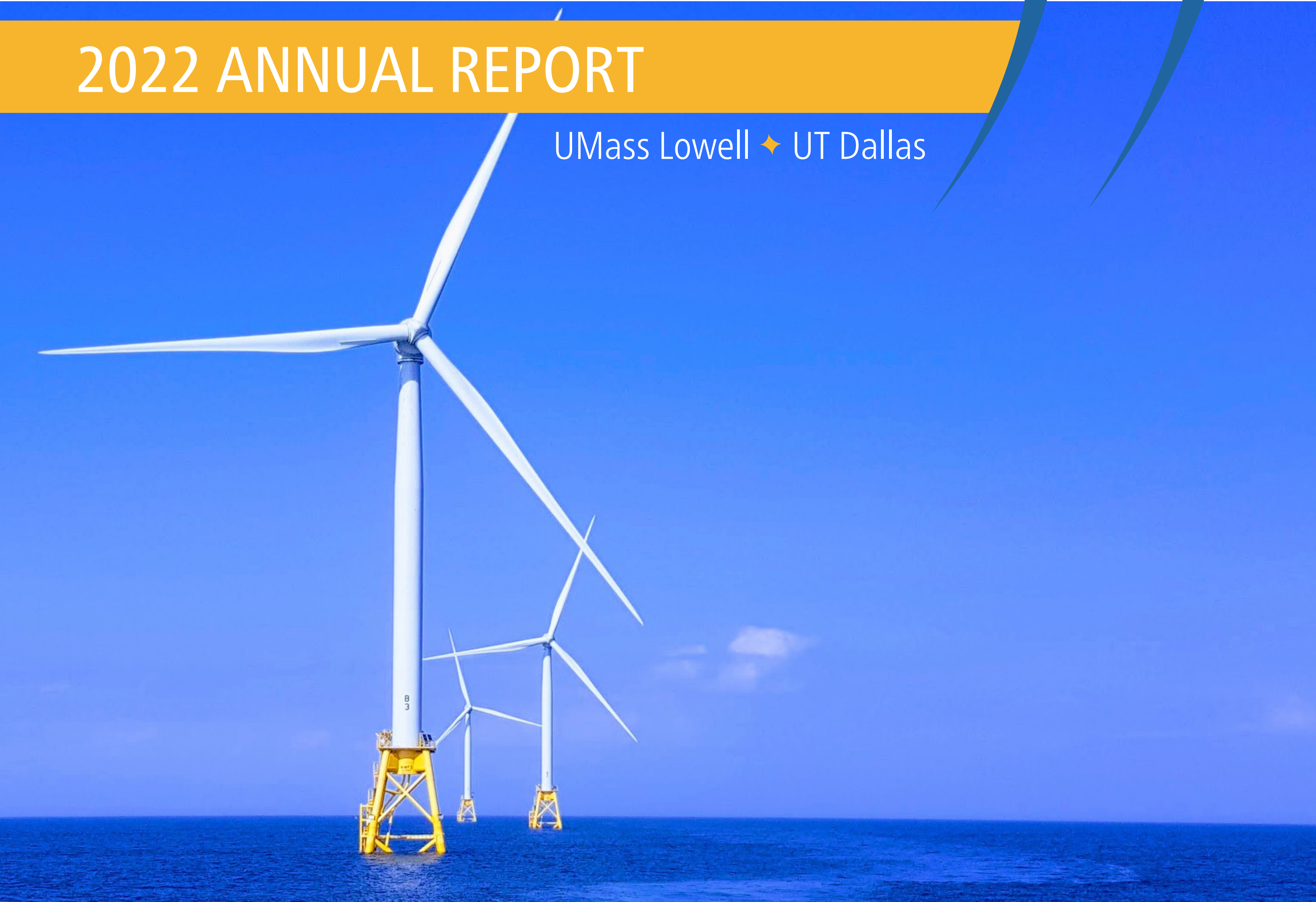
WindSTAR

Wind-Energy Science, Technology, and Research
Industry/University Cooperative Research Center

2022 ANNUAL REPORT

UMass Lowell ✦ UT Dallas



MESSAGE FROM OUR CENTER DIRECTORS

Center Director
Christopher Niezrecki, Ph.D.
University of Massachusetts Lowell

Site Director
Mario Rotea, Ph.D.
University of Texas at Dallas

Dear IAB Members,

On behalf of the WindSTAR I/UCRC Directors and Faculty members, we would like to thank you for your continued support and membership. We're proud of what we've accomplished having faculty and students work side by side with company members. We have finished our third year as a Phase II Center having completed dozens of projects, published numerous papers, had multiple M.S. and Ph.D. students graduate (several have been hired by member companies and national labs), implemented software and hardware systems that are in use by the WindSTAR company members, and created a new WindSTAR Webinar Series. For every dollar coming from a Full IAB member, $19 are invested in the Center from another source. Without operating through the National Science Foundation's I/UCRC program, this level of commitment and value to industry would not be possible.

We're proud to say that the WindSTAR Center exceeds national norms compared to other I/UCRC's, in all areas including Research, Center Administration, and Center Meetings. Dennis Gray, the WindSTAR NSF I/UCRC evaluator stated, "WindSTAR is one of the best organized I/UCRCs I have ever worked with."

Every year WindSTAR continues to grow and more people in the wind industry are learning that the Center is a platform that enables universities, industrial partners, and government to collaborate on developing novel solutions to wind energy problems. As we progress, we will continue to grow the Center, strengthen existing collaborations, and increase awareness of WindSTAR within the wind industry. In 2023, we believe there will be many new growth opportunities due to increased interest in the decarbonization of the electric grid and the planned U.S. procurements for offshore wind energy.

The WindSTAR Center is working to improve the performance, availability and resilience of wind energy conversion systems. Results from projects have provided valuable data to Center members who have acquired various multi-million dollar grants augmenting their R&D capacity. Through continued advancements in technology, we believe that wind power will be a major player in improving the sustainability of the Nation's electricity portfolio and enable new applications of this renewable source of energy. We are happy you are participating in the WindSTAR I/UCRC and look forward to working with you in the years to come.

Sincerely,
Christopher Niezrecki, Ph.D.
Distinguished University Professor, Mechanical Engineering
Co-Director, RIST Institute for Sustainability and Energy
Co-Director, Structural Dynamics and Acoustics Systems Laboratory
Director, WindSTAR I/UCRC
University of Massachusetts Lowell

Mario A. Rotea, Ph.D., F. IEEE
Professor, Mechanical Engineering
Professor (affiliate), Electrical and Computer Engineering
Director, Center for Wind Energy (UTD Wind)
Site Director, WindSTAR I/UCRC
University of Texas Dallas

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A NATIONAL SCIENCE FOUNDATION SUPPORTED INDUSTRY-UNIVERSITY COLLABORATION DRIVING DOWN THE COST OF WIND POWER

MISSION STATEMENT

The mission of WindSTAR is to bring together university and industry researchers to conduct basic and applied research on topics important to wind industry members. The Center combines capabilities, facilities, and knowledge to execute projects of interest to industry partners, train students in advanced technologies, and foster a community for industry/university networking and collaboration.

WindSTAR is an NSF-funded Industry/University Cooperative Research Center for Wind Energy, Science, Technology and Research, established in 2014. A collaboration between UMass Lowell, the University of Texas at Dallas, and its members, the Center aims to solve the pressing needs of the wind industry.

The University of Massachusetts Lowell is the lead WindSTAR site and focuses on projects that advance the materials, manufacturing, reliability, testing, modeling, and monitoring of turbines as well as energy storage, transmission and zero-carbon fuel generation. The University of Massachusetts Lowell is a public national research university in Lowell, Massachusetts.

The University of Texas at Dallas is a WindSTAR site with foci on high-fidelity simulation of wind power systems and components, LiDAR measurements and analysis of wind fields for diagnostics and model validation, wind tunnel testing, control system design for wind turbines and wind farms, large rotor design, grid integration and energy storage, data analytics for forecasting, performance and health assessment. The University of Texas at Dallas is a public research university in Richardson, Texas.

IAB MEMBER COMPANIES

WindSTAR's industry membership is diverse across the wind energy supply chain, including wind farm owner and operators; turbine, blade and tower manufacturers; material suppliers; condition monitoring & control electronics manufacturers; actuator technology developers; and other organizations with a stake in the growth of the wind energy market.

2022-2023 IAB Chair
Brandon Fitchett
Program Manager, Wind Power R&D
Electric Power Research Institute (EPRI)

2022-2023 IAB Vice Chair
Max Peter
Technology Partnership Manager
GE Renewable Energy

2021-2022 IAB Chair
Brian Hill
General Manager North America
Bachmann Electronic Corp

2021-2022 IAB Vice Chair
Brandon Fitchett
Program Manager, Wind Power R&D
Electric Power Research Institute (EPRI)

Past IAB Chairs:
2020-2021: Nathan Bruno, Westlake Epoxy
2019-2020: Neal Fine, Arctura
2018-2019: Nicholas Althoff, GE Renewable Energy
2017-2018: Ben Rice, Pattern Energy
2016-2017: Steve Johnson, GE Renewable Energy
2015-2016: Justin Johnson, EDP Renewables
2014-2015: Steve Nolet, TPI Composites, Inc

ARCTURA

AVANGRID RENEWABLES

bachmann.

eDF renewables

edp Renewables

EPRI ELECTRIC POWER RESEARCH INSTITUTE

GE Renewable Energy

LEEWARD renewable energy

MASSACHUSETTS CLEAN ENERGY CENTER

Nikon

Olin EPOXY

Pattern

tpi

Westlake Epoxy

WindESCo

Windscape AI

Xcel Energy

Previous Members include:

Huntsman
Keuka Energy
LM Wind Power
Maine Composites Alliance
National Instruments
NRG Renew
Texas Wind Tower

