Post-Deployment Characterization of Glass Fiber-Reinforced Thermoset and Thermoplastic Composite Tidal Turbine Blades

Paul Murdy
Research Engineer, National Renewable Energy Laboratory
Ariel Lusty
Post-Doctoral Researcher, National Renewable Energy Laboratory

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NREL Flatirons Campus

Photo by Josh Bauer, NREL 61821

The 307-acre Flatirons Campus, home of the National Wind Technology Center, is approximately 25 miles north of the main NREL facility in Golden.

- **Advanced Research on Integrated Energy Systems** and **Integrated Energy Systems at Scale**
- **Structural Research**: Characterization and validation of turbine blades and components
- **Dynamometer Research**: Validation on drivetrains and generators 1 kW–5 MW
- **Field and Technology Research Validation**: Field research pads, expert engineers, specialized facilities
- **Composites Manufacturing**: Industrial-scale workspace, research, and education center

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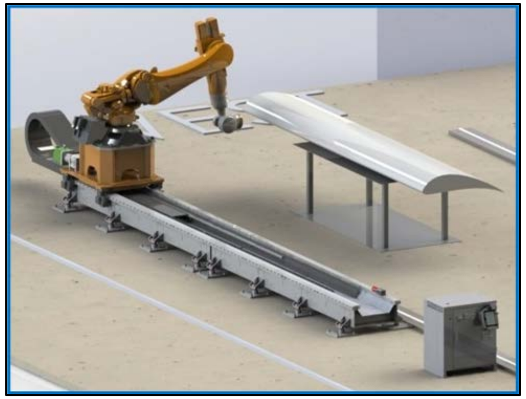
CoMET

Photo by NREL

- Composite Manufacturing Education and Technology (CoMET) facility
  - Established fall of 2016
  - 10,000 square feet for advanced composite materials and processing research
  - Megawatt-scale wind turbine blade tooling
- Network of public-private research partners
  - Academia, wind industry original equipment manufacturers, and composite materials suppliers
- Broad capabilities across multiple applications
  - Large-platform composites
  - Manufacturing automation
  - Circular economy materials
  - Scale-up (coupons) to full-scale products
  - Additive manufacturing (AM)



Process photos by Paul Murdy and David Snowberg, NREL

Structural Validation

Coupon Characterization

Photo by Paul Murdy, NREL

- ISO 17025 accredited
- Range of test stands
- Hydraulic infrastructure
- State-of-the-art data acquisition, sensor, and nondestructive test equipment

Subcomponent Validation

Photo by Taylor Mankle, NREL 67493

Full-Scale Validation

Photo by Taylor Mankle, NREL 67467

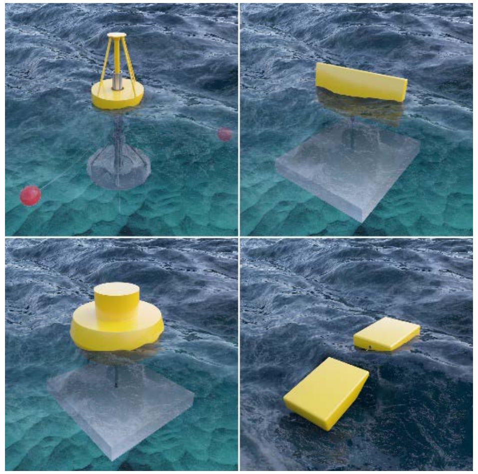
Full-Scale Validation

Photo by Scott Hughes, NREL 14708

What Is Marine Renewable Energy?

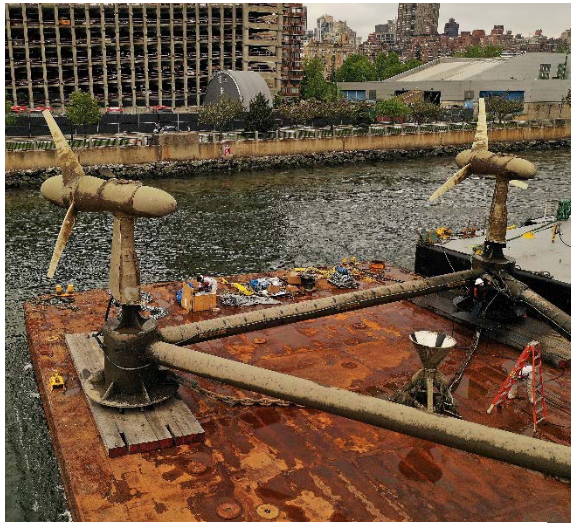
- Oceans are an abundant source of clean energy
- Current energy conversion
- Wave energy conversion
- Relatively nascent industry
- Utility scale, remote island communities, aquacultures, desalination, ocean exploration
- Large variety of concepts and machine architectures being developed
- Highly loaded structures in harsh environments
- Especially challenging from a materials perspective – how can we reduce deployment risk?
- Are composite materials the solution?

HERO-WEC desalination. Photo by John McCord, NREL 74187



Various wave energy converter architectures. Illustrations by Joshua Bauer, NREL 75391

ORPC RivGen. Photo from ORPC and Igiugig Village Council



Verdant Power Tri-Frame. Photo from Paul Komosinski / Drone Altitude LLC

NREL Water Power

Photo by Joe DelNero, NREL, 70307

Driving innovation in the design and use of next-generation **marine energy** and **hydropower/pumped storage** systems through foundational research, tool development, and laboratory and in-water optimization.

