# Methodology for Fast Iterations of Blade Designs Using Thermoplastic Composite Materials

## Preprint

Robynne Murray,[1] Kathryn Trubac,[1]
Stephanie Ordonez-Sanchez,[2] Song Fu,[2]
Tim O'Doherty,[3] and Cameron Johnstone[2]

*1 National Renewable Energy Laboratory*
*2 Strathclyde University*
*3 Cardiff University*

*Presented at the European Wave and Tidal Energy Conference*
*Napoli, Italy*
*September 1-6, 2019*

**NREL is a national laboratory of the U.S. Department of Energy**
**Office of Energy Efficiency & Renewable Energy**
**Operated by the Alliance for Sustainable Energy, LLC**

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

Contract No. DE-AC36-08GO28308

**Conference Paper**
NREL/CP-5000-73295
October 2019

# Methodology for Fast Iterations of Blade Designs Using Thermoplastic Composite Materials

## Preprint

Robynne Murray,[1] Kathryn Trubac,[1]
Stephanie Ordonez-Sanchez,[2] Song Fu,[2]
Tim O'Doherty,[3] and Cameron Johnstone[2]

*1 National Renewable Energy Laboratory*
*2 Strathclyde University*
*3 Cardiff University*

**Suggested Citation**
Murray, Robynne, Kathryn Trubac, Stephanie Ordonez-Sanchez, Song Fu, Tim O'Doherty, and Cameron Johnstone. 2019. *Methodology for Fast Iterations of Blade Designs Using Thermoplastic Composite Materials: Preprint*. Golden, CO: National Renewable Energy Laboratory. NREL/CP-5000-73295. https://www.nrel.gov/docs/fy20osti/73295.pdf.

**NREL is a national laboratory of the U.S. Department of Energy**
**Office of Energy Efficiency & Renewable Energy**
**Operated by the Alliance for Sustainable Energy, LLC**

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

Contract No. DE-AC36-08GO28308

**Conference Paper**
NREL/CP-5000-73295
October 2019

National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, CO 80401
303-275-3000 • www.nrel.gov

## NOTICE

This work was authored in part 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's Advanced Manufacturing Office. The views expressed herein 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.

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

U.S. Department of Energy (DOE) reports produced after 1991 and a growing number of pre-1991 documents are available free via www.OSTI.gov.

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

NREL prints on paper that contains recycled content.

# Methodology for fast iterations of tidal turbine blade designs using thermoplastic composite materials

Robynne E. Murray, Song Fu, Stephanie Ordonez-Sanchez,
Kathryn Trubac, Tim O'Doherty, and Cameron M. Johnstone

*Abstract*—**Tidal energy is still in the early research and development phases; therefore, the ability to quickly manufacture and evaluate prototype blades with new blade designs and materials is critical. This paper investigates using a Stratasys three-dimensional printer to rapidly prototype scale-model turbine blades by printing the blade tooling and using vacuum-assisted resin transfer molding to manufacture blades. This work outlines a methodology for cost-effectively modelling and manufacturing model-scale tidal turbine blades to be used in testing campaigns, and for evaluating new thermoplastic composite materials for tidal energy applications. Demonstration blades were modelled in ANSYS and manufactured using an infusible thermoplastic resin system called Elium. The development of scale-model thermoplastic blades enables research into their performance in realistic conditions at a cost-effective scale, and manufacturing using three-dimensional-printed tooling enables fast and low-cost blade design iterations.**

*Keywords*— **Finite element model, Thermoplastic composites, Structural validation, Manufacturing, Scale-model**.

## I. INTRODUCTION

Tidal energy is still in the early research and development phases; therefore, the ability to quickly manufacture and evaluate prototype blades with new blade designs and materials is critical. This paper investigates using a Stratasys three-dimensional (3D) printer to rapidly prototype scale-model turbine blades by printing the blade tooling and using vacuum-assisted resin transfer molding (VARTM) to manufacture blades. Further, although there are many advantages of composite materials, commonly used thermoset resin composites have been shown to have significantly reduced tensile static and fatigue strengths when exposed to seawater conditions [1]. New research on infusible two-part reactive thermoplastic resins has shown improved seawater-saturated properties and a higher percentage recovery of mechanical properties upon being dried after saturation [1]. Infusible thermoplastic resins are also recyclable at the end of their lives [2] and have reduced manufacturing cycle times [3], energy requirements, and manufacturing costs [4]. This work therefore also investigates new thermoplastic resin materials for tidal energy applications. The objective of this work is to develop a methodology for cost-effectively modelling and manufacturing model-scale tidal turbine blades to be used in testing campaigns, and to evaluate new materials that may have performance enhancements compared to traditional materials. The development of scale-model thermoplastic blades enables research into their performance in realistic conditions at a cost-effective scale, and manufacturing using 3D printed tooling enables fast and low-cost blade design iterations.

