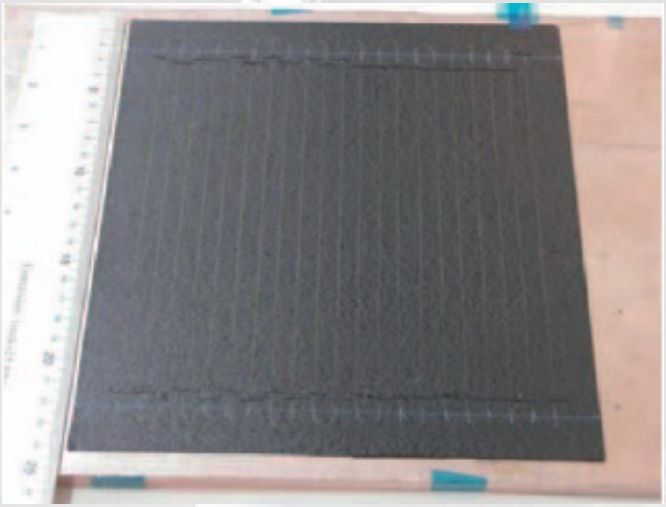
Rayleigh Distributed Strain*

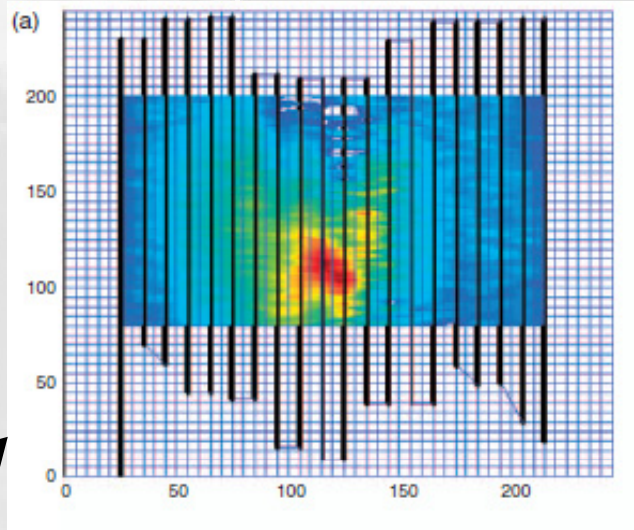
- Blue points represent strain gage data
- Pink line is strain measured using Luna's Rayleigh system (OBR)



*Optical Fiber Distributed Sensing – Physical Principles and Applications, Alfredo Guemes, Antonio Fernandez-Lopez, and Brian Soller, Structural Health Monitoring Vol 9(3): 233–245.