What's Next

- Improving performance, reliability, and cost-effectiveness of wave, tidal, ocean, and river energy systems
- Identifying energy and non-energy opportunities of hydropower and pumped storage energy systems

Successes

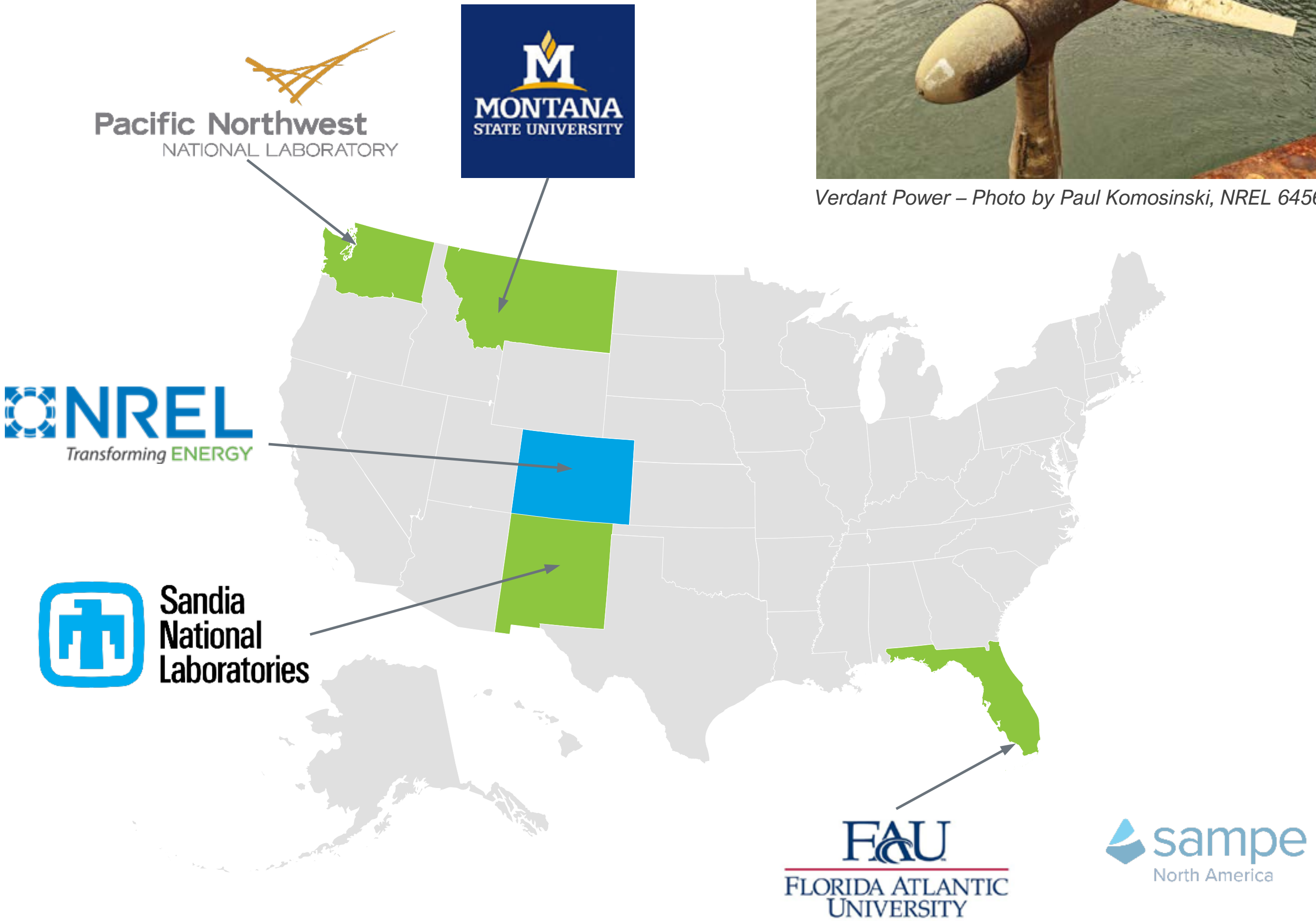
- Deployed NREL-designed, marine-powered desalination research platform, HERO WEC, in real ocean waters
- Published "An Examination of the Hydropower Licensing and Federal Authorization Process" report, which is helping decision-makers streamline the hydropower regulatory process without cutting environmental protection