## II. NUMERICAL MODEL

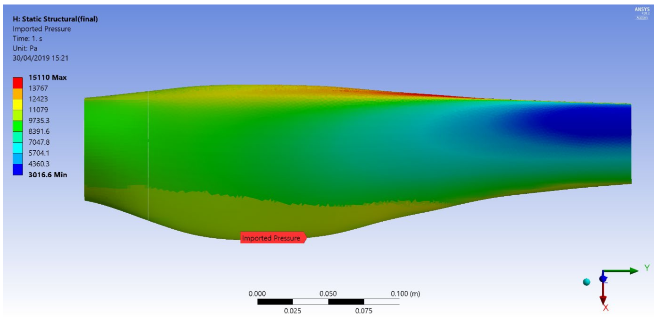
The 400-mm-long blade geometry was developed as part of an international collaborative project called "Dynamic Loadings on Turbines in a Tidal Array," led by Strathclyde and Cardiff Universities in the United Kingdom. The blade design used in this project is based on a Wortmann FX 63-137 profile and was optimised from a previous blade model using blade-element momentum theory [5]. To investigate the structural reliability of the thermoplastic composites at a small scale, the blade was analysed using ANSYS. The blade model was subjected to a pressure distribution similar to what a blade is expected to experience in a tidal environment following the methodology shown in [6].

The parameters used to analyse the blade were selected according to experiments carried out in a towing tank using a 0.9-m three-bladed horizontal-axis tidal stream turbine. For the purposes of this paper, the imposed loading on the blade was computed only for peak power conditions that occur in a tip-speed ratio region of 3.6 [7]. A uniform flow speed of 1.0 m/s along the water column was set during the calculations. The pressure distribution used in the modelling is shown in Fig. 1.

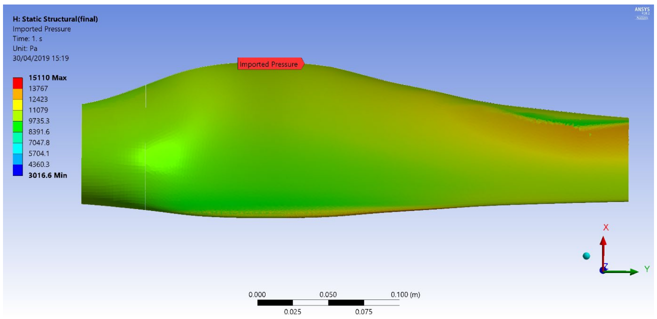
The static structural response of the blade using thermoplastics was compared to a typical aluminium blade prototype, similar to the one used for the testing campaign reported in [7]. The aluminium blade model was set as a solid piece contrary to the thermoplastic blade that was modelled with the default epoxy carbon unidirectional (UD) material from the ANSYS database.

Robynne E. MurrayKathryn Trubac areRobynne E. Murray). Song Fu, Stephanie Ordonez-Sanchez, and Tim O'Doherty aCardiff University, School of Engineering Queen's Buildings, The Parade, Cardiff CF24 3AA, Wales, UK. Cameron M. Johnstone is with the

The decision to use the epoxy material properties was justified by the structural characterisation presented in Section III. The composite blade had 1,772,290 elements, with tri and quad shell elements on the blade surface and tetrahedral elements for the rest of the blade. The thermoplastic blade was modelled using two plies with a unidirectional fibre direction from root to tip. The root was reinforced with two additional plies. All plies were set to a thickness of 0.36 mm. The ANSYS Composite PrepPost was employed.



(a)



(b)

Fig. 1. Pressure distribution of the (a) upper and (b) lower section of the blade.

