Submerged Fatigue Testing of Marine Energy Advanced Materials

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- Develops advanced composites materials and structural validation methods for marine energy systems.

Overview

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- Composites for Marine Energy Devices
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  - Fatigue Failure Modes
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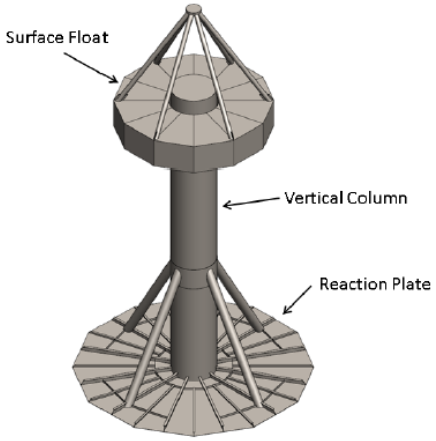
Marine Energy Devices

a)

b)



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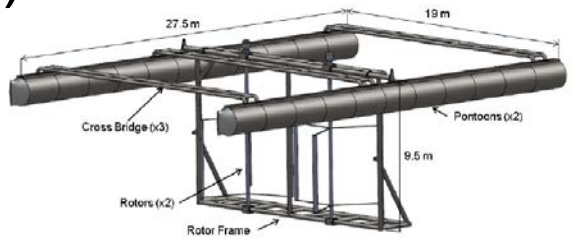

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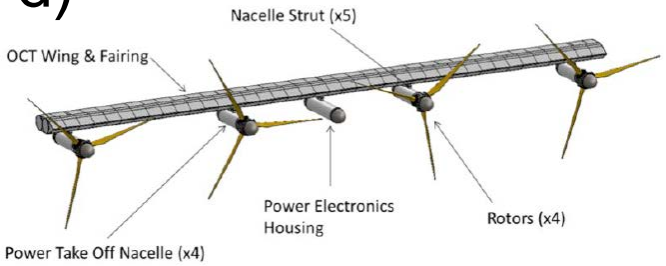


Marine energy device reference models: a) tidal current turbine, b) wave point absorber, c) river current turbine, d) ocean current turbine (Neary et al. 2014).

- Convert kinetic energy from moving fluids to electricity.
- Exposed to extreme environments
  - Periodic loading ➔ mechanical fatigue
  - Submerged ➔ water intrusion.
- Composites:
  - Strong
  - Lightweight
  - Durable.

