Blade Design and Optimization using NuMAD

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Outline

- NuMAD: Summary and description of new release
- Recent work in the Big Adaptive Rotor project (phase 1)
  - Overview of study and findings
  - Optimization procedure
  - Challenges encountered
- Current efforts and future aspirations
  - Sever dependence on commercial FEA codes
  - Enhance beam model performance/capabilities
  - Develop Python-based version of NuMAD

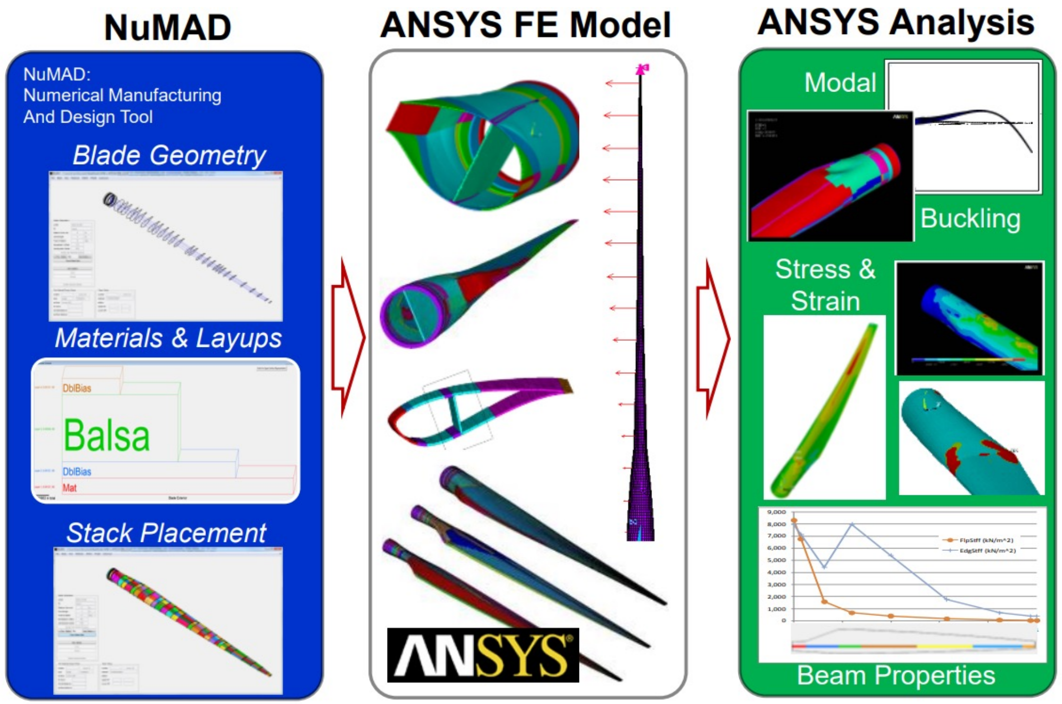
NuMAD: Summary and Overview

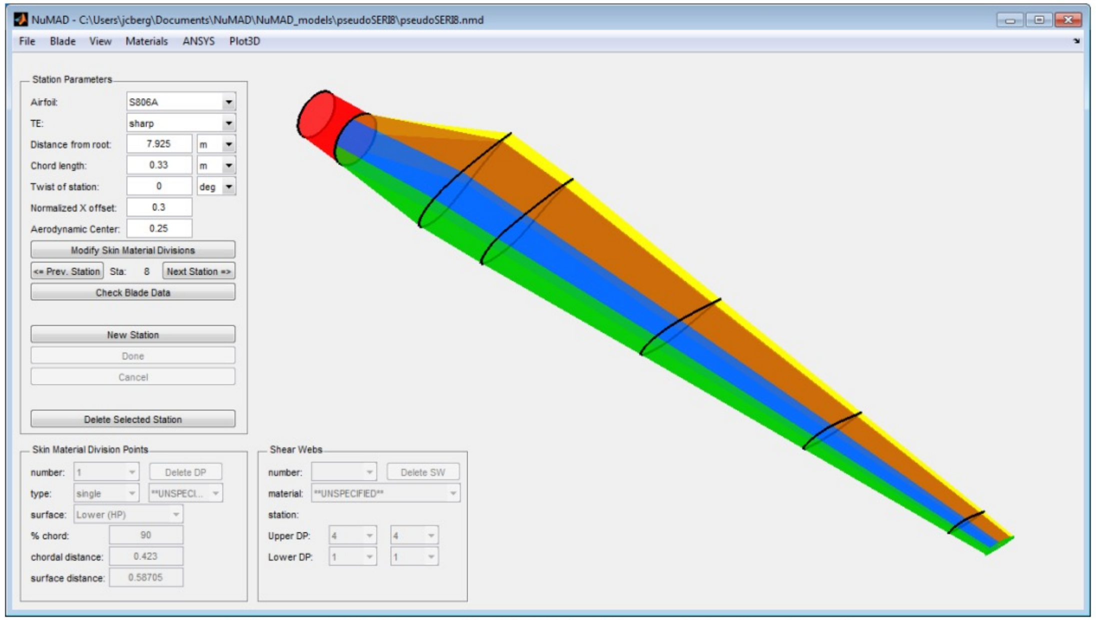
Numerical Manufacturing and Design (NuMAD) is a blade design tool 20 years in the making

