UNIVERSITY of WASHINGTON

Structural Design of Composite Blades for Wind and Hydrokinetic Turbines

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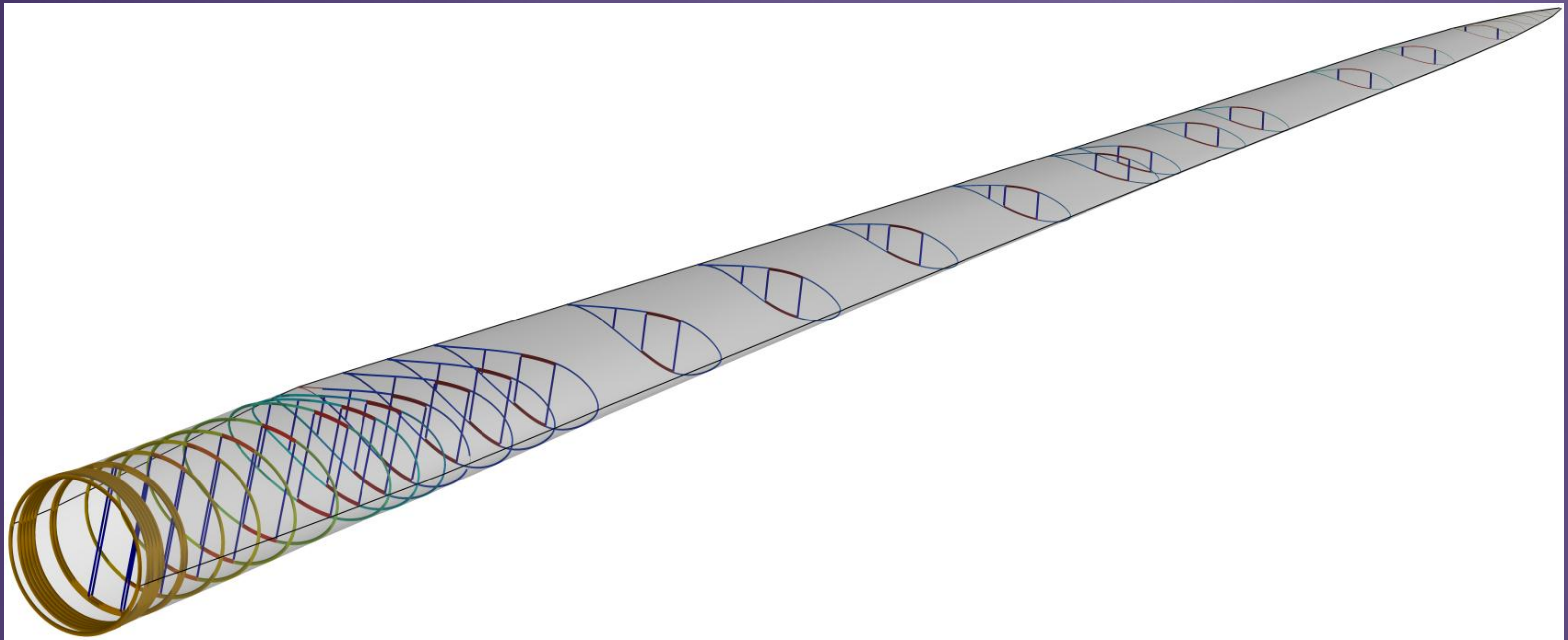


