A Numerical Model for the Analysis of Leading-Edge Protection Tapes for Wind Turbine Blades

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Abstract. This paper presents results of a numerical study on the effect of a standard leading-edge protection (LEP) tape on the aerodynamics of a NACA 64-618 airfoil. Two numerical models are used in STAR-CCM+ to estimate the impact of LEP tapes on airfoil $c_l$ and $c_d$. The objective is to determine which numerical model resolves the physical mechanisms responsible for the aerodynamic degradation observed with standard LEP tapes. Experimental $c_d$ data are collected for LEP tapes applied to the tip section of an utility-scale wind turbine blade for numerical validation. For a standard LEP tape, experiments indicate laminar-to-turbulent boundary-layer transition occurs at the LEP tape edge, resulting in a 62% increase in $c_d$. To capture the boundary-layer transition at the LEP step, transition modeling is required in STAR-CCM+. This is an important finding as the mesh techniques developed in this work can be used for future LEP tape design to prevent early transition, thereby reducing the associated adverse impact on wind-turbine tip-section airfoil aerodynamics and annual energy production.

1. Introduction

Wind turbines are one of the world’s leading sources of renewable energy. As of 2018, wind continues to be the United States’ leading source of renewable energy, supplying 6.5% of total U.S. electricity.[1] Wind also led European renewable energy production by meeting 11.6% of the EU’s total electricity demand.[2] Despite the steady growth of the wind energy industry in recent years, global wind energy capacity must grow significantly in the near future to meet sustainability targets set by the UN’s Sustainable Development Goals and those established in the most recent International Panel on Climate Change (IPCC) report.[3, 4] Many of the sites considered for new capacity installations include those in the Middle East, Northern Africa, as well as northern latitude countries and many offshore locations. Wind turbines in these environments, however, are subject to harsh environmental conditions that can negatively impact operational lifetime and annual energy production (AEP), notably impacting the ability to meet global sustainability goals required to further mitigate detrimental impacts of climate change.

Damaged wind-turbine blades account for about 41% of reported maintenance cases, making the rotor blades the most frequently repaired and replaced component.[5] One source of blade damage is the erosion of the blade surface due to repeated high-velocity impact at the leading edge of the blade tip region by rain, sand, and/or hail particles.[5, 6, 7, 8, 9] Erosion of the blade surface is observed as early as one year into the operational lifetime of the rotor, beginning with the formation of small pits on the upper and lower surfaces, which grow into larger gouges that can cause significant delamination at the leading edge with prolonged exposure to the damaging...
particles.[10, 11, 12, 13] In addition to posing structural concerns for the most severe cases, leading-edge erosion notably impacts blade aerodynamics and rotor power production at all stages of the erosion process.[12, 13]

Previous numerical and experimental studies [12, 13, 14, 15, 16] of airfoils with leading-edge erosion estimate two-dimensional (2-D) $c_d$ increases anywhere from 6% to 200%, depending on erosion severity, chordwise extent of the eroded area, operating conditions, and the baseline airfoil shape. The same studies predict $c_l$ decreases for eroded airfoils, although the effect is less significant than the impact of erosion on $c_d$. As a result, it was estimated that AEP decreased from 4% to 12% depending on severity of the erosion.[12] Losses of this magnitude mean significant reduction in number of homes a single rotor can power, as well as tens of thousands of dollars lost in revenue for wind turbine operating companies.

To prevent power and revenue losses incurred when operating a rotor with eroded blades, leading-edge protection (LEP) tapes are typically applied to the blades.[5, 17, 18] Previous studies [16, 17, 18] indicate, however, that there is aerodynamic performance degradation for airfoils equipped with LEP tapes, although the losses are notably smaller than those due to leading-edge erosion. It was estimated that $c_d$ increases of 5% to 15% for an airfoil with LEP tape applied results by itself in 1% - 3% AEP losses.[17]

In conjunction with the Minnesota Mining and Manufacturing (3M) Company, the effort reported herein seeks to develop a numerical model for the analysis of a standard LEP tape with future applications to the design of aerodynamically improved LEP tapes. To accomplish this task, objectives of the research include (i) developing two distinct numerical models to estimate 2-D $c_l$ and $c_d$ of an NACA 64-618 airfoil with an LEP tape applied and (ii) validating numerical models using experimental data.

