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

## Preprint

Paul Murdy, Ariel Lusty, Robynne Murray, Scott Hughes, and Ryan Beach

*National Renewable Energy Laboratory*

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*Cover Photos by Dennis Schroeder: (clockwise, left to right) NREL 51934, NREL 45897, NREL 42160, NREL 45891, NREL 48097, NREL 46526.*

# POST-DEPLOYMENT CHARACTERIZATION OF GLASS FIBER-REINFORCED THERMOSET AND THERMOPLASTIC COMPOSITE TIDAL TURBINE BLADES

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## ABSTRACT

In 2021, the National Renewable Energy Laboratory (NREL) supported Verdant Power with the most successful tidal energy deployment in U.S. history. Three of their Gen5d 5 m turbines were deployed as part of the Roosevelt Island Tidal Energy project. Initially, the three deployed rotors were manufactured from glass fiber-reinforced epoxy composites. Midway through the deployment, one rotor was replaced with one manufactured at NREL. The new rotor utilized a novel infusible thermoplastic resin system (Elium from Arkema). Since the deployment, one epoxy rotor and one thermoplastic rotor were returned to NREL for continued materials and manufacturing research. The two rotors underwent full-scale structural testing before being sectioned and cut into specimens for a variety of manufacturing quality tests, thermomechanical characterization, and evaluation of material performance in marine environments to understand the key differences between the fiberglass-reinforced epoxy and Elium composites used for the respective rotors. Matrix burn-off tests showed that the Elium blades had a considerably higher fiber volume fraction compared to the epoxy blades (61% vs. 49%). Environmental aging of the specimens showed that the epoxy laminates absorbed more water over the conditioning period; however, it was determined that the Elium laminates had higher diffusion coefficients, so they initially absorbed water faster. Finally, one full epoxy blade and one full Elium blade were conditioned at ambient temperatures for up to 11 months, while periodic mass measurements were taken. The datasets were extrapolated to assume a full 20-year operational life span, and it was determined that the blades would not reach full saturation during that time span.

Keywords: Marine renewable energy, tidal turbine, mechanical characterization, composite manufacturing, environmental degradation
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## 1. INTRODUCTION

The marine renewable energy (MRE) industry is a relatively nascent industry in which developers are working toward harnessing clean energy from our oceans' waves and tidal currents. Waves and tidal currents present a lucrative opportunity to generate significant power to support a large portion of the United States' utility power generation, especially for coastal cities and remote coastal communities [1,2]. However, ocean environments present some unique and difficult challenges to overcome, especially when considering materials and load-bearing structures. Marine environments are harsh and corrosive, which can significantly degrade materials over anticipated operational lifetimes (upward of 20 years) [3]. Coupled with significant hydrodynamic loading, this makes material selection particularly challenging when trying to assess trade-offs between mechanical performance, environmental resistance, and low costs.

Following suit with the wind energy industry, fiber-reinforced polymer (FRP) composites, specifically glass-reinforced epoxies, have often been highlighted as an optimal solution for tidal turbine blades due to their desirable mechanical properties, good resistance to environmental degradation and fatigue, and relatively low costs to manufacture [4]. Despite many favorable characteristics, FRPs still present some unique challenges in terms of long-term degradation in marine environments [5] and responses to manufacturing quality and defects, especially when using hands-on manufacturing processes such as vacuum assisted resin transfer molding (VARTM) [6]. Even thick composite laminates are susceptible to significant environmental degradation over the operational timelines required for MRE structures [7]. Because of this, extensive mechanical characterization must be performed at all scales to build understanding of those materials and mitigate failure risks in complex multi-material structures during deployments [8].

Another issue with FRPs, and particularly relevant to renewable energy industries, is recyclability. Currently, there are no clear ways to fully recycle and reclaim conventional fiber-reinforced epoxy composites. Therefore, there is a big push for recyclable-by-design composite resin systems, such as Recyclamines [9], novel, bio-derivable epoxy-anhydride systems [10], and infusible acrylic resin systems [11]. In particular, Arkema's Elium resin system (a novel, liquid infusible acrylic thermoplastic) has been gaining traction in the wind energy industry as a potential solution to the challenge of building a circular economy for energy materials [12,13]. Because of successful demonstrations in wind energy, the Elium resin system is also being evaluated for marine energy applications [11,14].

### 1.1 Verdant Power Research Measurement Campaign

In partnership with the U.S. Department of Energy's Water Power Technologies Office and the National Renewable Energy Laboratory, Verdant Power deployed a TriFrame$^{TM}$ with three of their Gen5d 5 m diameter downstream tidal turbines at the Roosevelt Island Tidal Energy (RITE) site in the East River (actually a tidal strait) in New York City, NY in 2020. The blades of the three rotors were manufactured from fiberglass-reinforced epoxy composites. Six months into the deployment, the TriFrame$^{TM}$ was retrieved from the tidal strait to perform maintenance and inspections. While the TriFrame$^{TM}$ was out of the water, one rotor was replaced with a fiberglass-reinforced Elium bladed rotor, which also housed a state-of- the-art data acquisition system and extensive strain gauging on the blades to measure operational loads (Figure 1) [15]. The TriFrame$^{TM}$ was again deployed in the tidal strait for a further 6 months and then retrieved at the end of the campaign. In terms of power generation, it was the most successful tidal energy deployment in the United States to date.

