Challenges in Assessing the Aerodynamic Performance Degradation due to Severe Leading Edge Erosion by means of Erosion-Resolved Computational Fluid Dynamics

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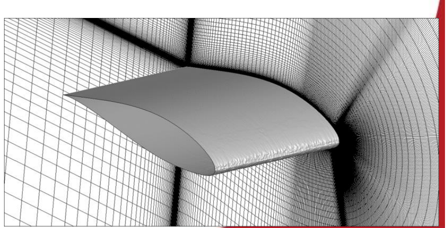
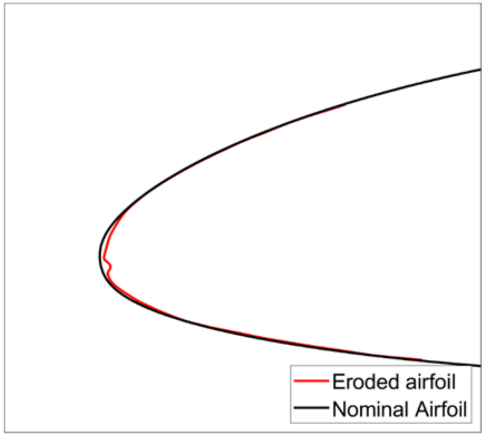


Background and Motivation

- Blade leading edge (LE) alterations (e.g. erosion, ice, dust, insects) impair aerodynamics, reduce rotor power and annual energy production (AEP).

- Resolving severe LE perturbations is necessary for reliably estimating wind turbine (WT) performance degradation and its cost penalty.



Outstanding questions in analysis of severe LE erosion (LEE) and other blade geometry perturbations:

- How to define 'severe' LEE?
- What is range of modeled and resolved roughness in LEE Computational Fluid Dynamics (CFD)?
- How to address model shortcomings (e.g. equivalent sand grain issue)?
- …

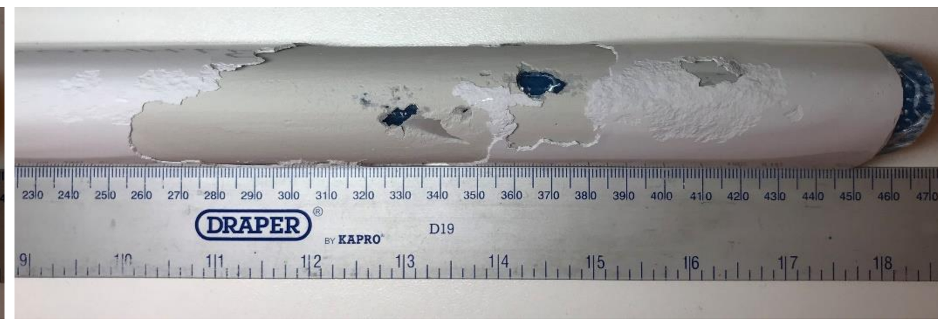
Outline

- LEE geometry sources
  - Rain erosion testing
  - LE scans of operational WT blades
- Analysis objectives
- Model and analysis definitions
- Results
- Summary

LE erosion geometry sources: RET data

- In addition to overall performance data (e.g. incubation time, mass removal, …) Rain Erosion Testing (RET) may provide useful geometry data[0] for aerodynamics:

LE protection A

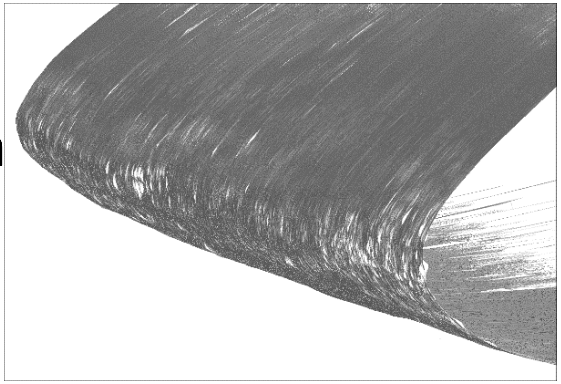


LE protection B

- Different protection systems with comparable erosion rates (mass removal rates) may yield notably different erosion geometries, i.e. notably different aerodynamic performance.