Marine Energy
Advanced Materials

Marine Energy Advanced Materials

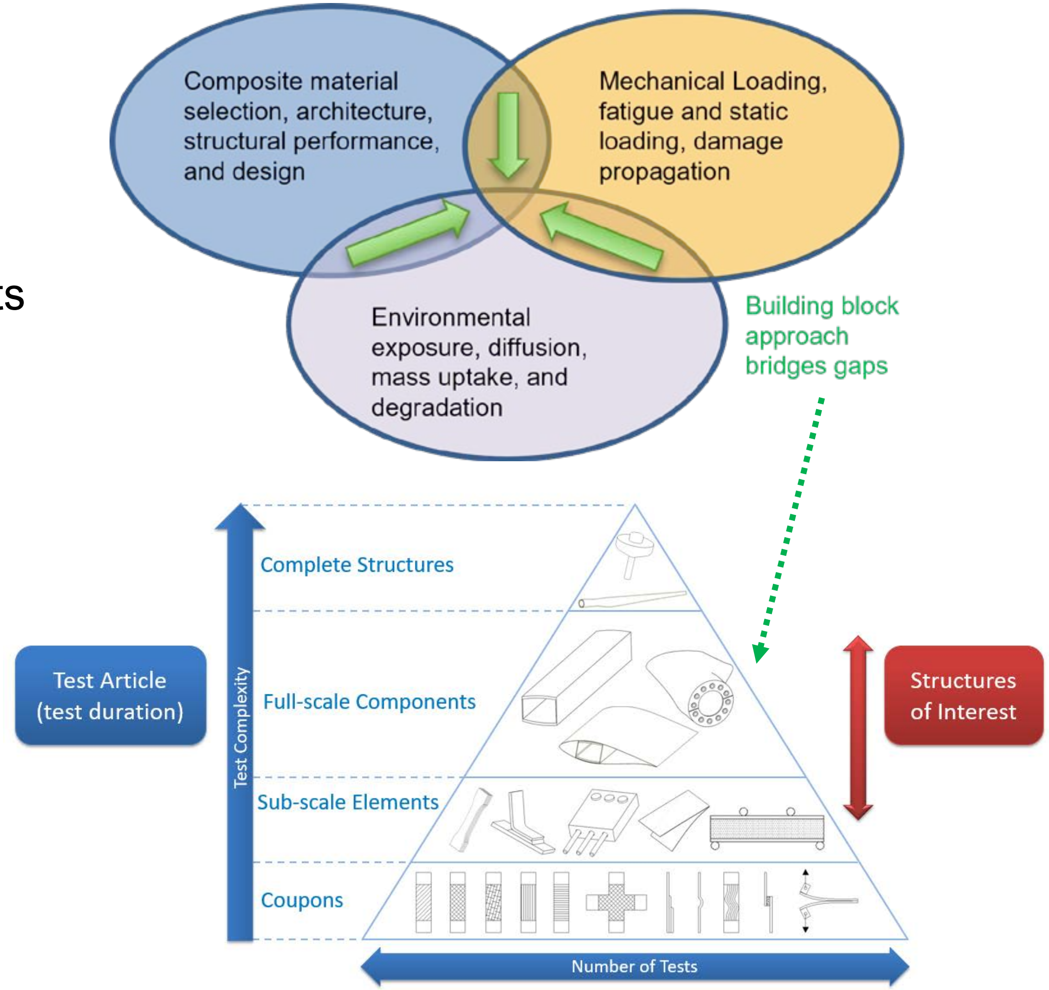
- Multiyear, multilaboratory materials research project
- Industry-driven research
- Reduce barriers and uncertainties to adopting advanced composite materials
- Understand environmental effects on complex structures
- Sandia – lead laboratory
- **NREL – subcomponent validation, additive manufacturing**
- MSU – material characterization
- PNNL – biofouling and coatings
- FAU – corrosion

Verdant Power – Photo by Paul Komosinski, NREL 64565

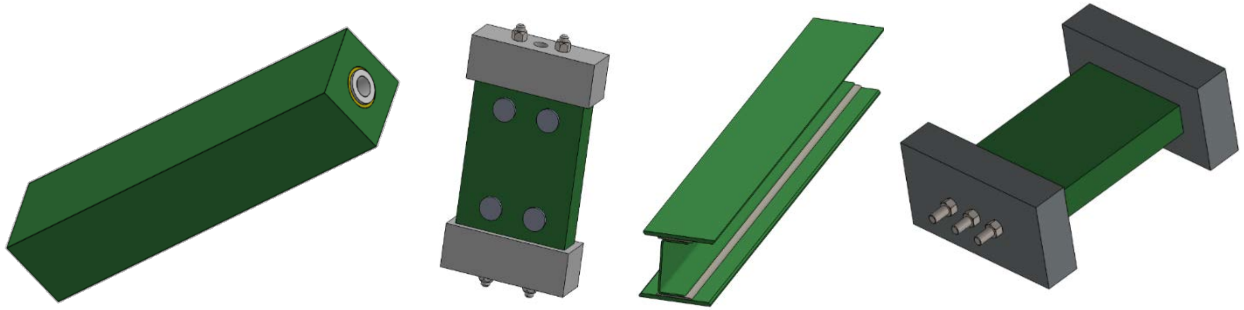


NREL Project Goals

- **Address knowledge gaps highlighted in industry surveys and workshops**
- Develop subcomponent-scale validation methods for marine energy materials
- Improve understanding of design allowables with environmental degradation of full-scale components and joints
- Reduce the time and cost required for full-scale structural validation
- Provide near-net-scale static and fatigue data on composite subcomponents of materials for marine energy systems
- Guide process and material selection
- Provide baseline environmental degradation data
- Define best practices for testing and evaluation at all scales



Illustrations by Scott Hughes, NREL



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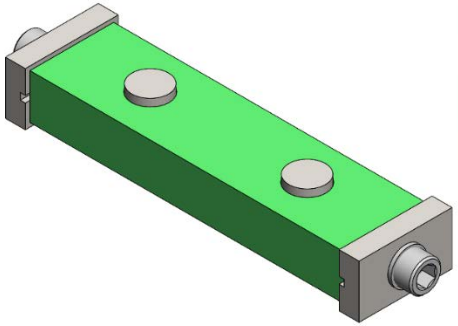
Subcomponent Testing – Phase I

