Investigating Marine Environmental Degradation of Additive Manufacturing Materials for Renewable Energy Applications

Paul Murdy

Research Engineer, Hydropower & Water Systems Deployment Team

National Renewable Energy Laboratory

THE COMPOSITES AND ADVANCED MATERIALS EXPO

October 30-November 2, 2023 | theCAMX.org

NREL at a Glance

2,926

Workforce, including

219 postdoctoral researchers

60 graduate students

81 undergraduate students

World-class

facilities and renowned technology experts

More than

900

Partnerships

with industry, academia, and government

Campus

operates as a living laboratory

Photo by Josh Bauer, NREL 59215

Flatirons Campus

Photo by Josh Bauer, NREL 61821

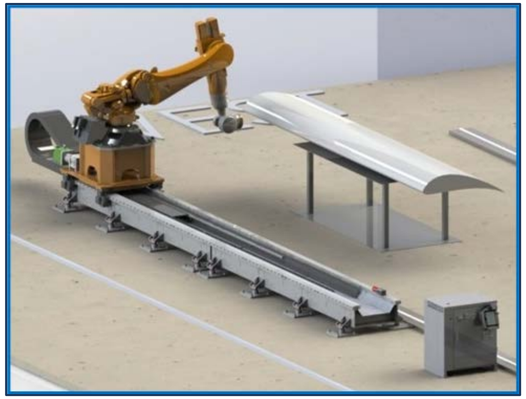
The 307-acre Flatirons Campus, home of the National Wind Technology Center, is approximately 25 miles north of the main NREL facility in Golden.

- **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

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 (13-m blade)
  - 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

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

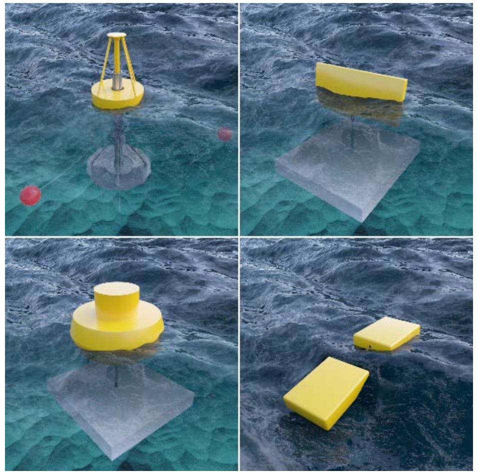
Successes

- 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

What Is Marine Renewable Energy?

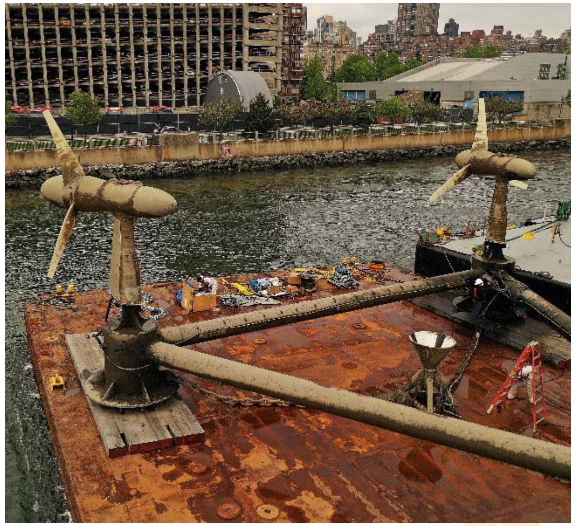
- Oceans are an abundant source of clean energy
- Current energy conversion
- Wave energy conversion
- Relatively nascent industry
- Utility scale, remote island communities, aquacultures, desalination, ocean exploration
- Highly loaded structures in harsh environments
- Especially challenging from a materials perspective

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



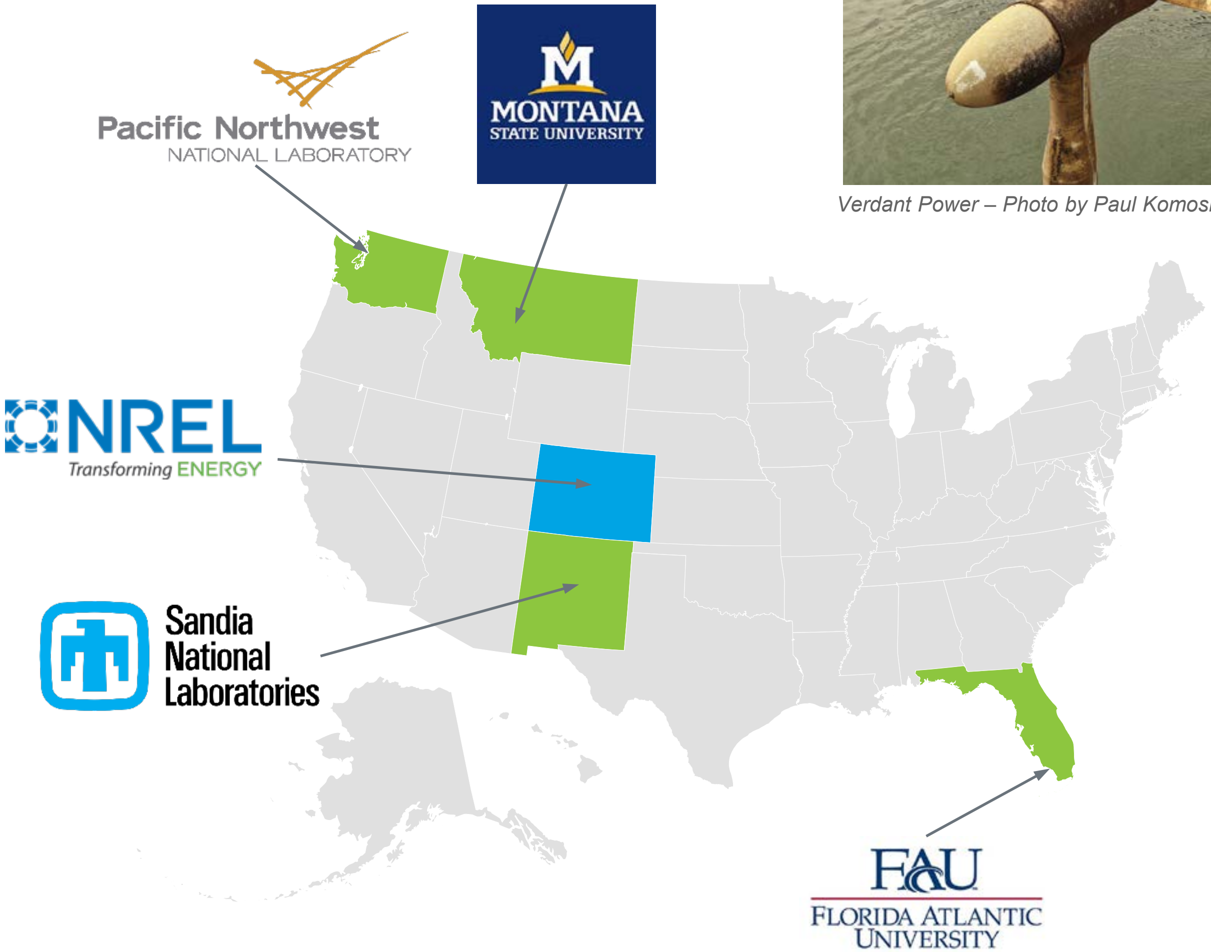
Verdant Power Tri-Frame. Photo from Paul Komosinski / Drone Altitude LLC