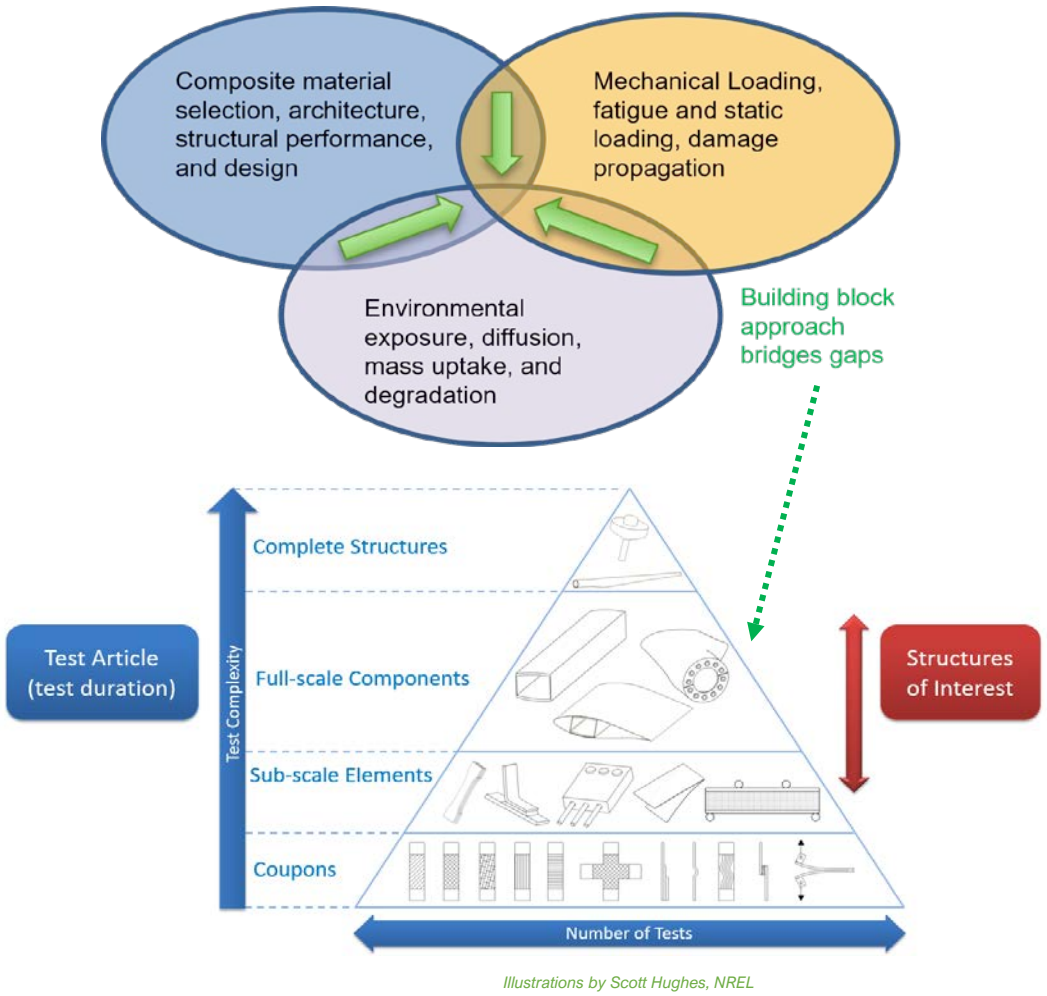
Composites for Marine Energy Devices

Advanced Materials Project:

- Multi-lab project with:
  - Sandia National Laboratories
  - Pacific Northwest National Laboratory
  - Montana State University
  - Florida Atlantic University.

Objectives:

1. Understand how experimental manufacturing development impacts final composite performance and reliability.
2. Provide foundational composites analysis to guide design, standardization, and certification. Supports the development of international standards and performance metrics for device performance.



Marine energy building block approach (Murdy 2022).

Background

- Past research:
  - Sequential: Hygrothermal Aging ➔ Mechanical Testing
- This research:
  - Combined: Submersion + Mechanical Testing