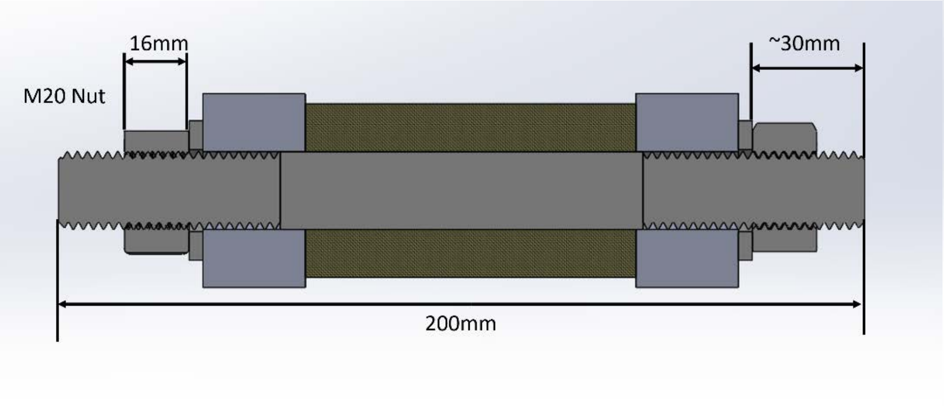
- Epoxy- and vinylester-fiberglass composites, adhesives, bolted connections
- Perhaps the largest marine environmental aging study of its kind (over 300 specimens)
- Conditioning at FAU and PNNL, structural validation at NREL
- Lots of interesting findings!
- Performance of composites varies a lot with loading conditions and environmental conditions: difficult trade-offs
- Adhesives can accelerate crevice corrosion
- Accelerated aging conditions are material dependent
- Report can be found here:
  - https://www.nrel.gov/docs/fy23osti/84487.pdf

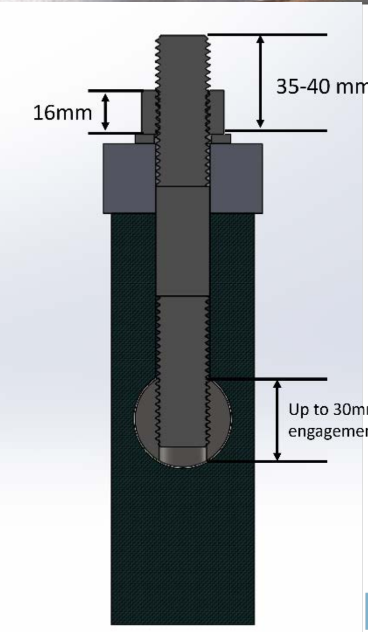


Photos by Paul Murdy, NREL

Phase II – Critical Design Details

- Using coupon-scale water absorption data to understand diffusion at larger scales
- Subscale components of varying complexity to validate diffusion models
- Bolted connections – combined water absorption, creep, and swelling (CWACS)
- How do you characterize composite bolted joint performance over realistic timelines?
- Novel approaches to instrumentation

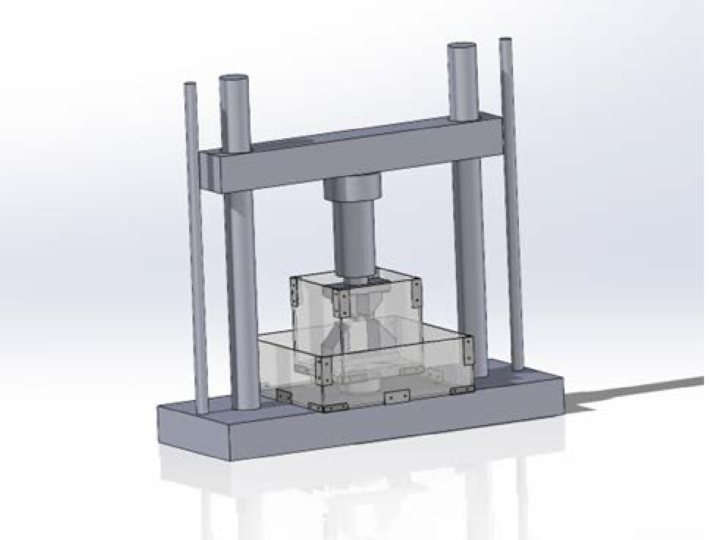


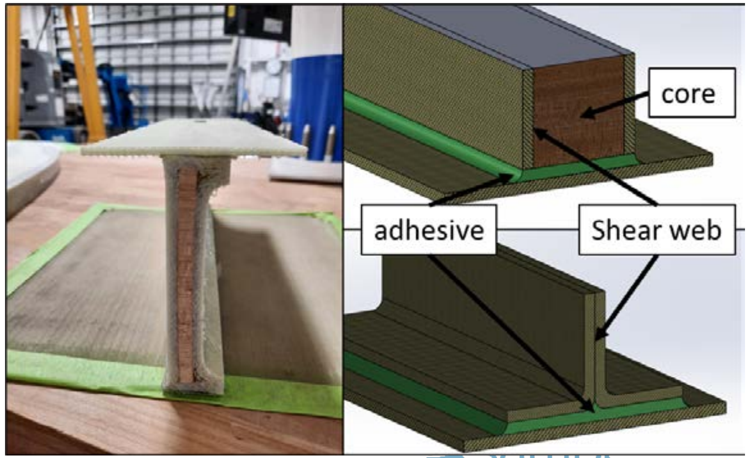


Photos and images by Paul Murdy, NREL

Phase II – Scaled Testing and Combined Effects

- Sequential testing: environmental conditioning then loading
- Research at coupon scale suggests combined loading and absorption effects are more complex
- Do we see the same at larger scales? Or is it driven by boundary conditions?
- Submerged testing at the coupon scale
- Use data to inform submerged testing at subcomponent beam scale