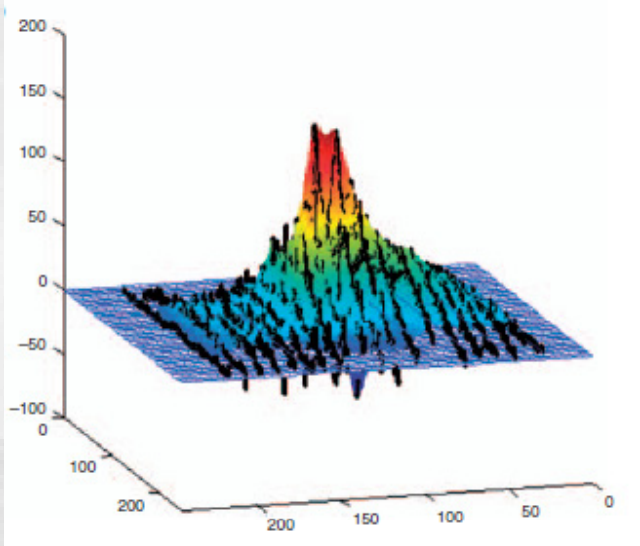
Strain in Composite Plate*





FIber integrated into cross-ply laminate composite in a zig-zag pattern

Strain results

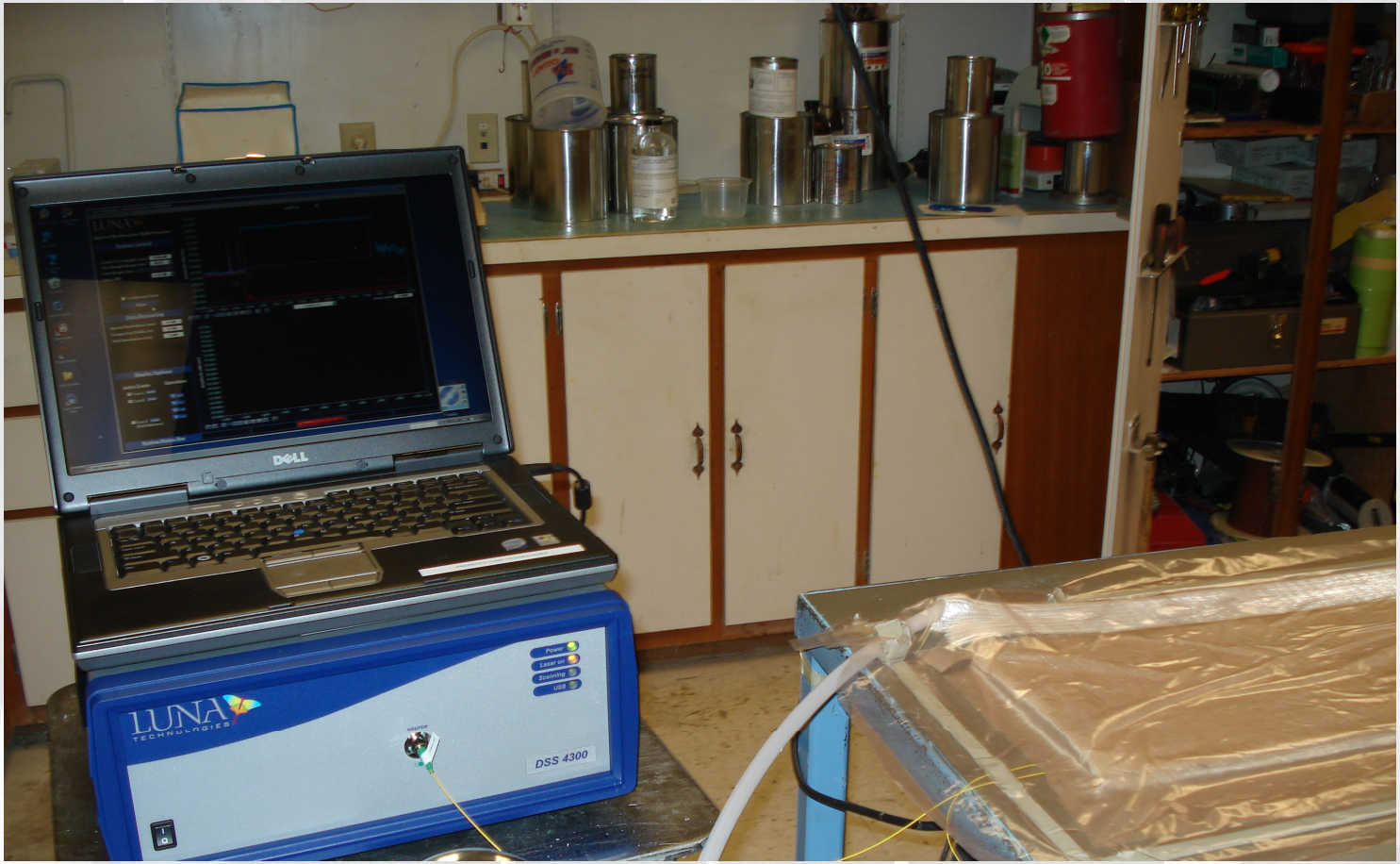


*Optical Fiber Distributed Sensing – Physical Principles and Applications, Alfredo Guemes, Antonio Fernandez-Lopez, and Brian Soller, Structural Health Monitoring Vol 9(3): 233–245.