Marine Energy
Advanced Materials

Marine Energy Advanced Materials

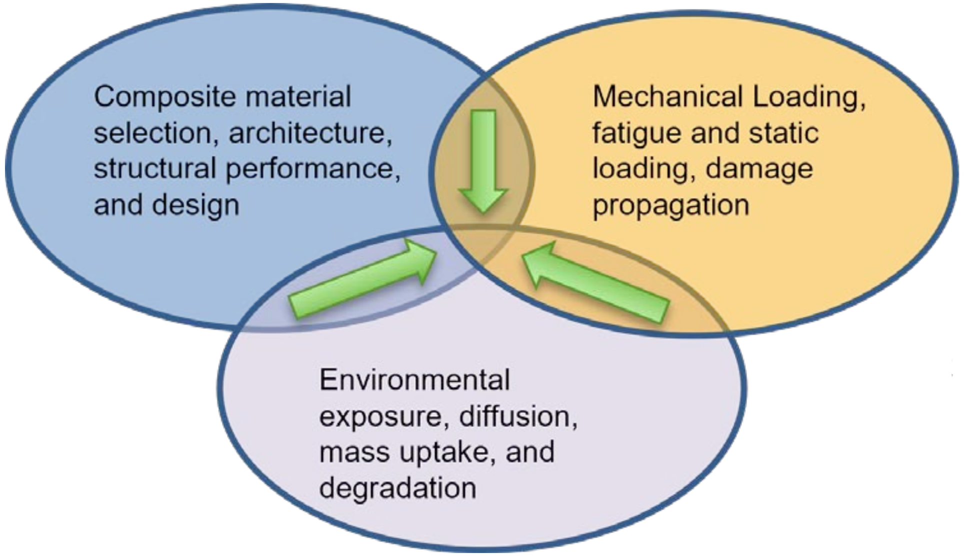
- Multiyear, multilaboratory materials research project
- Industry-driven research
- Reduce barriers and uncertainties to adopting advanced composite materials
- Understand environmental effects on complex structures
- Sandia – lead laboratory
- **NREL – subcomponent validation, additive manufacturing**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

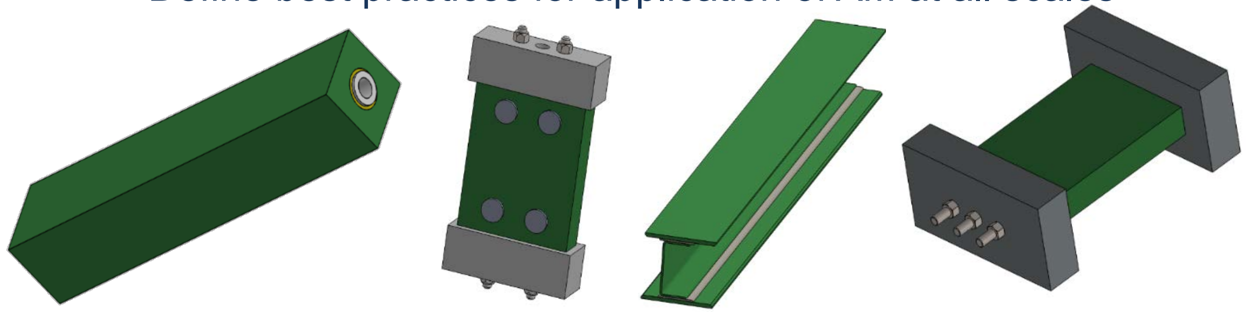
Verdant Power – Photo by Paul Komosinski, NREL 64565



NREL Project Goals

- **Address knowledge gaps highlighted in industry surveys and workshops**
- Subcomponent Testing:
  - 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
- Additive Manufacturing:
  - Guide process and material selection
  - Provide baseline environmental degradation data
  - Define best practices for application of AM at all scales