Figs. 2 and 3 show the equivalent von Mises stresses and total deformation. The maximum stresses along the blade appeared in similar regions for both the aluminium and the thermoplastic blades. As shown in Fig. 2, the blade geometry has an abrupt change right before the start point of the root section. This area is where we find the largest maximum equivalent stresses. It must be noted that the maximum affected area develops on the trailing edge along that blade section but only on the aluminium blade. This maximum equivalent von Mises stress for the aluminium blade is on the order of 5.76 MPa, and for the composite blade is 4.87 MPa in the first layer. A large stress concentration is found at about ¼ from the root section to the tip and it is of similar magnitude as that found in the trailing edge, with a magnitude of 5.76 MPa, and it is 15% greater than that found for the thermoplastic model. Future work will include a failure analysis and more refined design of the composite blade. Further analysis In will incorporate other failure criteria more applicable to composites such as Tsai-Hill and Tsai-Wu criteria which are adaptations of the Von Mises principle.

The maximum deformation occurring in the thermoplastic blade is 80% higher than that obtained for the aluminium blade. However, these values are 0.42 mm and 2.3 mm for the aluminium and for the thermoplastic blade tip, respectively. And those are equivalent to 0.13% and 0.66% of the total blade span, making them still relatively small. Furthermore, the composite design has not been fully optimized yet.

The use of ANSYS Composite PrepPost allowed the investigation of the stress distribution to be conducted layer by layer. It can be observed in Fig. 4 that the first layer has the largest maximum stresses, and this stress concentration decreases by 4.5% on the second layer. The third and fourth layer improved the structural integrity of this section. Fig. 4 (c) and (d) show that the maximum equivalent stress is as low as 2 MPa. The use of additional layers was considered in this section as this is usually the area where the highest stresses are observed in both marine and wind turbine blades.

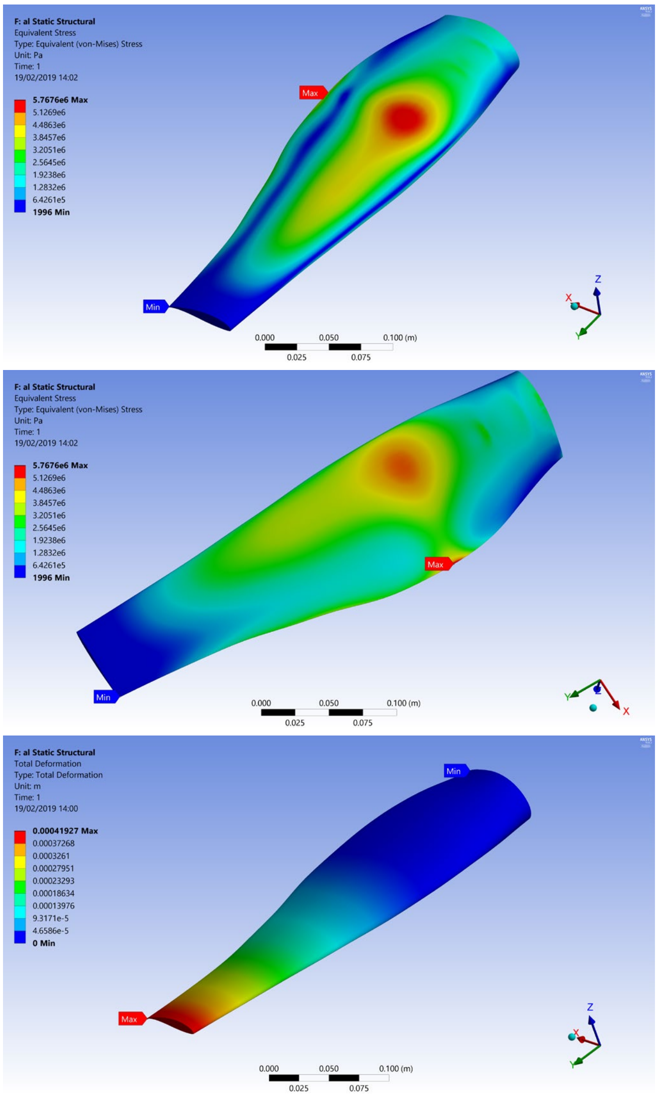


Fig. 2. Aluminum blade modelled in ANSYS showing the (a) upper and (b) lower equivalent (von Mises) stresses and the (c) total deformation.