FINANCIAL OVERVIEW: RETURN ON INVESTMENT

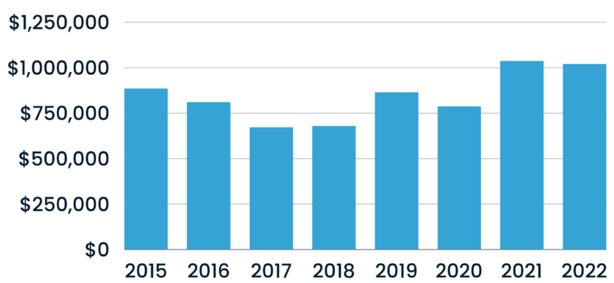
MEMBERSHIP LEVELS 2021-2022

Full Membership
$44,944 Annually

Small Business Associate
$16,856 Annually

CUMULATIVE INVESTMENT

TOTAL INVESTMENT: $6,737,886



NSF Awards
(Award # 1916715, 1916776, 1362022, 1362033)
$1,421,054

University Contribution (Cost Share)
$1,488,927

IAB Contributions
$3,300,397

In-Kind
$ 527,508

THRUST AREAS (PROJECT COUNTS ARE CUMULATIVE)

- (A) Composites and Blade Manufacturing - 24 Projects
- (B) Structural Health Monitoring, Non-Destructive Inspections, and Testing - 11 Projects
- (C) Wind Farm Modeling and Measurement Campaign - 9 Projects
- (D) Control Systems for Turbines and Farms - 2 projects
- (E) Energy Storage and Grid Intergration - 1 Project
- (F) Foundations and Towers - 5 Projects

2021-2022 PROJECTS

- Structural Wind Blade Repair Optimization
  Project ID: A1-21
- Long-Term Environmental Durability of Adhesive Joints
  Project ID: A3-21
- Cure Cycle Optimization of Low CTE Adhesives for Wind Turbine Blade Bondlines
  Project ID: A4-20
- Design of VARIM Process Based on A Digital Twin Approach
  Project ID: A4-21
- Analysis/Interpretation of Data Collected Using Robust Acoustic Blade Monitoring Sensors
  Project ID: B1-21
- Decision Support OpenFAST Digital Twin-Component Loads and Control System Extensions
  Project ID: B4-21
- Observations, Characterization and Modeling of Blockage for Utility-scale Wind Farms
  Project ID: C1-21
- Determining Best Practices for YAW Control In Real Window Farms
  Project ID: D1-21
- Wake Steering Control On Complex Terrain Under Time-varying Flow
  Project ID: D2-21
- Co-located Wind Farm and Hydrogen Plant Energy System Study
  Project ID: E1-21
- Assessment of Wind Turbines' Structural Dynamic and Foundation Integrity Using Optical Motion Amplification
  Project ID: F1-21
- Cost-Effective-Mobile-Retractable Meteorological Mast to Support Lidar Measurements
  Project ID: U1-22
- Development of a Unique Fiber-Optic Epoxy Resin Cure Sensor for Wind Turbine Blades
  Project ID: U2-22

For a cumulative list of all center projects 2014-2021 visit uml.edu/WindSTAR

RECENT CENTER EVENTS

Webinar Series:

- Enhanced Lightning Protection for Wind Turbine Blades, Neal Fine and John Cooney, Arctura, May 11, 2022

IAB Meetings:

- University of Massachusetts Lowell, June 15-16, 2022
- University of Texas at Dallas, January 26-27, 2022

Invited Keynote Speakers for Center Banquets:

- Beyond LCOE: wind-based power plants and energy systems, Dr. Katherine Dykes, Head of Section, System Engineering and Optimization, Department of Wind Energy, Technical University of Denmark, January 27, 2022
- Robotic Blade Care for the Wind Industry, Dainis Kruze, Chief Executive Officer, Aerones, June 15, 2022

Structural Wind Blade Repair Optimization

Principal Investigators:
Mariana Maiaru (University of Massachusetts Lowell)

Co-Principal Investigators:
Scott Stapleton, Christopher Hansen
(University of Massachusetts Lowell)

Student Researchers:
Michael Olaya, Evgenia Plaka, Joseph McDonald
(University of Massachusetts Lowell)

IAB Mentors:
Steve Nolet, Amir Salimi, Alexander Krimmer (TPI Composites)
Paul Ubrich, Nathan Bruno, Mirna Robles (Westlake Epoxy)
Ben Rice (Pattern Energy)
Jian Lahir (EDP Renewables)
Nicholas Althoff (GE Renewable Energy)
Ron Grife (Leeward Renewable Energy)
Rajesh Turakhia, Yi Ling Liang (Olin Epoxy)

Damaged wind turbine blades are typically repaired on-site and up-tower, which can take several days to complete. The time-consuming repair process can be attributed to the complexity and difficulty in accessing the damaged sections, as well as the need to replace and cure the fiber-reinforced composite (FRC) materials used in state-of-the-art blade design. As repairs are performed on-site, environmental conditions such as the temperature and relative humidity can have an impact on the steps necessary to rehabilitate the blade, and ultimately on the final properties of the restored structure. Currently, there are no best practices to repair damaged blades effectively, and each repair varies with respect to environmental conditions as well as the unique geometry and FRC materials used in each repair. Insights on the effect of these parameters thus presents opportunities for repair optimization to reduce the turbine downtime.

This work builds upon the material characterization of resin systems (infusion, hand lamination, bonding paste) commonly used in turbine blade repairs the computational tools developed in the previous years of this project. Four tasks which coupled experimental and computational work were executed during this year's project. A larger and more complex lab-scale experiment was performed, involving a balsa core as a repair material and heat blanket as the curing source, and validation of the computational tools developed in previous years and advanced in this years' work was performed. An additional laminate repair scenario which considered the hot plate as the heat source, was experimentally performed and modeled by finite element methods, to enhance the on-site repair application's portfolio. Preliminary experimental investigation of the thermal properties of a cured resin was performed to establish an appropriate methodology for measuring the thermal properties as a function of cure. Long-term absorption quantification of a composite substrate was performed to set a baseline for worst-case scenarios when evaluating the effect of moisture on adhesion strength of repairs to the existing blade structure. The knowledge gleaned from these tasks has been studied and implemented in ongoing development of the on-site repair tool/application for on-demand cure cycle optimization. The app now features a preliminary graphical user interface (GUI) designed for ease-of-use by repair personnel, and work continues on migration to an open-source platform more mobile device usage. This work continues to address and contribute to providing insight into factors which influence every repair, including environmental conditions, extent of the damaged area, and material systems used in state-of-the-art blade rehabilitation efforts. Ultimately, an understanding of these critical parameters offers a way to analyze and optimize each repair in a way that has never been done before. Through computation and experiment, the potential of extended repair season and thus cost savings for owners and operators is possible.

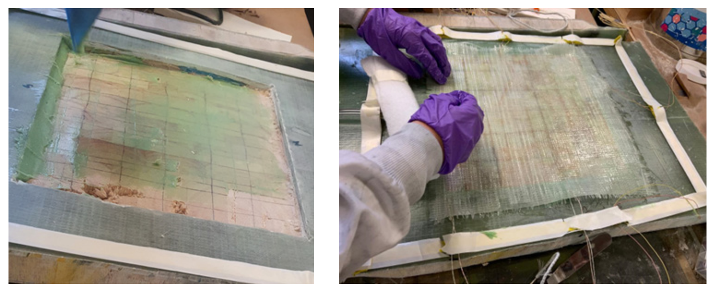


Figure 2. Thin bonding adhesive layer applied to balsa core (left) and e-glass fiber and resin plies were hand laminated to the panel (right).

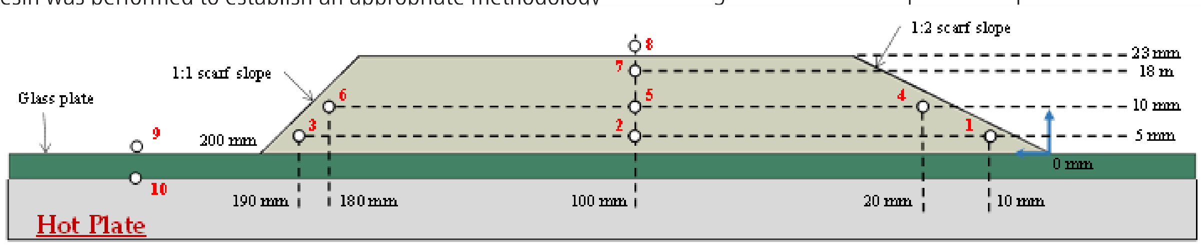


Figure 1. Schematic of the lab-scale laminate with thermocouple labels shown in red. Note that thermocouple node 8 is located on the top of the patch, between the vacuum bagging and the peel ply.

PROJECT ID: A1-21

Long-Term Environmental Durability of Adhesive Joints

Principal Investigator:
Amir Ameli (University of Massachusetts Lowell)

Student Researcher:
Nahal Aliheidari (University of Massachusetts Lowell)

IAB Mentors:
Paul Ubrich, Nathan Bruno (Westlake Epoxy)
Yi Ling Liang (Olin)
Steve Nolet (TPI Composites)

The long-term durability and reliability of structural adhesives employed in wind turbine blades are vital. Water ingress over a long time period can cause degradation in the composite/adhesive joints such that adhesive failure has become one of the leading causes of the blade's malfunction. Therefore, understanding and quantification of long-term durability in adhesive joints of wind turbine blades (WTB's) are vital. There is however no established accelerated method that can address this issue.

This research focuses on the establishment of a framework that will enable the lifetime prediction of in-service joints and the optimization of new joint designs. The residual mechanical properties (e.g., fracture toughness) are correlated to the aging condition (time, temperature, and relative humidity) using an Environmental Index. The framework unites fracture mechanics, open-faced accelerated hygrothermal aging, exposure Environmental Index, and finite element modeling. Open-faced specimen method significantly reduces the aging times.