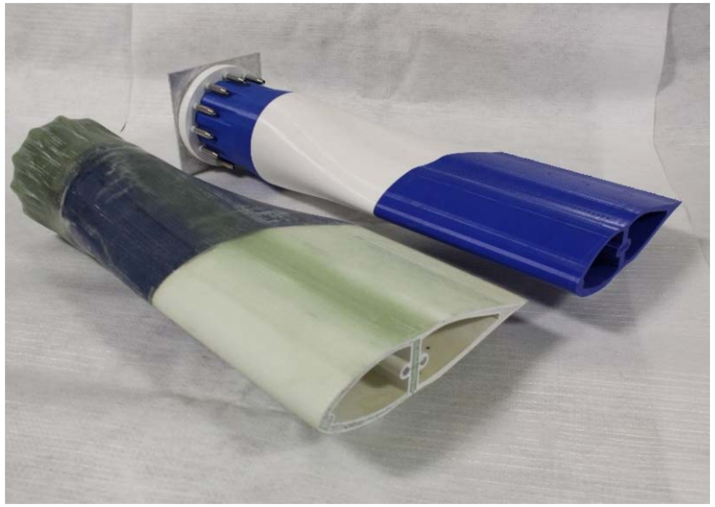


Markforged Mark 2 printer. Photo by Paul Murdy, NREL

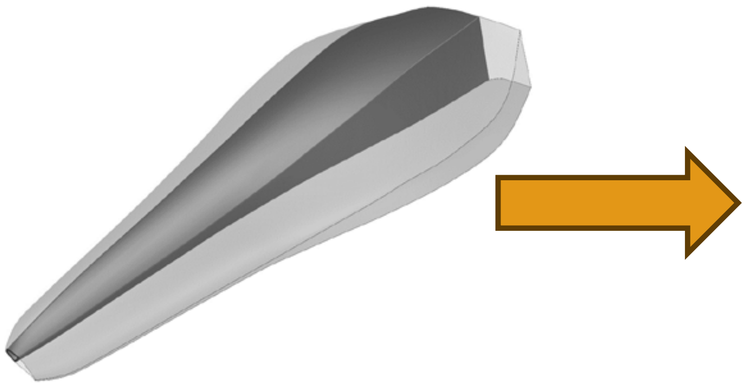
Additive Manufacturing

- Great need for rapid prototyping in marine energy industry: composite tooling, lab-scale testing, prototype deployments
- Explored unique tooling/composite manufacturing approach
- Metal AM for tidal blade components
- Exploring the unique design space
- Widely utilized in lab-scale testing; changes in mass and density are important!

3D-printed 13-m wind blade mold. Photo by Ryan Beach, NREL



Combined additive/composite manufacturing demonstration for tidal blades. Photo by Paul Murdy, NREL



Laser metal deposition for a 316L stainless steel tidal turbine blade structural box spar. Design by Miguel Gonzalez-Montijo, NREL

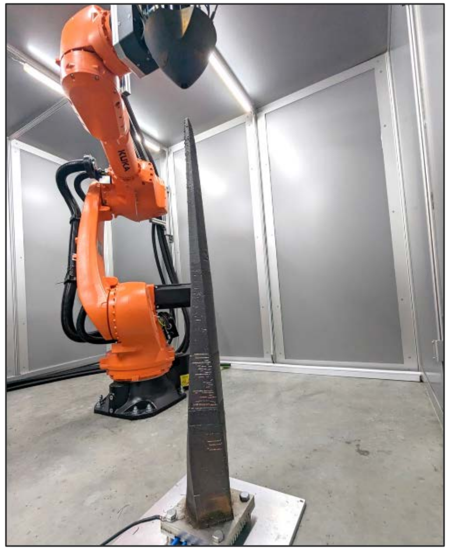
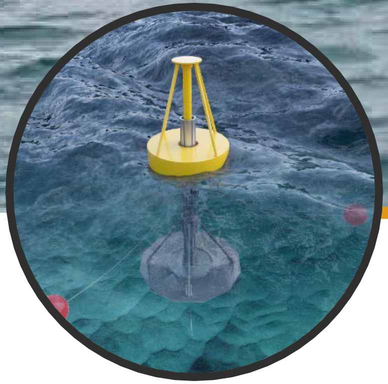


Photo from Phil Barden, AI-Build.

Environmental Effects on AM Materials

Project Timeline

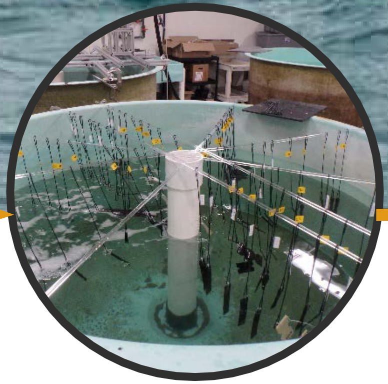


Material Selection

Selected AM polymers based on inherent characteristics and available capabilities (July 2022)

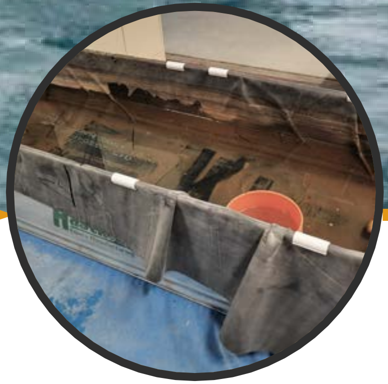
Specimen Manufacturing

Specimens manufactured at NREL (August 2022 to October 2022)



In-Water Conditioning

Specimens conditioned in ocean water at PNNL (October 2022 to April 2023)



Maintaining Conditions

Specimens returned to NREL to await testing (April 2021 to December 2021)

Mechanical Characterization

Static testing in 100-kN load frame (May 2023)

Top photo by Ocean Renewable Power Company. Image credits for circles, from left to right: Joshua Bauer (NREL), Paul Murdy (NREL), Christopher Rumple (PNNL), and Joshua O'Dell (NREL)

Material Selection

- Leveraged material choices from other marine energy projects—decision matrix approach
- Based on internal capabilities
- Materials with desirable mechanical properties and/or good chemical resistance
- Processes that are scalable
- Stratasys Fortus 400MC and Markforged Mark 2 printers

Material	AM Process	Defining Characteristic
Acrylonitrile Styrene Acrylate (ASA)	FDM – Stratasys	Low cost, environmental resistance
Ultem 9085*	FDM – Stratasys	High environmental resistance
Onyx†	FDM – Markforged	Moderate stiffness and strength
Carbon fiber-reinforced Onyx†	Continuous fiber FDM - Markforged	High stiffness and strength
Glass fiber-reinforced Onyx†	Continuous fiber FDM - Markforged	Lower cost, high stiffness and strength

*Polyetherimide blend from Stratasys
†Chopped carbon fiber-reinforced nylon from Markforged