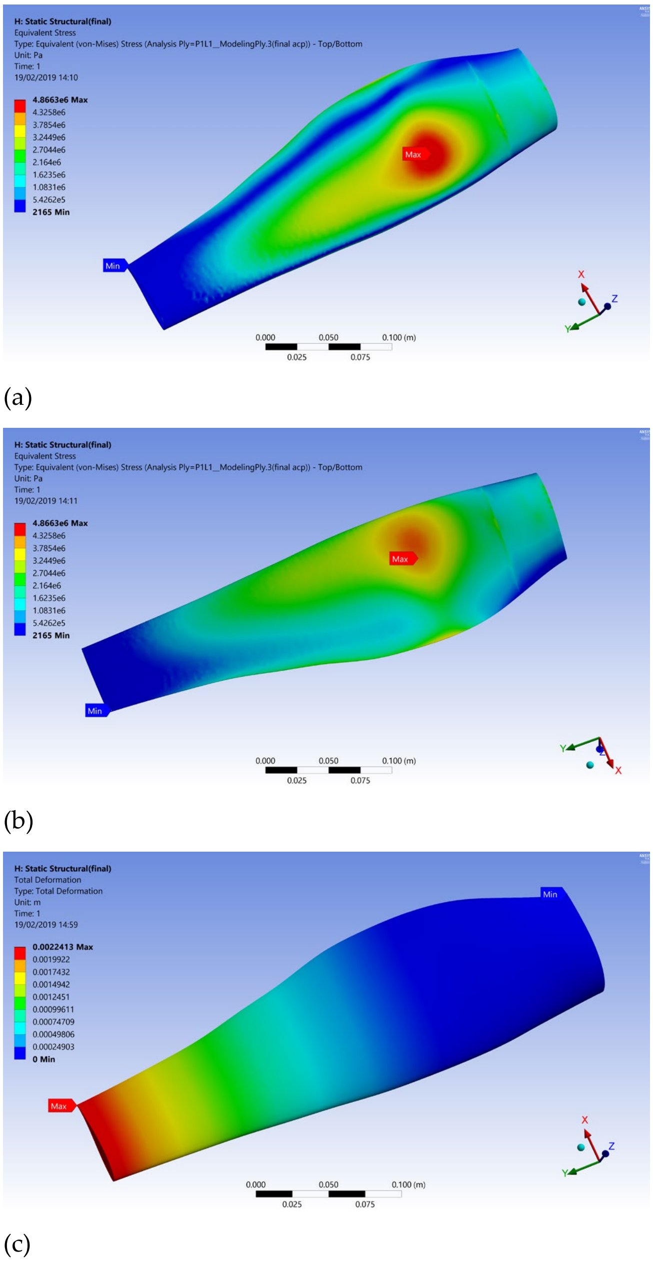



Fig. 3. Thermoplastic blade modelled in ANSYS showing the (a) upper and (b) lower equivalent (von Mises) stresses and the (c) total deformation.