0. Courtesy of the UK Offshore Renewable Energy Catapult.

LE erosion geometry sources: scans of WT LEs



- Present study[1,2] uses erosion geometry data from laser scan of blade LE of offshore WT in service for ~6 years.
- Scan covers ~30% of blade length from tip.
- Figure shows portion of LE scan at ~93% rotor radius.

1. A. Castorrini, A. Ortolani, M.S. Campobasso, *Assessing the progression of wind turbine energy yield losses due to blade erosion by resolving damage geometries from lab tests and field observations, Renewable Energy*, 2023, Vol. 218, 119256, 2023. DOI: 10.1016/j.renene.2023.119256.

2. A. Ortolani, A. Castorrini, M.S. Campobasso, *Multi-scale Navier-Stokes analysis of geometrically resolved erosion of wind turbine blade leading edges*, Journal of Physics: Conference Series, Vol. 2265, no.3, ref. 032102, June 2022. DOI: 10.1088/1742-6596/2265/3/032102.

Analyses objectives

- Assess ‘erosion severity’ in terms of performance sensitivity to damage pattern. In broad terms: *for given mass loss*.
- Assess performance sensitivity to level of equivalent sand grain roughness for unresolved roughness.
- Assess weight of ‘3D roughness effects’.

Model and analysis definitions - 1

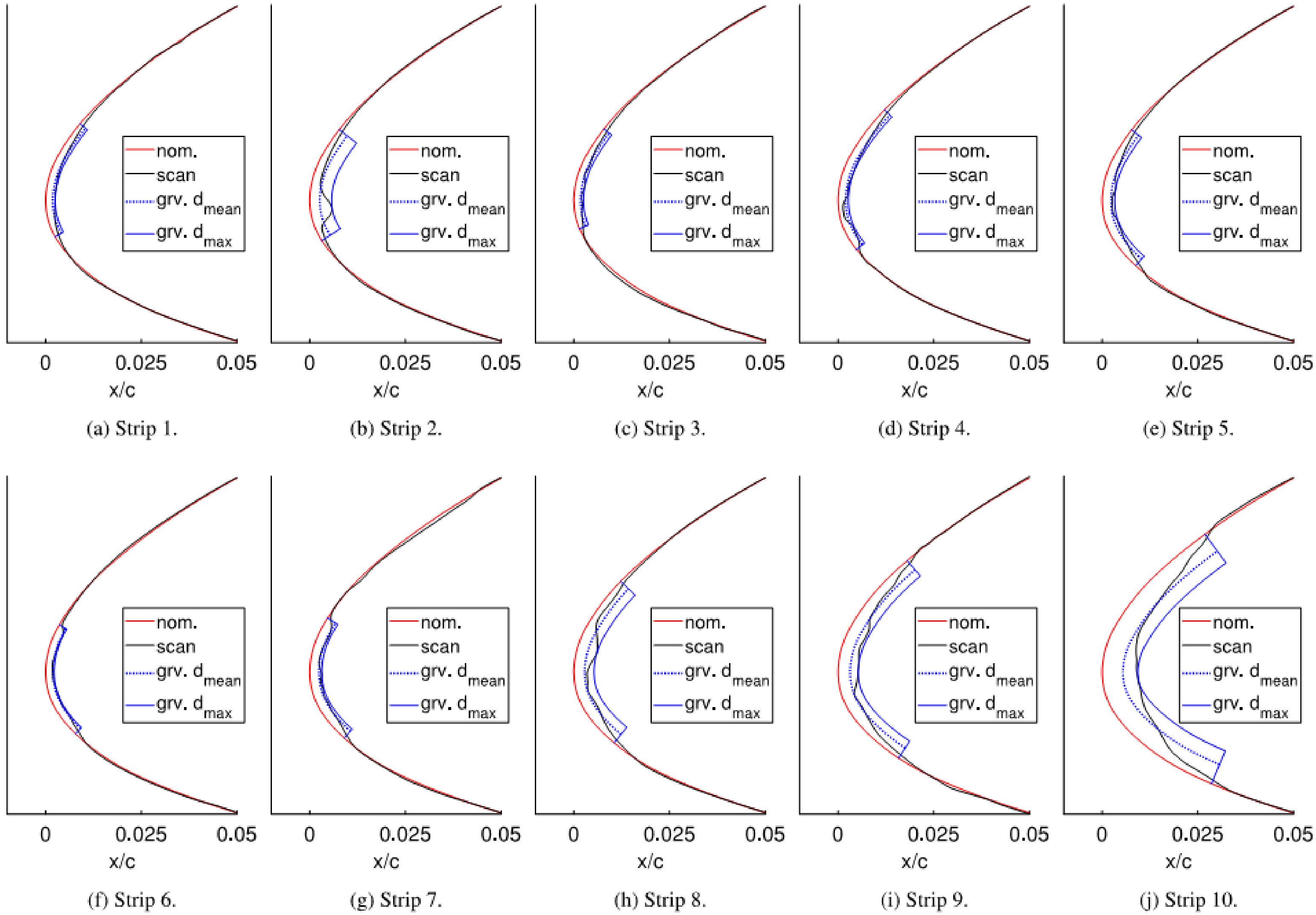
- Damaged LE data of scan fitted to 30% outermost part of NREL 5 MW WT. Considered 4 scan-based damages, mimicking time progression.

