Wind turbine blade leading-edge erosion: laboratory experiments and image processing under an engaged learning experience

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Abstract. This paper reports results from an engaged learning activity conducted within an integrated, multi-scale, multi-disciplinary project focused on wind turbine blade leading edge erosion. Actions and outcomes of a series of engaged learning activities by undergraduate and graduate students undertaken in spring 2019 are reported. In designing and conducting the numerical and laboratory experiments, the students learnt and applied a range of practical skills from 3D printing to working in the wind tunnel, creating controlled images and image processing techniques. The student team also engaged in substantial professional development and educational outreach activities.

1. Introduction
The levelized cost of energy from wind turbines (WT) has decreased substantially and onshore (land-based) WT are now the lowest cost, non-hydropower renewable electricity source. There are over 50,000 WT operating in the USA today [1]. Even if only a small fraction are experiencing excess leading edge erosion (LEE) and the associated reduction in annual energy production (AEP) [2], this represents tens or hundreds of millions of dollars per year in lost revenue to the industry (and individual wind farm operators). A key aspect of realizing continued cost efficiencies and lowering the levelized cost of energy from wind [3] is extending wind turbine blades lifetimes, and by association reducing the potential of excess leading edge erosion.

Impact fatigue caused by collision with rain droplets and hail stones is a severe problem for wind turbine blades. Although rain droplets fall at only modest velocities (of the order of 10 ms⁻¹), the tip of WT blades rotate quickly (70-140 ms⁻¹), thus the impact velocity (and kinetic energy transfer) is large. Each impact on the blade leading edge adds to the accumulated material damage such that eventually, the leading edge material may crack, causing a loss in the coating material and degrading the blade aerodynamics (and hence lift and electricity protection). Leading edge blade erosion (due in large part to precipitation impacts) is estimated to cause 1-5% reduction in annual energy production and blade repair/replacement to be a major source of O&M costs [2]. Comparison with the known largest causes of power production losses further illustrates the importance of WT LEE. Observed levels of curtailment...
over the eastern USA (i.e. deliberate down-rating of WT power production due to an inability to distribute that power) decreased AEP by ≤ 4% during 2007-2012 [4]. Total observed wake losses within land-based WT arrays (i.e. reduction in wind speeds due to the action of upstream WT) are estimated to decrease AEP by ≤ 5% [4,5].

LEE is inherently a multi-disciplinary issue (Figure 1) incorporating atmospheric science to quantify precipitation and hail climates [6-8], fluid dynamics and aerodynamics of wind turbines to model flow around blades [5,9], and mechanical engineering and materials science [10] to define how droplet impacts cause damage to composite materials [11]. It is also an issue that crosses a large expanse of temporal and spatial scales from the scale of thunderstorms (10^4 m) to the scale of droplet impacts (10^{-3} m) or that can occur during a single a large hail storm or accumulate over many years.

The overarching project in which the engaged learning is embedded comprises five work-packages:

i) Improved characterization of the precipitation erosion climate using both remote sensing data [8] and numerical modelling [7].

ii) Numerical modeling of flow around the blade [9] and raindrop collision with the blade [12].

iii) Laboratory experiments to investigate blade material properties.

iv) Laboratory tests to simulate conditions that lead to LEE.

v) Image processing of blade inspection images to quantify the type and extent of damage.

![Figure 1. Overview of the structure of the wind turbine blade leading edge erosion project](image)

The student projects focused on elements iii)-v). For this research WT blade sections were obtained from three sources (all are covered by Non-Disclosure Agreements (NDA)):

1. Manufacturer’s blades direct from the factory including both coated and uncoated blades. The sections are from close to the tip and about 0.4 m long.

2. Used blades from a local small wind turbine manufacture that operates with blades between 8-10 m long. The blades are coated and have an unknown history but visual inspection shows extensive LEE (Figure 2).

3. Blades recently removed from repowering at a NY wind farm. The blade sections of about 1 m length from near the tip were selected from visual inspection to show a range of damage from none to severely delaminated.

Further, a range of wind turbine blade inspection reports were supplied by a wind farm owner operator (again under an NDA).
The interdisciplinary and industry-relevant nature of LEE means that the project is well-suited to engaged learning courses. In this instance a range of pedagogic offerings at the senior undergraduate/masters student level within the Cornell College of Engineering were focused around different aspects of LEE. The primary courses involved were:

- Mechanical and Aerospace Engineering (MAE) MAE4120/4121 ‘Community Wind Energy Research’ (course cross-listed with Earth and Atmospheric Sciences EAS4120).
- MAE4900 Wind Energy Lab undergraduate research experience course.