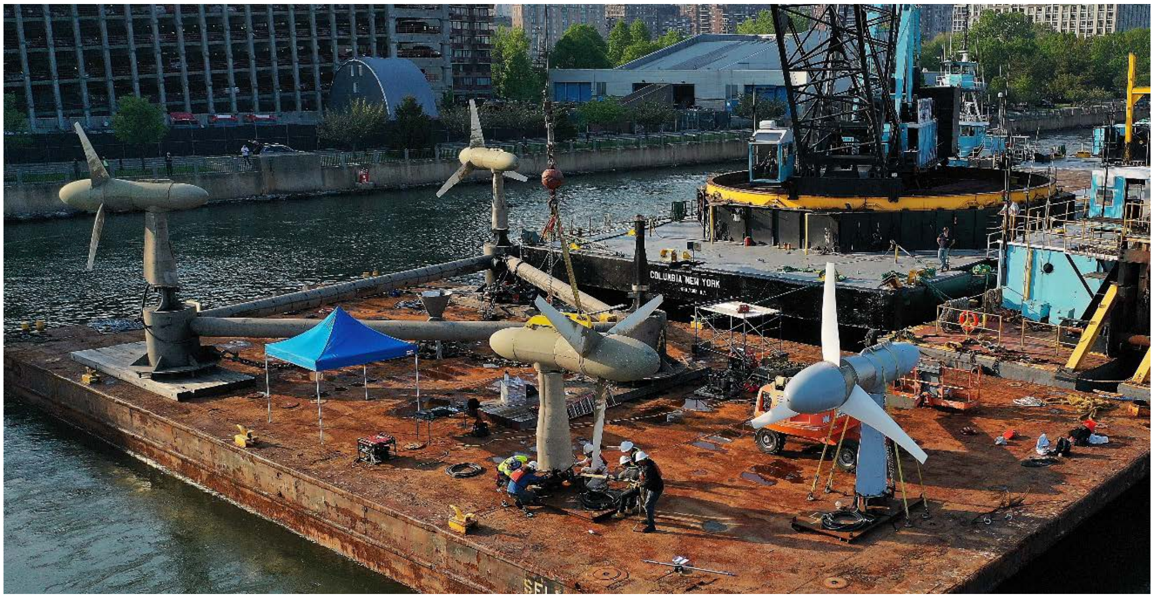

Figure 1. Photo showing the Verdant power retrieve-and-replace operation of their TriFrame at the RITE site with one fiberglass/epoxy rotor being replaced with the fiberglass/Elium rotor manufactured by NREL (photo by Paul Komosinski).

The epoxy matrix blades for the rotors were manufactured by Composite Builders LLC in Holland, Michigan. The blades were manufactured from Hexcel pre-impregnated (prepreg) fiberglass/epoxy laminates and were cured in an autoclave. High-pressure and low-pressure shells were cured separately and subsequently adhesively bonded together with an epoxy adhesive. The blades were then filled with an epoxy foam to tailor the final density of the blades. The blades were painted with an epoxy-based boat paint.

The Elium blades manufactured by NREL were manufactured using the same tooling to ensure geometric conformity. Unlike the prepreg epoxy blades, the Elium blades were manufactured using a VARTM process and cured at room temperature—a unique advantage of the Elium resin system [16]. Prior to bonding, strain gauges were applied to the inner surfaces of the cured laminates (Figure 2). The high- and low-pressure skins were then bonded with a methacrylate-based thermoplastic adhesive. The cavities of the blades were filled with the same epoxy foam. The same epoxy boat paint was used for the Elium blades.

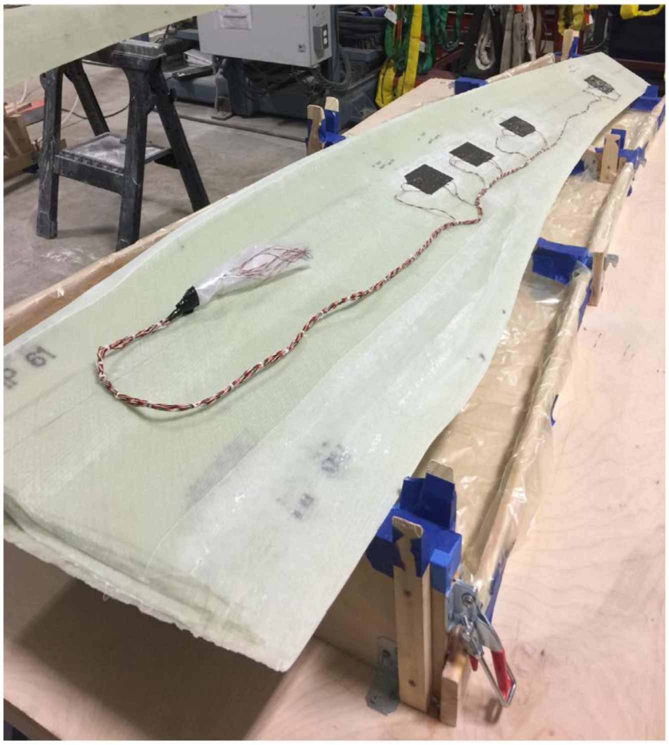

Figure 2. Fiberglass-reinforced Elium high-pressure skin with strain gauges bonded (photo by Robynne Murray).