This is a multi-year project. In the first year, as Figure 1 illustrates, the following tasks have been performed: a) substrate surface preparation, b) hygrothermal aging characterization by gravimetric measurement and diffusion modeling, c) evaluation of the mechanical performance of the aged adhesives, and d) establishment of the fracture specimen making, aging, and testing procedures for fresh and aged joints.

The results revealed that plasma treatment offers higher wettability according to the lower contact angle and higher free energy compared to the untreated substrate. For hygrothermal behavior, gravimetric measurements (both water adsorption and desorption) were conducted on two different adhesive systems using bulk adhesive wafers. The absorption was conducted under various environments (temperatures of 40, 50, and 60°C and RH values of 42, 75, and 96% for 17 days) and the desorption (drying) was conducted at vacuum oven at 40°C. Preliminary diffusion modeling results revealed that water absorption follows the simple Fickian behavior while desorption has a non-Fickian behavior. It was also found that the retained water never reaches zero after drying. To evaluate the permanent mechanical damage resulting from hygrothermal aging, tensile testing, and differential scanning calorimetry were conducted on fresh and aged/dried adhesives. A considerable drop in the modulus and strength was observed after aging while the change in the strain at break was not significant. ASTM D7905M was followed to fabricate the 3-point bending specimen and the adhesive and substrate thicknesses were modified to assure that the specimen would experience cohesive failure. The fracture test was performed on a universal testing machine with a speed of 0.5mm/min. the data reduction and an analytical method were used to obtain mode II critical strain energy release rate.

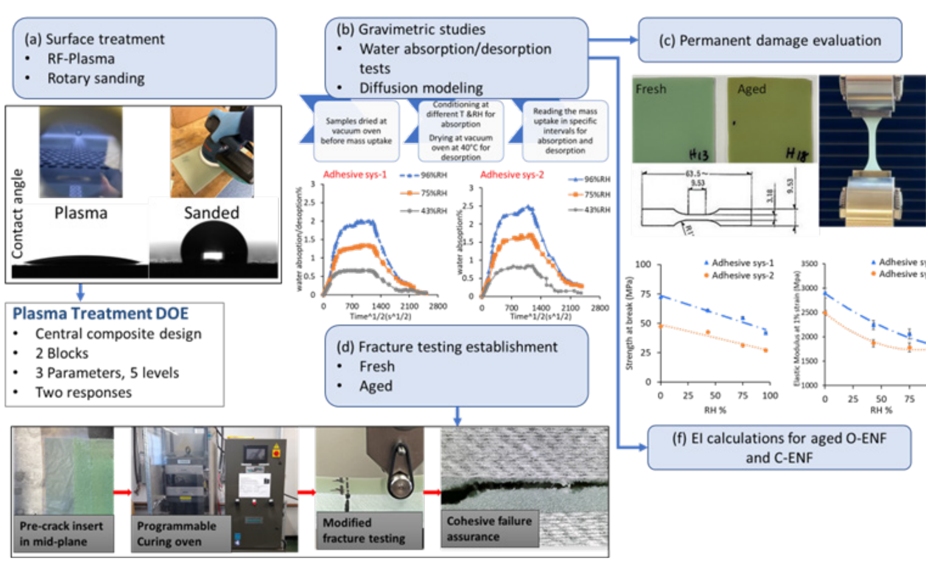


Figure 1. The graphical abstract of the project illustrates steps (a) to (f) of the experimental and modeling methodology established for the long-term environmental durability of adhesive joints

PROJECT ID: A3-21

Cure Cycle Optimization of Low CTE Adhesives for Wind Turbine Blade Bondlines

Principal Investigator:
Scott Stapleton (University of Massachusetts Lowell)

Co-Principal Investigator:
Mariana Maiaru (University of Massachusetts Lowell)

Student Researchers:
Samuel Hurvitz, Hengameh Ghaffari, Jamal Husseini (University of Massachusetts Lowell)

IAB Mentors:
Amir Salimi (TPI Composites)
Steve Nolet (TPI Composites)
Paul Ubrich (Westlake Epoxy)

Wind Turbine blade manufacturers often choose very long and conservative cure cycles for thick adhesive bond lines because they want to avoid damage to the adhesive's mechanical properties from elevated temperatures during curing. Furthermore, low coefficient of thermal expansion (CTE) adhesives were used for this experiment because it is suspected that they could handle faster curing cycles better than regular adhesives that have been used in previous studies. To explore solutions to the question of how fast can thick bondlines be cured without harming the structure, this research explores leveraging simulations and curing models to optimize the curing cycle for wind turbine blades. First, the heat generation during curing of the adhesive was characterized using Digital Scanning Calorimetry (DSC). The results from DSC were used to calculate the constants needed in the Prout-Tomkins cure kinetics model. With the cure kinetics model characterized for two low CTE adhesives, a validation experiment was conducted in the lab to see if heat profiles in these two adhesives could be accurately predicted using the model. The validation experiment was repeated for each low CTE adhesive for 3 different thicknesses of the bondline to prove that the model was robust enough to handle different geometries. The results of one set of these experiments are shown in Figure 1. After validation was conducted, the curing cycle was optimized, and an economic assessment was conducted to see how much profit could be gained from the time savings to justify this type of analysis. An example of looking at curing over time in the 2D blade cross section model can be seen in Figure 2. This study found that much faster cure cycles could be safely utilized, and that the additional profit amounts to several thousand dollars per blade.

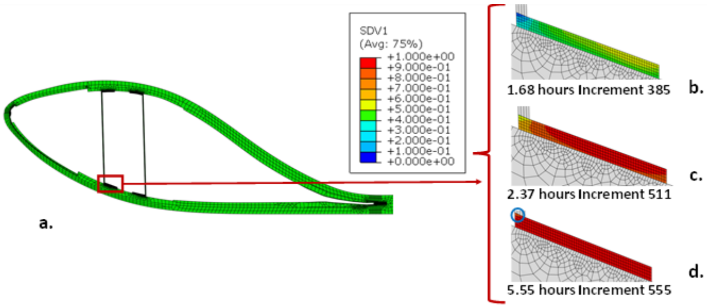


Figure 2. a) is the full 2D blade model with the bottom left shear web called out. Figure b), c), and d) are contours of the fraction of cure during different time steps in the simulation. Figure d) has the top left corner of the shear web circled because it is the last area to cure in the entire model.

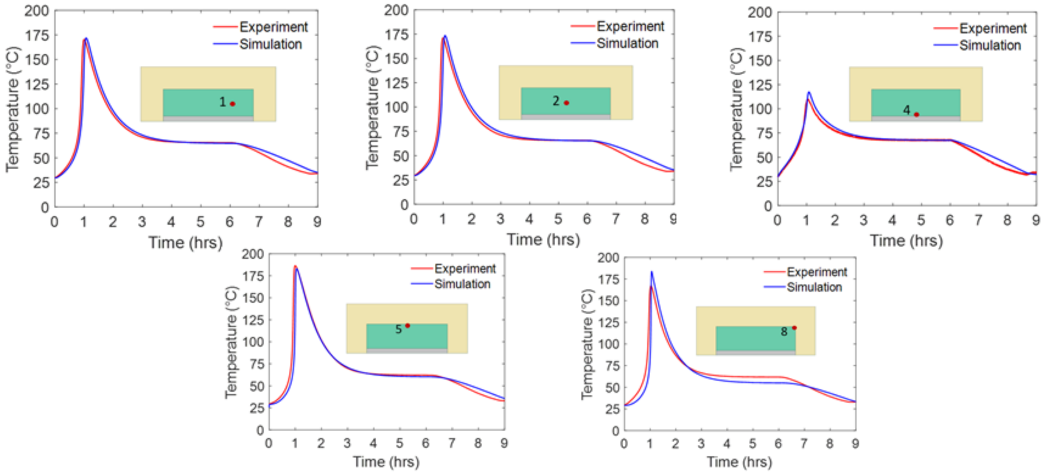


Figure 1. FE model of predicted temperatures and temperature sensor reading for G3-NEO adhesive system with a 26 mm thick adhesive layer

PROJECT ID: A4-20

Design of VARIM Process Based on A Digital Twin Approach

Principal Investigators:
Dong Qian, Hongbing Lu (University of Texas at Dallas)

Student Researchers:
Runyu Zhang, Yingjian Liu, Huiluo Chen
(University of Texas at Dallas)

IAB Mentors:
Stephen Nolet (TPI Composites)
Yi Ling "Ivan" Liang, Huifeng Qian (Olin Epoxy)
Paul Ubrich, Nathan Bruno, Mirna Robles (Westlake Epoxy)

The manufacturing of large wind turbine blades requires well-controlled processing conditions to prevent defect formation and thus produce high-quality composite blades. Physics-based models provide accurate computational capabilities for the epoxy resin infusion and curing process for the glass fiber composites, but they suffer from high computational costs, which makes it infeasible for fast prediction and process control during manufacturing. In light of the limitations, we describe a machine learning (ML) approach that employs a deep convolutional and recurrent neural network model to predict the spatio-temporal temperature distribution during the vacuum assisted resin infusion molding (VARIM) process. The ML model is trained with the "big data" that are generated from the physics-based high-fidelity simulation. Once fully trained, it serves as a digital twin of the blade manufacturing process. For validation purposes, a lab-scale infusion experiment of the composite laminate plate is performed. The trained and validated ML model is then extended to predict the effects of critical VARIM processing parameters. With the predictive accuracy of above 95% and over 100 times faster computation than the physics-based simulations, the proposed ML approach establishes a powerful and general framework for a digital twin of the composite manufacturing process.