Outline

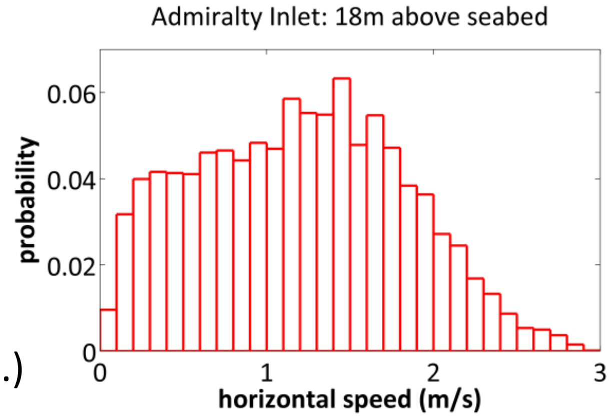
- **Previous Work**
  - coupled aero-structural optimization (*HARP_Opt* code)
  - simple structural model
- **Newly Developed Structural Analysis Tool (*CoBlade*)**
  - methodology & applications
- **Structural Optimization**
  - problem formulation
  - design of composite blade for tidal turbine
- **Recommended Future Work**

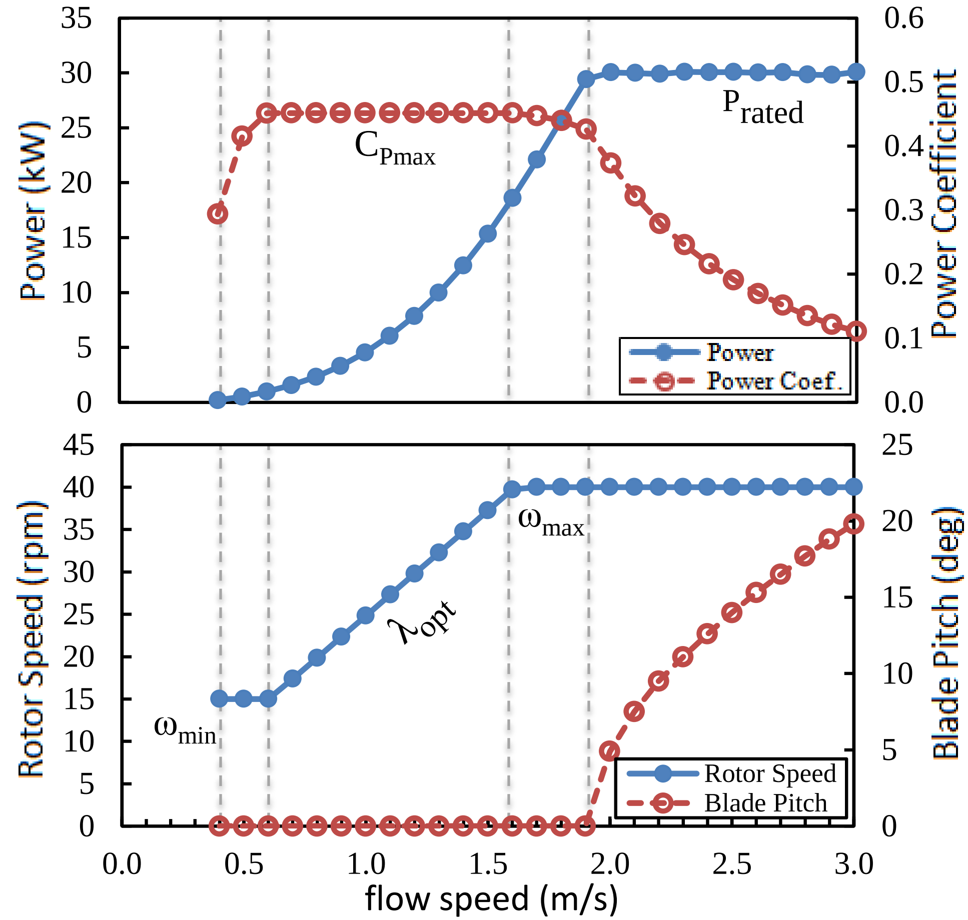
Previous Work: *HARP_Opt*

Horizontal ***A***xis ***R***otor ***P***erformance ***Opt***imization

- **given:** turbine & environmental specifications
- **optimizes:** blade shape, rotor speed & blade pitch control
- **satisfying:** maximum Annual Energy Production (AEP)

  performance constraints (power, cavitation, etc.)