### 1.2 Blade and Post-Deployed Rotor Structural Validation

Prior to deployment, one epoxy and one Elium blade were structurally validated under worst-case maximum static and 2-million-cycle lifetime fatigue loading conditions (Figure 3). Differences between the two blades' stiffnesses and dynamic responses were compared. These datasets are not presented in this manuscript.

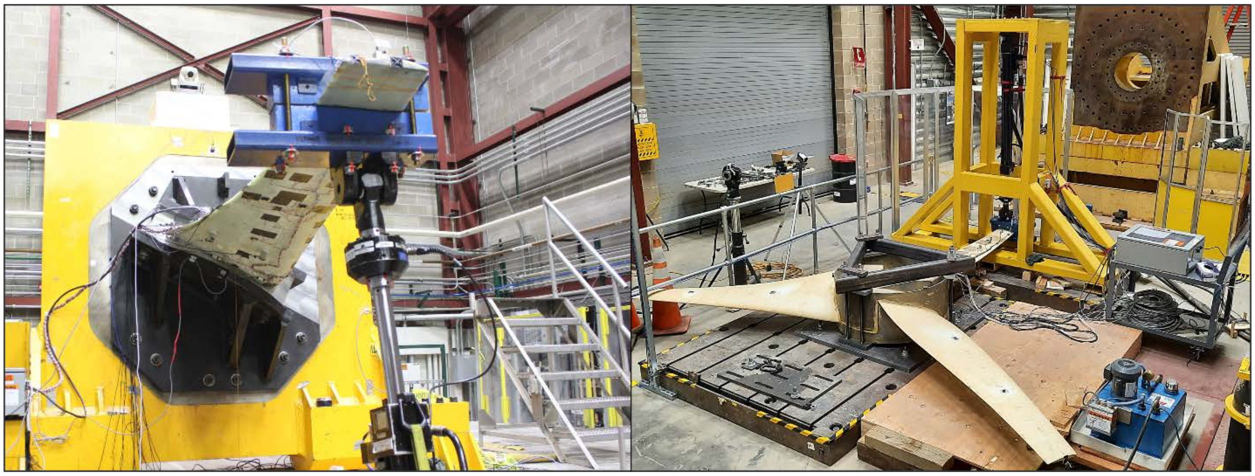

Figure 3. A single Verdant blade mounted to NREL's test stand for structural validation (left) and a blade connected to the full Verdant rotor being subjected to structural loading (right) (photos by Ryan Beach and Paul Murdy).

Once Verdant Power's deployment was complete, NREL had a unique opportunity to take possession of one fiberglass/epoxy rotor and the fiberglass/Elium rotor that was built at NREL for further structural validation and comparisons of their performance after they had been subjected to service loading and environmental conditions. Each blade was subjected to the same static loads individually, and one blade from each rotor was subjected to an accelerated lifetime of fatigue loading (see Figure 3). Again, the results of the full-scale structural testing campaign are not presented in this manuscript, but details have been provided to outline the timeline leading to the study presented herein.

### 1.3 Post-Deployment Characterization

Because NREL possessed the two rotors made from different matrix materials and manufacturing processes, another unique opportunity was presented to dissect the composite blades and perform further testing, analysis, and comparison of the material properties and manufacturing variations between the blades. This has been referred to as the Post-Deployment Characterization task, which is part of the Marine Energy Advanced Materials project. The Marine Energy Advanced Materials project is a multiyear, collaborative effort between Sandia National Laboratories, NREL, Pacific Northwest National Laboratory, Montana State University, and Florida Atlantic University, which has been funded by the U.S Department of Energy's Water Power Technologies Office. This manuscript presents the research that has been conducted to date on the Post-Deployment Characterization task and preliminary results from sections and specimens cut from the blades, which were then subjected to a variety of manufacturing quality tests, such as matrix burn-off tests to determine fiber volume fractions and assess fiber alignment, as well as additional environmental conditioning. These datasets can provide valuable insights to marine industry composite manufacturers and MRE developers on how to best utilize epoxy and thermoplastic composites in load-bearing structures subjected to marine environments.

# 2. EXPERIMENTATION

Once structural validation of the deployed blades was complete, the two blades from each rotor that were not subjected to fatigue loading were removed. Of those blades, one from each rotor was sectioned for material characterization experiments (see Figure 4), while the other blades were subjected to full-scale water absorption experiments, which are further outlined in Section 2.2.