The paper is organized as follows: Sections 2 outlines the computational methodology of the research, Section 3 compares the results of numerical simulations, and Section 4 details experimental validation methods. The content of Section 2 includes the development of two computational grids for analysis of an LEP tape when applied to the leading edge of an NACA 64-618 airfoil. Section 3 compares the results of the two computational methods discussed in Section 2 using plots of $\Delta c_l$, $\Delta c_d$, and skin friction coefficient, $c_f$. Section 4 describes the experimental set-up for validation of the numerical data. Experimental results for validation purposes include $\Delta c_d$ and oil visualization of the boundary layer over an utility-scale blade tip section. Using both numerical and experimental results, conclusions are drawn regarding the recommended computational method for studying the aerodynamics of LEP tapes.

2. Computational Methods

To investigate the aerodynamics of LEP tapes, numerical models are investigated using Computational Fluid Dynamics (CFD) to estimate $c_l$ and $c_d$ at Re = 3x10^6 for angles of attack between $\alpha$ = -2° and 8° of the NACA 64-618 airfoil. The initial model assumes a fully-turbulent boundary layer, and the second model includes a boundary-layer transition model. Two CFD mesh grids for LEP tapes are developed for comparison to identify the fidelity required to capture the physical mechanisms responsible for the observed aerodynamic impact of an LEP tape on a wind-turbine airfoil.

For both fully-turbulent and transition simulations, predictions of the flow field are computed using the 2-D, incompressible Reynolds-averaged Navier-Stokes (RANS) equations. Numerical integration is performed using Siemens’ commercial CFD software STAR-CCM+. Turbulence closure is achieved for all simulations with the k-$\omega$ SST two-equation turbulence model. This turbulence model is chosen at it is well-suited to boundary-layer studies at relatively low computational cost.[15, 20]

The computational domain for all studies is a square region of side length 100c, shown in Figure 1, yielding 50 chord-lengths upstream and downstream of the leading edge of the unit-
chord (c = 1) NACA 64-618 airfoil. Such a domain is desirable to eliminate the effect of the far-field boundary conditions on the surface flow around the airfoil to accurately approximate an airfoil in free-stream airflow. A majority of the computational domain is discretized using a total of 120,863 unstructured quadrilateral mesh cells, shown in Figure 2.

In the vicinity of the airfoil, the cells are structured using a C-type mesh. The use of a structured mesh near the airfoil allows for control of the first cell spacing at the surface of the airfoil and the total number of cells around the airfoil surface, both of which are refined until the results for $c_l$ and $c_d$ demonstrated less than 1% change with further grid refinement. The extent of the C-type refinement domain is 5c downstream of the leading edge and 1c above and below the center-line of the airfoil, see Figure 1. The structured cells at the boundary of the C-type region are merged with the surrounding unstructured cells using a least-squares approximation. Parameters of the structured mesh depend on the type of wall treatment used and on whether or not an LEP tape is applied to the leading edge of the airfoil.

To validate the numerical models, the tip section of a wind turbine blade was provided by EverPower Wind Holdings Inc for wind-tunnel testing, see Section 4. The airfoil comprising the tip section was not given, so the cross-section of the blade was digitized and compared to several common wind turbine tip-section airfoils. The NACA 64-618 airfoil represents the best match with respect to the leading-edge radius and the trailing-edge camber of the digitized cross-section. The NACA 64-618 airfoil - a representative wind turbine tip-section airfoil - is therefore selected as the baseline airfoil for all numerical simulations to maintain a consistent baseline with the experimental data.