Engaged learning encourages students to actively participate in their own learning (including via peer learning), to practice knowledge transfer across disciplines/contexts and to liaise with industry/community partners [13]. Thus, in this research the students have to; design the experiment(s), obtain access to appropriate facilities (including Makerspaces [14], and wind/water tunnels) and obtain appropriate materials (e.g. samples of coating materials). This paper briefly describes the overall project, but focusses on the student activities and their contributions to the overall project.

2. Precipitation climates

Improved characterization of precipitation climates at wind farm locations across the Continental United States (CONUS) is being undertaken using remote sensing observations from the National Weather Service (NWS) dual-polarization RADAR network [8] and high-resolution Weather Research and Forecasting (WRF) numerical simulations (at horizontal resolution of 1.3 km) [7]. These analyses are designed to quantify the relative importance of kinetic energy transfer from liquid (rain) and solid (graupel and hail) hydrometeors to the blade. Analysis of five years of five-minute data from dual-polarization RADARs at six sites distributed across CONUS has indicated high spatial variability in erosion potential (based on cumulative kinetic energy transfer) and that individual hail storms in the southern Great Plains may be sufficient to lead to cracking of blade coatings [8]. We are now evaluating the ability of the WRF to characterize such events when applied at horizontal resolutions of 1.3 km [7]. Initial results a simulation conducted over the southern Great Plains for June-July 2014 indicate some fidelity in terms of the occurrence of hail, but the WRF simulation exhibits a positive bias in terms of both the frequency and spatial extent of hail [7]. Ultimately, this research will be linked to the characterization of blade damage from different sites (see section 5) to determine whether there is a relationship between projected erosion climates (based on prevailing hydroclimate) and observed LEE in different locations around the USA.

3. Numerical simulations of blade aerodynamics and erosion

The purpose of this work is to improve the calculation of the kinetic energy transferred to the blade during precipitation events (section 2). Two key aspects are under investigation: (i) A model was developed in ANSYS-Fluent to simulate flow around the wind turbine with a view to characterizing blade collision efficiencies as a function of wind speed and hydrometeor particle size [9]. (ii) Numerical modelling for stress analyses of impacts from different raindrop sizes, impact speeds, and impact angles in order to generate fatigue damage estimates for the top coating and internal composite materials [12].
4. Laboratory experiments

Most WT blades use composites (e.g., epoxy or polyester, with reinforcing glass or carbon fibers) coated to protect the blade structure [15]. Thus, the leading edge actually comprises several layers of the main structural composite material (and thickening materials) and coatings. Given limited availability of blade sections for experimental research on LEE, the initial research involved fabrication of material specimens to replicate, as closely as possible, the properties of WT blade sections for use in developing the experimental workflow and for comparative analyses with actual blade samples. It is important to acknowledge that actual WT manufacture and materials are commercially confidential, that material properties of composites are challenging to characterize and that we can only approximate some of the blade material properties and cannot reproduce a full suite of material tests [16,17] available in commercial materials testing environments.

Students synthesized a range of samples using 3D printing in the MAE makerspace in two forms; small one-inch squares for hardness testing and dog-bones for strength/tensile tests. A number of configurations of fiberglass and carbon fiber were printed on the 3D printer and evaluated to establish which had material properties that were closest to the blade sections. We used five different fiber orientations of 3D printed fiberglass (FG), five different fiber orientations of 3D printed carbon fiber (CF), 3D printed and a sample nylon and a sample of the uncoated blade (Table 1). The hardness tests were performed using a Buehler Macromet 3000 hardness tester and employed two tests; the Rockwell 100E for substantial hardness and the 15W for surface hardness [18] (Figure 3, Table 1). Strain/stress tests were performed on an Instron tensile tester on 3D printed dog-bone samples using ASTM D683-14 [19] for the nylon sample and ASTM D3039M - 17 (Composites) [20] for the other samples. The Young’s Modulus describes the performance of the material in terms of its elastic behavior under loading. It is the ratio of the stress (force per unit area) to the strain (change in length per unit length) before deformation i.e. in the elastic region [17] (Figure 4, see Figure 5 for the study set-up). The Young’s modulus for the uncoated blade was $1.427 \times 10^6$ kPa. The closest of the samples tested was $1.376 \times 10^6$ kPa from the carbon fiber layer oriented in the configuration; 0, 45, 90, 135° (shown in Table 1 as 0 45 90 135). The closest ultimate strength results to the uncoated blade, which had a value of $7.419 \times 10^5$ kPa, was the uni-directional fiberglass (i.e. 0 Uni FG), which had a value of $4.925 \times 10^5$ kPa. Based on the materials testing, the samples reproduced for further laboratory experiments were 0 45 90 135 FG. These samples were then used in:

- An immersion experiment to simulate the effects of rainwater, seawater and humidity on the reproduced blade sample. The samples are soaked in pH-adjusted water or kept in humid (58 and 83%) conditions over time scales from a week to three months and the hardness testing repeated. Based on two weeks of soaking, no change in hardness (according to the Rockwell 100E hardness test) is observed but the FG in the most acidic sample (pH 5.4) is subject to visible damage i.e. the sample has started to breakdown.