Object-oriented approach to definition of blade structure, compatible with .yaml format geometry input

Calls on ANSYS and other external tools to perform structural analysis

Publicly available at github.com/sandialabs/NuMAD





Big Adaptive Rotor, Phase I

Exploration of potential future designs of large, low specific power rotors

Design optimization of 5 concept designs. Results published in *Wind Energy Science* (refs. 1, 2)

With carbon fiber spar caps and flexible designs, blade mass and LCOE could be reduced

Heavy-tow carbon fiber implicated as ~10% cost saving alternative to industry-standard

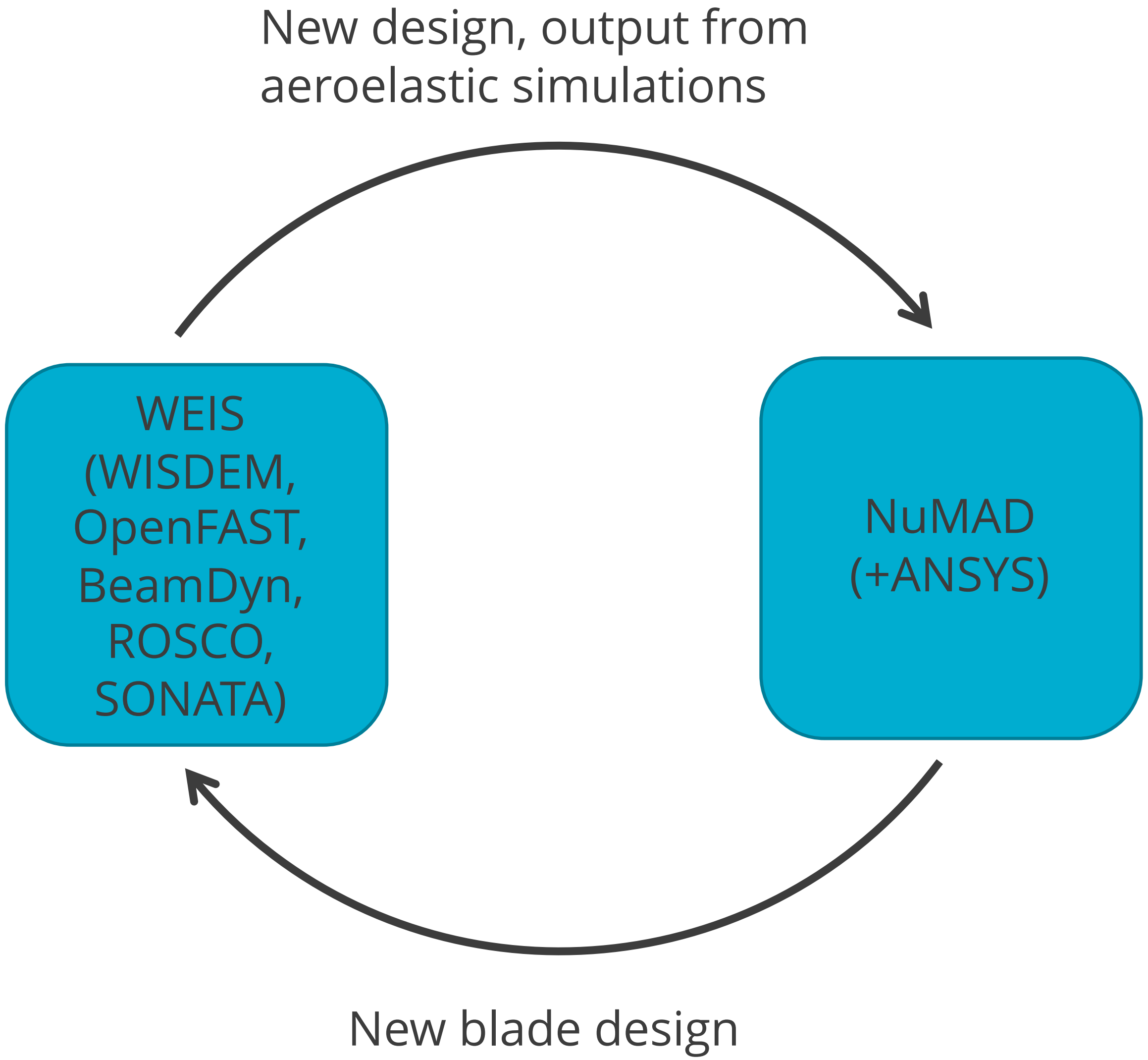
	BAR-UAG	BAR-USC	BAR-URC	BAR-DRG	BAR-DRC
Orientation		Upwind		Downwind	
Transport	Air	Segmented		Rail	
Spar Cap	Glass	Carbon	Carbon	Glass	Carbon
Blade Mass (tons)	64.8	49.4	41.2	53.0	41.6
LCOE ($/MWh)	44.9	45.0	43.7	44.9	44.4