2.1. Fully-Turbulent

Fully-turbulent simulations in STAR-CCM+ employ the ’All y+’ Wall Treatment function to define the viscous region near the airfoil surface. To satisfy the ’All y+’ Wall Treatment requirement of wall $y+ \leq 30$, the height of the first cell off the wall is set to $x/c = 1 \times 10^{-4}$, which is determined using a wall $y+$ calculator for the given airfoil chord length, fluid properties, and Reynolds number. Convergence of 2-d aerodynamic coefficients with increasing number of grid cells around the airfoil surface are included in Table 1. Grid independence is achieved with a total of 350 cells around the airfoil, leading-edge cell spacing of $x/c = 2 \times 10^{-4}$, and trailing-edge
Table 1. Aerodynamic coefficient convergence with increasing number of cells around the airfoil surface.

| Number of Cells |  $c_l$  |  $c_d$  |  $c_m$  |
|-----------------|---------|---------|---------|
| 178             | 0.4332  | 0.01200 | -0.10620|
| 350             | 0.4338  | 0.01191 | -0.10626|
| 500             | 0.4338  | 0.01191 | -0.10626|

cell spacing of $x/c = 2 \times 10^{-3}$. The final C-type mesh for all fully-turbulent simulations, shown in Figure 3, contains 139,320 cells for a total of 260,183 cells in the computational domain.

Figure 3. Structured C-type mesh around the clean NACA 64-618 airfoil for fully-turbulent CFD simulations at Re = $3 \times 10^6$.

Figure 4. Order of magnitude of first-cell spacing required for fully-turbulent simulations at Re = $3 \times 10^6$.

Computational data are generated from $\alpha = -2^\circ$ to $8^\circ$ - the representative operating range of a wind turbine tip-section airfoil. CFD estimates for $c_l$ and $c_d$ of the NACA 64-618 airfoil are compared to experimental data from Theory of Wing Sections [22] and XFOIL [23] data, both at Re = $3 \times 10^6$, for verification. Additional data for comparison from Theory of Wing Sections are included for an NACA 64-618 airfoil with a roughened surface. Plots of $c_l$ versus $\alpha$ and $c_l$ versus $c_d$ are detailed in Figures 5 and 6, respectively.

At $\alpha = 0^\circ$, the difference between the fully-turbulent CFD and the smooth-surface experimental data [22] is $\Delta c_l = -4.6\%$ and $\Delta c_d = 103\%$, with the latter discrepancy being attributed to the absence of laminar flow in the CFD predictions. Compared to experimental data [22] at $\alpha = 6^\circ$, fully-turbulent CFD varies by $\Delta c_l = -4.1\%$ and $\Delta c_d = 78\%$. The variation between fully-turbulent CFD and XFOIL at $\alpha = 0^\circ$ is $\Delta c_l = -18.5\%$ and $\Delta c_d = 117\%$. At $\alpha = 6^\circ$, the variation becomes $\Delta c_l = -11.1\%$ and $\Delta c_d = 86\%$. Trends at both $\alpha = 0^\circ$ and $6^\circ$ for $c_l$ indicate reasonable agreement between fully-turbulent CFD, XFOIL, and smooth-surface Theory of Wing Sections data [22] at Re = $3 \times 10^6$. On the other hand, fully-turbulent CFD $c_d$ estimates are notably different, which is reflected by the absence of the drag bucket in Figure 6. When compared to Theory of Wing Sections [22] data for the NACA 64-618 with a rough surface at Re = $6 \times 10^6$, it confirms that the fully-turbulent CFD $c_l$ vs $c_d$ data are representative of an airfoil with a rough surface and associated turbulent boundary layer.

2.2. Transition Modeling

The second model for LEP tape analysis includes the $\gamma$-transition model, a simplified version of the $\gamma$-Re$_\theta$ transition model,[21] The $\gamma$-transition model estimates laminar-to-turbulent boundary-layer transition using the intermittency parameter, which signals the production of
turbulent kinetic energy in the boundary layer when the local Reynolds number reaches a critical value. Inclusion of this transition model is intended to identify whether or not the backward-facing step of a LEP tape has an effect on early transition to a turbulent boundary layer.