- Two chordwise groove-type patterns also considered to account for LE protections eroding with sharper edges.

	mild	mean	severe	critical	grv-mean	grv-max
scan	Y	Y	Y	Y		
groove					Y	Y

- For all 6 erosion patterns, outer 30% of blade length discretized with 10 blade strips.

Model and analysis definitions - 2



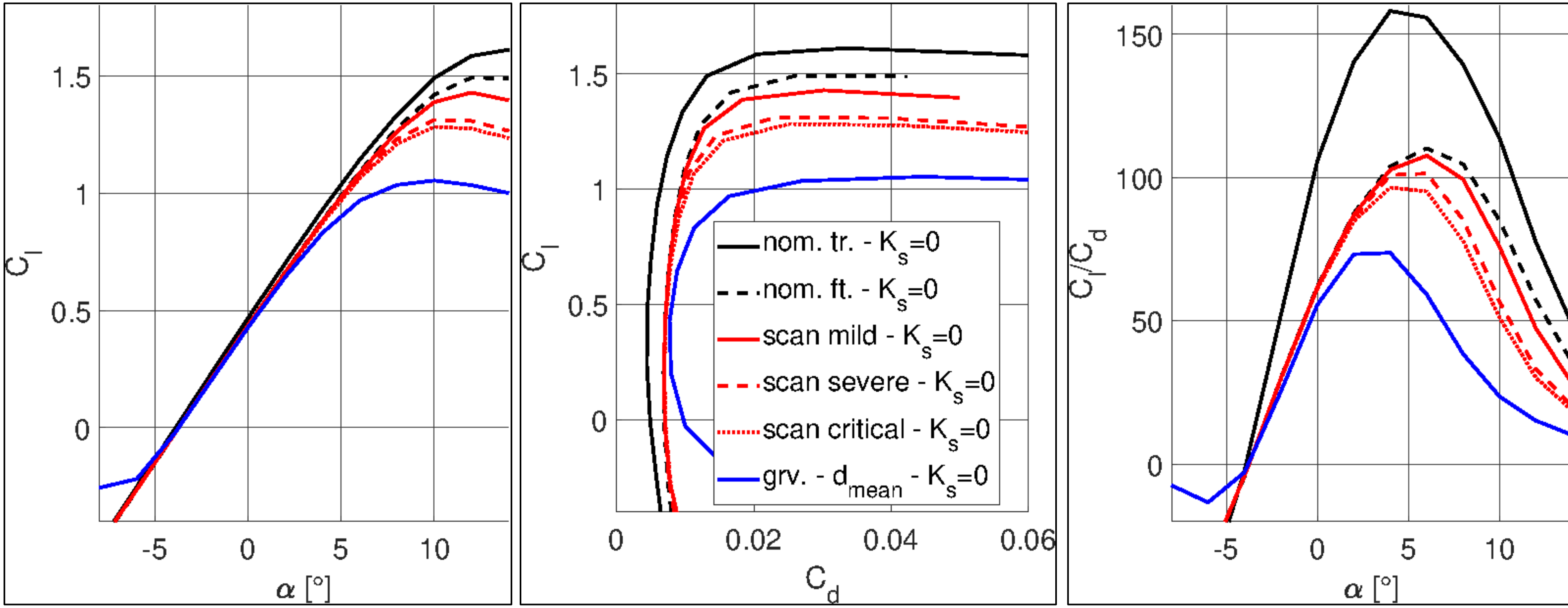
(a) Strip 1. (b) Strip 2. (c) Strip 3. (d) Strip 4. (e) Strip 5.