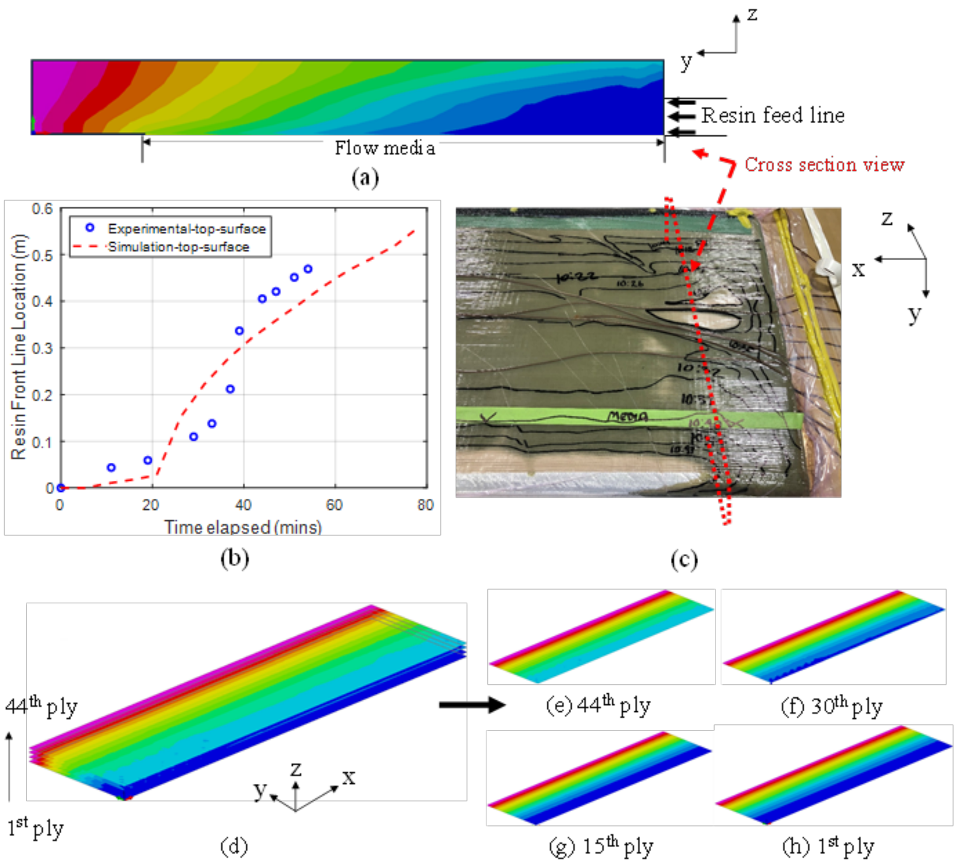


Figure 1. Calibration process of heterogeneous permeabilities of the glass fiber composite: (a) The 2D transverse y-z cross-section of the finite element infusion simulation results; (b) Comparison of the epoxy resin front flow on the top surface from the experiment and the simulation results; (c) An image of the VARIM experiment showing the cross sections used in the calibration process as marked by the red dashed line; (d) 3D visualizations of the epoxy resin infusion simulation results; (e-h) Infusion results from the 3D model on different plies of the composite.

PROJECT ID: A4-21

Interpretation of Data Collected using Robust Acoustic Blade Monitoring Sensors

Principal Investigator:
Murat Inalpolat (University of Massachusetts Lowell)

Co-Principal Investigators:
Christopher Niezrecki, Yan Luo
(University of Massachusetts Lowell)

Student Researchers:
Caleb Traylor, Fei Zhou
(University of Massachusetts Lowell)

IAB Mentors:
Nathan Post (WindSECo)
Ben Rice (Pattern Energy)
Lothar Breuss (Bachmann Electronic Corp)
Adam Johs (EDP Renewables)
Ilsa Maria Silekens (Shell)

Currently, operating wind turbine blades do not have a structural health monitoring system. There are several methods of detecting damage for wind turbine blades that have been investigated; however, each of these approaches has drawbacks, both in terms of cost and challenges to implementation in operational wind turbines. The proposed detection system would be low-cost and capable of monitoring a wind turbine blade in operation. To date, published wind farm acoustic studies have only included external sound analysis but not the sound transmitted inside the wind turbine blades. An acoustic monitoring technique has been developed based on the principle of acoustic transmission loss through the blade when the blade is damaged, i.e. more sound will leak into or out of the internal blade cavity compared to when it is undamaged. This would allow for automated data collection on the health of the turbine blade while the turbine is still in operation. Recently, sensors were shipped to a wind farm to be installed in an operational wind turbine for long duration testing. With this extended testing, the actual sound pressure levels and environmental and operational effects on damage detection will be studied. These real-world recordings will be analyzed with machine learning and damage identification techniques that were developed during previous blade experiments. Additionally, the sensors will be redesigned for improved reliability, with specific focus on protecting from temperature, vibration, and lightning effects. This blade monitoring method can be applied to new turbines, and existing turbines as a retrofit as will be demonstrated in this project. The monitoring system enables damage to be detected before it becomes catastrophic. This would reduce the need for total blade replacement and allow unscheduled emergency maintenance to be replaced with scheduled minor repairs. This will reduce turbine down time (increasing energy production), and decrease operational costs (reducing the LCOE).

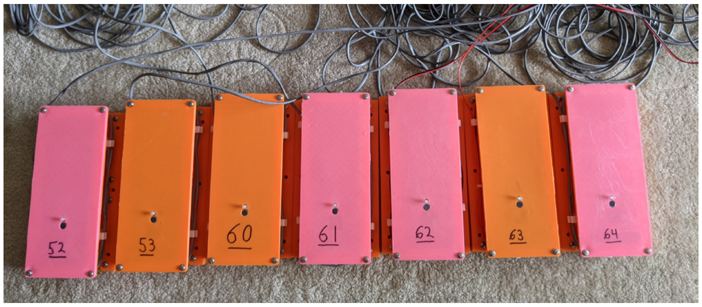


Figure 1. Acoustic monitoring sensors implemented on a wind turbine in this project.

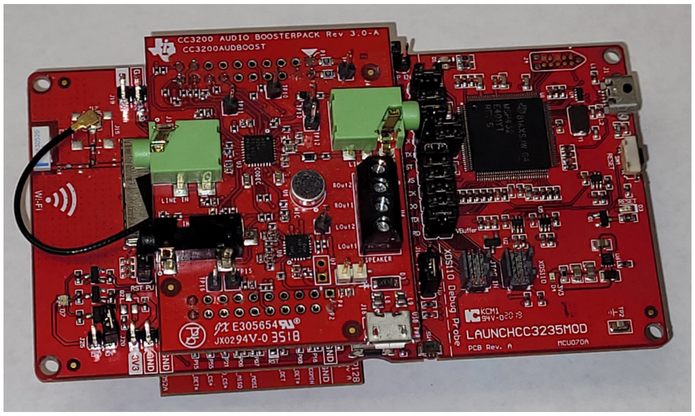


Figure 2. The electronics used within the acoustic sensor.

PROJECT ID: B1-21

Decision Support with OpenFAST Digital Twin – Component Loads and Control System Extensions

Principal Investigator:
Todd Griffith (University of Texas at Dallas)

Co-Principal Investigator:
Mario Rotea (University of Texas at Dallas)

Student Researchers:
Chang Liu, Ipsita Mishra (University of Texas at Dallas)

IAB Mentors:
Adam Johs (EDP Renewables)
Brandon Fitchett (EPRI)
Lothar Breuss, Brian Hill (Bachmann Electronic Corp)
Ron Grife (Leeward Renewable Energy)
Benjamin Rice (Pattern Energy)
Neal Fine (Arctura)
Nathan Post (WindESCo)
Nick Smith, Wouter Haans (Shell)

Accurate numerical tools for both design and asset management are one of the key needs for achieving and maintaining a market-competitive levelized cost of energy (LCOE) throughout the lifetime of the turbine. This research project addresses this need by developing and evaluating a new approach for creating an aero-servo-elastic digital twin model. The overall aim of this project is to deliver wind turbine aero-elastic models for existing turbines to support decision-making in wind farm operations. Maximizing the revenue of an operating wind fleet requires making decisions involving power performance, component maintenance costs, and selection of performance upgrades. In the developed technique, experimental data from an operating wind turbine is used to calibrate the properties of a baseline turbine model to represent the loads and dynamic behavior of the target wind turbine of interest.

The focus of the current study for the B4-21 project has been to deliver the following results: (1) an OpenFAST digital twin aero-elastic model for an actual operating wind turbine (selected by the WindSTAR IAB) of size 3-5+ MW, (2) Implementation of higher-fidelity component models for life-extension use cases (e.g.; detailed blade models, failure models for pitch actuators), and (3) extension of control system in digital twin model (e.g.; individual pitch control); with simulated use cases documenting loads analysis and LCOE impacts of the digital twin for decision support. Each of these results were completed, documented and presented to the WindSTAR members.