Transition modeling simulations employ the 'Low y+' Wall Treatment function. To satisfy the Low y+ Wall Treatment requirement of wall $y^+ \leq 1$, the size of the first cell off the wall is set to $x/c = 1 \times 10^{-5}$. Grid independence for transition modeling simulations is achieved with a total of 600 cells around the airfoil, leading-edge cell spacing of $x/c = 6 \times 10^{-5}$, and trailing-edge cell spacing of $x/c = 2 \times 10^{-5}$. The final C-type mesh for all fully-turbulent simulations, shown in Figure 7, contains 294,000 cells for a total of 414,863 cells in the computational domain.

Data are generated from $\alpha = -2^\circ$ to $8^\circ$. Verification of the transition model estimates for $c_l$ and $c_d$ of the clean NACA 64-618 airfoil is achieved by comparing to experimental data from Theory of Wing Sections [22] and XFOIL [23] data, both for $Re = 3 \times 10^6$. Plots of $c_l$ versus $\alpha$ and $c_l$ versus $c_d$ are detailed in Figures 9 and 10, respectively.
Transition model CFD predictions of $c_l$ and $c_d$ are representative of the expected performance. At $\alpha = 0^\circ$, the difference between the CFD and the experimental data is $\Delta c_l = 13.6\%$ and $\Delta c_d = 0.4\%$. Compared to experimental data from Theory of Wing Sections at $\alpha = 6^\circ$, CFD varies by $\Delta c_l = 8.9\%$ and $\Delta c_d = -13.1\%$. The variation between CFD and XFOIL at $\alpha = 0^\circ$ is $\Delta c_l = -4.0\%$ and $\Delta c_d = 7.5\%$. At $\alpha = 6^\circ$, the variation becomes $\Delta c_l = -0.1\%$ and $\Delta c_d = -9.5\%$. Trends at both $\alpha = 0^\circ$ and $6^\circ$ indicate very good agreement between CFD, XFOIL, and Theory of Wing Sections data in the narrow angle-of-attack range of interest. In the operating range of interest for this work, trends for both $c_l$ and $c_d$ are sufficiently predicted by the transition model.

![Figure 9](image1.png)
**Figure 9.** Transition CFD (■) lift coefficients compared to experimental data from Theory of Wing Sections [22] (——) and obtained by XFOIL [23] (♦) for the NACA 64-618 airfoil at $Re = 3 \times 10^6$.

![Figure 10](image2.png)
**Figure 10.** Transition CFD (■) drag coefficients compared to experimental data from Theory of Wing Sections [22] (——) and obtained by XFOIL [23] (♦) for the NACA 64-618 airfoil at $Re = 3 \times 10^6$.

### 2.3. LEP Tape Model
From previous studies [16, 17, 18], the application of an LEP tape causes notable $c_l$ losses and $c_d$ increases, the magnitude of which depends on the airfoil and operating conditions. Applying the meshing techniques, see above, for the clean airfoil, fully-turbulent and transition models are used to estimate $c_l$ and $c_d$ of the NACA 64-618 airfoil equipped with a 6-in wide standard LEP tape applied to the leading edge.

An example of a standard LEP tape on the market today is the 3M™ Wind Protection Tape 2.0 W8750, consisting of a polyurethane-based material that is $350 \mu m$ thick and 6-in to 12-in wide.[24] Figure 11 is a 2-D representation of a 6-in wide standard LEP tape. When applied to the NACA 64-618 airfoil, as in Figure 12, a 6-in wide standard LEP tape protects $x/c = 6\%$ on the upper and lower surfaces.

The structured mesh parameters for the clean NACA 64-618 are used to generate fully-turbulent and transition LEP tape grids. Additional refinement around the backward-facing step at the edge of the tape is needed, however, to resolve the flow in this critical location. Local grid refinement includes two equal-size cells added across the LEP tape backward-facing step and expansion of the cells upstream- and downstream of the step. A representative structured C-type grid for an LEP tape model is displayed in Figure 13. Included in the figure are images of
Figure 11. Cross-section of a standard 6-in wide LEP tape (not to scale).