Big Adaptive Rotor, Phase I

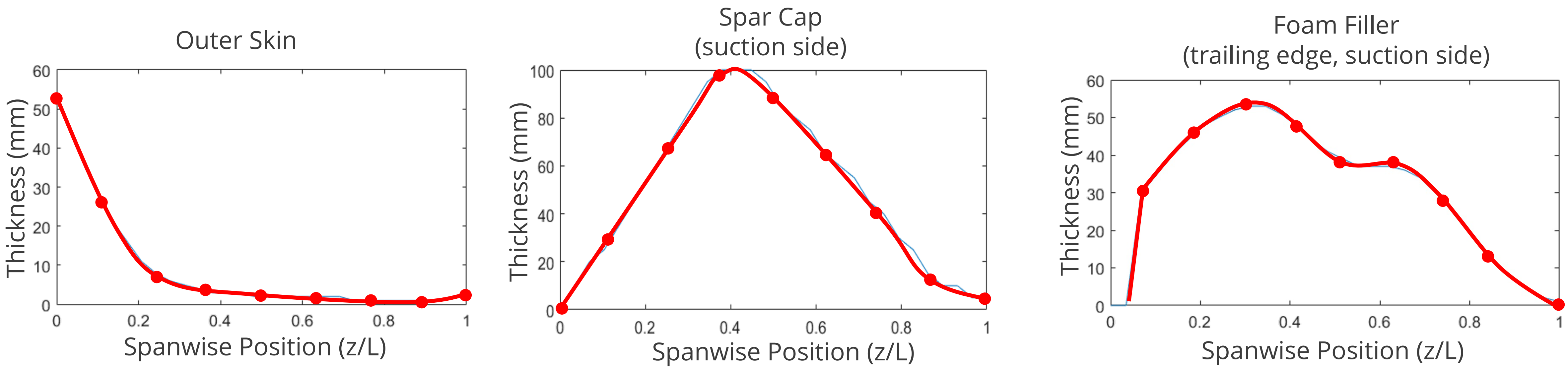
Iteratively perform high-level turbine optimization of LCOE with WEIS, high-fidelity detailed structural optimization of blade mass with NuMAD

NuMAD calls upon ANSYS commercial FEA software for detailed analysis.