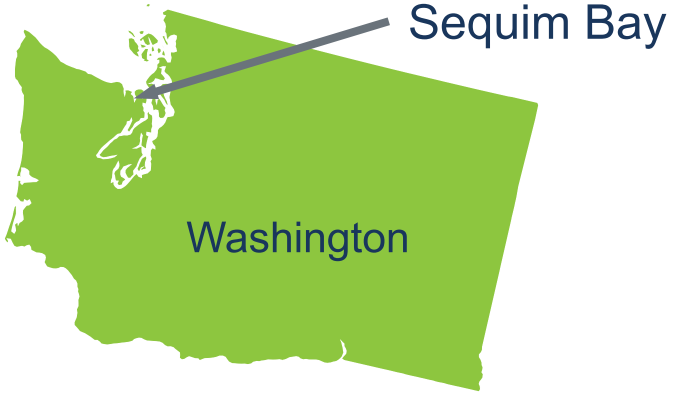
Specimen Manufacturing

- Ultem 9085 and ASA specimens CNC cut from large panels
- Onyx and fiber-reinforced Onyx specimens were printed individually
- Low interlaminar strength made it difficult to machine or water jet cut
- Limited control over print directions, so study only focuses on dry-wet comparisons (not directional properties)
- Half specimens conditioned at PNNL and half remained dry controls
- V_f = ~10% and $[0/90]_{ns}$ layup for fiber-reinforced specimens
- Limited by specimen warpage

Photo by Paul Murdy, NREL

Environmental Conditioning

- Specimens conditioned at PNNL's Marine and Coastal Research Laboratory, Sequim, Washington
- Circulated with untreated seawater from Sequim Bay
- Ambient temperatures (~12°C)
- Marine organisms free to grow and interact with test specimens
- Comparable environment and time scale to short-term deployments
- 155 days total conditioning time
- Masses measured before and after



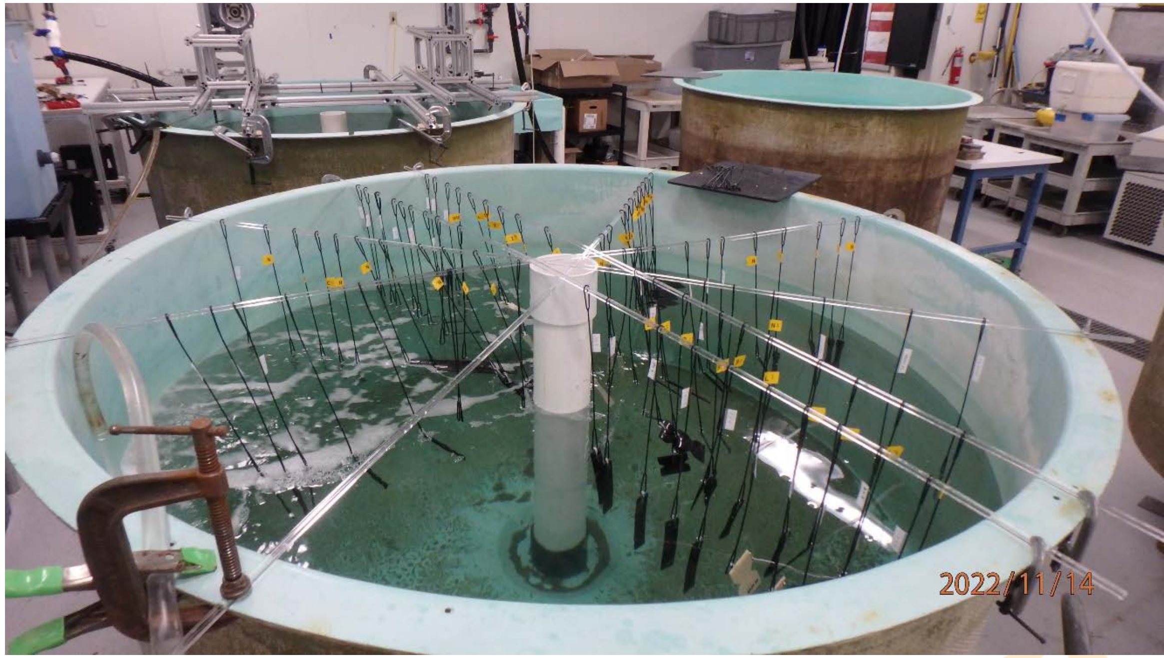
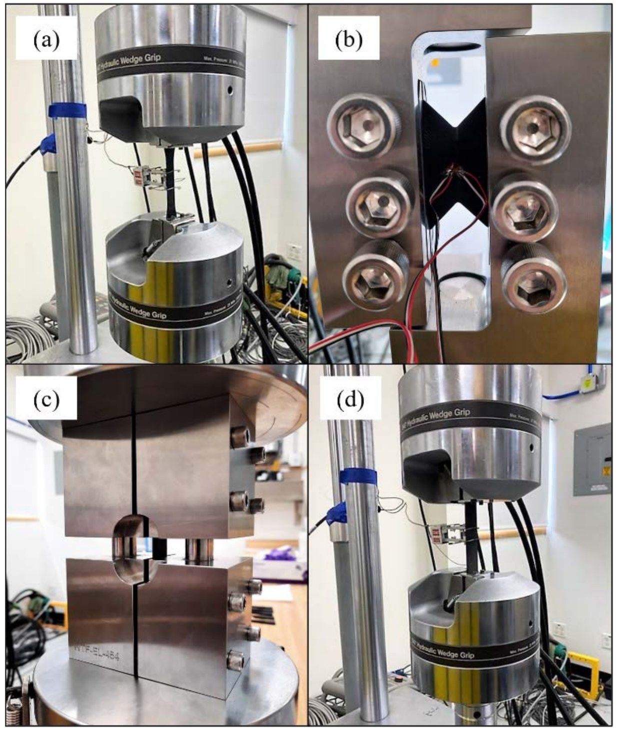


Photo by Christopher Rumple, PNNL

Mechanical Characterization

- Intended for material down-selection
- Not looking at orthotropic properties
- Testing performed on 100-kN servo-hydraulic load frame
- Tension (ASTM D638 and D3039)
- Compression (ASTM D6641)
- V-notch rail in-plane shear (ASTM D7078)