Composites - Embedded Sensor Integration

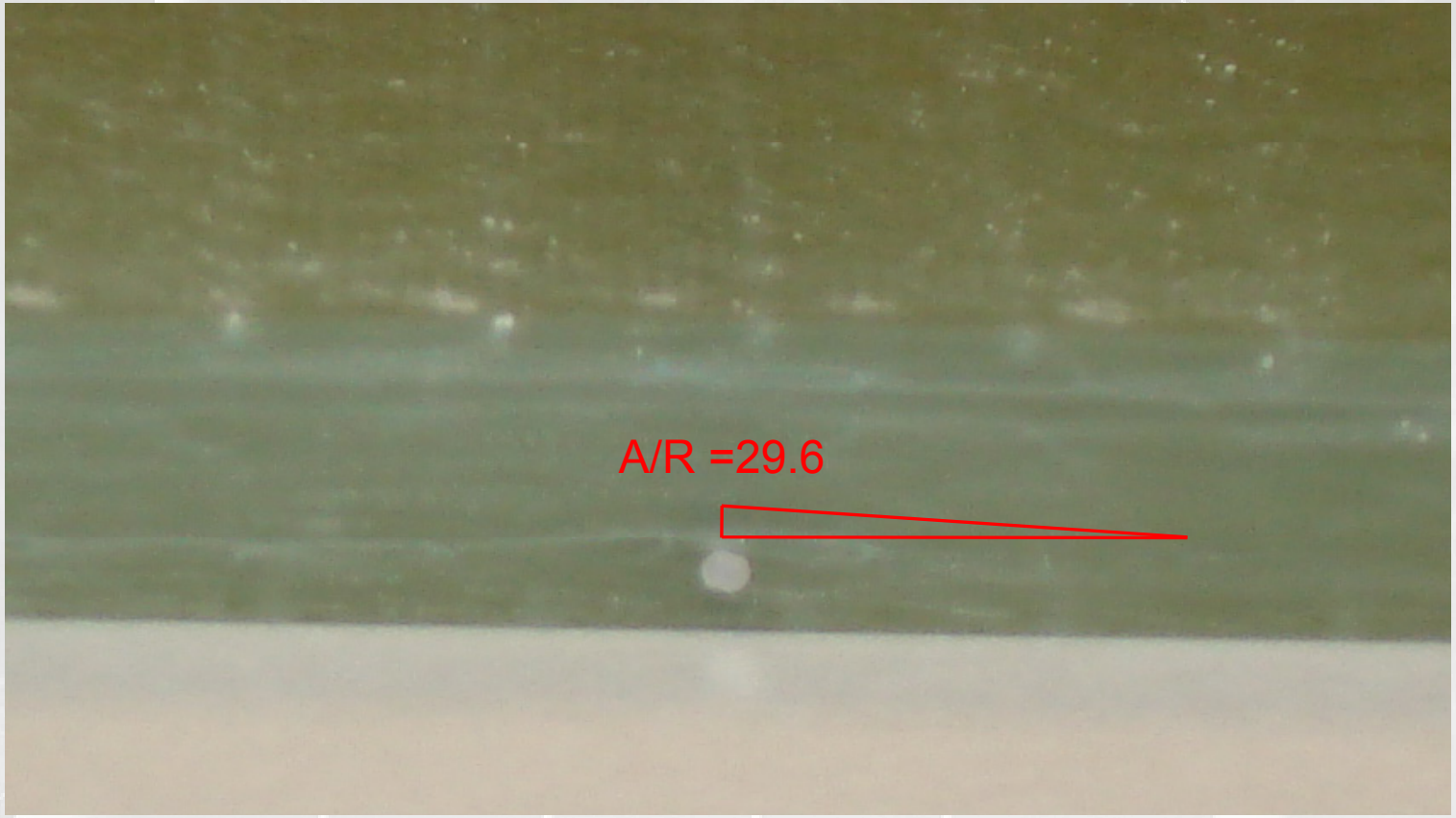
- **Sensors may be integrated into composites by most processing methods:**
  - ***VARTM***
  - ***Autoclave/ press lamination***
  - ***Hand layup***
  - ***Pultrusion***