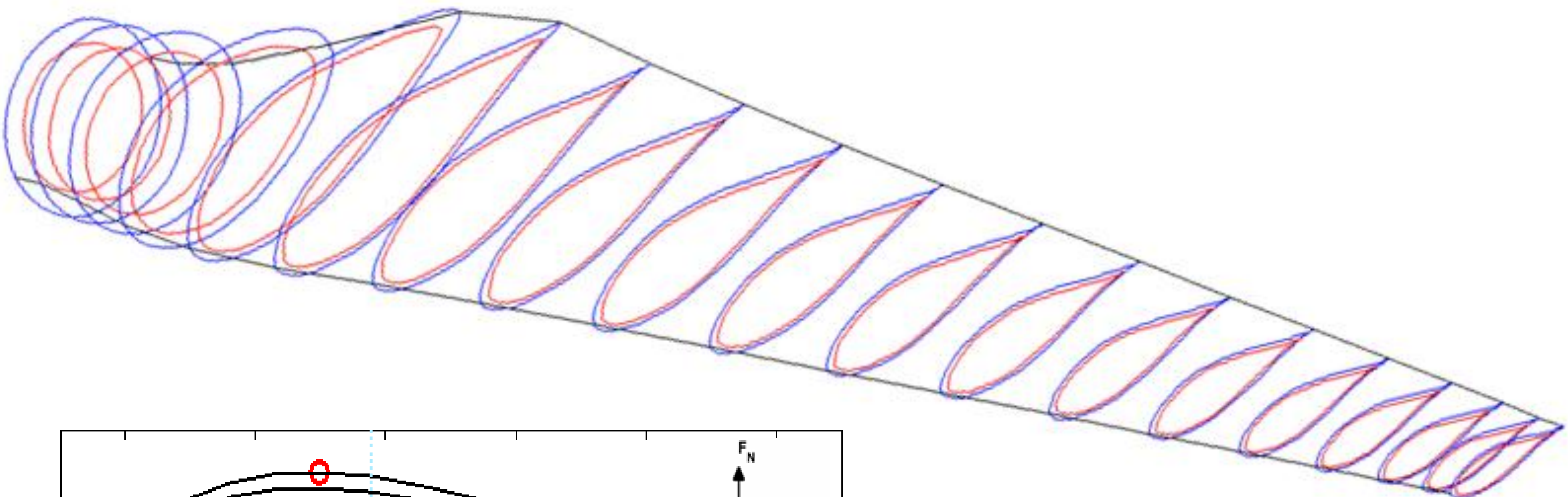


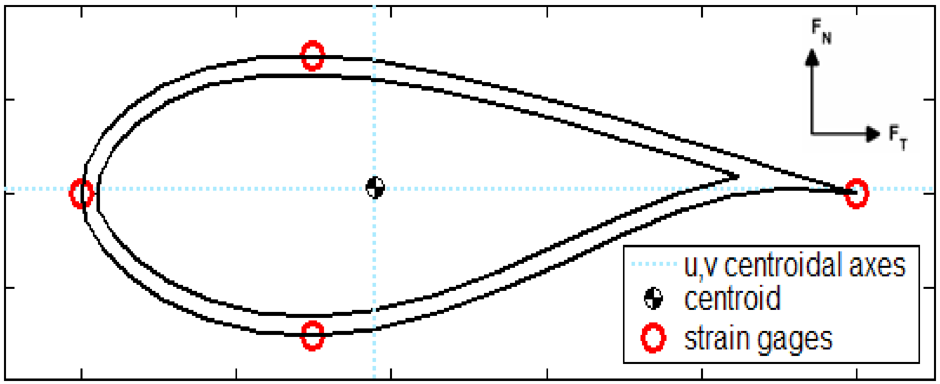


Previous Work: *HARP_Opt*

Simple Structural Model

- Thin-shelled cantilever beam
- One material w/ isotropic properties
- Bending strain is only constraint
- Shell thickness is only design variable