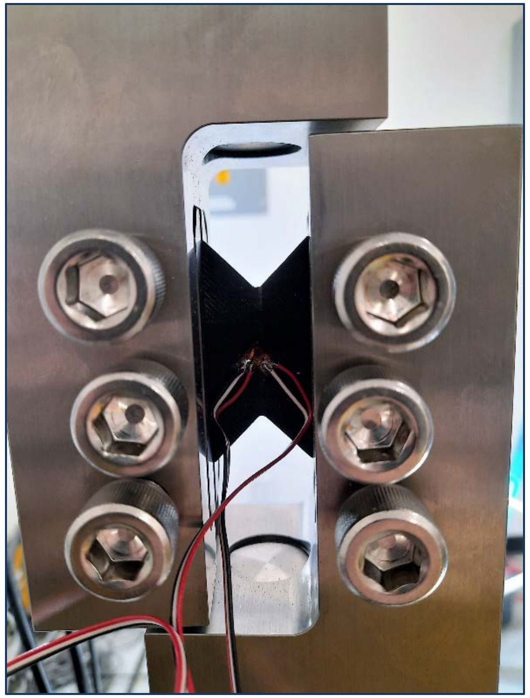
Test Method	Geometry	Length (mm)	Outer Width (mm)	Gauge Width (mm)	Thickness (mm)
D638	Type I dog bone	150	19	13	3
D6641	Rectangular	140	13	13	3
D7078	V-notched	76	56	32	3
D3039	Rectangular	200	25	25	2



Characterization setups for (a) ASTM D638 tension, (b) ASTM D7078 V-notched rail, (c) ASTM D6641 compression, and (d) ASTM D3039 FRP tension. Photos by Joshua O'Dell, NREL

Instrumentation

- Extensometers for tensile testing
- Front and back 0° foil strain gauges for compression
- Front and back ±45° foil strain gauges for shear
- $\gamma = |\varepsilon_{+45}| + |\varepsilon_{-45}|$
- Micro Measurements M-Bond 200 CA adhesive and M-Bond AE-10 two-part epoxy
- Difficulty adhering gauges to substrates, particularly Ultem 9085