Use of CONTINUOUS Fiber Optic Strain Sensing for In-situ Process Monitoring of Laminate Waves

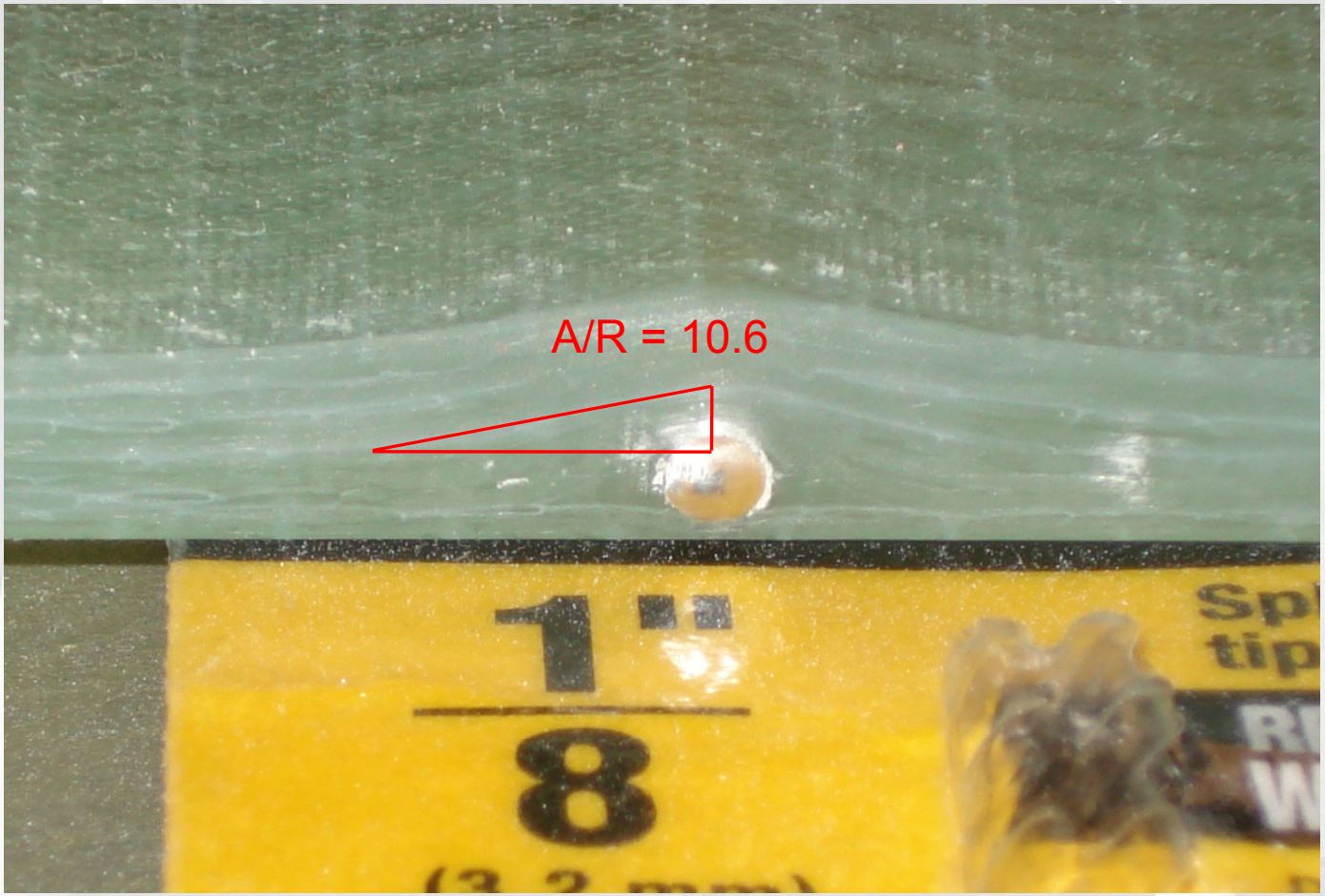


Continuous Fiber Optic Strain Sensing is a Viable Technology

1.0mm Drill Rod A/R Measurement (At FO Layer)



3.2mm Drill Rod A/R Measurement (At FO Layer)