- Experiments to reproduce leading edge erosion in the wind tunnel deployed in the Cornell high-voltage laboratory. The facility was selected because it has a suitable size section, it is possible to generate wind speeds of up to 20 m s$^{-1}$, and water droplets can be used in the test section. To reproduce damage a high-pressure hose was used to accelerate the process and approximate the energy transfer from the droplets to the blade surface that was needed to cause physical damage. The blade leading edge samples were scanned in 3D scanning facility at Cornell University and printed at half-scale in the MAE makerspace with uniaxial fiber aligned along the blade perimeter following the curvature of the test piece. A holder for the blade was designed and constructed in aluminum frame material (Figure 6a). The wind tunnel has a test section with dimensions of 122 by 91 by 142 cm and was run at a maximum wind speed of 13.2 m s$^{-1}$. The power washer has a pressure of 12.06 MPa with an adjustable nozzle, focused in this experiment to the narrowest beam. The diameter of the flow stream, $d$, is 2.8 mm and the volumetric flow rate, $r$, is 0.3634 m$^3$ hr$^{-1}$. Thus, the flow velocity, $v$, is 16.4 m s$^{-1}$ and the kinetic energy of the flow, $KE$, given by:

$$ KE = \frac{1}{2} \rho v^2 = \frac{1}{2} \rho \frac{n d^2}{2} v^3 $$

(1)
is 13.56 Js\(^{-1}\). Under the assumption that all the kinetic energy of the flow is transferred to the blade, the amount of energy required to create the damage observed (Figure 6b) is 4135 J. As shown in Figure 6b, the damage to the leading edge is a pit with raised material surrounding the hole. This implies that the continuous flow impact, created enough accumulated impact energy to break through the nylon casing and further damage the fiberglass. The damage did not spread past the impact zone. There were no cracks or fissures extending out from the pit in the material.

Table 1. Rockwell 100E and 15W laboratory printed and blade samples hardness results

| #  | Material       | 100 E (substantial) | 15W (surface) |
|----|----------------|----------------------|---------------|
| 1  | 0 45 90 135 CF | 14.5                 | 45.6          |
| 2  | 90 Uni CF      | 3.5                  | 57.4          |
| 3  | 45 Uni CF      | 6.3                  | 58.8          |
| 4  | 0 90 CF        | 14.7                 | 53.1          |
| 5  | 45 135 CF      | 11.2                 | 45.7          |
| 6  | 0 45 90 135 FG | 34.8                 | 36.1          |
| 7  | 90 Uni FG      | 20.7                 | 46.9          |
| 8  | 0 Uni FG       | 29.2                 | 44.5          |
| 9  | 0 90 FG        | 11.6                 | 41.3          |
| 10 | 45 135 FG      | 16.4                 | 46.7          |
| 11 | Nylon          | N/A                  | N/A           |
| 12 | Uncoated blade | 57.0                 | 70.1          |
| 13 | Coated blade   | N/A                  | 56.7          |
| 14 | Uncoated Blade 2 | 30.1        |                |
| 15 | Coated Blade 2 |                      | 83.2          |

Figure 3. Results of the two hardness tests (15W in dashed lines and 100E in solid lines ± 1 standard deviation) for; CF carbon fiber samples, FG fiberglass samples and for four coated/uncoated blade samples (Blade). The sample numbers correspond to the materials in Table 1.
Figure 4. Strain/stress results for the materials shown in Table 1.

Figure 5. Tensile testing the uncoated blade section.

Figure 6. a) Aluminum mounting of the 3D printed blade section and b) Photograph of the resulting damage to the blade section. Note the green lines are the approximate area of the leading edge and the angle of impingement was 30° resulting in damage just outside of the leading edge area.
A key aspect of project-based engaged learning is encouraging students to reflect upon their initial study design. In retrospect the student team concluded that the major error in their experimental design was the replication of materials for testing. They could have replicated the blade material properties more closely by 3D printing the mold and then layering FG sheets. 3D printers work by printing thermoplastics and fibers in layers. The layers start from the build platform and build on top of each other in a direction normal to the build surface. The printer prints plastic in the $xy$ plane, moves up one layer thickness in the $z$ direction, prints more plastic in the $xy$ plane, and repeats. In blade manufacturing FG sheets are laid on a mold, layer by layer to build the wind turbine blade with resin injection [10]. Because the sheets are laid on a mold, the layers are normal to the surface of the mold building the blade from the outside inwards. In this case, there is no single plane that the fibers are laid in but an infinite number of planes at the tangent point on the surface of the blade. Because 3D printers only print in one plane, there was no way they could replicate the entire blade with 3D printing with the right fiber orientations.