(f) Strip 6. (g) Strip 7. (h) Strip 8. (i) Strip 9. (j) Strip 10.

Model and analysis definitions - 3

- Fairly coarse scan resolution, ~200 μm.
- Simulation Reynolds number: 6.5M, 8.2M, 11.5M. Accounts for variation with rotor speed.
- Largest erosion scales sufficient to trip LE transition: all CFD analyses are fully turbulent.
- Smaller erosion scales accounted for by using range of equivalent sand grain roughness K_s, from 0 to 1,000 μm.

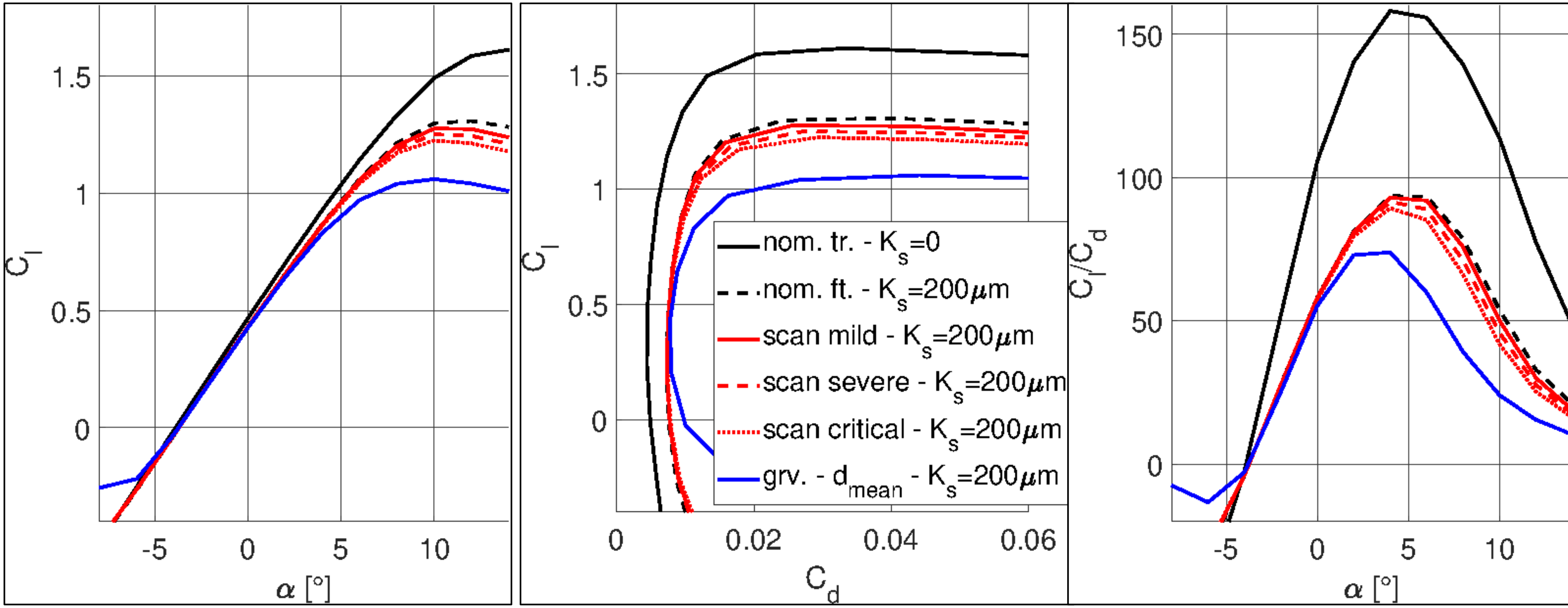
Results: force coefficients. Strip 8, Re 8.2M, K_s=0