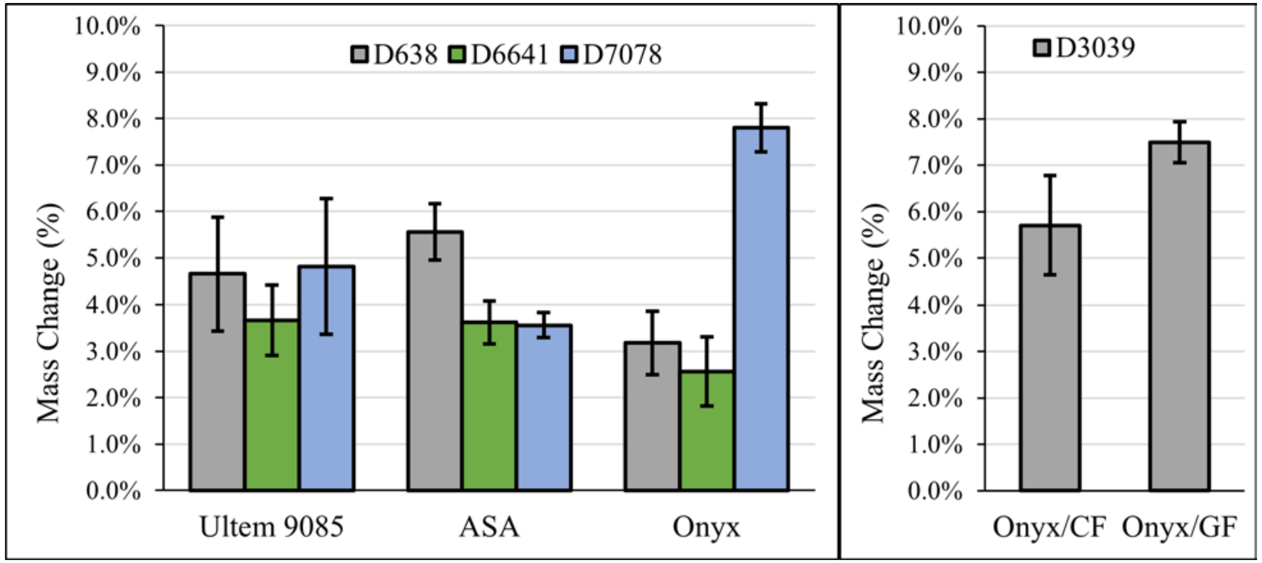


Photos by Joshua O'Dell, NREL

Characterization Results

In-Water Conditioning and
Mechanical Testing

In-Water Conditioning

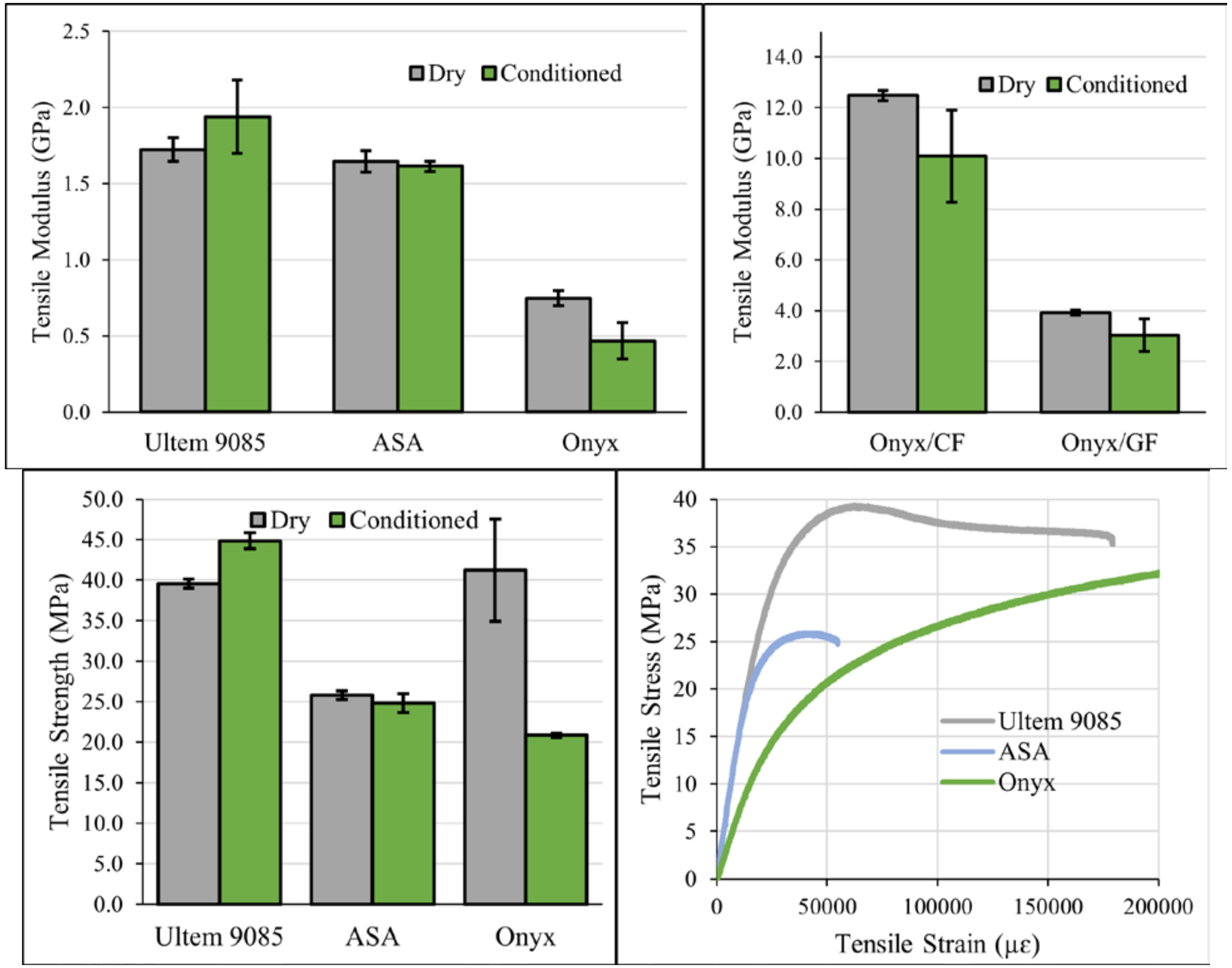


Pre- and post-conditioning measured mass changes by material and specimen geometry. Graphic by Paul Murdy, NREL

- No obvious visual changes in the materials
- Large variations in mass changes between specimens
- Difficult to remove surface water and water trapped in porous structure
- Potential biofouling in the pores
- Larger mass changes for fiber reinforced specimens—capillary action along fibers
- Mass changes would certainly affect dynamic response of test articles for lab-scale tank testing

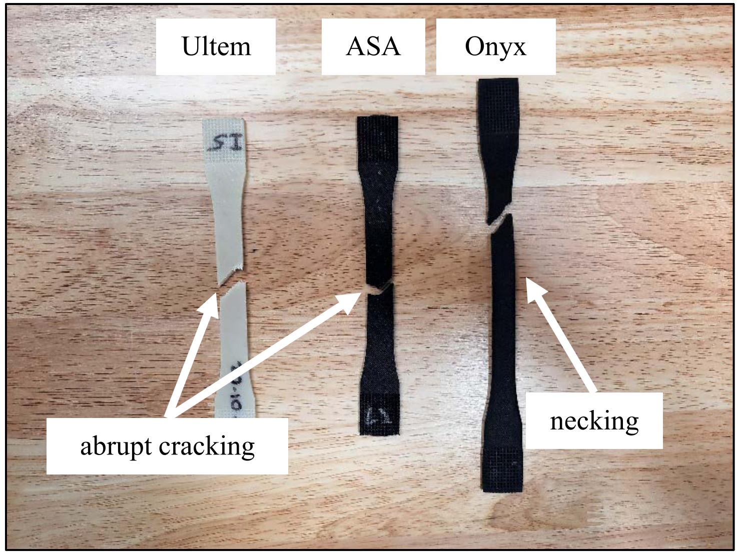
Mechanical Characterization: Tension

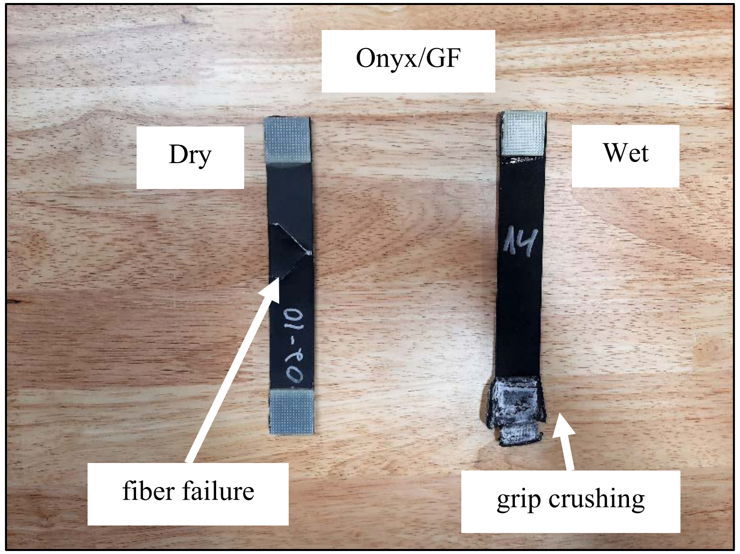
- Ultem 9085 and ASA moduli and strengths relatively unchanged
- Onyx and fiber-reinforced Onyx exhibited some stiffness degradation
- Onyx strength degraded by ~50%
- Could not produce tensile failures with conditioned CF/ and GF/Onyx specimens—grip crushing failures
- Yield and ultimate stresses and strains can be found in paper



Pre- and post-conditioning tensile moduli and strengths for the tested materials. Graphics by Paul Murdy, NREL