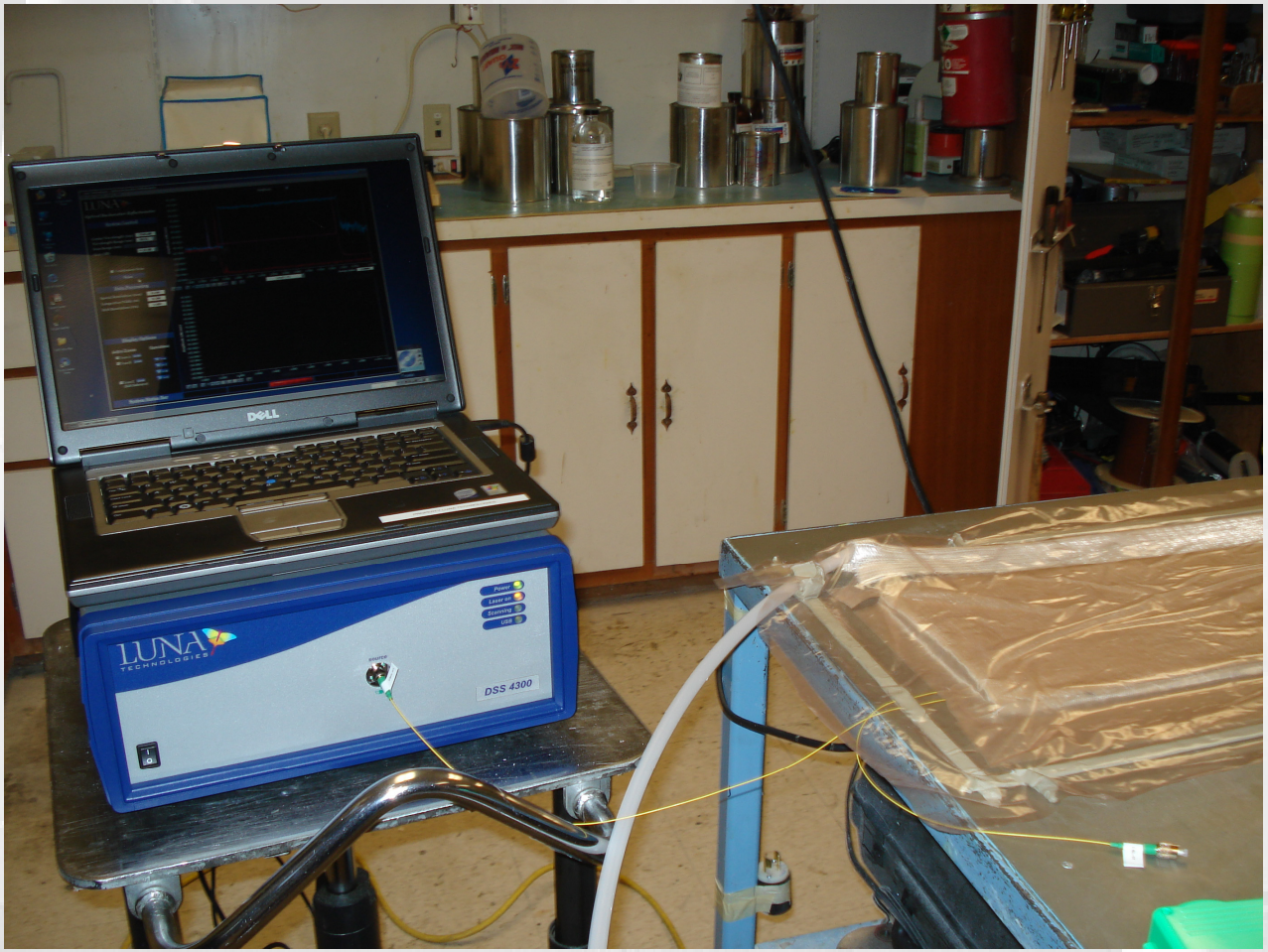


Resulting Wave A/R's After Infusion

Embedded Waves in 930gsm UD Material

Wave #	Drill rod (mm)	A/R (mm/mm)	Strain Signal (μstrain)