Photos and images by Paul Murdy and Ariel Lusty, NREL

Post-Deployment Characterization

Project Timeline

Blade Manufacturing

- Blades for three rotors manufactured from glass/epoxy by Composites Builders
- Blades for one rotor manufactured from glass/Elium by NREL
- 2020

Verdant RMC Deployment

- Three glass/epoxy rotors deployed in East River tidal strait, New York
- 2021

Rotor Retrieve and Replace

- One glass/epoxy rotor replaced with one glass/Elium rotor
- TriFrame deployed again
- 2021

Structural Validation

- Glass/epoxy rotor and glass/Elium rotor returned to NREL to apply structural loads to the blades
- 2022

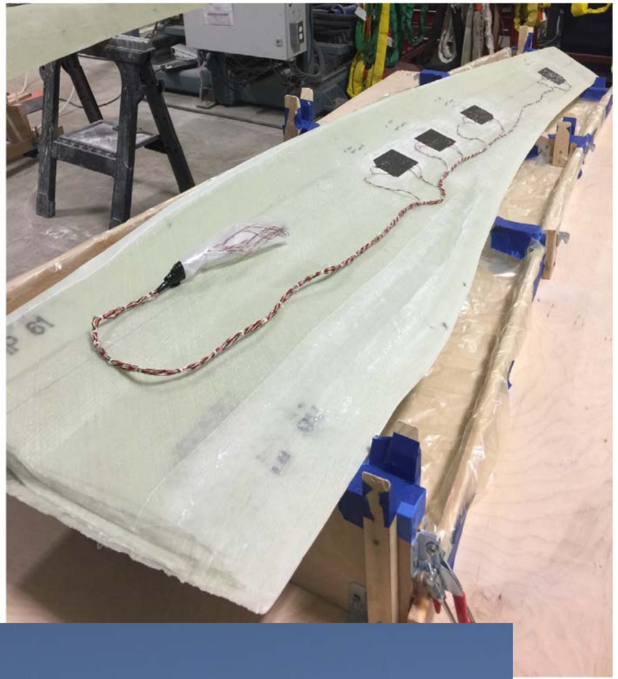
Post-Deployment Characterization

- Glass/epoxy and glass/Elium blades sectioned and subjected to various thermo-mechanical tests
- 2023

Top photo by Paul Komosinski / Drone Altitude. Image credits for circles, from left to right: Robynne Murray (NREL), Paul Komisinski, David Dawkins, and Ryan Beach (NREL)

Blade Manufacturing

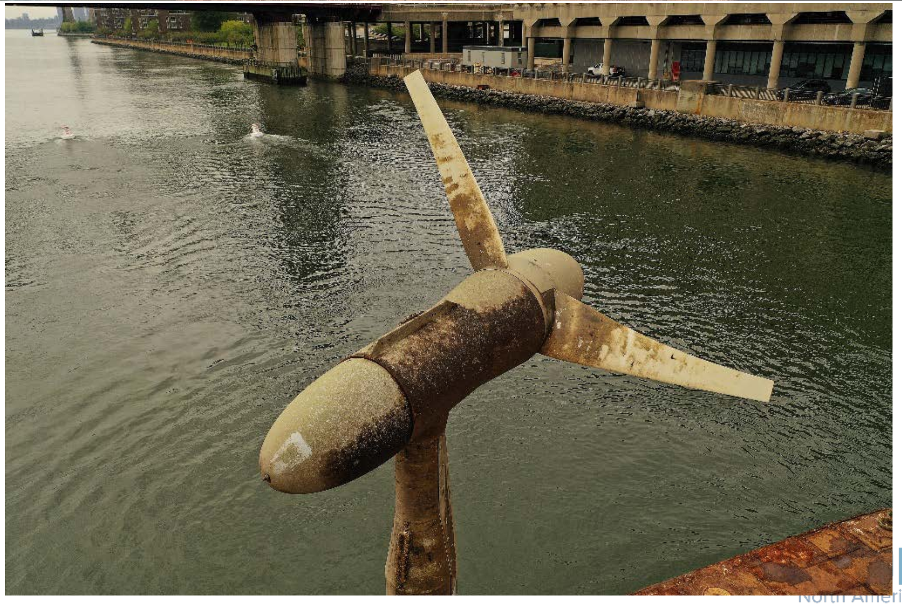
- Two-part bonded shell construction
- Glass/epoxy rotor blades:
  - Composite Builders, LLC, Holland, MI
  - Hexcel glass prepreg
  - Several debulking steps
  - Autoclave cure
  - Epoxy adhesive
  - Epoxy foam fill
- Glass/Elium rotor blades:
  - NREL's CoMET facility, Boulder, CO
  - Same molds
  - Elium – novel, liquid infusible methacrylate resin system from Arkema
  - Vacuum infusion process
  - Ambient cure
  - Methacrylate adhesive
  - Epoxy foam fill



Photos by Dennis Schroeder, NREL (top left), Robynne Murray, NREL (top right), and David Dawkins (bottom)

Verdant Power Deployment

- Verdant Power TriFrame^{TM} deployed in East River, NY (a tidal strait)
- Three glass/epoxy bladed rotors operated for ~3 months
- Verdant Power performed a retrieve and replace operation to demonstrate operations and maintenance capabilities
- One glass/epoxy bladed rotor replaced with one glass/Elium bladed rotor
- Verdant TriFrame redeployed for a further 3 months before ending the deployment
- Murray, R.E. et al. Toward the Instrumentation and Data Acquisition of a Tidal Turbine in Real Site Conditions. *Energies* **2023**, 16.