Tension – Failure Modes



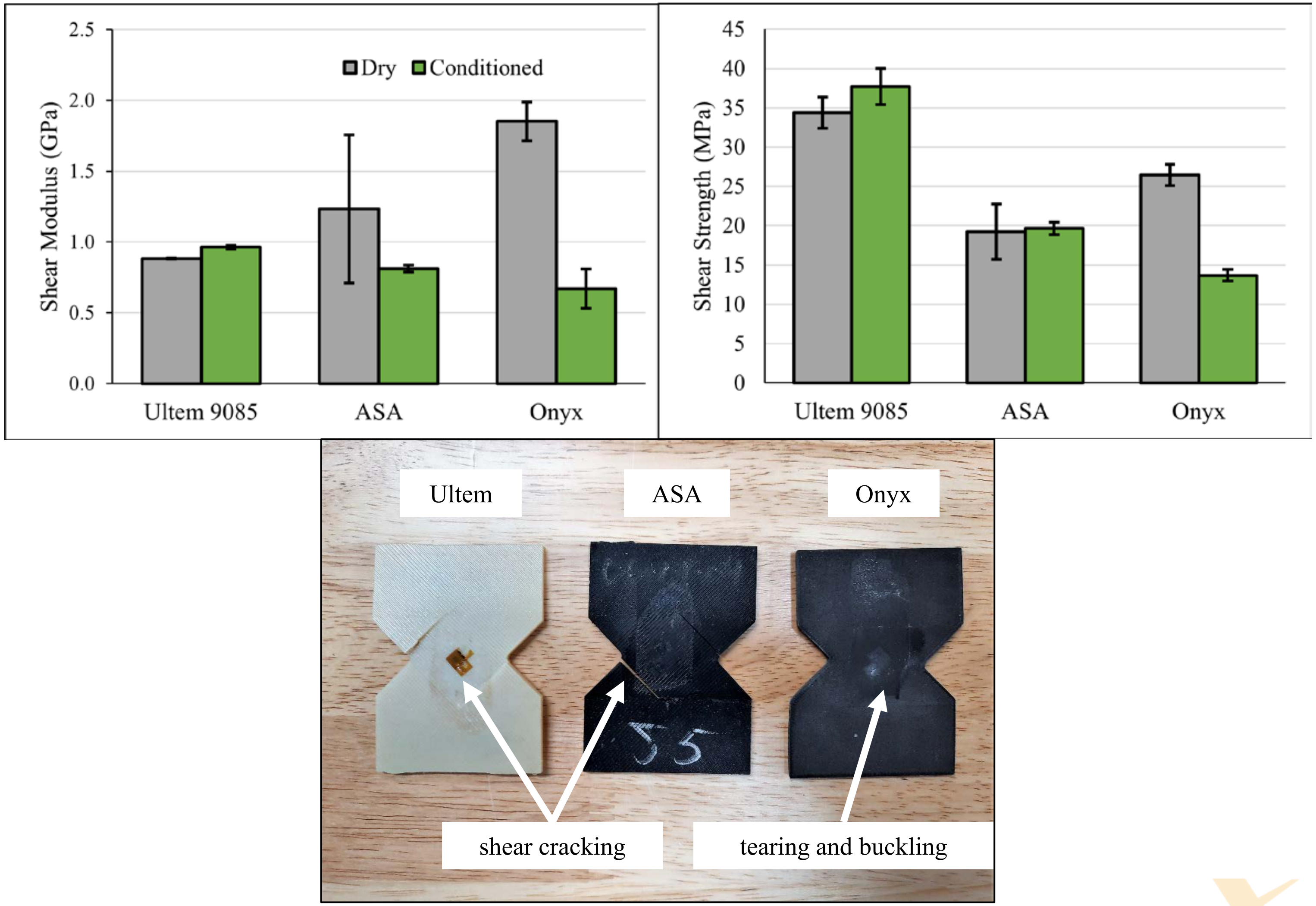


Photos by Paul Murdy, NREL

- Ultem, ASA, and Onyx failure modes were consistent pre- and post-conditioning
- Ultem and ASA – sudden failures
- Onyx – slow necking
- Dry CF/ and GF/Onyx – fiber failures in gauge section
- Wet CF/ and GF/Onyx – grip slippage and crushing due to Onyx degradation

Mechanical Characterization: Shear

- Similar to tensile results
- Failure of several strain gauges during specimen installation—reduced repeat modulus measurements
- Ultem and ASA relatively unchanged
- Severe stiffness and strength degradation for Onyx
- Abrupt shear cracking for Ultem and ASA
- Tearing and buckling for Onyx



Pre- and post-conditioning shear moduli, strengths, and failure modes for the tested materials. Graphics and photo by Paul Murdy, NREL