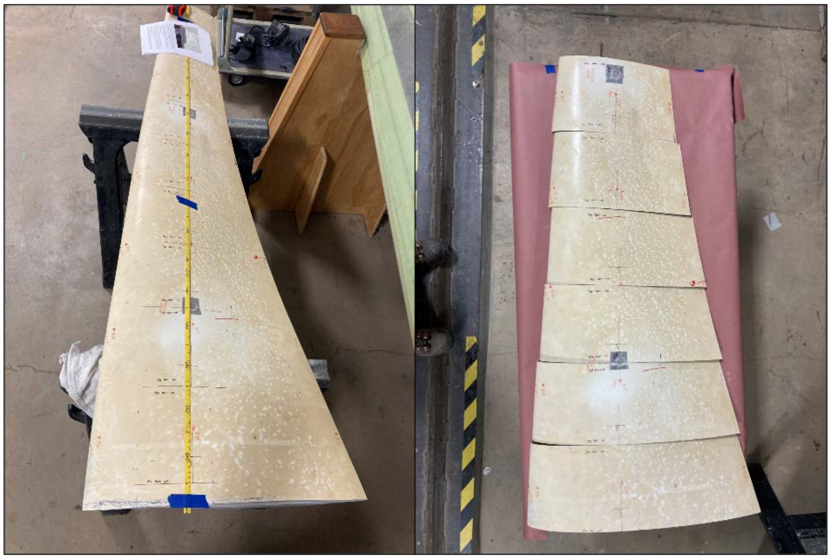

Figure 4. A single fiberglass/epoxy Verdant blade that had been removed from the rotor (left), and the same blade sectioned into 200 mm long sections for further material characterization (right) (photos by Ryan Beach).

## 2.1 Fiber Volume Fraction Testing

Slices of one of the root sections were cut into 30 × 30 × 2 mm specimens and matrix burn-off tests were performed to determine fiber volume fractions ($V_f$), following ASTM D3171 Standard Test Method for Constituent Content of Composite Materials, Procedure G. The volumes and masses of the specimens were measured prior to removing the polymer matrices in a muffle furnace at 550 °C for 2 hours. The masses of the remaining fibers were measured, and $V_f$ for each material was determined based on the known density of fiberglass.

## 2.2 Environmental Conditioning

From some of the blade sections, ASTM D3039 static tensile and dynamic mechanical analysis (DMA) specimens were cut from the spar caps (see Figure 5). Tensile specimens were 175 × 15 × 1 mm, and the DMA specimens were 25 × 15 × 1 mm. Specimens were named based on the location of the blade that they were cut from. These specimens were grouped and subjected to environmental conditioning prior to static tensile and DMA testing (see Figure 5).

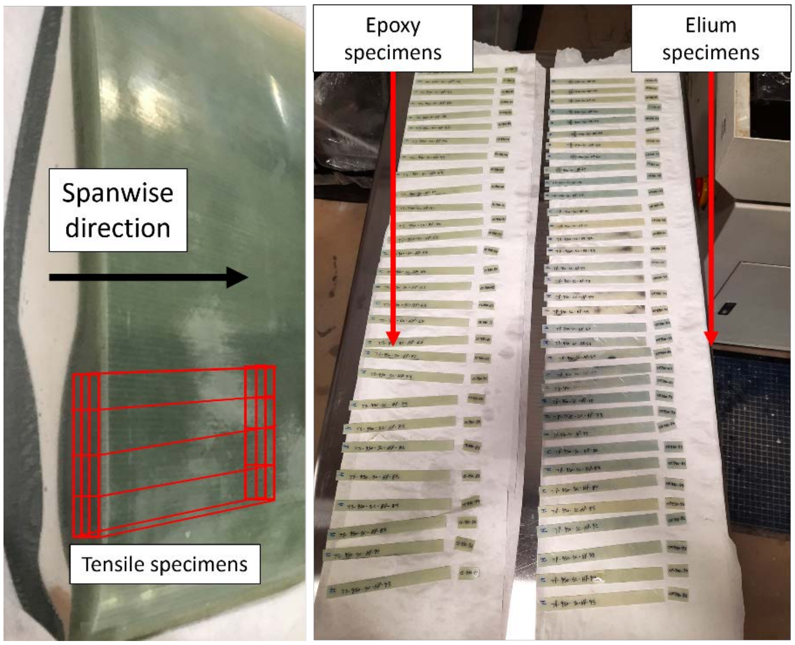

Figure 5. A schematic of how tensile and DMA specimens were cut from the blade spar caps (left) and the cut fiberglass/epoxy and Elium specimens organized after cutting (right) (photos by Robynne Murray and Paul Murdy).

Of the cut specimens, 25% remained dry and untested, 25% were conditioned in water at 50 °C for 2 months, 25% were conditioned in water at 50 °C for 4 months, and 25% were conditioned dry at 50 °C for 4 months as a control group for comparison. Conditioning was conducted following ASTM D5229 Standard Test Method for Moisture Absorption Properties and Equilibrium Conditioning of Polymer Matrix Composite Materials. All specimens were weighed before and after the environmental conditioning to a precision of ± 0.0001 g. Four specimens from the 4-month conditioning group were weighed periodically to determine Fickian water diffusion coefficients and total mass uptake values per Shen et al. [17].