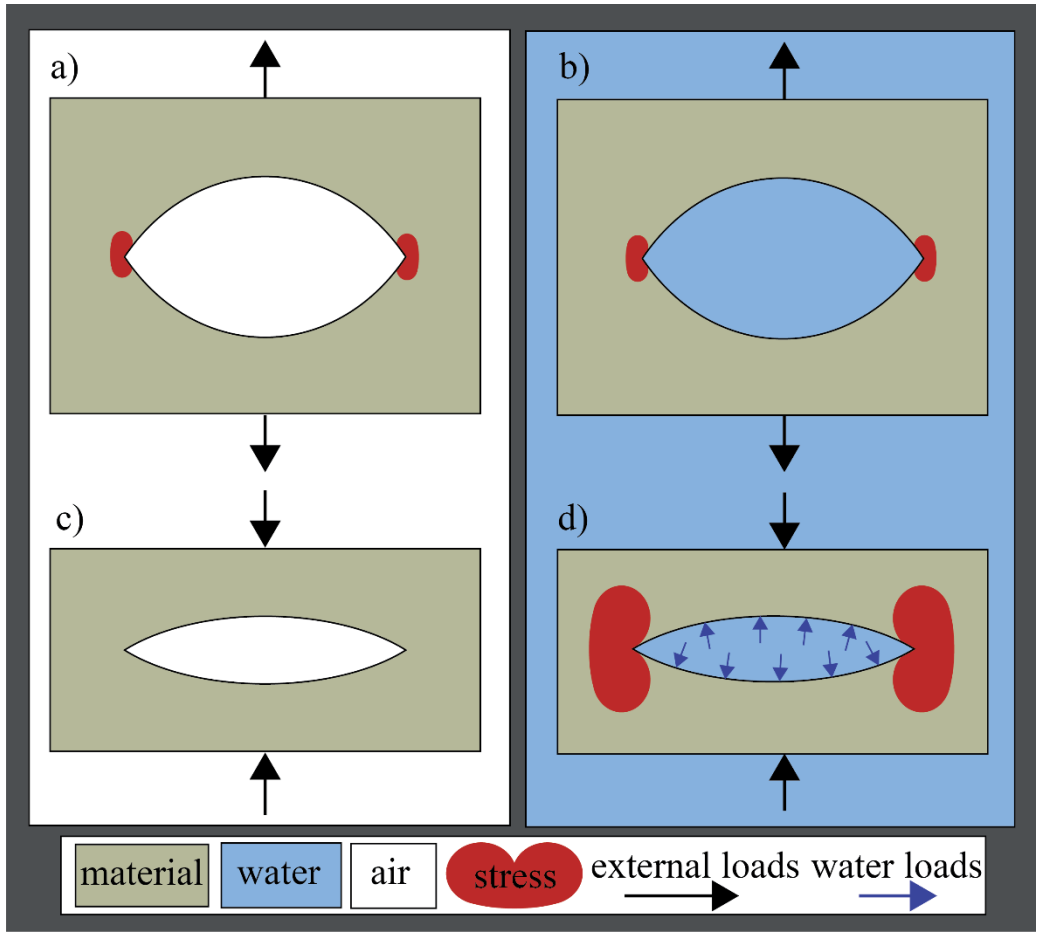


Illustration by Ariel Lusty, NREL

Schematic of enclosed, internal cracks: a) dry and opening in dry conditions, b) moisture-intruded and opening in submerged conditions, c) dry and closing in dry conditions, and d) moisture-intruded and closing in submerged conditions.

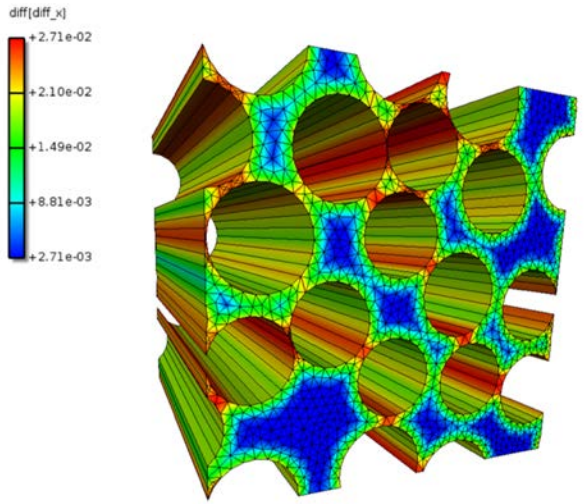
Background

Fatigue life:

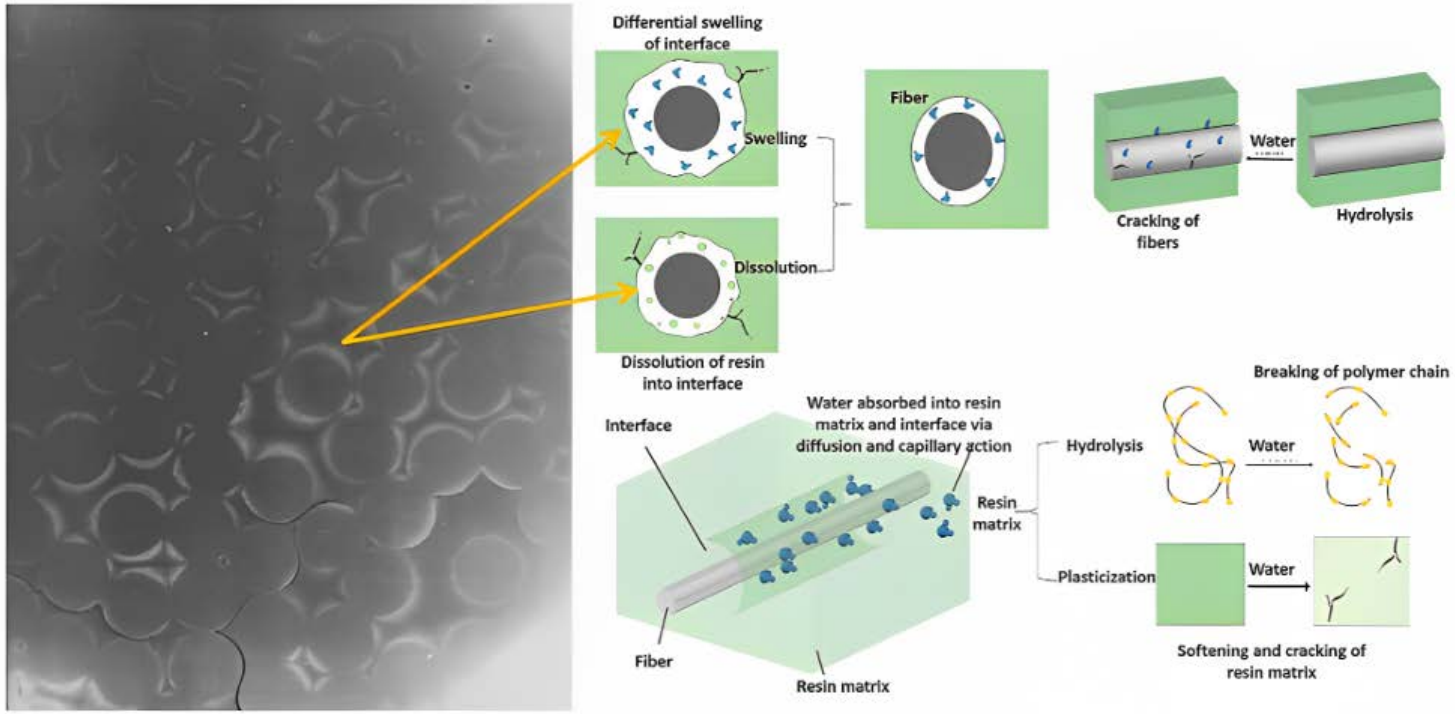
1. Initial fatigue damage produces crack initiation.
2. One or multiple cracks result in the partial separation of a specimen.
3. Specimen fractures.