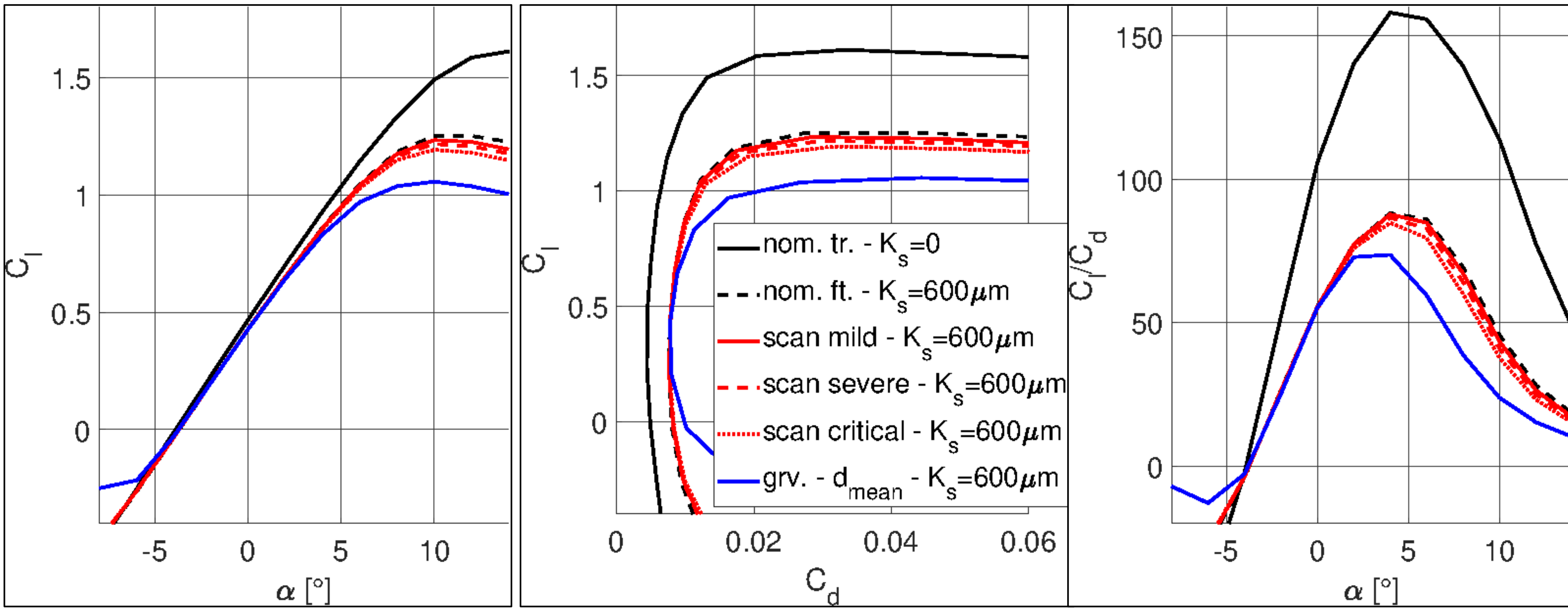
Damage 'grv. d_{mean}'