Information exchanged remotely, many hours for each phase of process.



Big Adaptive Rotor, Phase I, Detailed Design Optimization



Spanwise thickness of blade components + spar cap width set as design variables, with smooth interpolation between key points

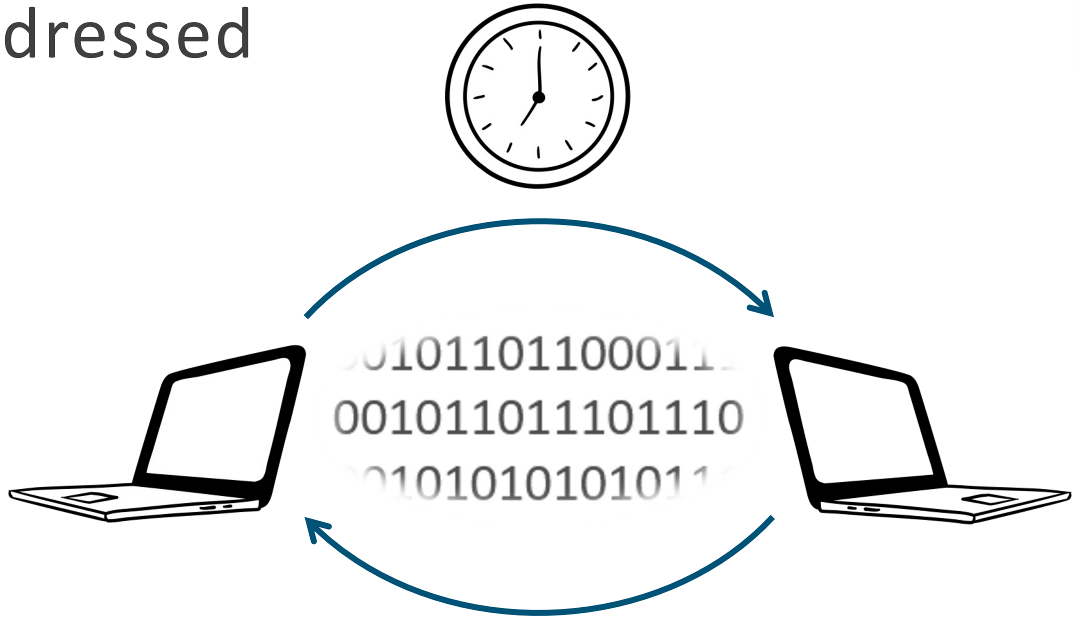
Structural analysis performed on shell FEA models using ANSYS

Sensitivity “sweep” performed to determine the most influential design variables

Visual inspection for any suspicious behavior in results

Gradient-based optimization performed to minimize mass while preventing ultimate failure, buckling, fatigue failure, preserving natural frequencies and max tip-deflection

Challenges in Recent Work to be Addressed

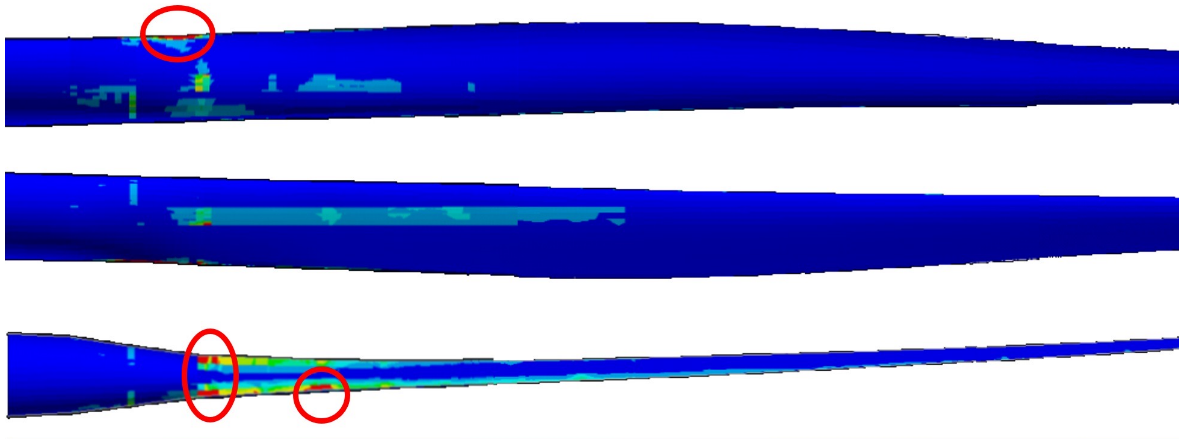


Time-consuming to run simulations and exchange large amounts of data between labs