Water absorption:

- Diffusion is anisotropic.
  - Occurs along fiber-matrix interfaces more than in the bulk resin.



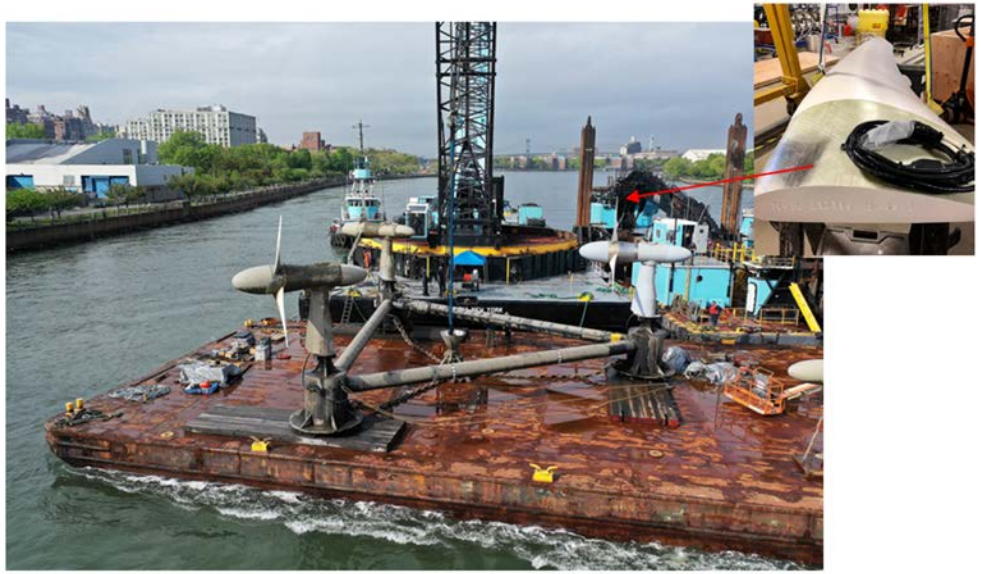
Simulated diffusivity field in composite resin (Rocha et al. 2016).



Moisture absorption in composites (Barreira-Pinto et al. 2023).

Materials

- Selected based on:
  - Subcomponent materials in Murdy et al. (2023).
  - Marine turbine blade materials in Murray et al. (2023).
- Fabric:
  - Vectorply E-QX 9000 quadriaxial
  - $\theta_w = 7.6° \pm 1.4°$
- Resins:
  - Derakane 411C-350 vinyl ester-epoxy
  - Arkema Elium thermoplastic



Thermoplastic marine turbine blade (Murray et al. 2023).

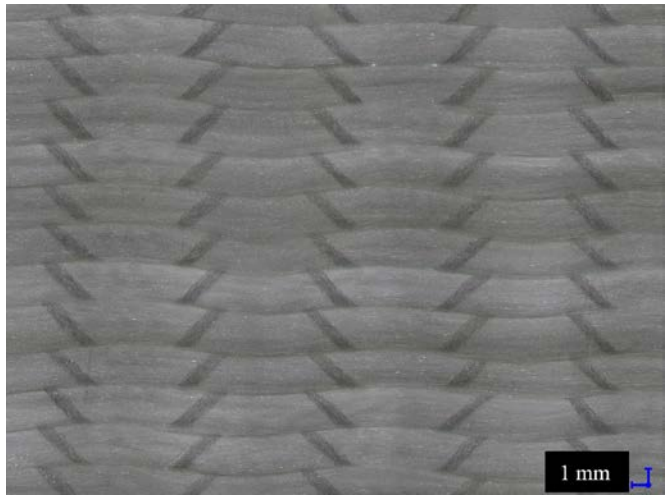


Image by Ariel Lusty, NREL

Microscope image of the Vectorply E-QX 9000 quadriaxial fabric.