$s_u/c*100$	$s_l/c*100$	$d/c*100$
2.77	2.17	0.29

Results: force coefficients. Strip 8, Re 8.2M, K_s=200 μm

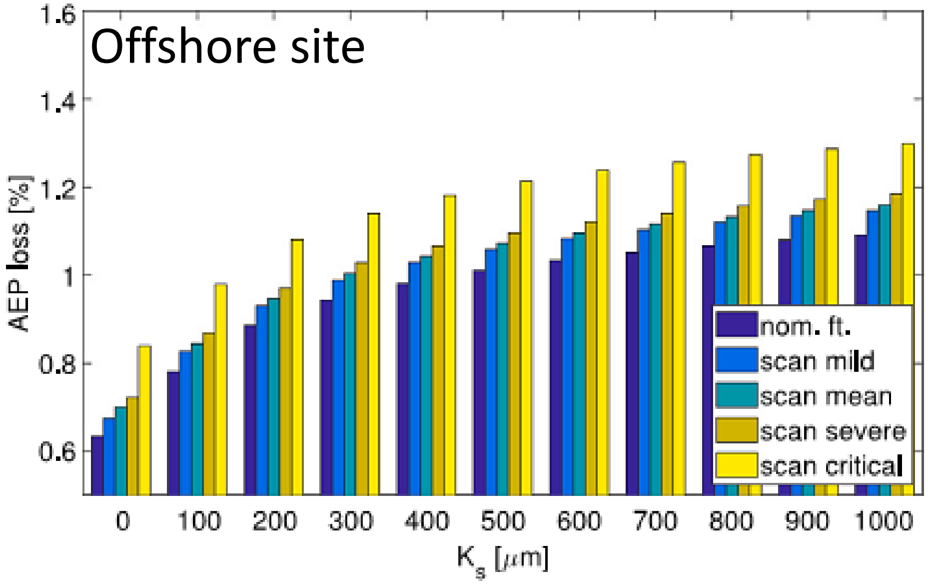


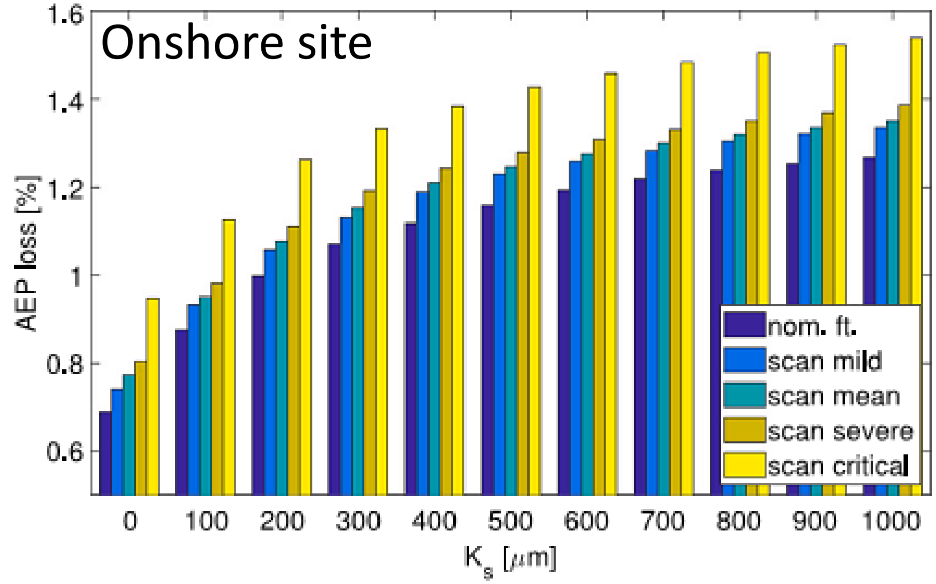
Results: force coefficients. Strip 8, Re 8.2M, K_s=600 μm



- K_s impacts notably c_l and c_d of nominal & 'smoothly' eroded blade.
- At K_s ~200 μm, modeled roughness starts driving performance loss.
- Larger performance loss due to jagged LEE is independent of K_s.

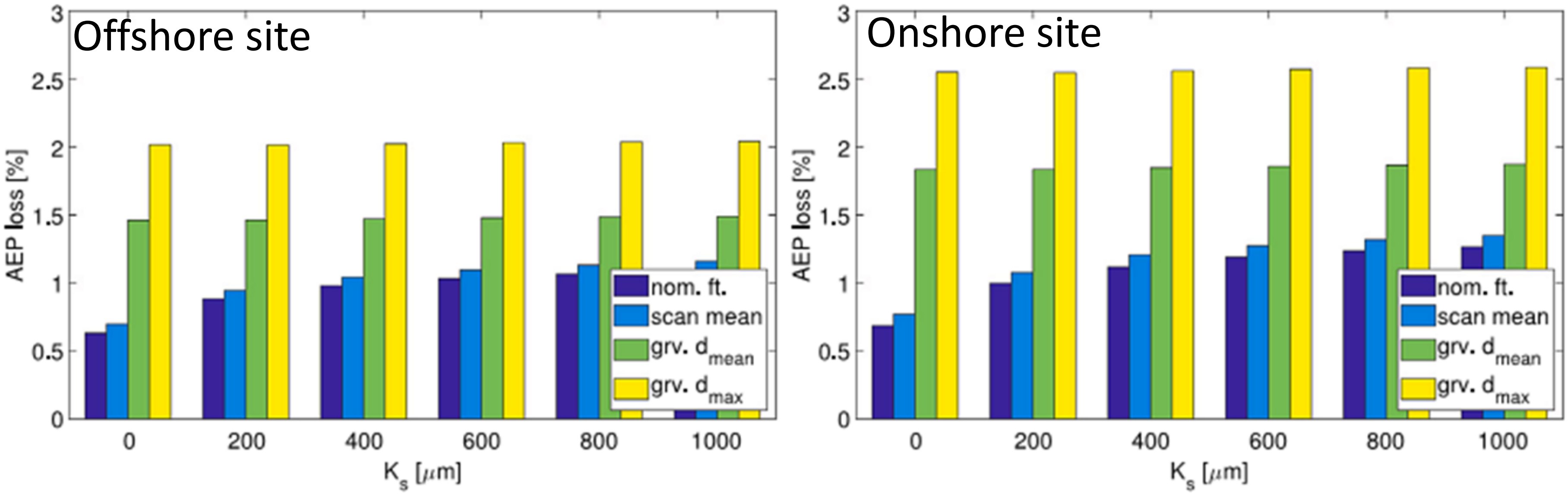
Results: AEP losses for ‘smoothly’ eroding LE