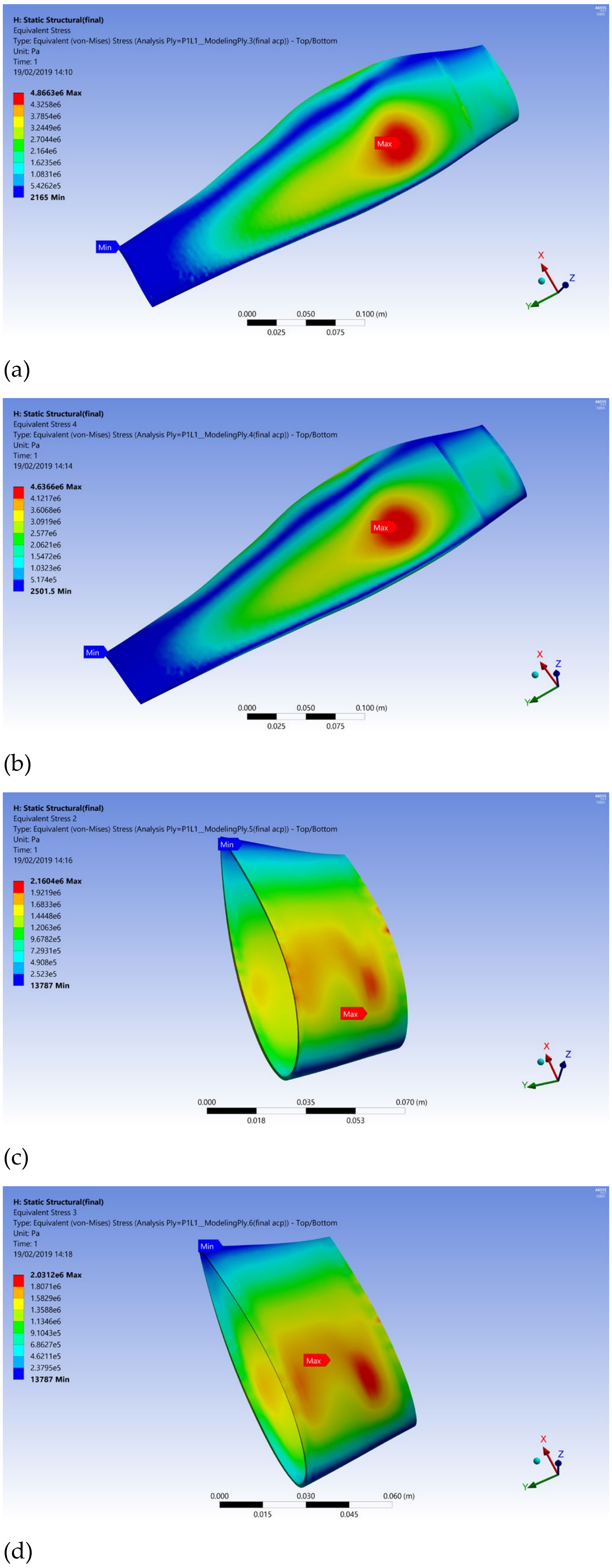



Fig. 4. Equivalent stresses shown layer by layer: (a) layer 1, (b) layer 2, (c) layer 3, and (d) layer 4.

The results of this model are not meant to be a final design, but an example of how to build capabilities, and will be further refined with future work.

## III. Materials

Demonstration blades were modelled in ANSYS finite-element analysis (FEA) modelling software, as discussed previously, and manufactured using an infusible acrylic-based thermoplastic resin system called Elium. Thermoplastics are often thought of as being used in their polymeric form in the composites industry. However, Elium is a reactive, monomeric, liquid resin that is polymerized into a solid thermoplastic after being mixed with an initiator in an analogous way to epoxy resins, which facilitates drop-in replacement for original equipment manufacturers who are familiar with using a two-part resin system. This resin technology can significantly reduce the manufacturing cycle times and the embodied energy due to the room temperature cure, resulting in manufacturing cost reductions [8]. The Elium thermoplastic resin is also recyclable and has been shown to have improved seawater-saturated mechanical properties compared to epoxies [1].

To validate the structural properties of this thermoplastic resin, Elium-188-infused Johns Manville 086 unidirectional fiberglass (area weight 1200 g/m$^2$, product name BAT UD 0°1200 C-1270 mm) was characterized at a coupon scale as part of an Institute for Advanced Composites Manufacturing Innovation (IACMI) project for wind turbine blades [9], with properties shown in Table 1. These data show that fiberglass infused with the Elium thermoplastic resin has similar and, in some cases, higher moduli and strengths than the epoxy composite.

Table 1: Thermoplastic and epoxy coupon properties

| | | **Epoxy** | | **Thermo-plastic** | |
|---|---|---|---|---|---|
| | | Mean | Std dev. | Mean | Std dev. |
| **Tensile Longitudinal** | Modulus (GPa) | 36.9 | 2.9 | 40.6 | 4.1 |
| | Failure stress (Mpa) | 722.8 | 29.8 | 916.5 | 25.6 |
| **Tensile Transverse** | Modulus (GPa) | 10.9 | 1.2 | 11.4 | 1.4 |
| | Failure stress (Mpa) | 40.3 | 4.3 | 47.9 | 1.3 |
| **Short Beam Shear** | Failure stress (Mpa) | 53.5 | 1.1 | 49.0 | 1.3 |

Although coupon-scale results from the IACMI project are promising, it is also important to consider how these properties scale up with thickness as tidal turbine blades tend to be constructed of thick composite materials (up to several inches thick at the root sections). To evaluate the thermoplastic resin at a realistic thickness for a tidal turbine blade, thick spar caps were manufactured using both a thermoplastic resin and an epoxy resin, with geometries shown in Fig. 5. They were manufactured using VARTM with 45 layers of the same Johns Manville 086 unidirectional E-glass (area weight 1200 g/m$^2$, product name BAT UD 0°1200 C-1270 mm) with Elium thermoplastic resin for one spar cap and Hexion epoxy resin for the other. The elastic performances of the spar caps were characterized in three-point bending according to the ASTM D790 [10] standard, with setup shown in Fig. 6. Digital image correlation (DIC), as well as several strain gauges and string potentiometers, were used to monitor the flexural properties of the spar caps during characterization.