1	1	36.3	
2	1.6	26.7	
3	2	18.7	
4	2.4	8.95	
5	3.2	10.6	

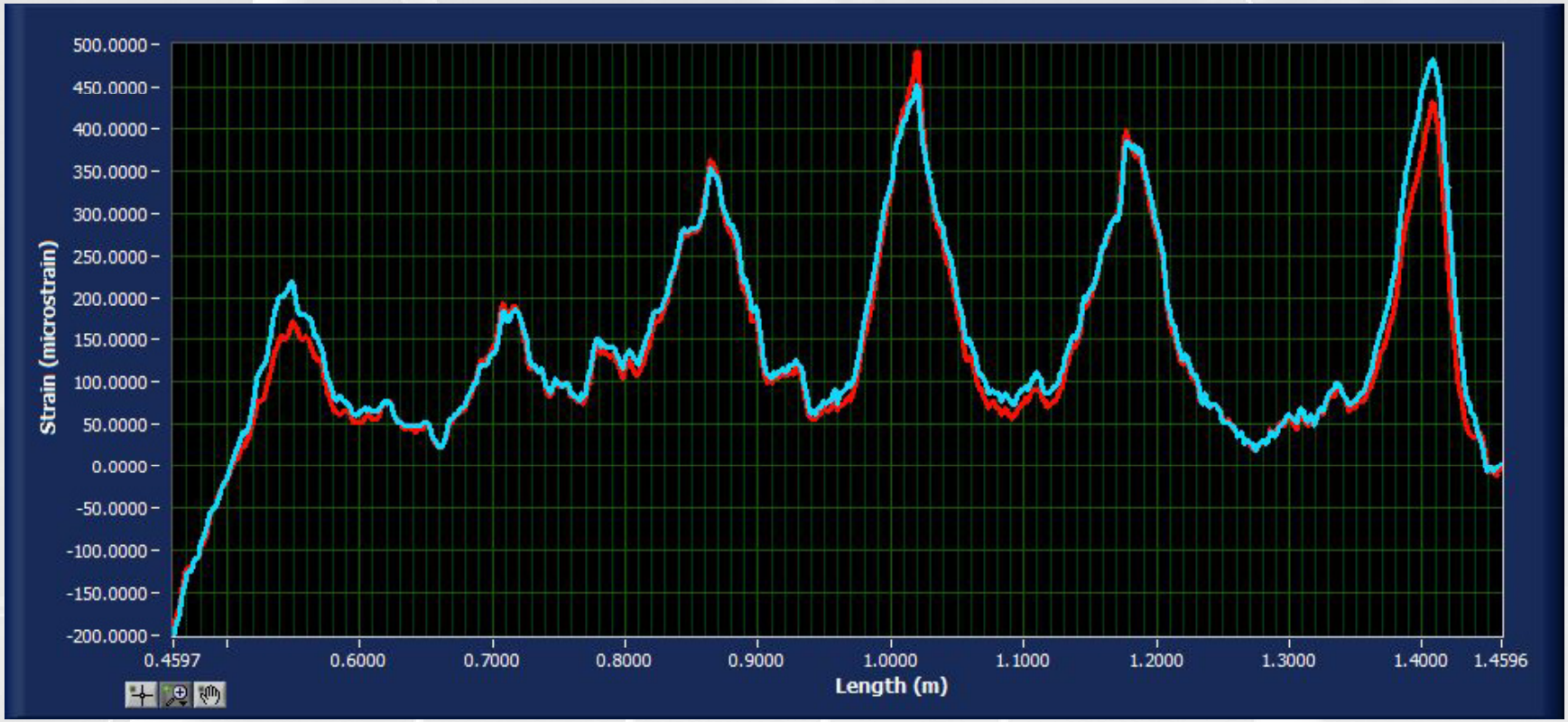
Luna OBR Unit Connected to UD Stack with Embedded Rods for Wave Creation