Additionally, the epoxy and Elium blades that were not sectioned were subjected to full-scale environmental aging under ambient conditions (see Figure 6). The blades are weighed every 2 months to a precision of ± 0.1 g with the goal of comparing with the coupon-scale datasets and extrapolating the data to estimate times for the blades to reach full saturation. Additionally, these datasets will be used in the future for validation of complex, multimaterial water diffusion models.

Figure 6. Fiberglass/epoxy and fiberglass/Elium blades being environmentally conditioned at ambient temperatures in a water tank.

# 3. RESULTS

## 3.1 Fiber Volume Fraction Testing

Table 1 shows a comparison of the calculated $V_f$ for each blade that was sectioned. Even though the specimens were only taken from one section of each blade, the differences in $V_f$ between the two blades are significantly different and unexpected when considering the manufacturing processes that were used. The epoxy blade was manufactured using prepregs, which typically leads to volume fractions greater than 60%, but the resulting volume fraction was significantly lower. The Elium blade was manufactured using VARTM, which typically results in volume fractions of 55–60% in ideal cases, but potentially less for the thick laminates that were used. Overall, these results show that good fiber compaction and consolidation was achieved during the infusion of the Elium blade. Despite the two blades containing the same amount of fiber reinforcement by weight, the skins and spar caps of the epoxy blades were ~30% thicker than those of the Elium blades.

Table 1. A comparison of $V_f$ for the epoxy and Elium blade from the matrix burn-off tests with standard deviations.

| **Blade Matrix Material** | $V_f$ **(%)** |
|---|---|
| Epoxy | $48.8 \pm 0.3$ |
| Elium | $60.9 \pm 1.5$ |

Figure 7 shows a photo comparing the remaining fibers after the burn-off process for one epoxy blade sample and one Elium blade sample. Good fiber alignment can be observed for both cases. One significant difference was the packing of the fibers in the laminate. The epoxy blade used unidirectional prepregs with no stitching of fiber bundles. This resulted in very well-distributed fibers within the spar cap samples. In comparison, the Elium spar caps were constructed of a stitched unidirectional fabric with a small amount of transverse backing strands. The fibers are arranged into tows, which are evident in Figure 7. These differences in construction can have considerable effects on the structural response of the blades in both stiffness and strength under static and fatigue loading, due to differences in how well the fibers were distributed throughout the laminates.

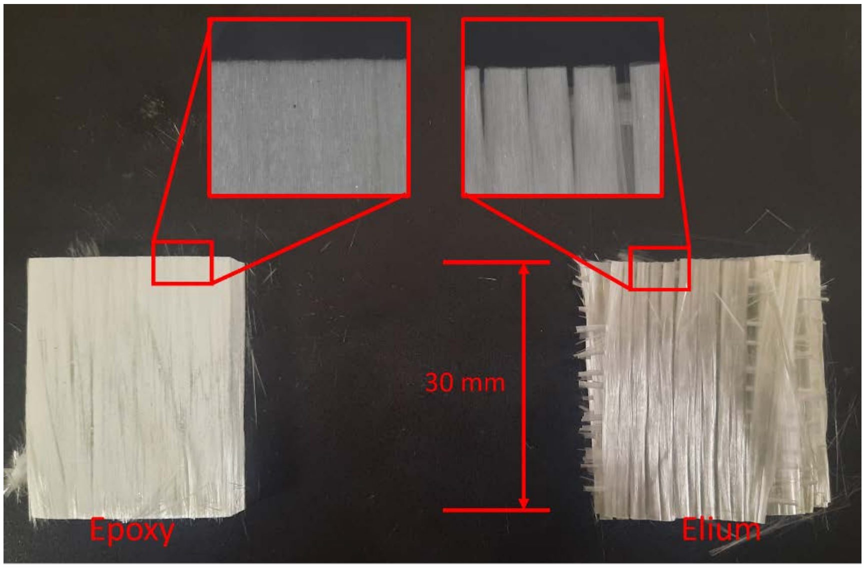

Figure 7. A comparison of optical microscope images for the fiberglass reinforce epoxy and Elium laminates that were cut showing the differences in fiber packing and alignments between the blade laminates.