Limitation of licenses for ANSYS software, lengthy optimization with many design variables

Need for frequent qualitative inspection of results make for highly manual process

Potential for infinite design-correction loop with two toolsets iterating on one another's results



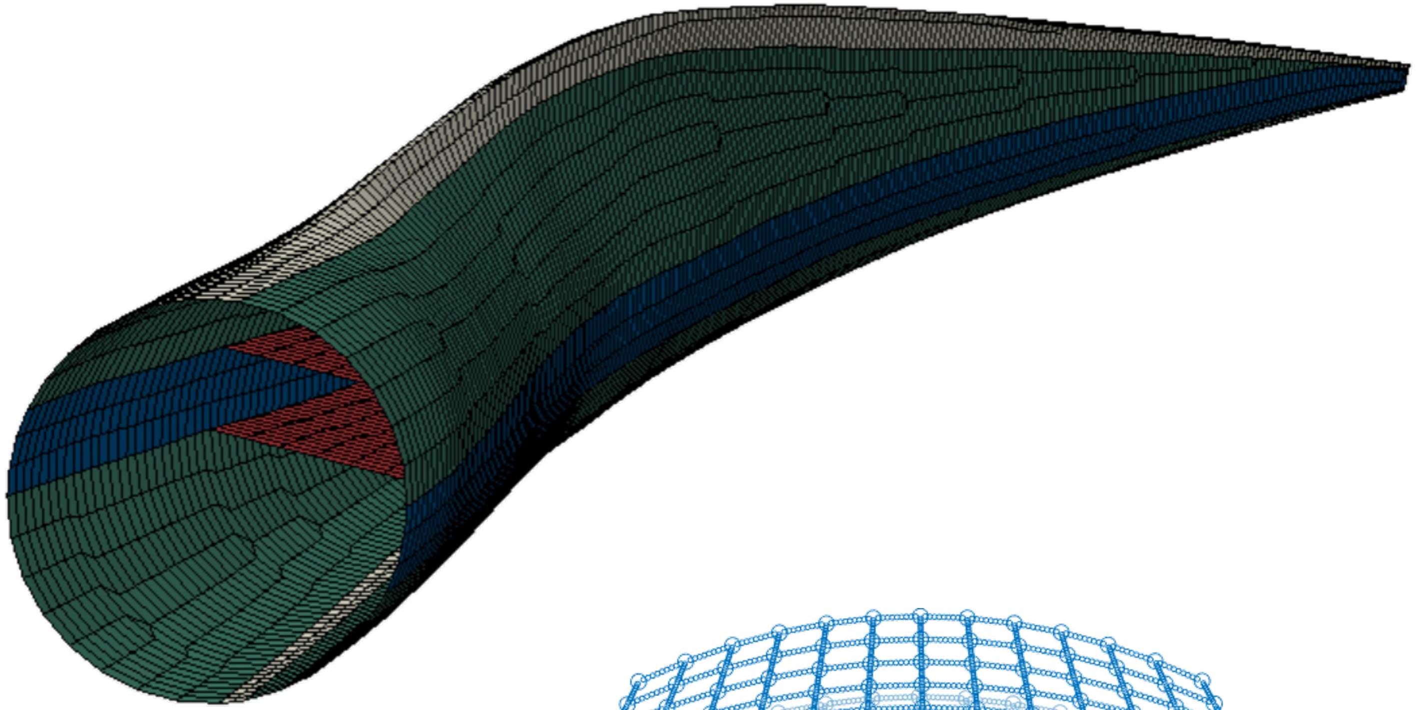
Failure index plot for BAR-DRC (ref. 2)