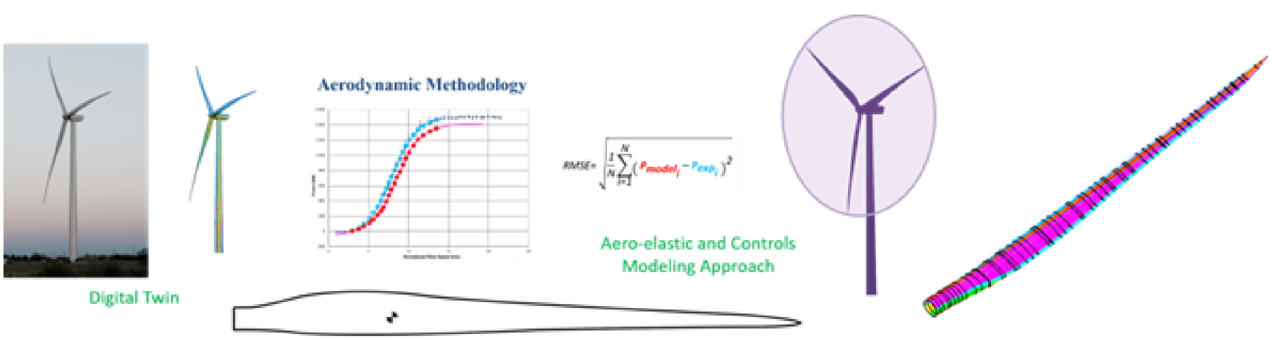


Figure 1. Graphic representation of the digital twin model development process: (1) Experimental data such (such as power curve data) is used to calibrate model parameters at the turbine-level for the aerodynamic, structural, and control system elements of the aero-servo-elastic model, (2) higher-fidelity component models (e.g.; for blades) can also be integrated into a multi-fidelity digital twin model.

Observations, Characterization, and Modeling of Blockage for Utility-scale Wind Farms

Principal Investigator:
Giacomo Valerio Iungo (University of Texas at Dallas)

Student Researchers:
Matteo Puccioni, Coleman Moss, Stefano Letizia
(University of Texas at Dallas)

IAB Mentors:
Clément Jaquet (GE Renewable Energy)
Nick Smith (Shell)
Lothar Breuss (Bachmann Electronic Corp)
Brandon Fitchett (EPRI)
Neal Fine (Arctura)

The interaction between operating wind turbines and the incoming flow field can produce effects that include the reduction of velocity downstream of the turbines, referred to as wakes, as well as upstream of the turbine, referred to as induction. When turbines are installed in arrays, additional reductions in front of the turbines can occur, termed blockage. Wakes have been extensively studied by the wind energy community, but blockage has received much less attention. Blockage reductions usually occur only on a scale of a few percent, which can easily fall under the instrument or statistical uncertainty. Over time, however, the wind speed reduction can account for up to a 2% reduction in the annual energy production of the farm. Thus, most studies of blockage have been performed with computer simulations while field data are lacking. This project utilizes profiling and scanning LiDARs installed before and after the installation and operation of a row of utility-scale turbines to capture field data on blockage effects.

The profiles are assessed using k-means clustering and random-forest machine learning algorithms to understand the climatology of the site. These novel methods reveal the high occurrence of noncanonical flows for the site as well as interesting velocity profiles such as low-level jets. Further definition of unique characterization parameters and application of a binning analysis show blockage effects of up to 3% reduced wind speed, varying with inflow conditions and distance from the operating turbines. Analysis of the scanning LiDAR data shows velocity reduction in the form of wakes trailing from the operating turbines as well as velocity increases in the channels between the turbines. These effects vary with incoming flow conditions as well. These results confirm other studies on blockage, give a better understanding of the variability of blockage due to inflow conditions, and show promise in improving new models for blockage.

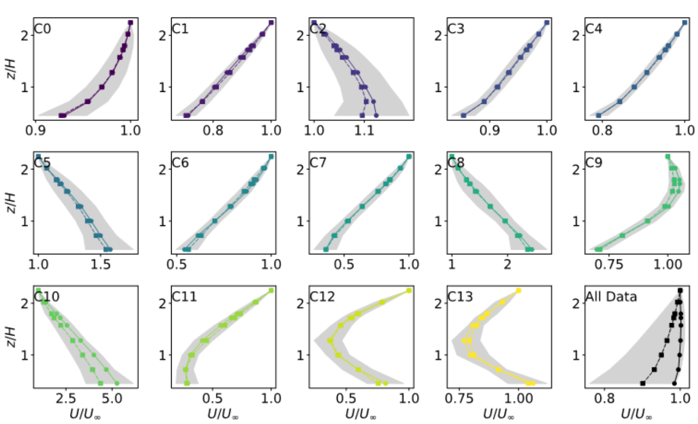


Figure 1. Profiling LiDAR velocity profile clusters generated via k-means clustering.

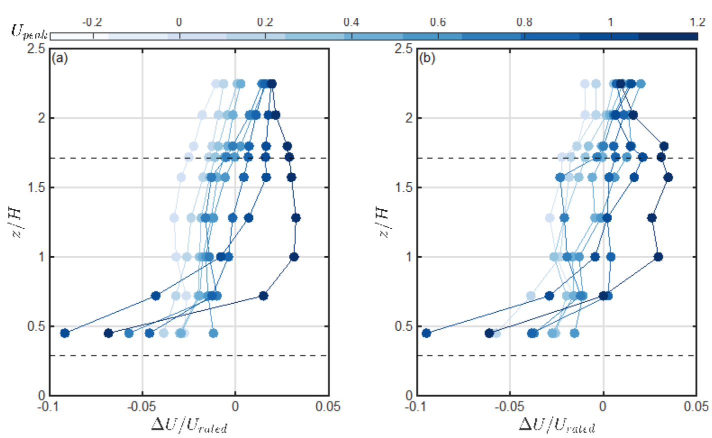


Figure 2. Median (a) and mean (b) differences between freestream profiling LiDAR and profiling LiDAR 1.5D upstream of an operating turbine for various bins in novel parameter Upeak showing reductions of up to 3%.

PROJECT ID: C1-21

Determining best practices for yaw control in real wind farms

Principal Investigator:
Stefano Leonardi (University of Texas at Dallas)

Co-Principal Investigator:
Mario Rotea (University of Texas at Dallas)

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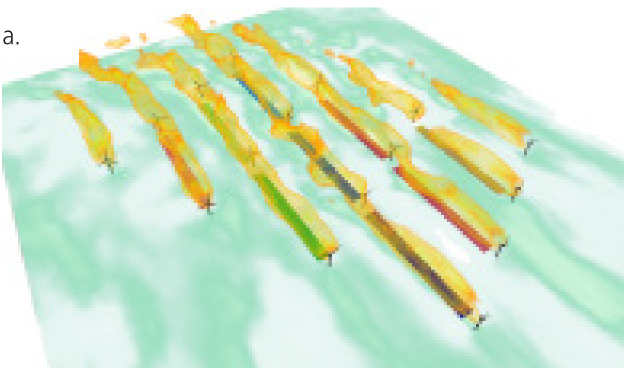
IAB Mentors:
Neal Fine, John Cooney (Arctura)
Lothar Breuss (Bachmann Electronic Corp)
Nathan Post (WindESCo)
Nick Smith, Wayne Jones (Shell)
Brandon Fitchett (EPRI)

The implementation of coordinated control strategy requires the knowledge of which clusters of turbines are coupled through wake. However, changing wind conditions require a tool that identifies in real time the cluster of turbines. In a previous study, we identified turbine clusters in real-time by evaluating the correlation among the power production signals of the turbines in the farm. In this study we reproduce the more challenging scenario with large-scale variation of the wind direction. We found that an actual power gain from yaw control is obtained only when the wind direction remains consistent over a prolonged amount of time. During transients of the wind direction, yaw control may result in power production losses respect to the individual control where all turbines are aligned with the wind direction. Therefore, the wind farm controller should be able to promptly identify variation in the wind direction to avoid power losses due yaw misalignment. The cluster identification methodology based on the correlation of the power production signals correctly identify such wind direction transition with a time within a few minutes.

Despite the success of coordinated yaw misalignment to optimize the power production of an array of aligned turbines, little is known on how the blockage and the secondary flow, induced by the wind farm, influence its performance under wake steering via yaw control. We found that the yaw angle must be consistent with the blockage and secondary motion induced by the wind farm. The application of yaw control may increase the load fluctuations on both upstream and downstream turbines, therefore decreasing the fatigue life of the turbine. In order to quantify the impact of the yaw control on the wind farm maintenance, we study the variation of the loads on the turbines due to the application of yaw misalignment under different levels of turbulence intensity. We found that the variation in the Damage Equivalent Load (DEL) depends on the direction of the yaw misalignment. In presence of low turbulence intensity, the application of yaw misalignment is found to induce critical increase of DEL mainly in the most downstream row of turbines.

We also studied the impact of the individual yaw controller on the performance of the single turbine, of the wind farm with and without imposed yaw misalignment. We tested different level of responsiveness of the individual yaw controller to estimate how that affects the power cumulative power production of the wind farm. It was found that changing the responsiveness of the individual yaw controller may increase the power production of the farm in presence of wake interaction while a low responsiveness of the individual yaw controller may hinder the power gain resulting from the application of coordinated yaw misalignment.

a.



b.

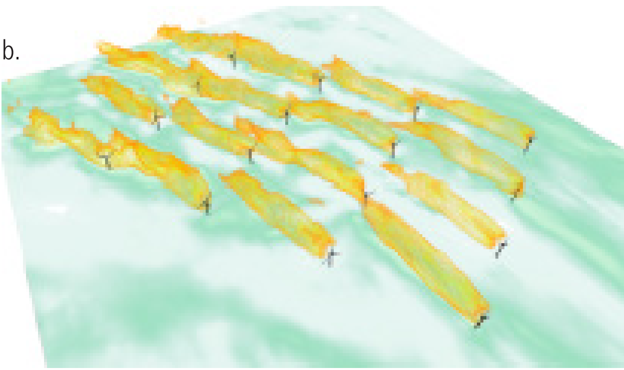


Figure 1. a) Turbine clusters (colored lines linking the turbines) superposed to color contours of velocity; b) color contours of velocity denoting the wake direction during a change on the incoming wind direction.