Figure 12. Application of a standard 6-in wide LEP tape to the leading edge of the NACA 64-618 airfoil.

the mesh across the LEP tape backward-facing step for fully-turbulent and transition modeling simulations.

Figure 13. Structured C-type mesh around the clean NACA 64-618 airfoil with an LEP tape applied for CFD simulations in STAR-CCM+ at Re = 3x10^6 including the refined mesh at the backward-facing step for fully-turbulent and transition models.

3. Results

3.1. Lift and Drag Coefficient
Aerodynamic performance of an NACA 64-618 airfoil with a standard LEP tape applied is investigated with the change in $c_l$ and $c_d$ compared to the clean baseline airfoil. Results for $\alpha = -2^\circ$ to $8^\circ$ at Re = $3\times10^6$ are presented below. Figure 14 compares estimated changes in $c_l$
and Figure 15 the percent change in $c_d$ for fully-turbulent and transition CFD models. Data for change in $c_l$ are not computed as percentages, as the effect on $c_l$ is small in the operating range considered here.

![Figure 14. Predicted change in $c_l$ for the NACA 64-618 with a standard LEP tape applied for fully-turbulent (♦) and transition (◊) models for Re = 3x10^6.](image)

![Figure 15. Predicted change in $c_d$ for the NACA 64-618 with a standard LEP tape applied for fully-turbulent (♦) and transition (◊) models for Re = 3x10^6.](image)

The fully-turbulent LEP tape model estimates that $c_l$ increases relative to a clean NACA 64-618 airfoil. Estimated $c_l$ increase is relatively constant across the angle-of-attack range considered, with a maximum change of $\Delta c_l = 0.033$ at $\alpha = 0^\circ$. Fully-turbulent simulations predict $c_d$ to increase due to an LEP tape application. The magnitude of the increase is also relatively constant across the operating range and reaches a maximum of $\Delta c_d = 7\%$ near $\alpha = 6^\circ$. Predictions of $\Delta c_l$ and $\Delta c_d$ for the fully-turbulent model indicate that there is very little impact of a standard LEP tape on the aerodynamic performance of an NACA 64-618 airfoil.

Notable differences arise in the results when transition is modeled. When the $\gamma$-transition model is applied, $c_l$ is predicted to decrease relative to the clean NACA 64-618 value - the exception being $\alpha = -2^\circ$, which is near the zero-lift angle of attack for this airfoil. Transition modeling also predicts more notable increases in $c_d$ across the entire operating range, with a maximum of $\Delta c_d = 90\%$ at $\alpha = 4^\circ$. Based on observations from previous studies, the $c_l$ losses and $c_d$ increases of the NACA 64-618 with a standard LEP tape applied predicted using transition modeling appears to be more representative of expected trends.

3.2. Skin Friction Coefficient
The notable difference in $c_l$ and $c_d$ predicted by the two numerical models is investigated using plots of skin friction coefficient, $c_f$. The largest observed difference between the fully-turbulent and transition models is with respect to the increase in $c_d$. The drag coefficient of a 2-D airfoil is the summation of form and skin friction drag. Form drag depends on the shape of the airfoil. Since the thickness of a standard LEP tape is significantly smaller than the chord-wise dimension of the airfoil, it has little impact on the airfoil shape and thus form drag. Rather, the impact of an LEP tape arises from changes in skin friction drag, where the skin friction contribution to $c_d$ is proportional to the integration of $c_f$ around the airfoil surface.
A comparison of the $c_f$ distribution along the upper surface of both the clean and taped airfoil at the operational angle of attack $\alpha = 6^\circ$ are shown below. Fully-turbulent data are shown in Figure 16 and transition data are shown in Figure 17. For a laminar boundary layer, values of $c_f$ are expected to be lower than for a turbulent boundary layer that has notably larger values due to increased mixing from turbulence.