Fig. 7 shows the flexural strain for both the thermoplastic and epoxy spar caps measured by two strain gauges (left and right), and the digital image correlation. From the three-point bending characterizations, the flexural stiffness of the epoxy spar cap was 43.2 ± 1.7 GPa, and the flexural stiffness of the thermoplastic spar cap was 40.4 ± 1.7 GPa, about a 6% difference. This difference is within the experimental uncertainty, showing that even at a larger scale the thermoplastic resin performs similarly to a traditional epoxy resin.

With similar properties to traditional epoxies, and the improved seawater-saturated properties as highlighted by Davies [1], as well as the recyclability and manufacturing cost savings, these new thermoplastic resins have the potential to be a game-changing material in the tidal energy industry. Recent work has also shown that these materials can be thermally welded together, resulting in potentially higher strength bonds than adhesives that are currently used [11].

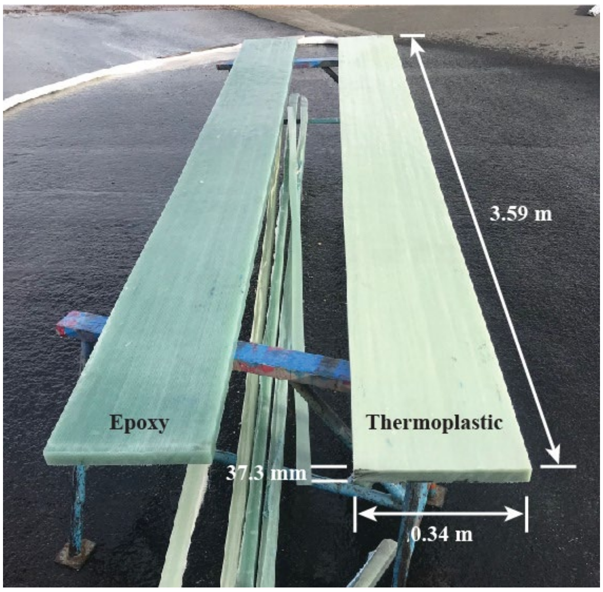



Fig. 5. Hexion epoxy resin fiberglass spar cap and Elium thermoplastic resin spar cap.

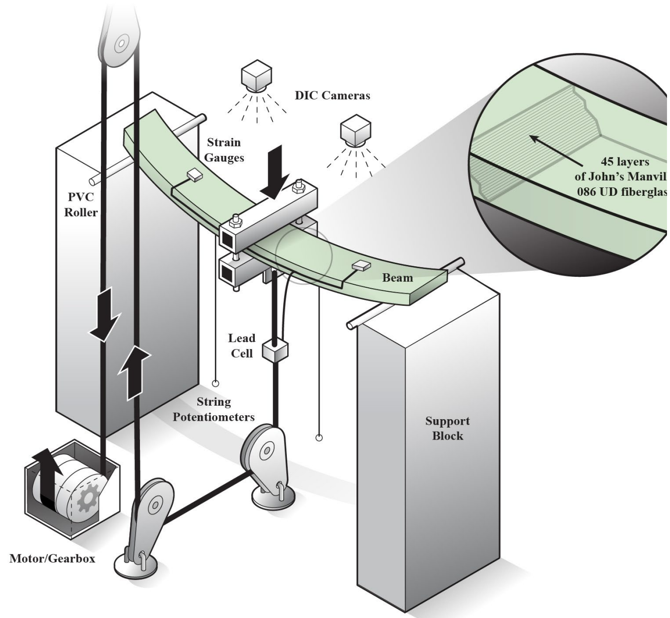



Fig. 6. Three-point bending spar cap characterization setup schematic showing beam, support blocks, strain gauge, and string potentiometers, and the DIC cameras. *Illustration by John Frenzl, National Renewable Energy Laboratory*