In-House Mesh Generation for NuMAD

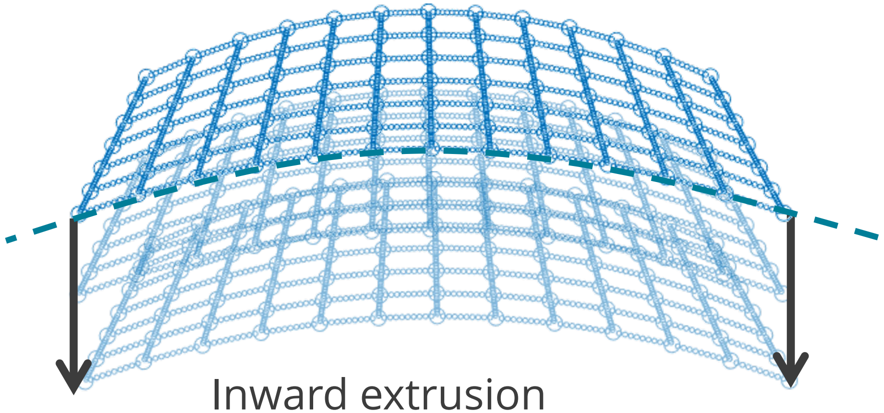
Functionality underway to generate finite element meshes for shell and solid element blade models

Mesh output provided in a platform-agnostic format, for user flexibility

Long-term goal to generate full 3D solid models from user-provided 2D mesh profiles



BAR-UAG constructed with in-house meshing

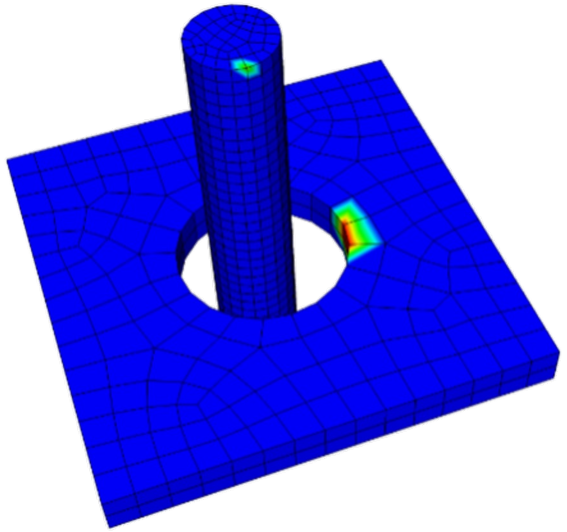


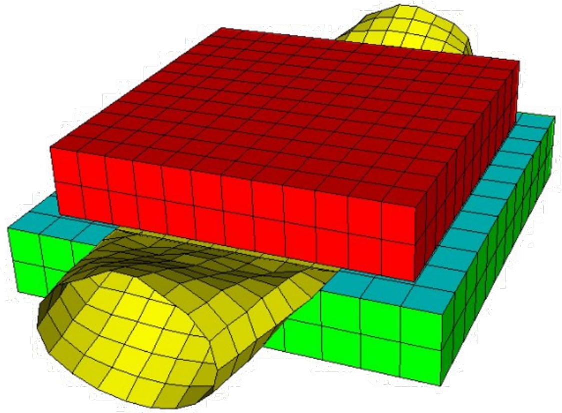
Inward extrusion from outer mold line

Open-Source FEA Analysis Alternatives

Commercial FEA software to be substituted with license-free, open-source alternatives such as:

- Sierra (advanced 3D FEA capability out of Sandia Labs, license for general use)
- ANBA4 (publicly available 2D cross-section analysis tool with adjoint-based sensitivity analysis, github.com/ANBA4/anba4)
- AStrO (general 3D FEA modeling capability with adjoint-based sensitivity analysis)





Graphical model renderings from Sierra FEA software (ref. 3)

Adjoint-Based Sensitivity Analysis

Given an objective function L that depends on a vector of design variables $\boldsymbol{D}$, and on the solution of an analysis/simulation $\boldsymbol{U}$,

$$L = L\big(\boldsymbol{D}, \boldsymbol{U}(\boldsymbol{D})\big)$$

The total derivative of the objective with respect to a given design variable D_i can be expressed

$$\frac{dL}{dD_i} = \frac{\partial L}{\partial D_i} + \frac{\partial L}{\partial \boldsymbol{U}} \cdot \frac{\partial \boldsymbol{U}}{\partial D_i}$$