![Figure 16. Fully-turbulent CFD $c_f$ distributions on the upper surface of the clean NACA 64-618 airfoil (- - - -) and with a standard LEP tape applied (——) for $\alpha = 6^\circ$ and Re = 3x10^6.](image1)

![Figure 17. Transition CFD $c_f$ distributions on the upper surface of the clean NACA 64-618 airfoil (- - - -) and with a standard LEP tape applied (——) for $\alpha = 6^\circ$ and Re = 3x10^6.](image2)

Using a fully-turbulent model, little difference is observed between the upper-surface $c_f$ distributions in Figure 16. The only notable difference observed is a brief discontinuity in the distribution at the backward-facing step location for the NACA 64-618 with a standard LEP tape applied. When integrated to compute the contribution of skin friction to the total $c_d$, the change in $c_f$ induced by the presence of the backward-facing step results in the relatively small increase in $c_d$ compared to the clean airfoil observed in Figure 15 for the fully-turbulent model.

With transition modeling, values for $c_f$ are smaller near the leading edge of the airfoil in Figure 17. For the clean NACA 64-618 airfoil, values of skin friction remain small (indicating a laminar boundary layer) until $x/c = 45\%$ when a large increase in $c_f$ occurs. Beyond this point, the profile resembles the fully-turbulent $c_f$ distribution, indicating the boundary layer transitions from laminar to turbulent at $x/c = 45\%$ for the clean airfoil.

For the NACA 64-618 airfoil with a standard LEP tape applied, the area under the $c_f$ vs $x/c$ curve increases notably in Figure 17. Near the leading edge of the airfoil, the two distributions are indistinguishable when the boundary layer remains laminar. When the backward-facing step of the LEP tape is encountered, however, a peak in the $c_f$ distribution occurs similar to that of the fully-turbulent distribution. Beyond the peak at the backward-facing step, values for $c_f$ increase notably and resemble the fully-turbulent profile in Figure 16. Transition modeling indicates that the boundary layer transitions at the backward-facing step of the LEP tape, explaining the notable increased $c_d$ and decreased $c_l$ relative to the clean airfoil.

4. Experimental Validation

4.1. Wind Tunnel and Airfoil Model
To validate whether the fully-turbulent or $\gamma$-transition model most reasonably captures the aerodynamic impact of a standard LEP tape on an NACA 64-618 airfoil, wind tunnel
Experiments are conducted at similar operating conditions. Experiments are conducted in The Pennsylvania State University Low-Speed, Low-Turbulence Wind Tunnel. A schematic of the facility is included in Figure 18. It is a closed-circuit, single-return, atmospheric tunnel.

The test section measures 1.013-m (40 in) high by 1.476-m (58 in) wide. Measured turbulence intensity in the test section is approximately 0.05% at a wind speed of 46 m/s. Models are mounted vertically in the test section as shown in Figure 19. For this validation study, the full-scale chord model used is assembled from an 8-ft tip section of a decommissioned utility-scale wind turbine blade provided by EverPower Wind Holdings Inc., the cross-section of which most closely matches an NACA 64-618 airfoil. The model is wet-sanded to reduce the impact of any previously acquired surface defects on the data. The mid-chord of the portion of the tip section inside the tunnel measures approximately 32-in. When applied to the model, a 6-in wide LEP tape extends approximately \( x = 1.8 \)-in downstream of the leading edge on the upper and lower surfaces, as shown in Figure 20.

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**Figure 18.** Top-down schematic of The Pennsylvania State University Low-Speed, Low-Turbulence Wind Tunnel facility.

**Figure 19.** Side-view schematic of The Pennsylvania State University Low-Speed, Low-Turbulence Wind Tunnel test section.

**Figure 20.** Installed wind-turbine tip section, provided by EverPower Wind Holdings Inc., with LEP tape applied to the model leading edge.
4.2. Measurement Method
Drag coefficients were measured at the mid-chord of the model with a pitot-static pressure wake-survey probe. The probe is mounted to an actuating mechanism to traverse the wake behind the model. It is positioned 0.3 chord-lengths downstream of the trailing edge of the model. Tunnel and wake pressures are measured with precision transducers. Data from the wake probe are collected and processed with an electronic data-acquisition system.