- Predicted AEP loss levels offshore and onshore are ~1.1 and ~1.2%.
- For given K_s, loss due to resolved damage increases with damage jaggedness.
- Increasing K_s up to ~500 μm reduces weight of resolved LEE.

Results: AEP losses for edgy LEE

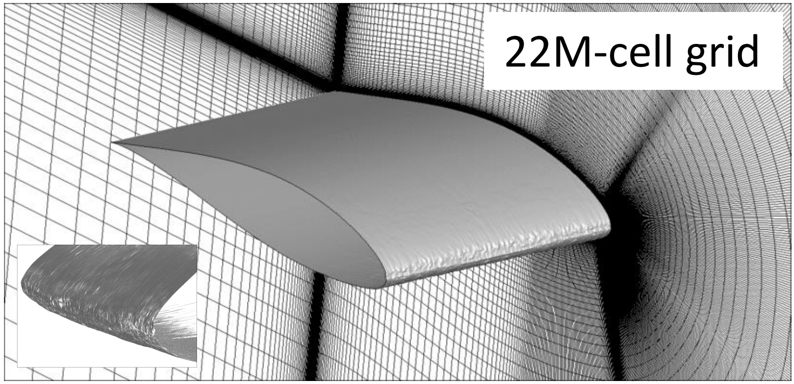


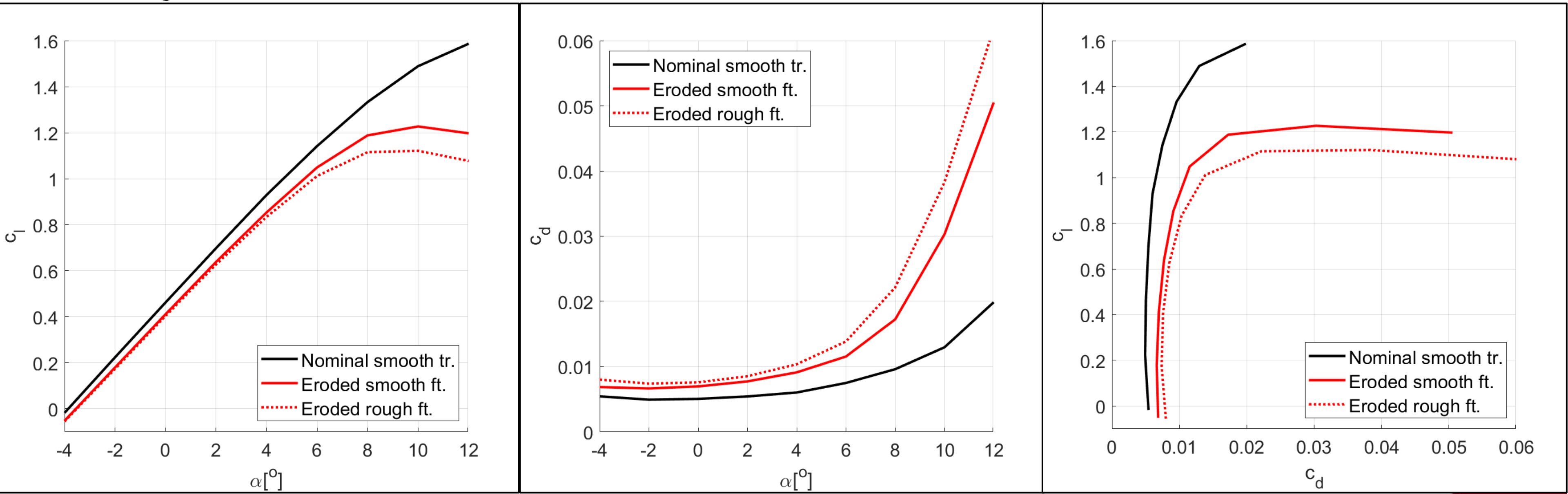
- Predicted AEP loss level offshore: about 1.5% to 2%.
- Predicted AEP loss level onshore: about 1.8% to 2.5%.
- AEP losses of step-shaped LEE is independent of K_s.