Photos by Paul Komosinski

Structural Validation

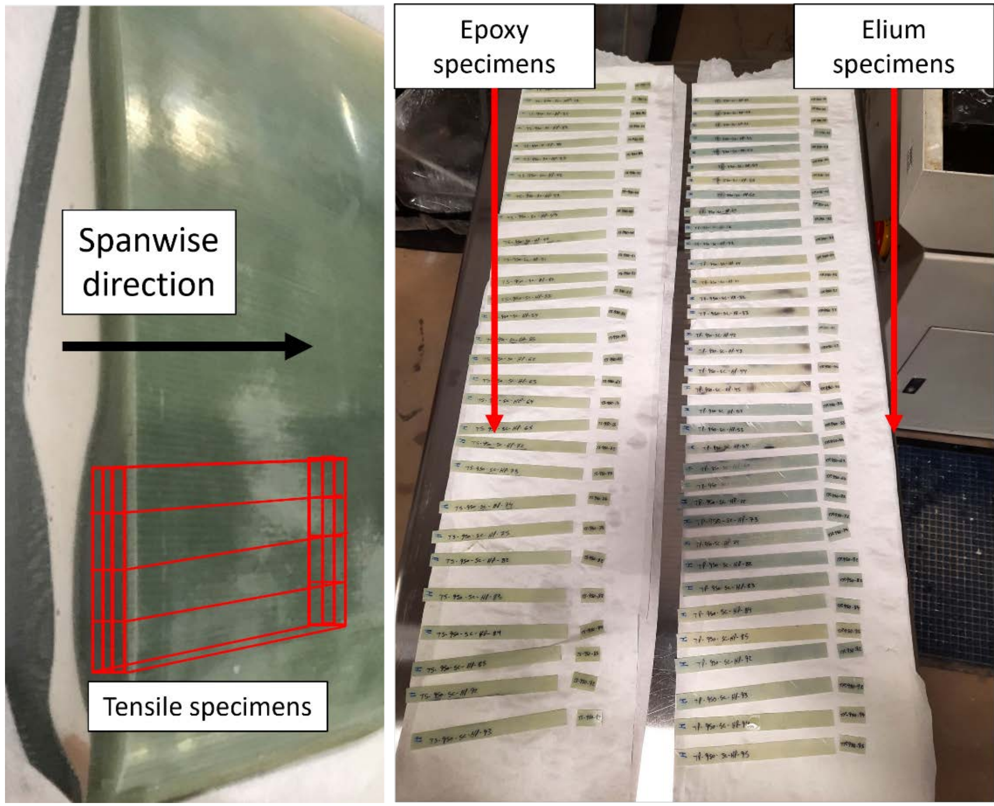
- Dry glass/epoxy and glass/Elium blades structurally validated prior to deployment
- A glass/epoxy and glass/Elium rotor returned to NREL for further structural characterization
- Maximum expected static loads applied to all blades
- Single blades subjected to 20-year lifetime fatigue loading
- Murray, R.E. et al. *Structural Characterization of Deployed Thermoplastic and Thermoset Composite Tidal Turbine Blades;* NREL TP/5000-88713, 2024.

Photos by Paul Murdy and Ryan Beach (NREL)

Post-Deployment Characterization

- A unique opportunity to continue materials research with realistic marine energy structures subjected to realistic manufacturing processes and real-life loading and environmental conditions
- Dissected blades to cut specimens to assess manufacturing quality, thermomechanical properties, and environmental resistance:
  - Matrix burnoff – fiber volume fraction
  - Hygrothermal aging – coupons and blades
  - Dry and conditioned longitudinal tension
  - Dynamic mechanical analysis

Photos by Ryan Beach (NREL)



Photos by Robynne Murray (left) and Paul Murdy (right) (NREL)