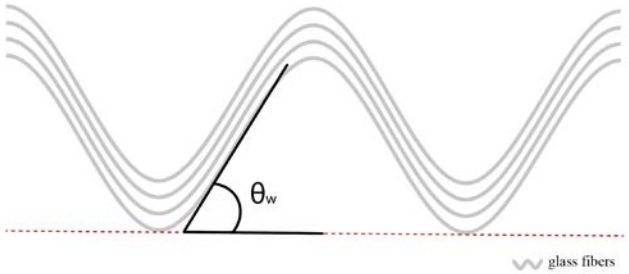


Illustration by Ariel Lusty, NREL

Fiber waviness angle (θ_w) measurement method for one tow.

Photo by Ariel Lusty, NREL

Composite coupons with a) vinyl ester and b) thermoplastic resin systems.

Submerged Testing Setup

Photo by Ariel Lusty, NREL

Submerged four-point bend testing setup in a 250 kN load frame.

- Dry testing: tank was emptied
- Submerged testing: tank was filled with water
- Support span: 140 mm
- Load span: 70 mm
- R-value: 0.1
- Frequency: 0.65 Hz
- 75% of the static flexural strength average of the thermoplastic composites

Submersion	Loading Regime	Output	Composite Type	Number of Tests
Dry	Static	Flexural strength values, failure modes	Vinyl ester	5
			Thermoplastic	5
	Fatigue	Cycles to failure, failure modes	Vinyl ester	5
			Thermoplastic	5
Submerged	Fatigue	Cycles to failure, failure modes	Vinyl ester	5
			Thermoplastic	5

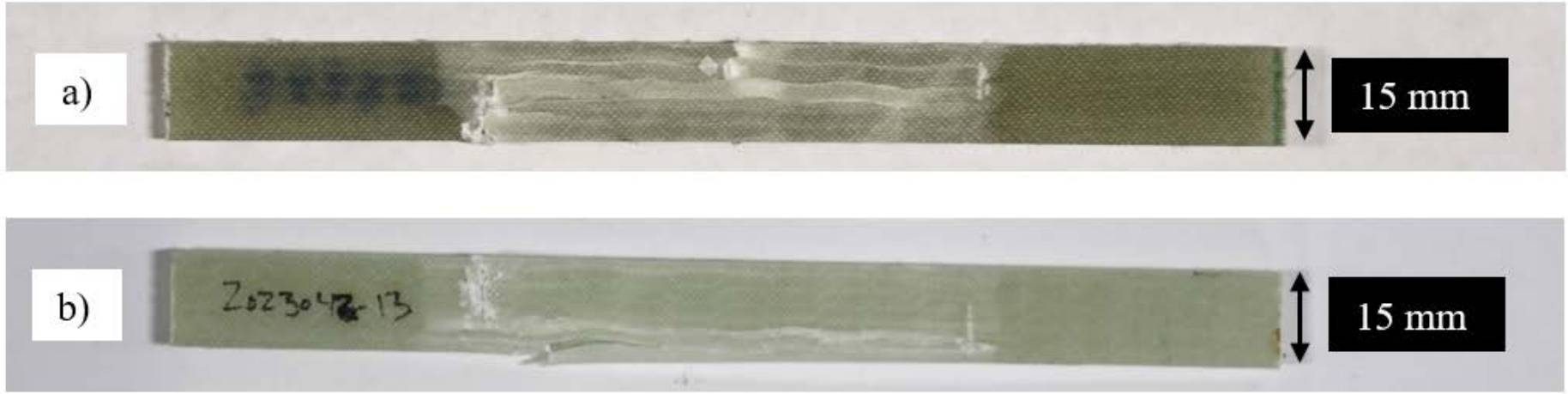
Four-point bend testing test matrix.

Results – Static Testing

Material	Flexural strength (MPa)
Vinyl ester composite	693.4 ± 21.2
Thermoplastic composite	663.1 ± 29.0

Static testing flexural strength results.

- Flexural strength of the vinyl ester composites was 5% higher than the thermoplastic composites.