### 3.2 Environmental Conditioning

The average mass changes between the different batches of specimens (~8 per material and test condition) subjected to the different environmental conditions were compared in Figure 8. Figure 9 shows the changes in mass of the specimens that were periodically weighed plotted against the square root of time. The first observation to note is the control specimens exhibited a measurable amount of desorption during the 4 months at 50 °C in dry conditions. Therefore, the specimens had already absorbed some water, but it is unknown whether this was due to the blades being submerged during the 6-month deployment at the RITE site or being exposed to water during the sectioning and specimen cutting processes with wet saws. The epoxy specimens gained 0.76–0.78% of their original mass on average over the 2–4-month period, with relatively small deviations between specimens. There is little difference in average mass changes from 2 to 4 months, which indicated the specimens were fully saturated with water before the 2-month conditioning period was complete. On the other hand, the Elium specimens showed very large differences in mass changes between the 2- and 4-month batches, as well as specimen-to-specimen variations. In fact, the average mass change of the specimens for the 4-month conditioning batch was less than that for the 2-month conditioning batch. It is possible that this mass loss could be caused by leeching of unreacted monomers or hydrolysis of ester bonds [18]. These aspects are also shown in Figure 9, where large specimen-to-specimen variation can be observed for the Elium specimens. We suspect the larger variations were caused by the cutting of the specimens themselves. The spar cap plies used for the Elium blades also contained a small percentage of transverse backing tows, which led to resin-rich regions between plies at the micro-scale, despite the higher fiber volume fraction when measured at the macro-scale. The fibers in the epoxy blade's spar caps were better distributed, so fiber volume fractions at the micro-scale were likely more consistent. Because the specimens were cut in the laminate plane, some may have contained more resin than others.

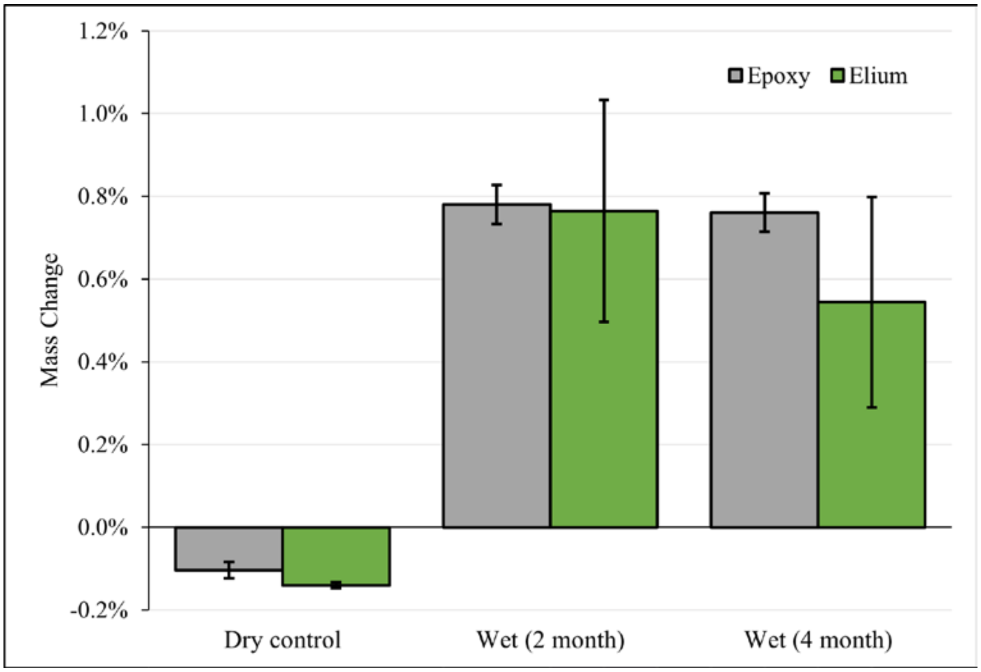

Figure 8. Average changes in masses of all specimens subjected to environmental conditioning. Error bars represent standard deviations.