Fiber Optic Signal, No Vacuum Applied

Fiber Optic Signal After Vacuum Applied

Screen Shot of Pre-infusion FO Strains

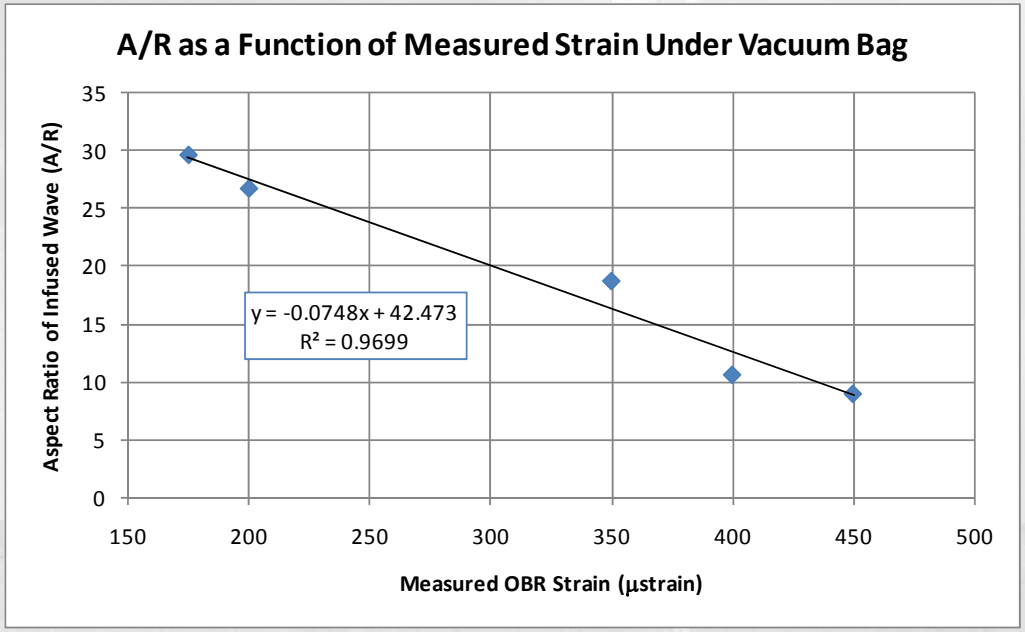


Resulting Wave A/R's After Infusion

Embedded Waves in 930gsm UD Material

Wave #	Drill rod (mm)	A/R (mm/mm)	Strain Signal (μstrain)
1	1	29.6	175
2	1.6	26.7	200
3	2	18.7	350
4	2.4	8.95	450
5	3.2	10.6	400

- Aspect ratio of embedded waves closely correlates with strain measurement



Continous OBR Strain Sensing

- Effective method for "near" real time process monitoring.
- Useful for evaluation of lay-up quality in critical areas prior to infusion/cure
- Post-process use can include health monitoring applications, active feed back for load mitigation and/or IPC.

tpi