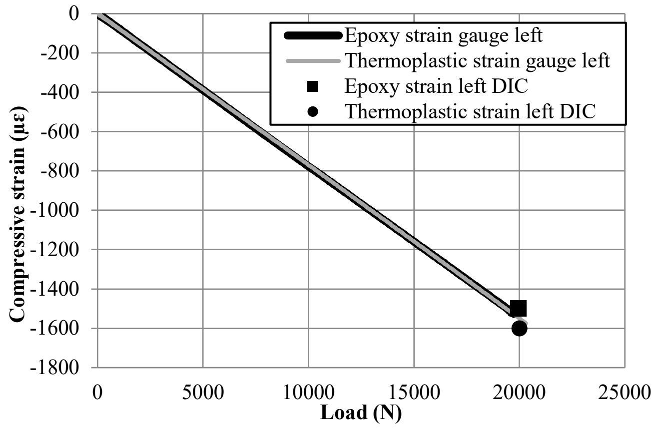



Fig. 7. Strain measured by strain gauges and DIC as a function of applied load (compression)

## IV. Manufacturing of Demonstration Blade

Traditionally, the tidal energy industry has used manufacturing processes such as 5- or 6-axis computer numerical control (CNC) machining of aluminium material to produce model-scale blades, or CNC machining of aluminium, steel, or MDF wood to produce tooling to be used in a composite infusion process. This machining process is time consuming and expensive and limits the number of blade geometries that can be validated. The development of a process to manufacture blade tooling quickly and cost effectively means that turbine developers can iterate blade designs efficiently and try many variations of different designs.

As a demonstration of one potential method to achieve this objective, a Stratasys 3D printer was used to manufacture acrylonitrile butadiene styrene (ABS) material tidal turbine blade tooling for a 400-mm-long model-scale blade. The 3D printer was a fused deposition modelling printer, meaning that it heated a thermoplastic filament to its melting point and then extruded, layer by layer, to create a 3D object. The tooling geometry was developed in CAD software. For a 400-mm-long blade, it required 500 g of raw materials and took 8 hours to print each half of the mold. After printing, the surface of the mold was covered with off-the-shelf Teflon tape and released with four coats of Chemlease RB EZ release coat (selected based on compatibility with the thermoplastic resin used to make the blade). Fig. 8 shows one side of the final printed tooling, with and without the Teflon coating.

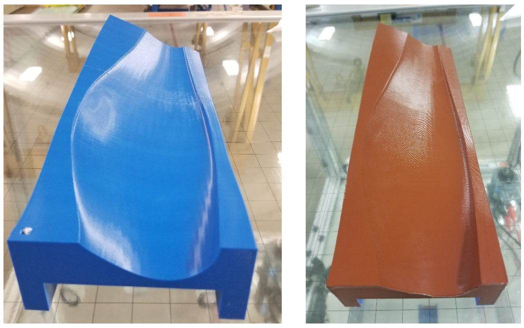


Fig. 8. (left) 3D-printed mold, ABS material; (right) 3D-printed mold with Teflon tape surface preparation

The 400-mm-long blade that was outlined in the modelling section was manufactured using the VARTM manufacturing process and Elium thermoplastic resin. The 3D-printed tooling was placed on a glass infusion table, and the carbon fiber was laid up on the mold as shown in Fig. 9. The entire part was put under a vacuum and the infusion front proceeded from the leading edge across the blade skin to the trailing edge. Because this resin polymerizes at room temperature, after the infusion, the part was left on the tool to cure. The total infusion/cure process took about 2 hours. The blade skins were then demolded, trimmed, and bonded together with an epoxy adhesive.

To create a smooth surface finish of the blade, clear polyurethane was sprayed onto it. A total of three layers of clear coat were added to the surface of the blade, as shown in Fig. 10. Root inserts were not included at this time but could be incorporated into the infusion process. Further, a foam or other material core could be incorporated into the blade as desired. The final blade is shown in Fig. 11.

Fig. 9. (left) infusion process; (right) blade skins in mold after infusion

Fig. 10. (left) adhesive bonding process; (right) wet sanding and surface preparation

Fig. 11. Final blade

## V. CONCLUSION AND FUTURE WORK

The outcome of this work is a fast and low-cost methodology for rapid prototyping of small-scale tidal turbine blades. A proof-of-concept blade was manufactured as a demonstration of this method. Additionally, a new thermoplastic resin material was investigated as a structural material for tidal turbine blades. This material was used in the demonstration blade.

An ANSYS model was used to study the stress patterns of the prototype blade using thermoplastics and aluminium. The use of a composite software application allowed the investigation of the integrity of the composite blade layer by layer, thereby showing the advantages of reinforcing the root of the blade. Future work will include more detailed modelling to optimize the blade design for a thermoplastic composite materials.