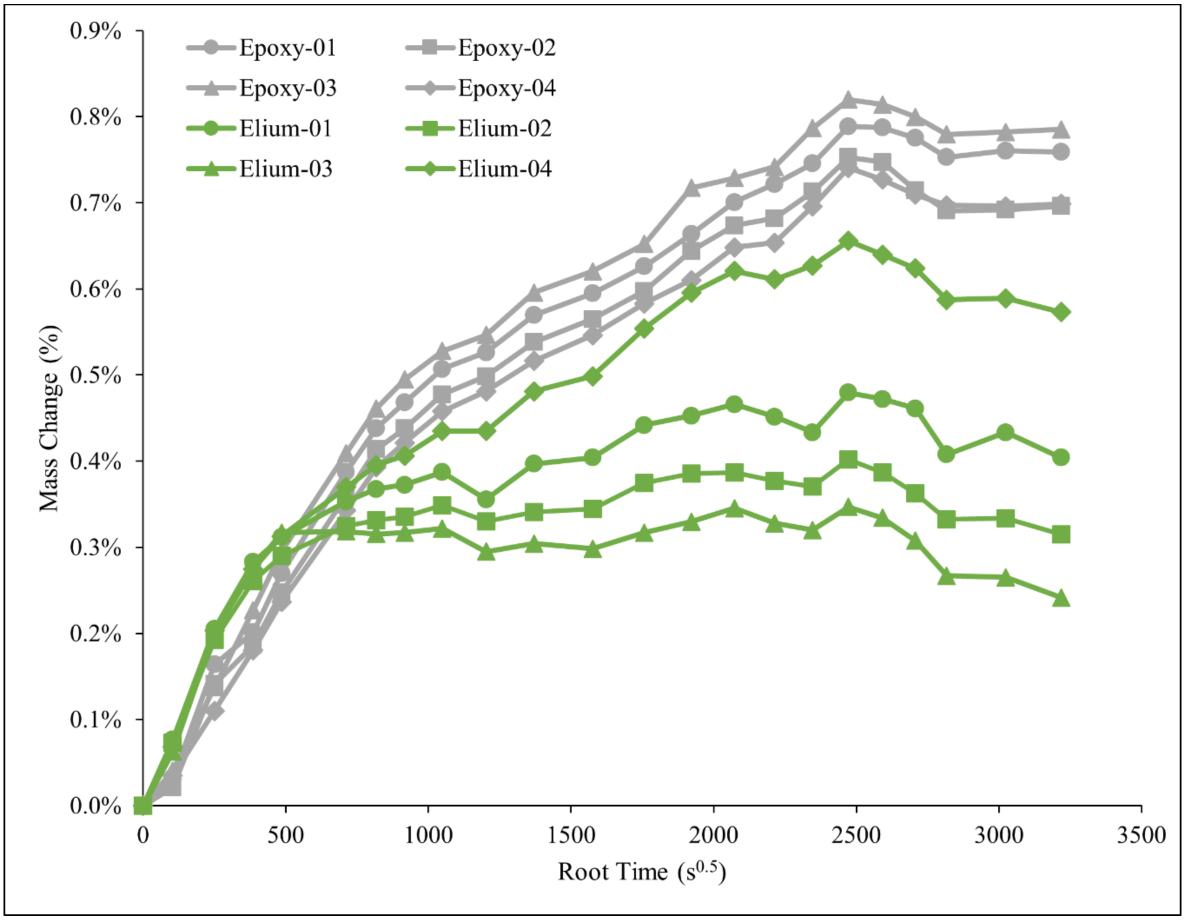

Figure 9. Mass changes against square root of time for the specimens that had their masses measured periodically throughout the 4-month conditioning period.

Using the data presented in Figure 9, water diffusion properties were determined by assuming one-dimensional Fickian diffusion [17]. The water diffusion properties are presented in Table 2, where $m_\infty$ is the maximum mass change taken from each specimen, and D was determined from the initial linear portion of the mass change/root time plot in Figure 9. Although the Elium specimens absorbed less water than the epoxy specimens on average, the Elium specimens' diffusion coefficients were 5 times higher. The higher diffusion coefficients indicate that less time was taken for the Elium specimens to reach full saturation—an important consideration when designing a structure that accounts for the transient water diffusion and the associated environmental degradation. This also assumes that the effects of leaching of unreacted hydrolysis of ester bonds discussed previously were negligible.

Table 2. A comparison of $m_\infty$ and diffusion coefficients for the epoxy and Elium specimens that were measured periodically.

| | **Epoxy** | **Elium** |
|---|---|---|
| $m_\infty$ (%) | $0.776 \pm 0.031$ | $0.471 \pm 0.117$ |
| D ($m^2.s^{-1}$) | $2.10 \pm 0.12\ (\times 10^{-13})$ | $12.1 \pm 4.66\ (\times 10^{-13})$ |

Figure 10 shows the results of periodic mass measurements of the full-scale epoxy and Elium blades under ambient conditions to date against the square root of time. Linear regressions have been added to the plot, assuming that the datasets are still in the linear phase of Fickian diffusion. Over 11 months, the mass of the epoxy blade increased by 0.07%, and over 6 months, the mass of the Elium blade increased by 0.14%. It was observed that the paint had failed in many areas across the Elium blade. The paint formed many bubbles on the surface that are filled with water, which has artificially inflated the mass measurements of the blades (Figure 11). Figure 10 also shows the same mass change plot, but with the linear regressions extrapolated to a 20-year lifetime (or 25,100 $s^{0.5}$). For the epoxy blade, this shows that even after 20 years in the water, the composite laminate will have absorbed less than 0.4% of its mass in water. When compared to the dataset in Figure 9, this would still be in the linear portion of the Fickian diffusion curve. The Elium dataset is difficult to interpret because paint bubbles affecting the measurements It is expected that neither blade would be close to full saturation after 20 years in water at ambient temperatures, especially when considering that the epoxy foam fill in the blades is likely to be artificially inflating the mass changes assumed to be in the composite laminates.