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Environmental Conditioning

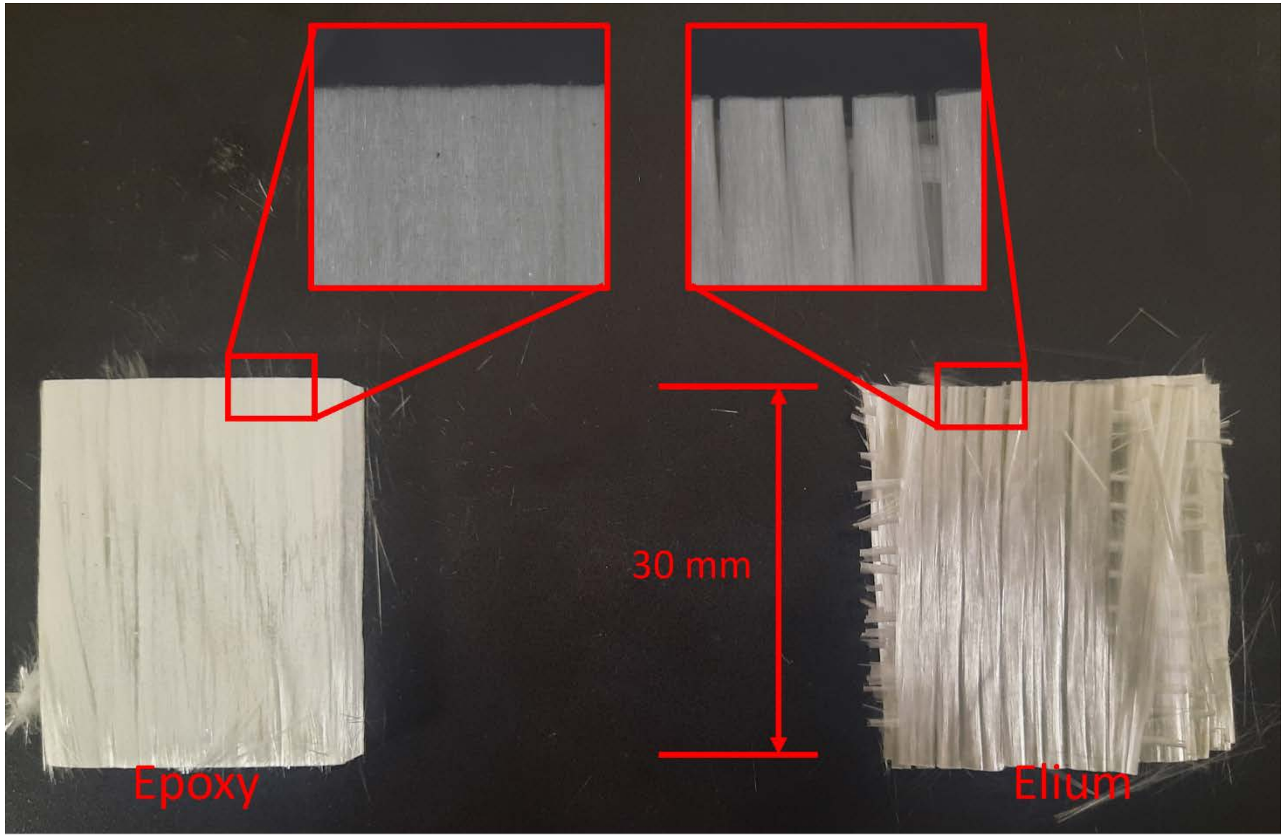
- Coupon-scale environmental conditioning:
  1. 25% dry
  2. 25% in distilled water at 50°C for 2 months
  3. 25% in distilled water at 50°C for 4 months
  4. 25% dry control at 50°C for 4 months
- A subset of condition 3 used to take periodic mass measurements and track water absorption trends (diffusion coefficients)
- One glass/epoxy blade and one glass/Elium blade environmentally aging under ambient conditions for ongoing water absorption measurements – can we extrapolate data to realistic lifetimes?

Photos by Paul Murdy (NREL)

Current Results

Manufacturing Quality

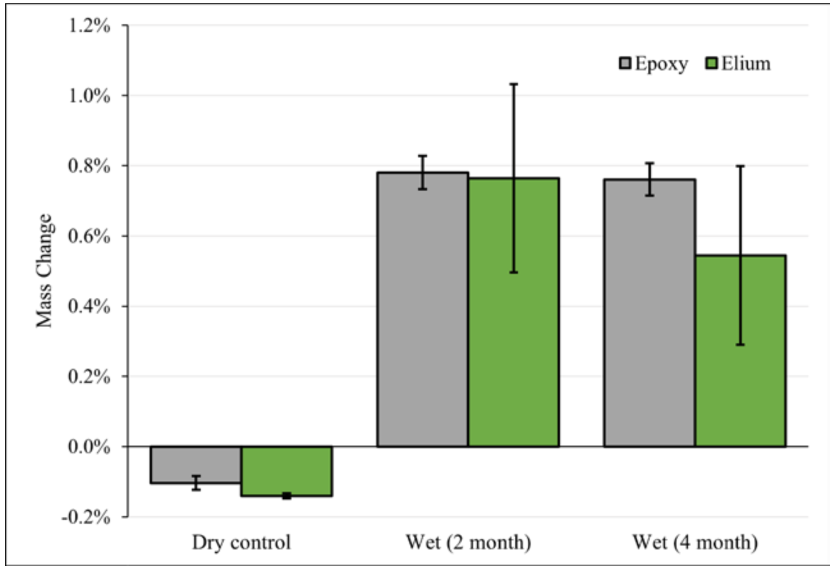
- Glass/epoxy blade:
  - Fiber volume fraction = 48.8 ± 0.3 %
  - Unexpectedly low from prepreg/autoclave manufacturing process
  - Limited manufacturing information, so may be intentional
  - Good distribution and alignment of fibers
- Glass/Elium blade:
  - Fiber volume fraction = 60.9 ± 1.5 %
  - Good consolidation from vacuum infusion process
  - Good alignment of fibers but less consistent distribution due to fabric tows and backing strands
- What influence will this have on the global material properties and overall blade performance?