Photos by Ariel Lusty, NREL

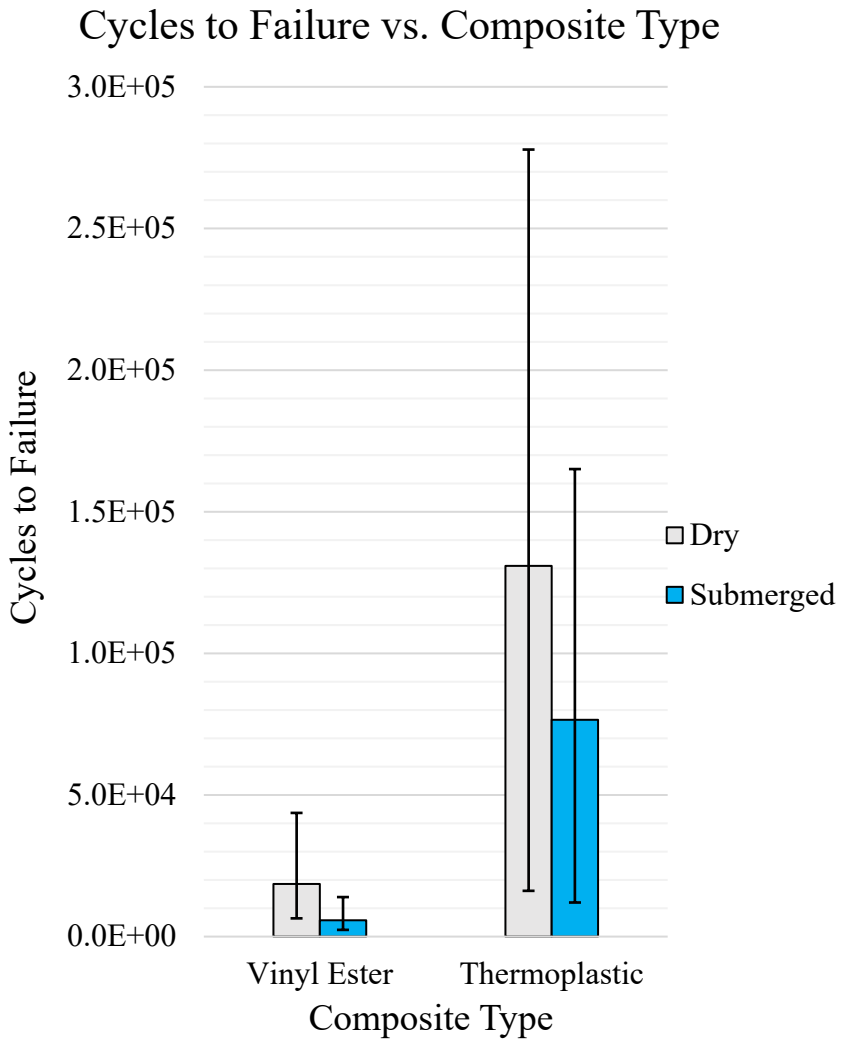
Compression side top ply delamination after static four-point bend testing for a) vinyl ester and b) thermoplastic coupons.

Results – Fatigue Testing

Composite Type	Submersion	Cycles to Failure	Cycles to Failure Decrease From Dry to Submerged (%)
Vinyl ester	Dry	18,593 ± 12,932	69
	Submerged	5,780 ± 4,745	
Thermoplastic	Dry	130,863 ± 32,285	42
	Submerged	76,523 ± 24,065	

Fatigue testing cycles to failure results.

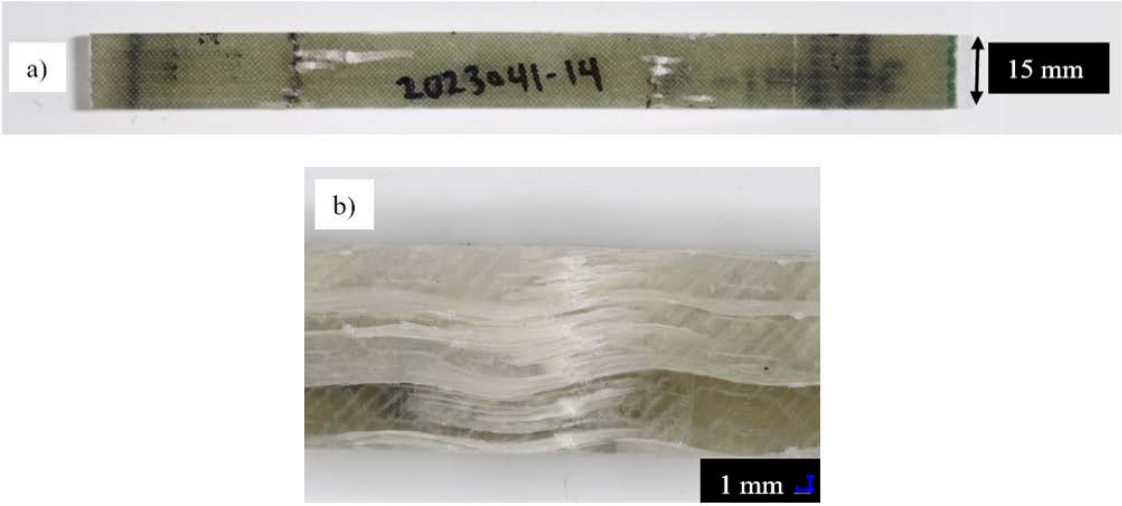
- Dry vinyl ester composites had 86% lower cycles to failure than the thermoplastic composites.
- Both vinyl ester and thermoplastic composite fatigue lives dropped significantly between dry and submerged.