A. Castorrini, A. Ortolani, E. Minisci, M.S. Campobasso, ***Opensource machine learning metamodels for assessing blade performance impairment due to general leading edge degradation***, TORQUE 2024, under review.

Results: 3D CFD analysis of real erosion - 1

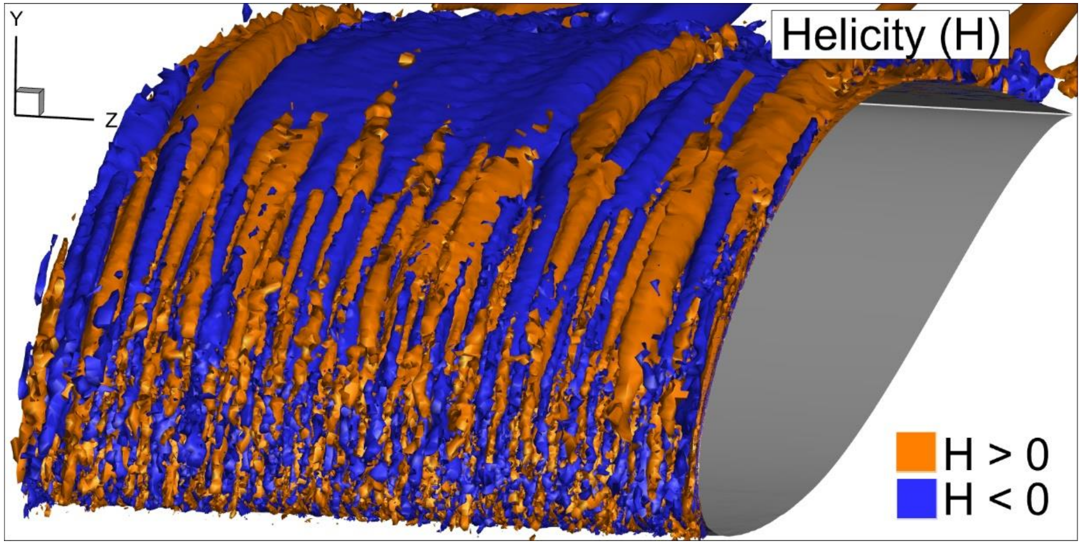
- Mean radius: 58.6 m.
- Mean chord: 2.1 m.
- Spanwise length: 0.735 m.
- K_s/c: 200 μm/m (modelled roughness).
- Reynolds number: 9M.





Results: 3D CFD analysis of real erosion - 2

- K_s has similar, seemingly smaller, impact as in 2D; quantitative sensitivity requires further investigation.
- 3D erosion-resolving analysis predicts larger losses than 2D analyses: loss of 3D strip > mean loss of ~2000 cuts of same strip.



- <u>Helicity contours</u> highlight notable spanwise gradients, expected to further weaken BLs.

Conclusions

A. Performance reduction due to severe LEE depends significantly on profile jaggedness, i.e. also on LE material properties.

B. Impact of K_s in scale-separated LEE analysis decreases with erosion jaggedness.

C. Sharp severe LEE appears assessable with 2D CFD.

D. 3D analyses of resolved deep but smooth erosion point to 3D effects unresolvable with modeled 2D/3D roughness: **2D analyses underpredict losses**.

E. Key epistemic uncertainty sources need to be addressed.

Thank you for your attention!

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Any questions?