PROJECT ID: D1-21

Wake steering control within a wind farm on complex terrain under time-varying flow

Principal Investigator:
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John Cooney (Arctura)
Lothar Breuss (Bachmann Electronic Corp)
Danian Zheng (WindESCO)
Nick Smith (Shell)

The effectivness of wake steering control strategies for improving power production on flat terrains and steady wind flows has been demonstrated. However, this is not the case for wind farms on complex terrains and impinged by time-varying flows. Such operating conditions remain a challenge for optimizing the performance of existing control strategies in complex environments. In this project, we investigated these problems via systematically designed experiments and state-of-the-art Log-of-Power Extremum Seeking Control (LP-ESC) and Log-of-Power Proportional-Integral Extremum Seeking Control (LP-PIESC). Model turbines based on the layout of a real wind farm established on a complex terrain were fabricated and tested. The turbine blades were redesigned to achieve similar thrust and power coefficients compared to the utility-scale ones, and a servo motor was mounted on the base of each turbine to control its yaw angle. To achieve gusty incoming wind flows, rotatable grids controlled by servo motors were used to change the wind tunnel blockage ratio and therefore the instantaneous incoming wind speeds. Results from the static map show that, the wind farm power output can increase up to 9% with two of the first-row turbines yawing at -30o. The implementation of the LP-PIESC shows that the algorithm can find the unknown optimal yaw angles for the two turbines 30 to 40 times faster than the LP-ESC algorithm. Multiple runs were done and for each case across various initial yaw misalignment angles and incoming wind speeds, and the real-time algorithm converged to the vicinity of the unknown optimal yaw angles for both the turbines as predicted by the static map. We also evaluated the performance of the LP-PIESC in the presence of gusty winds. Results show that the LP-PIESC could find the unknown optimal yaw angles even in the presence of gusty winds.

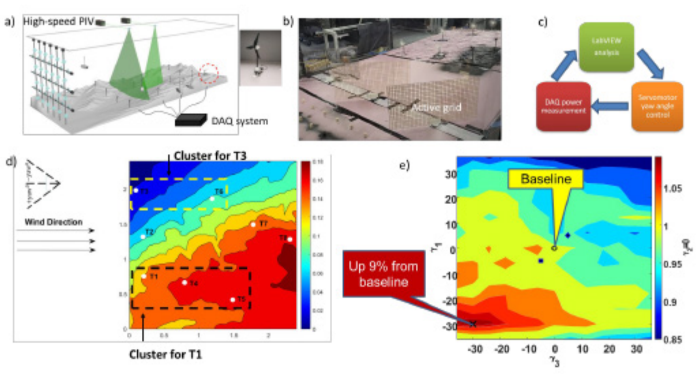

Figure 1. a) Schematic of experimental setup; b) Photograph of wind farm in wind tunnel; c) Control schematic for turbines; d) Turbine layout over complex terrain; e) Static map of wind farm power output.

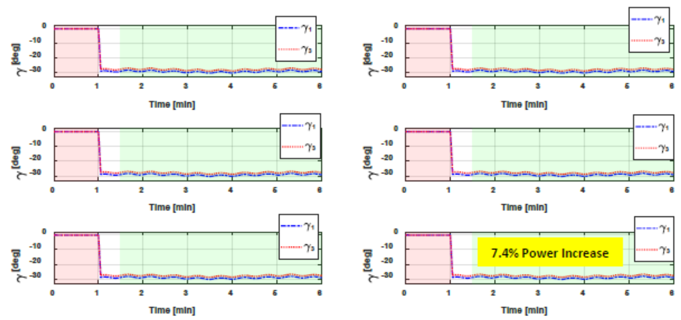

Figure 2. Turbines reaching optimal yaw angles with LP-PIESC for six different runs. Run increasing total power by 7.4% shown in the bottom wight hand corner.

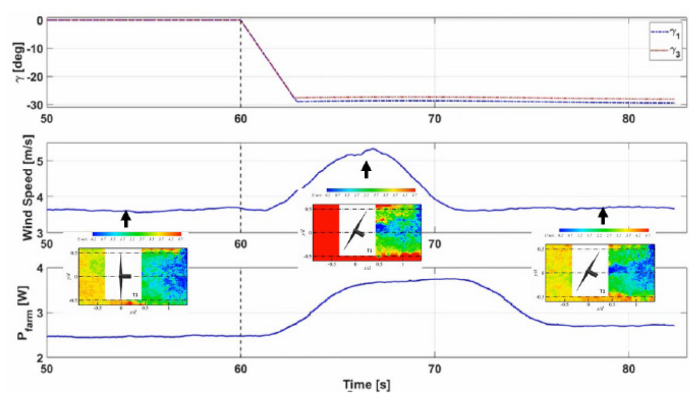

Figure 3. Coupling of wind gust (middle), total wind plant power (bottom) and turbine yaw angles (top) with LP-PIESC. The subplots show the snapshots of turbine yaw angle and streamwise velocity distributions during wind gust, where red color indicates higher wind speeds. (Wind speed and power signals are filtered).

PROJECT ID: D2-21

Co-located Wind Farm and Hydrogen Plant Energy System Study

Principal Investigator:
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Student Researchers:
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Yin Sun (Shell)
António Fayad, Marta Díaz Cosmen (EDP Renewables)
John Cooney (Arctura)

Green hydrogen produced using renewable electricity could play an important role in a clean energy future. This project seeks to analyze the techno-economic performance of integrated wind and hydrogen systems under different conditions. A co-located wind and hydrogen hybrid system is optimized to reduce the total system cost. We have adopted and improved a state-of-the-art techno-economic tool REopt, developed by the National Renewable Energy Laboratory (NREL), for optimal planning of the integrate energy system (IES). In addition to wind and electrolyzer components, we have also considered battery energy storage, hydrogen tank, and hydrogen fuel cell in the IES. The following three scenarios are investigated and compared in this study.

- Case I: Wind+Battery+Grid (Benchmark): A grid-connected wind energy system with a battery energy storage is considered to meet the electricity demand. Both the wind and battery storage systems can provide electricity during grid outages. The battery system could be charged from either the grid or the wind energy system, depending on the electricity price and wind energy production.

- Case II: Wind+Battery+Hydrogen+Grid: In addition to the setup in Case I, an electrolyzer is added in Case II. The electrolyzer can take electricity from both the grid and the wind system to produce hydrogen, depending on the electricity price, hydrogen price, wind power generation, and load demand.

- Case III: Wind+Battery+Hydrogen+Fuel Cell+Grid: In addition to the setup in Case II, a hydrogen storage tank and a hydrogen fuel cell system are added in Case III, which can supply electrical power to the grid when necessary. In addition to selling the hydrogen in real time, Case III allows the hydrogen to be stored for later use (through the fuel cell system) to provide electricity at peak load periods or during power outages.

Results show that (i) adding electrolyzers to the grid-connected wind energy system could reduce the total system cost by approximately 8.9%, and (ii) adding electrolyzers, hydrogen tank, and hydrogen fuel cells could reduce the total system cost by approximately 30%.

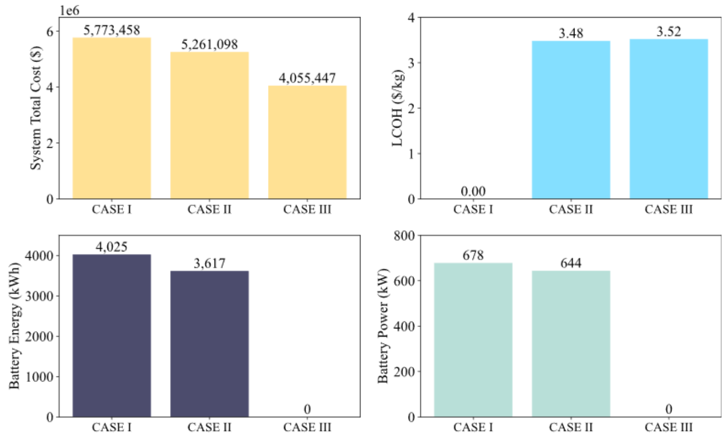

Figure 1. Comparing the three cases in terms of total system cost, levelized cost of hydrogen (LCOH), and battery capacity.

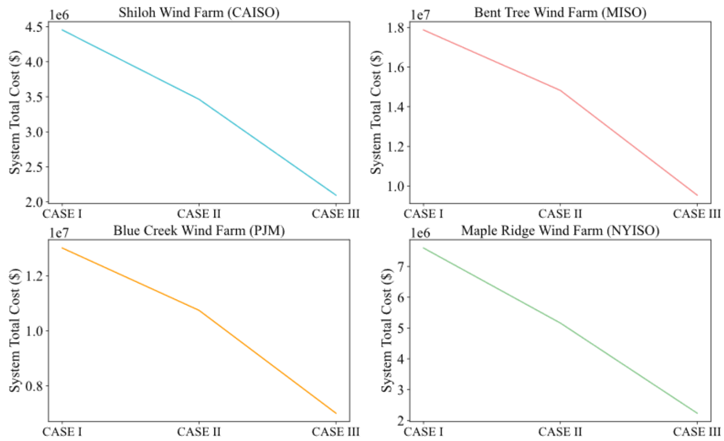

Figure 2. System total cost changes of four different wind farms in the three cases.