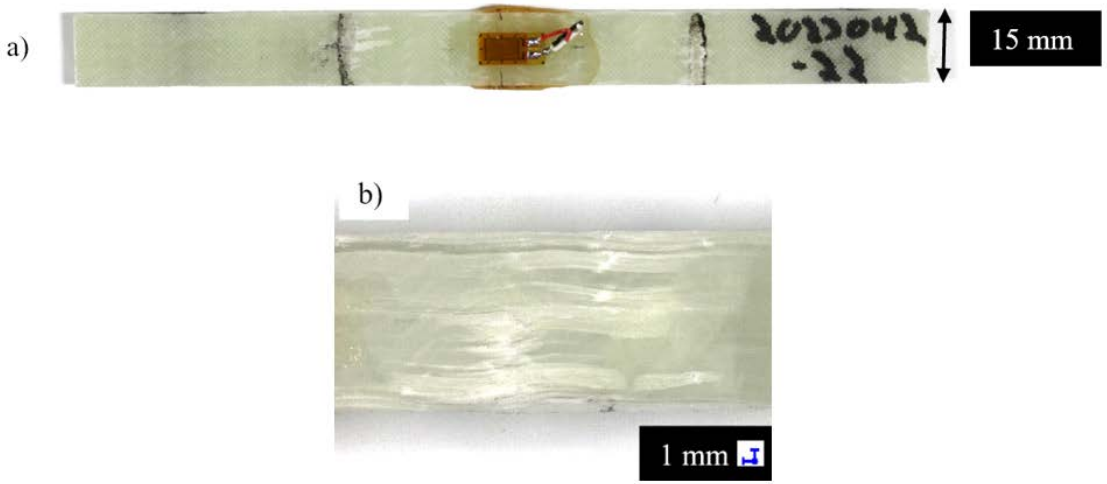
Drops in cycles to failure between dry and submerged fatigue-tested composites.

Results – Dry Fatigue Failure Modes

Vinyl Ester



Thermoplastic



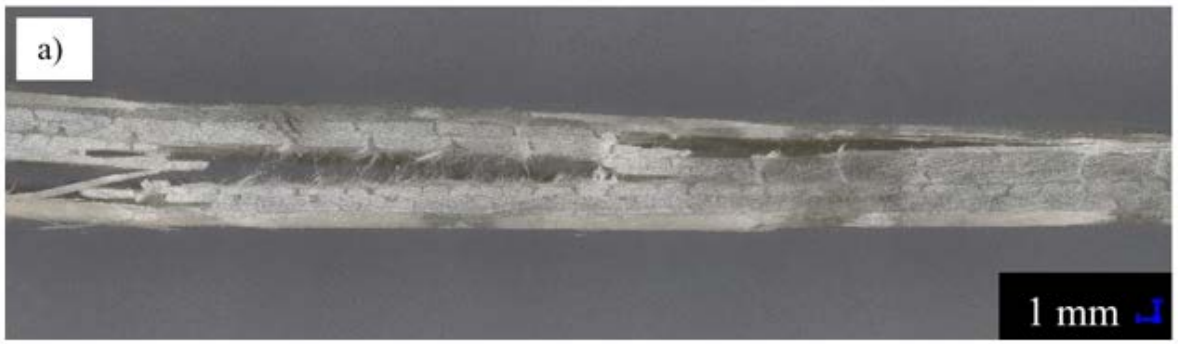
Photos by Ariel Lusty, NREL

Dry fatigue-tested composite specimens: a) photos of the compression sides and b) microscope images at 3.7x magnifications of the tension sides.

- Both dry vinyl ester and thermoplastic composites had tension-side face sheet delamination.
- Delamination was more severe in the vinyl ester specimens.