The analysis solution is governed by the discretized equations of motion

$$\boldsymbol{R}\big(\boldsymbol{D}, \boldsymbol{U}(\boldsymbol{D})\big) = 0$$

$$\Rightarrow \frac{d\boldsymbol{R}}{dD_i} = \frac{\partial \boldsymbol{R}}{\partial D_i} + \left[\frac{\partial \boldsymbol{R}}{\partial \boldsymbol{U}}\right] \frac{\partial \boldsymbol{U}}{\partial D_i} = 0$$

$$\Rightarrow \frac{\partial \boldsymbol{U}}{\partial D_i} = -\left[\frac{\partial \boldsymbol{R}}{\partial \boldsymbol{U}}\right]^{-1} \frac{\partial \boldsymbol{R}}{\partial D_i}$$

Adjoint-Based Sensitivity Analysis

Then the total derivative of the objective can be written:

$$\frac{dL}{dD_i} = \frac{\partial L}{\partial D_i} - \frac{\partial L}{\partial \boldsymbol{U}} \left[\frac{\partial \boldsymbol{R}}{\partial \boldsymbol{U}}\right]^{-1} \frac{\partial \boldsymbol{R}}{\partial D_i}$$

First compute the *adjoint* $\boldsymbol{\Lambda}$, solve

$$\left[\frac{\partial \boldsymbol{R}}{\partial \boldsymbol{U}}\right]^{\boldsymbol{T}} \boldsymbol{\Lambda} = \frac{\partial L}{\partial \boldsymbol{U}}$$

Then apply the result to find sensitivities for all design variables:

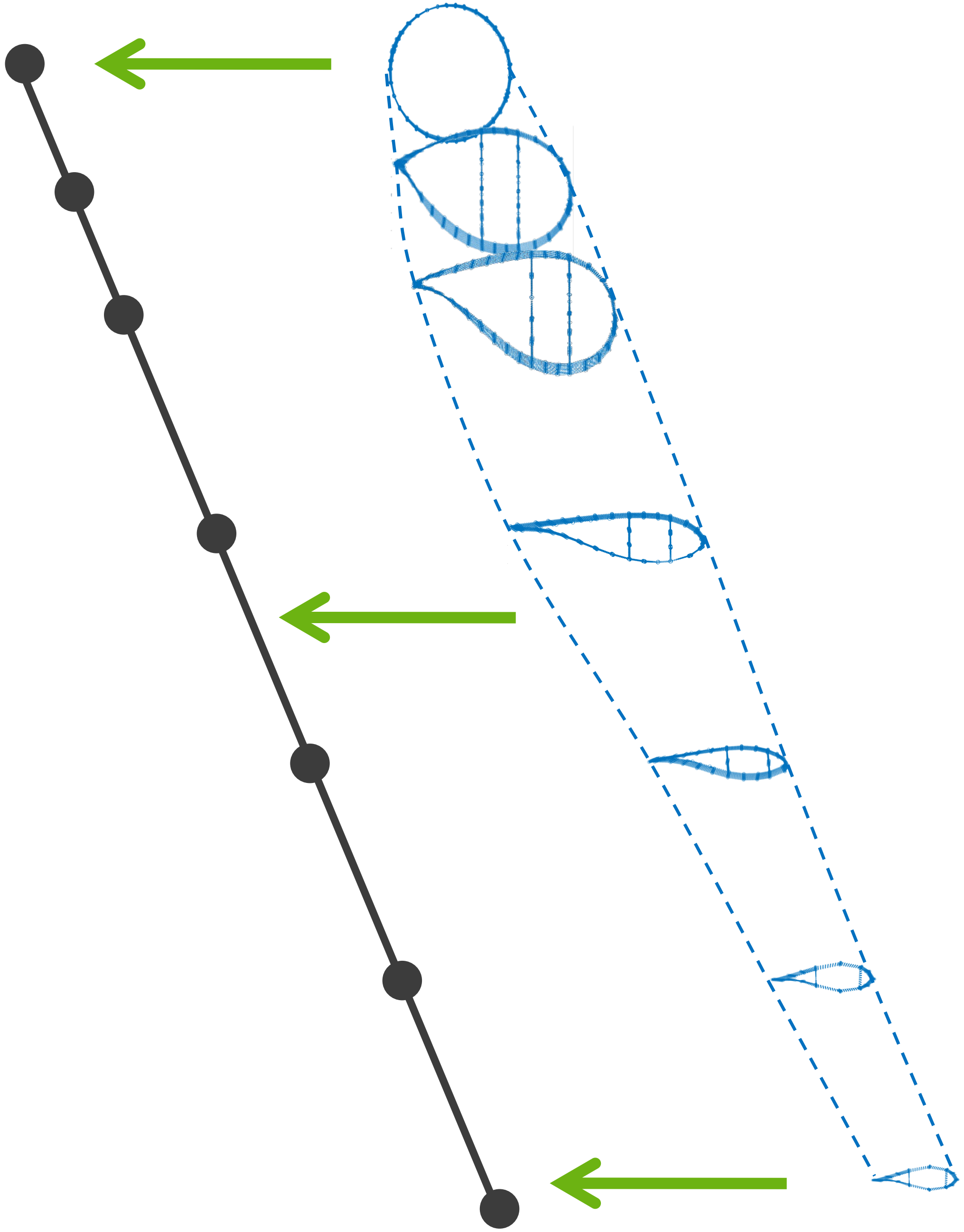
$$\frac{dL}{dD_i} = \frac{\partial L}{\partial D_i} - \boldsymbol{\Lambda} \cdot \frac{\partial \boldsymbol{R}}{\partial D_i}$$