5. **Image processing**

To assist in understanding of LEE, thousands of images from blade inspection reports were provided to the group by a wind farm operator for seven wind farms around the US under an NDA. These images are generally taken manually when blade damage is observed or during end of warranty inspection. They therefore differ in terms of the image orientation (i.e. position of the blade within the image), lighting conditions, image resolution and the presence/absence of other components (e.g. cloud/ground/tower) within the image. This image variability presents many challenges to development of an automated methodology for determining the location of the leading edge, categorizing damage type, magnitude, depth etc [21].

A subjective classification was undertaken of a sub-sample of 246 of the images to provide a test set against which the automated image processing results could be evaluated. The samples are not random samples but were rather selected to represent a high frequency of damage conditions of various types. They are all from one wind farm that uses the same angle of photograph for the images and photographs all three blades when damage is noted on one (or more). Major delamination is present in 27% of images, while minor pits occur on only 4% of images (Table 2).

| Pit | Gouge | Minor delam. | Major delam. |
|-----|-------|--------------|--------------|
| Depth/diam (mm) | 0.5 | 2.5 | 3.8 | >3.8 |
| Blade images (%) | 4 | 24 | 44 | 27 |
| Identified (%) | 20 | 60 | 80 | 90 |

To further aid in the development of an automated image processing methodology a range of images controlled for light, camera angle, and pixel quality were created using blade sections acquired from the repowering (Figure 7). In parallel, maps of damage were created on the blade sections taken from repowering using brass rubbing techniques (Figure 7).
The students evaluated a number of automated image processing techniques. Canny Edge detection was used to define the leading edge in each image and K-mean clustering in three spectral bands was applied to categorize the damage at the leading edge into pits, gouges and delamination (broadly in line with the damage classification in [2]) (Table 2 and Figure 8). As expected, major damage is easier to identify for both image detection algorithm and subjective analysis with 90% of the subjectively classified images being correctly identified by the algorithm while very minor damage (pits) is difficult for both to identify.

Figure 8. Example of image processing a) blade image b) Canny edge detection c) results of the K-mean clustering that gives the amount of damage on this part of the blade; as i) pits 0.8% ii) gouges 2.7% iii) delamination 7.3%

6. Summary and future work
Our integrative project focuses on increased understanding of LEE of wind turbine blades using numerical simulations, big data analytics and experimental research. It is designed to quantify LEE, reduce uncertainty associated with key processes responsible for LEE and improve characterization of damage states. It thus encompasses activities focused on: (1) Improved characterization of precipitation climates. (2) Calculating the impact efficiency as a function of hydrometeor size and blade response. (3) Laboratory experiments to investigate the role of material properties and environmental conditions on LEE. (4) Image processing for damage characterization/ quantification. (5) Characterization of damage severity from decommissioned wind turbine blades/blade inspection images. This paper focusses on participation of undergraduate and graduate students in engaged projects focused on components (3)-(5).

Key student activities and learning outcomes are:
- Students conducted a range of material fabrication and testing projects. We have shown that uncoated blade properties can be reasonably reproduced in terms of hardness and tensile strength by
3D printed glass fiber in specific configurations. Our 3D printed samples, while useful in developing experiments, are insufficiently strong to withstand collisions with hydrometeors in the same way as wind turbine blade samples although this could be improved using coatings. Ongoing experiments are being conducted to evaluate how immersion in rainwater of different pH and ambient humidity impact the hardness results of the uncoated blade samples with a view to repeating the testing on coated samples.

- Students printed a half-scale model of a blade leading edge and used it to evaluate how much energy is needed to produce damage on an uncoated blade. The experiment was limited to impaction velocities below those of a wind turbine blade tip but indicated that damage could be produced in a very short-time frame with sufficient energy expenditure (~4000 J).
- Students developed a set of controlled images with a known amount of LEE damage to condition and evaluate different image processing techniques to quantify both the amount and type of damage. The automated algorithm developed was applied to over 200 blade inspection images and compared with results from a subjective categorization. Severe damage (i.e. delamination) was much more easily identified by both, with 90% of the images classified as severe delamination correctly identified by the image processing algorithm. Minor damage (pits) are very difficult to identify solely from photographs, even when zoomed in to the maximum amount and only 20% of the subjectively identified cases were also classified in the same way by the image processing algorithm.

Thus, the image processing requires considerably more effort in order to improve its utility.

Within this project 14 students have learnt new technical skills and contributed to the overall project. The engaged learning philosophy also incorporated further professional development and communication and pedagogic skills. All students presented their results at a seminar on WT blade leading erosion and at Cornell University’s Energy Day. Further they made ‘rainy day’ educational materials for the Fenner Renewable Energy Education Center and participated in additional outreach during the ‘Winging It Day’ at Ithaca Sciencenter that attracted 50 school age students and their parents to design and test their own wind turbine blades.

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