Compression – Failure Modes

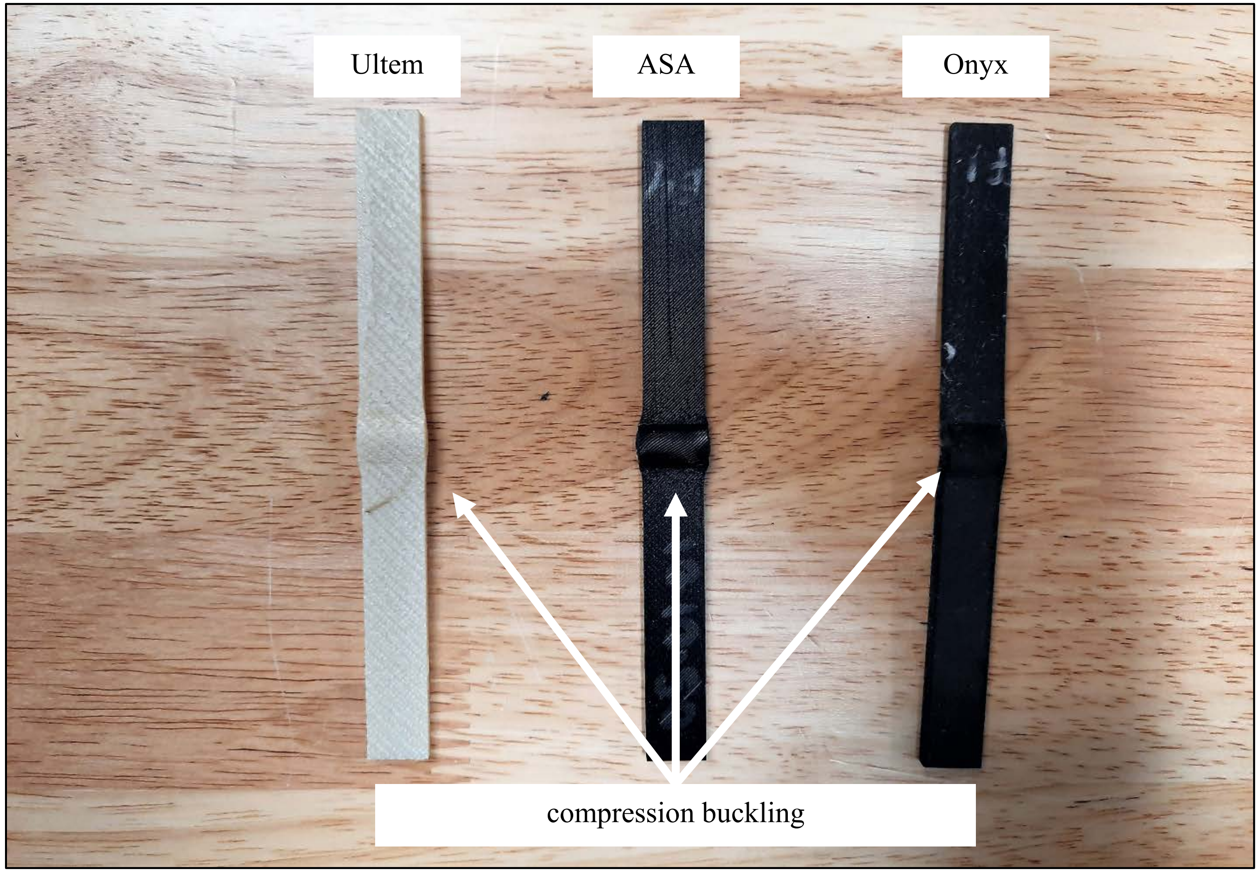
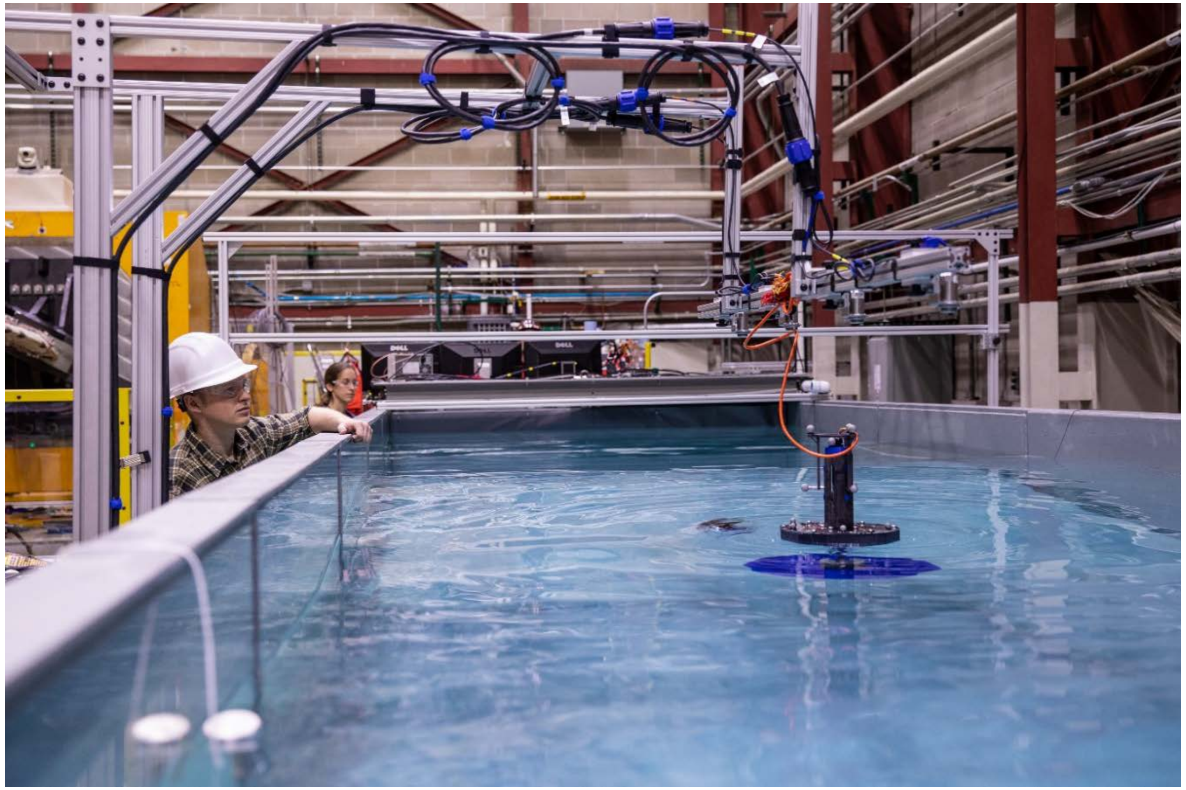


Photo by Paul Murdy, NREL

- All specimens failed by buckling
- Overestimated through-thickness shear modulus and flexural modulus
- $h \geq \frac{l_g}{0.9069\sqrt{\left(1-\frac{1.2F^{cu}}{G_{xz}}\right)\left(\frac{E^f}{F^{cu}}\right)}}$
- Specimens should be thicker
- ASTM D6641 may not be the appropriate test method

Conclusions

- Ultem 9085 and ASA preformed well all around for the limited in-water conditioning period.
- Onyx and fiber-reinforced Onyx specimens have desirable dry properties but exhibited severe degradation over the short in-water conditioning period
- ASTM D6641 may not be the best method for determining compressive properties of FDM polymers.
- Mass changes of FDM printed materials can vary a lot due to their porous structure—very important for lab-scale testing.



Wave tank testing at NREL's Flatirons Campus. Photo by Joe DelNero, NREL 79176

Future Work


Northwest Energy Innovation's Azura™ waver energy device. Photo from Northwest Energy Innovations

- Investigate protective coating to prevent water and biofouling intrusion
- Adhesion: protective coatings, biofouling coatings, composite overlaminates for reinforcement, and instrumentation
- Combine previous research, this study, and upcoming investigations into best practices guide for additive manufacturing materials in marine environments
- Continue to support and grow marine renewable energy industry by accelerating testing and deployments

Thank You

www.nrel.gov

NREL/PR-5700-87673

This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Water Power Technologies Office. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.