Enhanced Beam Model Analysis

Beam models are advantageous for blades in aeroelastic simulations, but generally lack fidelity in cross-sectional stress/strain

Effort soon to be underway to implement advanced techniques like *mechanics of structure genome* (ref. 4) to obtain high-fidelity mechanical behavior from beam model results

Goal to interface the procedure into with WEIS for a more rigorous structural check in the turbine-level optimization process



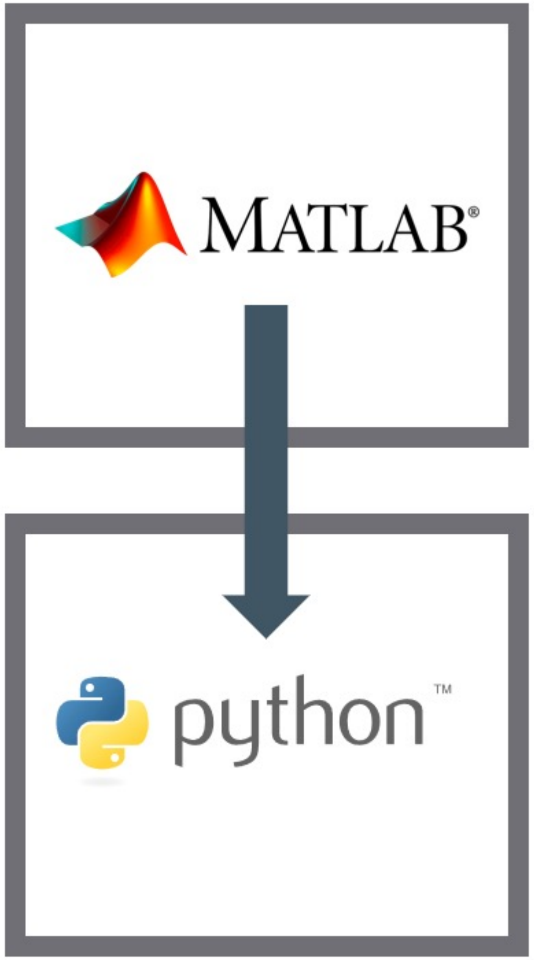
Python-Based Version of NuMAD

Development underway for Python-based version of NuMAD

Aim to be more accessible to users without MATLAB license

More easily integrated with NREL's largely Python-based toolset

Summer work has seen successful conversion of some core classes such as main blade object, and source code within NuMAD



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THANK YOU

Questions?