## ACKNOWLEDGEMENT

This material is based on work supported by the U.S. Department of Energy's (DOE's) Office of Energy Efficiency and Renewable Energy (EERE) under the support of Task 4.2 of the Institute for Advanced Composites Manufacturing Innovation (IACMI), Award Number DE-EE006926 managed by John Winkel from DOE and John Unser from IACMI. As well as funding from EPSRC "Dynamic Loadings on Turbines in a Tidal Array (DyLoTTA)" EP/N020782/1 EPSRC "United Kingdom Centre for Marine Energy Research" EP/P008682/1. Academic and national laboratory partners for the IACMI component of this project are Derek Berry and David Snowberg (NREL), Aaron Stebner (Colorado School of Mines), Nathan Sharpe (Purdue), Dayakar Penumadu and Stephen Young (University of Tennessee), and Douglas Adams (Vanderbilt). The industrial consortium for this project was led by Dana Swan (Arkema), Mingfu Zhang (Johns Manville), and Stephen Nolet (TPI Composites). The views and opinions of authors expressed in this paper or referenced documents do not necessarily state or reflect those of the U.S. government or the identified collaborating partners. Authors acknowledge that important insight and ideas were obtained from academic and industrial collaborators during the project activities who are not being formally acknowledged in this manuscript as co-authors. Materials supplied, and manufacturing methods developed by the industrial collaborators are gratefully acknowledged.

This work was authored [in part] 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 Wind Energy 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.

## REFERENCES


1. P. Davies and M. Arhant, "Fatigue Behaviour of Acrylic Matrix Composites: Influence of Seawater". *Applied Composite Materials*, 2018. p.
2. D. S. Cousins, Y. Suzukia, R. E. Murray, J. R. Samaniuk, and A. P. Stebner, "Recycling glass fiber thermoplastic composites from wind turbine blades". *Journal of Cleaner Production*, 2018. **209**: p. 1252-1263.
3. R. E. Murray, S. Jenne, D. Snowberg, D. Berry, and D. Cousins, "Techno-Economic Analysis of a Megawatt-Scale Thermoplastic Resin Wind Turbine Blade". *Renewable Energy*, 2018. **Available online 11 July 2018, In Press, Accepted Manuscript**: p.
4. R. E. Murray, D. Swan, D. Snowberg, D. Berry, R. Beach, and S. Rooney. "Manufacturing a 9-Meter Thermoplastic Composite Wind Turbine Blade". In *ASC 32nd Technical Conference*. 2017. Purdue University, USA.
5. M. A. R. Ellis, T. O'Doherty, S. Ordonez-Sanchez, A. Mason-Jones, K. Johannesen, and C. Johnstone. "Design process for a scale horizontal axis tidal turbine blade". In *4th Asian Wave and Tidal Energy Conference*. 2018. Taipei.
6. K. Porter, S. Ordonez-Sanchez, T. Nevalainen, S. Fu, and C. Johnstone. "Comparative Study of Numerical Modelling Techniques to Estimate Tidal Turbine Blade Loads". In *Asian Wave and Tidal Energy Conference*. 2016. Singapore.
7. S. Ordonez-Sanchez, M. Allmark, K. Porter, R. Ellis, C. Lloyd, I. Santic, and C. Johnstone, "Analysis of a horizontal-axis tidal turbine performance in the presence of regular and irregular waves using two control strategies. ". *Energies*, 2019. **12** (3): p.
8. IACMI. "The Composites Institute Facilitates Thermoplastic Composite Development for Wind Turbine Blades through Innovative Project". [2017; Available from: http://iacmi.org/2017/01/17/iacmi-composites-institute-facilitates-thermoplastic-composite-development-wind-turbine-blades-innovative-project/.
9. A. S. Dylan Cousins, Dayakar Penumadu, Stephen Young, David Snowberg *Elium and Epoxy Composite Structural Comparison* in *IACMI 4.2 Project Deliverable* 2018.
10. A. International, *Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials D 790*. 2002.
11. R. E. Murray, J. Roadman, and R. Beach, "Fusion Joining of Thermoplastic Composite Wind Turbine Blades: Lap-Shear Bond Characterization". *Renewable Energy*, Submitted 2018. **RENE-D-18-03815**: p.