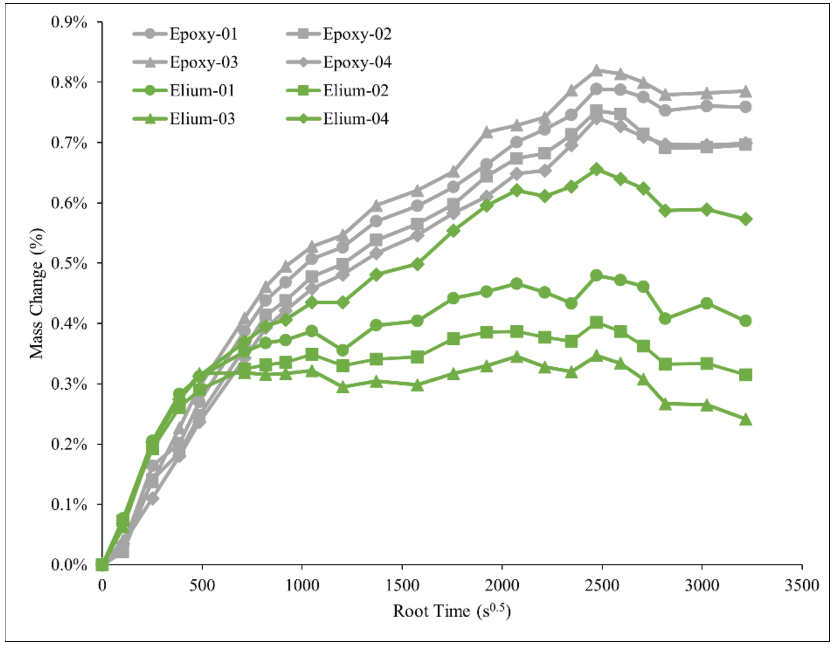


Images by Paul Murdy and David Barnes (NREL)

Environmental Conditioning – Coupon-Scale

- Dry control specimens lost weight – water absorbed during deployment or due to cutting operations
- Over 2-month period epoxy and Elium specimens absorbed comparable amounts of water (~0.8%)
- Over 4-month period epoxy mass changes did not change, but Elium masses dropped (~0.55%) – potential leaching of unreacted monomers
- Large degree of variability for Elium specimens (~±0.25%) – uneven distribution of longitudinal tows through the thickness

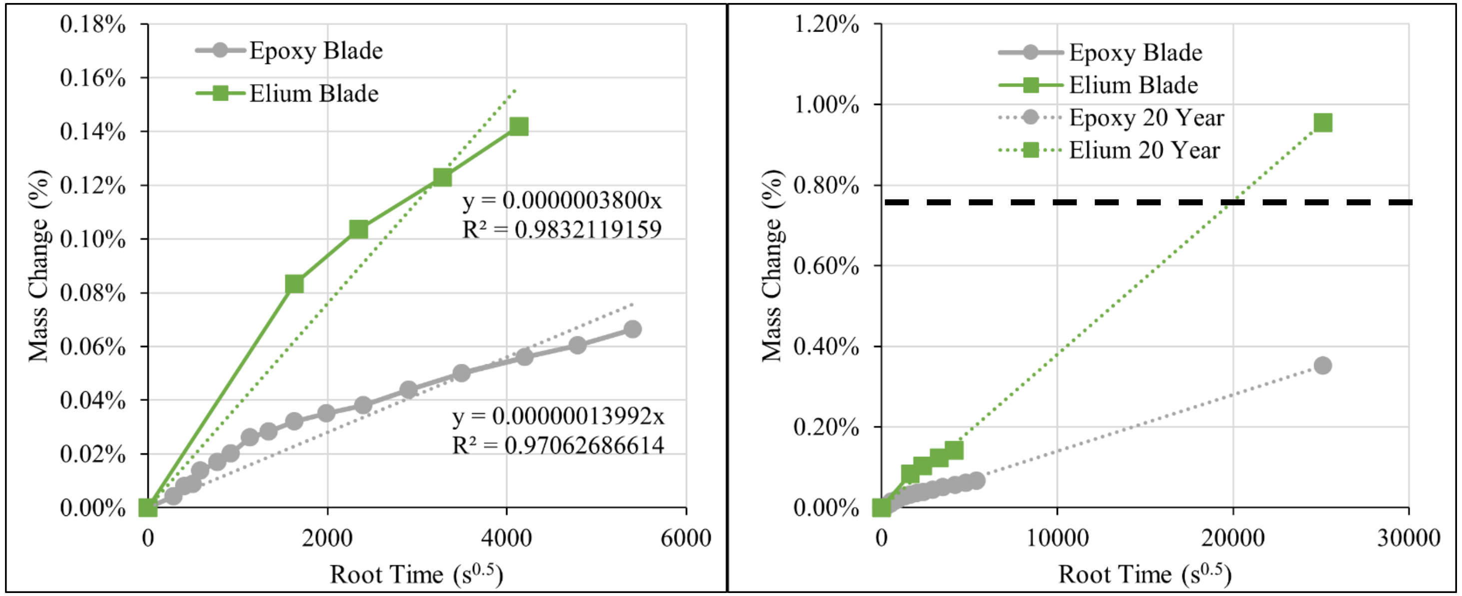




	Epoxy	Elium
m_∞ (%)	0.776 ± 0.031	0.471 ± 0.117
D ($m^2.s^{-1}$)	2.10 ± 0.12 (x 10^{-13})	12.1 ± 4.66 (x 10^{-13})

Environmental Conditioning – Blades

- Large differences between epoxy and Elium blades – paint failure on Elium blade
- Data extrapolated to 20-year lifetime – broad assumptions
- Unlikely they will be close to fully saturated



1 year vs. 20 years

Photos by Paul Murdy (NREL)

Future Considerations

- Tensile data, thermomechanical data, and blade geometric differences in a forthcoming publication
- What does this mean for the long-term performance of thick composite laminates in marine environments?
- How valid are dry vs. fully saturated comparisons if the structure will never reach full saturation?
- How do we properly account for environmental degradation in a safe-life design?
- How do we account for multi-physical interactions (loading, diffusion, temperature, swelling) to improve upon current structural test standards?
- Ultimately, how do we build confidence in composite structures in marine environments and ensure the success of future deployments?

Photo by Paul Komosinski / Drone Altitude

Thank You

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NREL/PR-5700-89623

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