Drag coefficient data were obtained for both the clean airfoil and the model with a standard LEP tape applied. The standard tape applied to the model is the 3M\textsuperscript{TM} Wind Protection Tape 2.0 W8750.\cite{24} Measurements were taken exclusively at $\alpha = 0^\circ$. For a full-scale model of this size, data at other angles of attack are subject to significant tunnel blockage effects. Data were collected at $Re = 3 \times 10^6$, corresponding to that at which numerical computations were performed. The boundary layers over both models were visualized by applying Aeroshell\textsuperscript{TM} W80 Aviation Oil, which is luminescent under black light exposure, to the upper surface of the model to identify if a standard LEP tape transitions the boundary layer.

4.3. Results
Results of the boundary-layer visualization over the upper surface of the clean model are presented in Figure 21. At approximately $x/c = 45\%$ a dark line is observed along the span of the model, indicating laminar separation of the boundary layer and subsequent reattachment as a turbulent boundary layer. Full-scale wind tunnel experiments indicate transition occurs at this chord-wise location for the clean airfoil, verifying the clean $c_f$ distribution in Figure 17.

![Figure 21. Oil visualization of the boundary layer transition location on the upper surface of the clean NACA 64-618 airfoil model at $\alpha = 0^\circ$ and $Re = 3 \times 10^6$.](image1)

![Figure 22. Oil visualization of the boundary layer transition location on the upper surface of the model with a standard LEP tape applied at $\alpha = 0^\circ$ and $Re = 3 \times 10^6$.](image2)

The upper-surface boundary layer of the model with a standard LEP tape applied is included in Figure 22. Boundary-layer transition is no longer observed at $x/c = 45\%$. Immediately downstream of the LEP tape backward-facing step, the boundary layer transitions at $x/c = 6\%$, as indicated by the stagnant flow at the edge of the LEP tape where the boundary layer separates from the surface. This experimentally observed phenomenon verifies the transition model $c_f$ distribution for the NACA 64-618 with a standard LEP tape applied in Figure 17.
Also included in Figure 22 is the experimentally measured \( \Delta c_d = 62\% \) at \( \alpha = 0^\circ \) and \( \text{Re} = 3 \times 10^6 \) relative to the clean model. From Figure 15, for \( \alpha = 0^\circ \), recall that the fully-turbulent model predicts \( \Delta c_d = 3\% \) while the transition model predicts \( \Delta c_d = 54\% \). Estimates from the transition model are of the same order as those of the full-scale section experiment. Comparing the experimental results to numerical predictions of \( \Delta c_d \) and upper surface \( c_f \) distributions for fully-turbulent and transition models indicates that transition modeling is needed to resolve the physical mechanisms responsible for the aerodynamic degradation due to LEP tape application on a representative wind turbine tip-section airfoil.

5. Conclusions
Two numerical models were applied to estimate the impact of an LEP tape on an NACA 64-618 airfoil - a representative wind turbine tip-section airfoil. Wind tunnel experiments were also conducted to validate the results of both models with the following conclusions:

- Fully-turbulent modeling predicts \( c_l \) increases around 0.03 counts and \( c_d \) increases on the order of 7% across the operating range.
- Transition modeling estimates small \( c_l \) losses (<0.05) and \( c_d \) increases as high as 90% due to laminar-to-turbulent transition at the backward-facing LEP tape step.
- Measured \( c_d \) from full-scale experimental tests are within 10% absolute \( c_d \) compared to those estimated by the transition model at \( \alpha = 0^\circ \).
- Oil visualization of the upper-surface boundary layer validates the boundary-layer transition at the backward-facing step of a standard LEP tape predicted by the transition model.

Comparing fully-turbulent and transition models for LEP tape numerical analysis indicates that transition modeling is needed to resolve the boundary-layer transition at the LEP tape edge. Early transition at this location is responsible for observed wind turbine tip-section airfoil aerodynamic losses. Additionally, the transition model validated in this work can be applied to the future design of aerodynamically improved LEP tapes.

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