PROJECT ID: E1-21

Assessment of Wind Turbines' Structural Dynamic and Foundation Integrity Using Optical Motion Amplification

Principal Investigator:
Alessandro Sabato (University of Massachusetts Lowell)

Co-Principal Investigator:
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Mike Purcell (Leeward Renewable Energy)

An inexpensive, quick, and robust condition monitoring (CM) technique to assess the integrity of wind turbine foundations and components remains elusive. The most common techniques used to inspect the integrity of a foundation rely on destructive methods such as concrete cores or contact-based approaches that combine strain gage, accelerometer, and tiltmeter measurements. Because of the complexity of the inspection and the high cost per turbine, widespread interrogation and CM is not financially attractive or practical to implement. Due to the heavy dynamic loading conditions and the severe hazards of wind turbine failure, material testing of components during fabrication and active monitoring during turbine operation is necessary. Flaws or imperfections in the turbine components can increase fatigue stresses and the potential for catastrophic failure. Optical motion magnification (OMM) is a vision-based monitoring technique that is growing in popularity in the structural health monitoring (SHM) and modal analysis research communities. OMM algorithms take ordinary video, extract and magnify imperceptible motion of part of the structure, and highlight issues that may lead to failure. Not only can OMM produce qualitative magnified motion videos revealing the points of largest displacements in the object, but also quantitative analyses of displacement time histories and vibrational frequency spectra can be generated. The objective of this work was to study the feasibility of OMM as a quick, inexpensive, and non-invasive SHM method for wind turbine foundations and components. Firstly, a comparative study is performed on three OMM systems to determine the advantages and disadvantages of each respective algorithm. OMM has shown to be capable of measuring displacements as low as 3µm with an accuracy of ~95% compared to integrated accelerometer results. During the project, a set of field tests on several operating wind turbines (i.e., healthy and compromised) was performed to quantify the motion of i) the foundation; ii) the turbine's tower and nacelle; and iii) a utility-scale blade at the WTTC to characterize modal parameters. The field tests' results supported that OMM can quantify the motion of wind turbine blades and foundations that are consistent with traditional measurements. Finally, a study was also performed to determine the efficacy of different camera motion compensation methods. The outcomes of this project were very encouraging and showed how OMM could potentially eliminate issues inherent in traditional testing and monitoring processes.

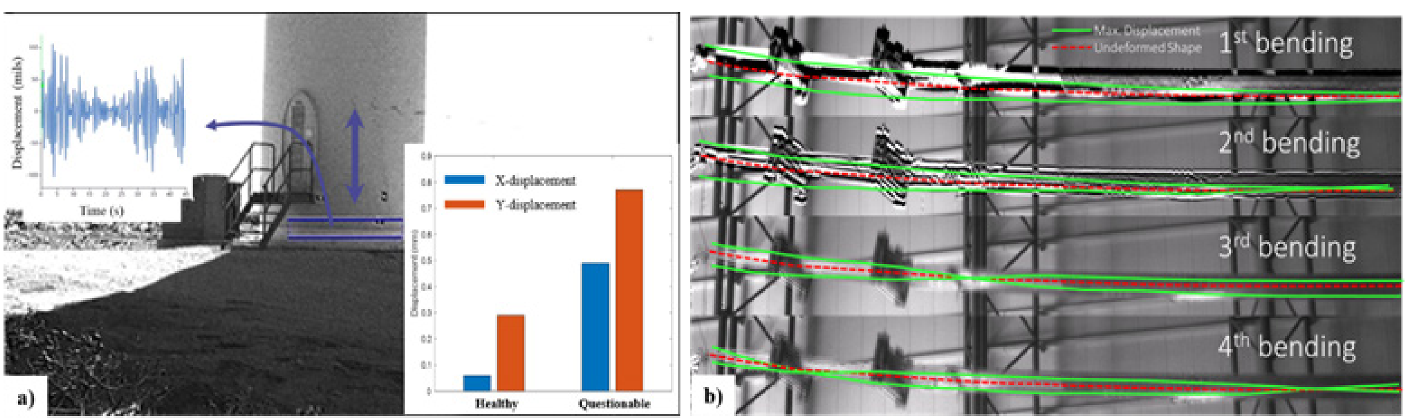

Figure 1. Outcomes of project F1-21: (a) Use of OMM for measuring the vertical and horizontal displacements of a wind turbine foundation for detecting healthy and questionable structures; and b) use of OMM for determining the natural frequencies and operating deflection shapes of a utility-scale wind turbine blade during a modal test.

PROJECT ID: F1-21

Cost-Effective-Mobile-Retractable Meteorological Mast to Support Lidar Measurements

Project Instructor:
Christopher Niezrecki (UMass Lowell)

IAB Mentor:
Teja Dasari (Xcel Energy)

Student Researchers:
Greg Regis, David DiPlacido, Dan Fedynyshyn, Nick Rasmussen (UMass Lowell)

The goal of this capstone was to design cost-effective mobile and retractable meteorological mast to support LiDAR measurements. The original design objectives were to raise sensors to elevations of 10m, 30m, and 40m for the purpose of wind/air condition data collection; however, without the use of guide wires, the maximum mast height of 15m was set. The mast also needed to be able to be transported to test sites via a trailer, towed behind a pickup truck and be able to be set up by a single person in ~15 minutes. After extensive analysis, the design settled with the use of a commercially-available retractable 30.5 m mast because it can be partially raised for un-guyed use and offered the flexibility to be used at greater heights if guide wires were utilized. The outrigger radius and needed trailer weight are dependent on mast height. This design provides for greater ease of scouting out new locations for wind farms, the ability to record more meteorological data will lead to wind farms being built in more efficient locations, and the optionally unguyed, non-permanent mast allows for data to more quickly and more easily be acquired in agricultural regions where farmers may not want the soil or crops to be disturbed.

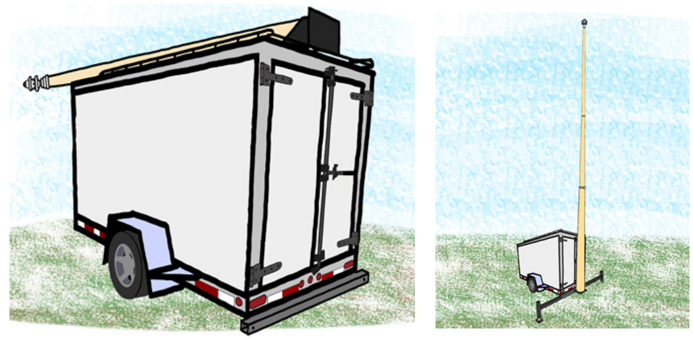

Figure 1. Concept drawings of the mobile-retractable meteorological mast

PROJECT ID: U1-22

Development of a Unique Fiber-Optic Epoxy Resin Cure Sensor for Wind Turbine Blades

Project Instructor:
Christopher Niezrecki (UMass Lowell)

IAB Mentor:
Steve Nolet (TPI Composites)

Student Researchers:
Connor Capobianco, Justin Cruickshank, Jacqueline Hayes, Shreyas Patel (UMass Lowell)

The goal of this capstone project was to design and fabricate a novel fiber-optic epoxy resin cure sensor to be used in the production of wind turbine blades to detect the exact stage of epoxy resin cure using fiber optics that have a similar index of refraction to the resin. Sensor should act as a wave guide and light passing through sample should decrease as resin cures. The fabrication of the sensors was challenging because the cleaving of fibers had to be precise to avoid light loss through the resin samples. Overall, the project furthered the design method for these sensors and prototypes were created with good preliminary results enabling the feasibility of these sensors to be used more widely.

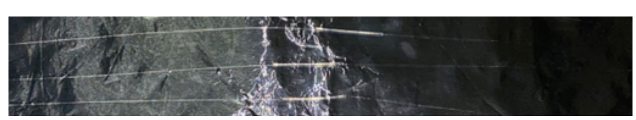

Figure 1. Fiber-optic epoxy resin cure sensor

Figure 2. Fiber-optic epoxy resin cure sensor with light passing through

PROJECT ID: U2-22

2020-2022 OUTCOMES

Through August 31, 2022

For a cumulative list of all center outcomes visit uml.edu/WindSTAR

Products:

1. Software: OpenFAST digital twin model developed for Gamesa 3.465MW turbine
2. Software: Multiphysical computational model for predicting process-induced residual stress and distortion in fiber-reinforced composites
3. Software: FAST Model V1.0: Aero-elastic Model
4. Software: Matlab code for cure optimization as a function of the repair thickness, kinetic of two resin systems as a function of temperature and humidity.
5. Software: A user-based subroutine written in Fortran for use in the finite-element software Abaqus, to calculate the degree of cure and temperature of an adhesive under exothermic curing reaction.
6. Software: A tool to simulate blade active load control systems using NREL FAST and any actuation system (plasma actuators in particular) that can command changes in the local lift coefficient along the blade span.
7. Software: A Matlab-based GUI that can predict the axial, transverse, and shear properties of composite laminates used in wind turbine blades based on CPFM advanced micromechanics model
8. Software: A Matlab based GUI for prediction of power production and wind turbine wakes for the Panhandle Phase II wind farm.
9. Software: Simulink code for Extremum Seeking Control of NREL CART3 (Controls Advanced Research Turbine, 3-bladed).
10. Patent: Foundation and Deflection Monitoring Device #10808374, Awarded 10/20/20.
11. Hardware: Fiber Optic Interrogator for Strain Monitoring
12. Hardware: Passive Acoustic Damage Detection System for Blades
13. Hardware: Active Acoustic Damage Detection System for Blades

Journal Papers:

1. Devesh, K., Rotea, M.A., Aju, E., & Jin, Y (2022). Wind plant power maximization via extremum seeking yaw control: a wind tunnel experiment. Wind Energy.
2. Shah, Sagar P., Sagar U. Patil, Christopher J. Hansen, Gregory M. Odegard, and Marianna Maiarù. "Process Modeling and Characterization of Thermoset Composites for Residual Stress Prediction." Mechanics of Advanced Materials and Structures, December 20, 2021, 1–12.
3. Cao, D., Malakooti, S., Kulkarni, V. N., Ren, Y., Liu, Y., Nie, X., Qian, D., Griffith, D. T., & Lu, H. (2021). The effect of resin uptake on the flexural properties of compression molded sandwich composites. Wind Energy.
4. Letizia, S., Zhan, L., & Iungo, G. V. (2021). LiSBOA (LiDAR statistical Barnes objective analysis) for optimal design of lidar scans and retrieval of wind statistics-part 1: Theoretical framework. Atmospheric Measurement Techniques, 14(3), 2065-2093.
5. Letizia, S., Zhan, L., & Iungo, G. V. (2021). LiSBOA (LiDAR statistical Barnes objective analysis) for optimal design of lidar scans and retrieval of wind statistics-part 2: Applications to lidar measurements of wind turbine wakes. Atmospheric Measurement Techniques, 14(3), 2095-2113.
6. S. P. Shah and M. Maiarù, "Effect of Manufacturing on the Transverse Response of Polymer Matrix Composites," Polymers, vol. 13, no. 15, Art. no. 15, Jan. 2021.