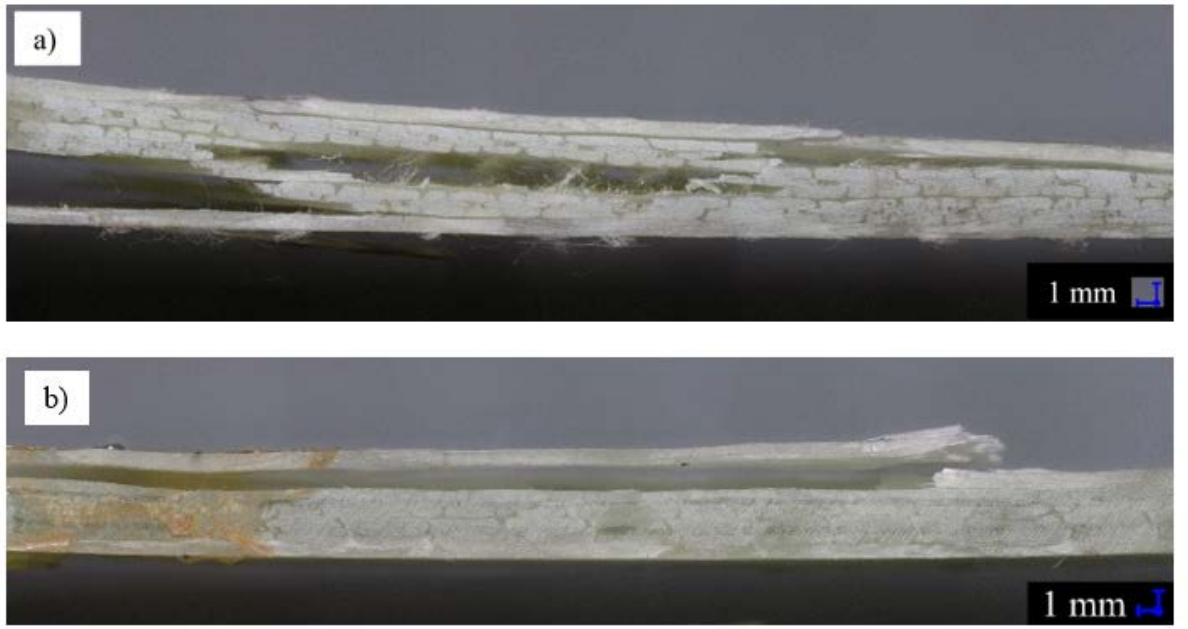
Results – Fatigue Failure Modes

Vinyl Ester



- Dry: more through-thickness fiber bridging.
- Submerged: more fiber breakage on tension sides.

Thermoplastic



- Dry: Full through-thickness delamination.
- Submerged: Top-ply delamination.

Images by Ariel Lusty, NREL

Composite failure modes after a) dry fatigue testing and b) submerged fatigue testing.

Conclusions

- **Higher composite strength does not necessarily indicate higher fatigue life.**
  - Vinyl ester composites had 86% lower cycles to failure than the thermoplastic composites despite having 5% higher flexural strength values.
- Percent drops in cycles to failure from dry to submerged fatigue tests for:
  - Vinyl ester: 69%.
  - Thermoplastic: 42%.

- **Different failure modes between static, dry fatigue, and submerged fatigue specimens.**
  - Static failure modes:
    - Top ply delamination along the gauge section of the compression side for both vinyl ester and thermoplastic specimens.
  - Fatigue failure modes:
    - Vinyl ester:
      - Dry: more through-thickness fiber bridging.
      - Submerged: more fiber breakage on tension sides.
    - Thermoplastic:
      - Dry: Full through-thickness delamination.
      - Submerged: Top-ply delamination.
- Cycles to failure and failure mode differences between the vinyl ester and thermoplastic resins could be due to differences in **the rubber elasticity behavior differences between thermosets and thermoplastics**.
  - Higher elasticity in the thermoplastic composites compared to the vinyl ester composites.

Future Work

Planned:

- University Marine Energy Research Community (UMERC) 2024
  - Strain gauge coatings (ongoing).
- Submerged beam-type subcomponent testing.

Suggested:

- Direct hygrothermal vs. submerged fatigue testing comparisons.
- Increasing coupon widths – surface area effects.
- Machined defects in coupons for consistent failure initiation locations.
- Comparisons with tension-tension fatigue studies.
- Seawater submersion.
- Submerged fatigue testing of composites with straighter unidirectional tows.

MHK F1 Tidal Turbine (Neary et al. 2021).

NREL's 500 kN load frame (Murdy 2022).

Ongoing Testing

Submersion	Loading Regime	Output	Composite Type	Strain Gauge Coating Type	Number of Tests
Dry	Static	Flexural strength values, failure modes	Vinyl ester	None	5
			Thermoplastic	None	5
			Epoxy	None	5
	Fatigue	Cycles to failure, displacement vs. life fraction, failure modes	Vinyl ester	None	5
			Thermoplastic	None	5
			Epoxy	None	5
Submerged	Fatigue	Cycles to failure, failure modes	Vinyl ester	Polyurethane	5
				Polysulfide	5
			Thermoplastic	Polyurethane	5
				Polysulfide	5
			Epoxy	Polyurethane	5
				Polysulfide	5

Four-point bend ongoing testing.

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Questions?

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