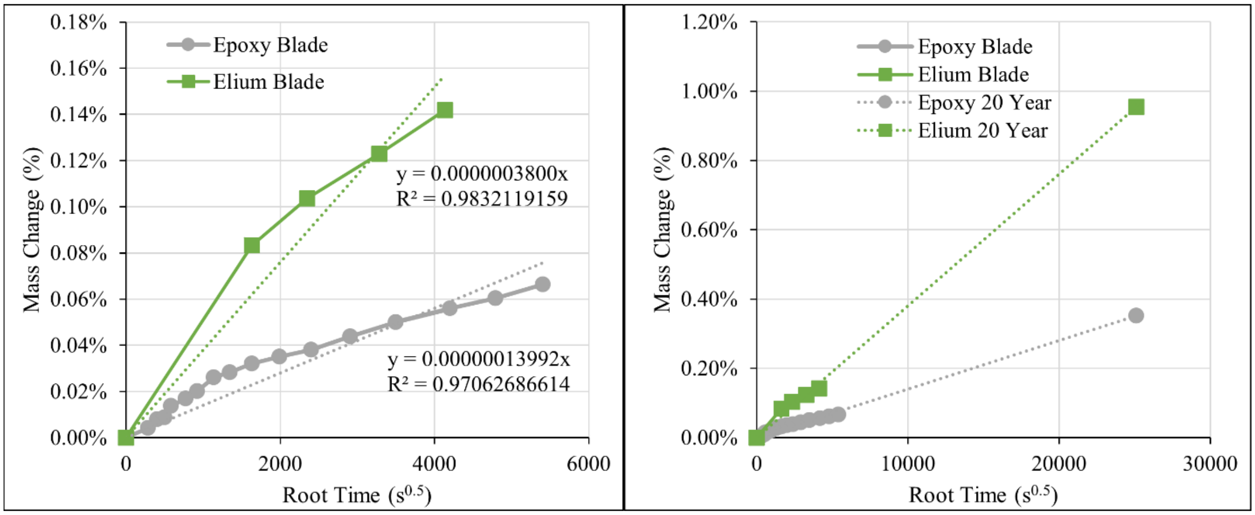

Figure 10. Measured changes in masses for the epoxy and Elium blades conditioned in water at ambient temperatures with linear regression added to the datasets (left) and the same datasets with the linear regressions extrapolated to 20 years (right).

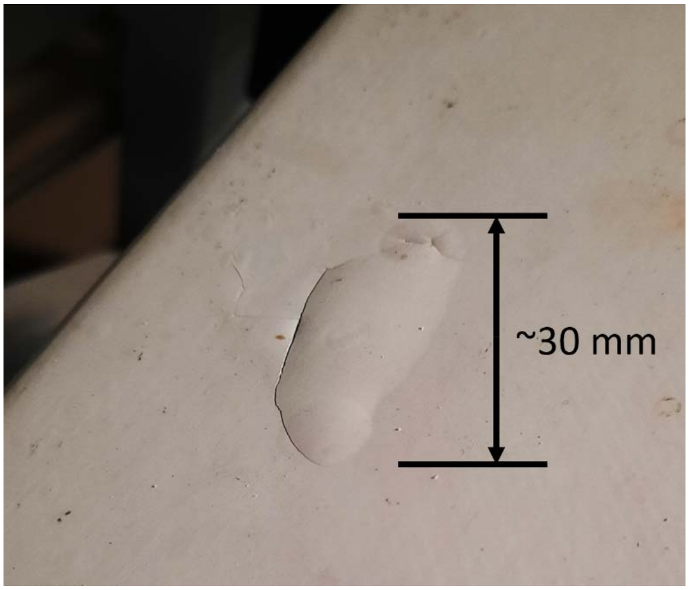

Figure 11. One of the paint bubbles on the surface of the Elium blade that formed during the conditioning period.

## 4. CONCLUSIONS

Following on from the Verdant Power deployment at the RITE site on New York's East River and subsequent full-scale rotor structural testing, the fiberglass-reinforced epoxy and Elium blades were sectioned and dissected to investigate the as-manufactured geometries, mechanical properties, and performance in marine environments. To date, there are key differences between the manufacturing processes and materials that were used. To summarize the key findings:

- Fiber volume fractions were considerably different between the two blades —61% for vacuum-infused Elium vs. 49% for prepreg epoxy.
- Distribution of the fiber reinforcements in the spar caps of the epoxy blade was considerably better than that of the Elium blade (prepreg vs. vacuum infusion).
- The Elium matrix specimens absorbed less water than their epoxy counterparts, but the rate at which water was absorbed was much higher (Figures 8 and 9 and Table 2).
- The full blades conditioned in water at ambient temperatures are not close to full saturation, and it is unlikely that they will reach that point after 20 years—an important consideration when designing for transient water absorption and subsequent composite degradation (Figure 10).

Research in this area is still ongoing. The spar cap specimens that were conditioned will soon be subjected to static tensile testing and DMA testing. Pairing these results with the absorption data presented in this paper will provide valuable insights into the water-induced degradation of the fiberglass-reinforced epoxy and Elium laminates. Also, an analysis of the as-manufactured blade geometries will be performed on the blade cross sections to compare chord lengths, laminate thicknesses, spar cap locations, and adhesive bond line widths. This information will be used to inform numerical models, which will then be validated by the full-rotor structural testing that was performed prior to this study. Finally, the long-term conditioning study of the full blades will be continued for as long as is feasible in the hopes of providing long-term conditioning data under more realistic conditions (not accelerated). Eventually, this dataset could be used for validating complex, multi-material water absorption models.

Ultimately, the research presented in this paper and the other tasks associated with the Marine Energy Advanced Materials Project will continue to inform industry on the best materials, manufacturing, and testing practices, as well as provide meaningful datasets for making informed design decisions.

## 5. ACKNOWLEDGEMENTS

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