Conference Papers:

1. Letizia, S., Moss, C., Puccioni, M., Jacquet, C., Apgar, D., & Iungo, G.V. (2022). Effects of the thrust force induced by wind turbine rotors on the incoming wind field: A wind lidar experiment. Journal of Physics: Conference Series, 2265(2), 022033.
2. Li, H., Rahman, J., & Zhang, J. (2022). Optimal planning of co-located wind energy and hydrogen plants: A techno-economic analysis. Journal of Physics: Conference Series, 2265(4), 042063.
3. Yang, F., Pu, S., Akin, B., Butler, S. W., & Wang, G. (2021). Package degradation's impact on SIC mosfets loss: A comparison of Kelvin and Non-Kelvin Designs. 2021 IEEE Applied Power Electronics Conference and Exposition (APEC).
4. Zhang, N., Pu, S., & Akin, B. (2021). An automated multi-device characterization system for Reliability Assessment of Power Semiconductors. 2021 IEEE 13th International Symposium
5. Gondle, Raj K., Pradeep U. Kurup, and Christopher Niezrecki. "Evaluation of Wind Turbine-Foundation Degradation." In International Conference of the International Association for Computer Methods and Advances in Geomechanics, pp. 21-28. Springer, Cham, 2021.
6. Shah, Sagar, Evgenia Plaka, Mathew Schey, Jie Hu, Fuqiang Liu, Tibor Beke, Scott E. Stapleton, and Marianna Maiaru. "Quantification of Thermoset Composite Microstructures for Process Modeling." In AIAA Scitech 2021 Forum, p. 1774. 2021.
7. Sagar Shah, Marianna Maiaru – Effect of Manufacturing on the Transverse Response of Polymer Matrix Composites, ASC 2021, Proceedings of American Society for Composites
8. Gondle, R.K., Kurup, P.U., and Niezrecki, C. "Evaluation of Wind Turbine-Foundation Degradation," Paper accepted to the 16th International Conference of the International Association for Computer Methods and Advances in Geomechanics (IACMAG), Torino, Italy, May 5-8, 2021.

Selected Presentations:

1. Hammerstrom, B., Niezrecki, C., Jin, X., Cimorelli, J., "Estimate of the Wind Energy Needed to Replace Natural Gas with Hydrogen and Electrify Heat Pumps and Automobiles in Massachusetts," NAWEA/WindTech 2022 Conference, University of Delaware, DE, USA, September 20-22, 2022.
2. Diltz, N., Avitabile, P., and Niezrecki, C., "Assessment of Wind Turbine Foundation Degradation from Dynamic Measurements Made at the Nacelle," NAWEA/WindTech 2022 Conference, University of Delaware, DE, USA, September 20-22, 2022.
3. Yujie Zhang, Mario Rotea, Federico Bernardoni, and Stefano Leonardi, Wind Direction Estimation using Neural Networks , NAWEA/WindTech 2022 Conference, Newark, Delaware, September 20-22, 2022.
4. Aju, E., Kumar, D., Rotea, M., & Jin, Y. Wake steering of wind farm over complex terrain, APS Division of Fluid Dynamics Meeting 2022, Indianapolis, Nov 20-22, 2022
5. Mishra, I., Griffith, D.T., Sensitivity Analysis Of Wind Turbine Digital Twin Model To Uncertain Model Input Parameters, NAWEA/WindTech 2022 Conference, Newark, Delaware, September 20-22, 2022.
6. Moss, C., Puccioni, M., Maulik, R., Jacquet, C., Apgar, D., & Iungo, G.V., Machine Learning Analysis of Profiling Wind LiDAR Data to Quantify Blockage for Onshore Wind Turbines, NAWEA/WindTech 2022 Conference, Newark, Delaware, September 20-22, 2022.
7. Bernardoni, F., Ciri, U., Rotea, M.A., Leonardi, S., Identification of interacting turbines with time variant wind direction In: EAWE PhD Seminar 2021, November 3rd-25th, Porto, PT, 2021

8. Aju, E., Kumar, D., Rotea, M., & Jin, Y. (2021). On the wake dynamics, flow loading and power output of wind farms under wake steering control: a wind tunnel experiment. In APS Division of Fluid Dynamics Meeting Abstracts (pp. T27-009).

Master of Science Thesis:

1. Joseph McDonald – "Composites for Wind Turbine Blade Repair," M.S. in Mechanical Engineering, December 2021.
2. Diltz, Natalie Lynne. "Monitoring and Assessment of Wind Turbine Foundation Degradation." M.S. Thesis., University of Massachusetts Lowell, 2021.

PhD Dissertations:

1. Chang Liu, "Active Load Control of Wind Turbines Using Plasma Actuation," Ph.D. in Mechanical Engineering, University of Texas at Dallas, Fall 2022.
2. Caleb Traylor, "Computational Investigation into the Aeroacoustics of Wind Turbine Blades for Structural Health Monitoring," Ph.D. in Energy Engineering, UMass Lowell, August 2022.
3. Joshua Morris, "Design, Characterization, and Analysis Methods for Low Frequency Mechanical Metamaterials" Ph.D. in Mechanical Engineering, UMass Lowell, August 2022.
4. Sagar Shah, "Transverse Property Prediction of Thermosetpolymer Matrix Composites," Ph.D. in Mechanical Engineering, UMass Lowell, November 2022.
5. Federico Bernardoni, "Identification of wind turbine clusters for effective real time yaw control optimization," Ph.D. in Mechanical Engineering, University of Texas at Dallas, Fall 2022.
6. Matteo Puccioni, "Investigation on the organization of turbulence for high Reynolds-number boundary-layers through LiDAR experiments," Ph.D. in Mechanical Engineering, University of Texas at Dallas, Fall 2022.
7. Jaclyn V. Solimine, "Development of Robust, Data-Driven Damage Identification Techniques for the Passive Acoustics Based Structural Health Monitoring of Wind Turbine Blades", Ph.D. in Mechanical Engineering, UMass Lowell, December 2021.
8. Stefano Letizia, "Wind farm flow and power capture: optimal design of LiDAR experiments, flow physics, and mid-fidelity modeling," Ph.D. in Mechanical Engineering, University of Texas at Dallas, Fall 2021.

Interns at Member Companies:

1. Thor Westergaard, Intern at Leeward Renewable Energy, Summer 2020.
2. Stefano Letizia, recipient of WindSTAR NSF INTERN at UT Dallas, Intern at EDP Renewables.
3. Alessandro Cassano, recipient of WindSTAR NSF INTERN at UMass Lowell, Intern at TPI Composites, Spring 2020.

Students Hired at Member Companies:

1. Liliana Haus, MS,University of Texas at Dallas, EPRI
2. Sara Najafian, PhD, University of Massachusetts Lowell, TPI Composites

ACTIVE PROJECTS: 2022-2023

» **Machine Learning-Based Optimization of VARIM Process for Composite Blade**
Project ID: A1-22
PI: Dong Qian (University of Texas at Dallas)
Mentors: TPI Composites

» **Long-Term Environmental Durability of Adhesive Joints**
Project ID: A2-22
PI: Amir Ameli (University of Massachusetts Lowell)
Mentors: Westlake Epoxy, TPI Composites

» **Investigation of riblets on the performance of wind turbine blades**
Project ID: A3-22
PI: Yaqing Jin (University of Texas at Dallas)
Mentors: Arctura, Nikon, Shell

» **Improving Wind Blade Recycling**
Project ID: A4-22
PI: Stephen Johnson (University of Massachusetts Lowell)
Mentors: Olin Epoxy, EDP Renewables, EFP Renewables, TPI Composites, Shell

» **Structural Wind Blade Repair Optimization**
Project ID: A5-22
PI: Marianna Maiaru (University of Massachusetts Lowell)
Mentors: Olin Epoxy, Westlake Epoxy, EDP Renewables, EFP Renewables, TPI Composites

» **Development and Testing of an Integral Acoustic Blade Monitoring System**
Project ID: B2-22
PI: Murat Inalpolat (University of Massachusetts Lowell)
Mentors: Bachmann Electronic Group, EDP Renewables, WindESCo, GE Renewable Energy, Shell

» **Modeling Rotor-induced Effects on the Wind Resource for Onshore Wind Farms**
Project ID: C1-22
PI: Giacomo Valerio Iungo (University of Texas at Dallas)
Mentors: Xcel Energy, EDP Renewables, WindESCo, EDF Renewables, GE Renewable Energy, Shell

» **Short-term wind forecasting via surface pressure measurements**
Project ID: C2-22
PI: Armin Zare (University of Texas at Dallas)
Mentors: WindScape AI, EDF Renewables, Shell

» **FAST Digital Twin Model Creation: Numerical tools for custom model creation and validation**
Project ID: C3-22
PI: D. Todd Griffith (University of Texas at Dallas)
Mentors: Arctura, Bachmann Electronic Corp, EDP Renewables, WindESCo, EDF Renewables, Shell

» **LP-PIESC for wake steering via yaw control**
Project ID: D1-22
PI: Mario Rotea (University of Texas at Dallas)
Mentors: Arctura, Bachmann Electronic Corp, EDF Renewables,Shell

» **Wind Farm Foundation Monitoring Using Optical Motion Magnification**
Project ID: F1-22
PI: Alessandro Sabato (University of Massachusetts Lowell)
Mentors: EDP Renewables, Leeward Energy

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