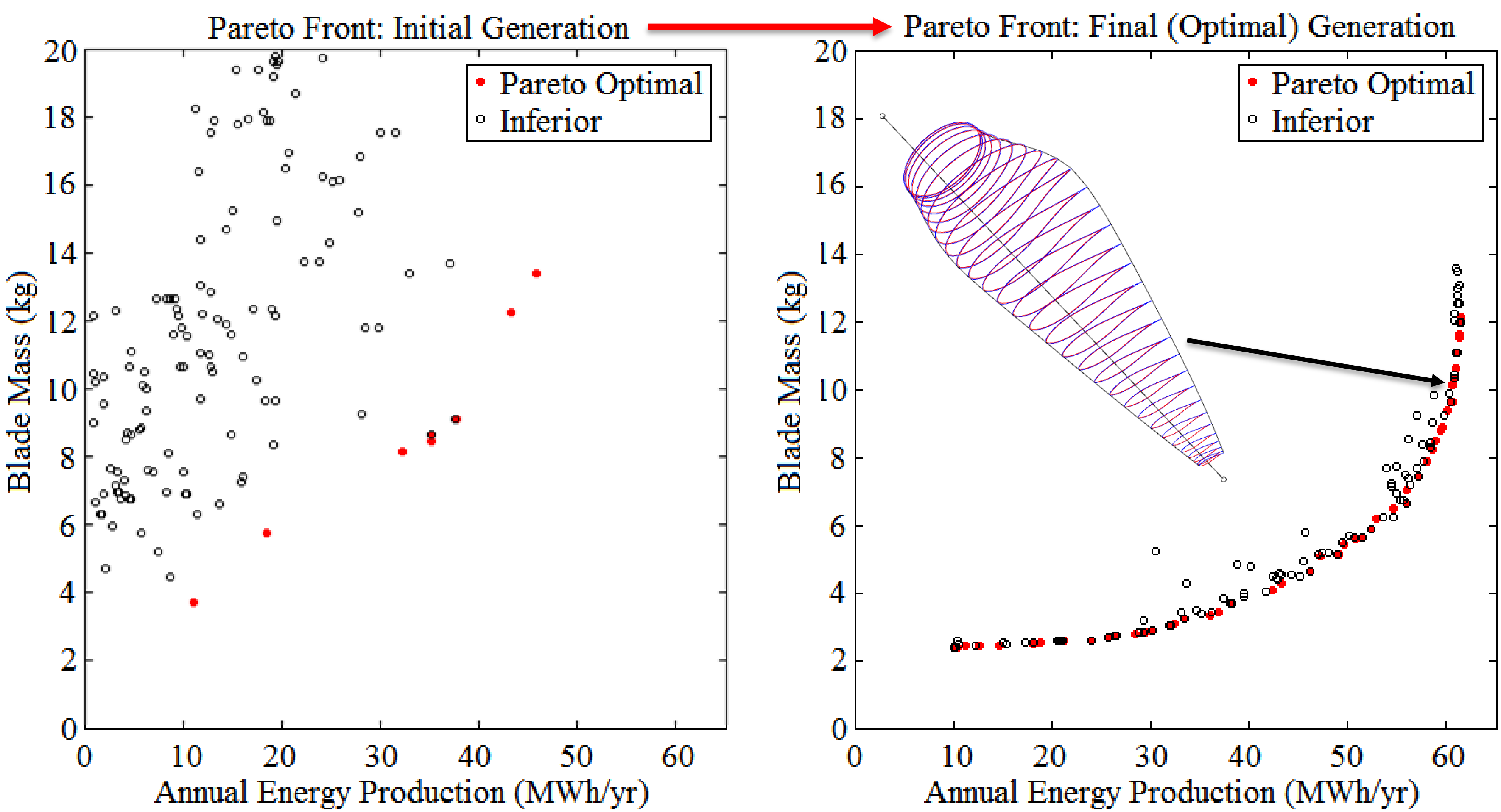
Bending Strain:

$$\varepsilon = \frac{Mc}{EI} < \varepsilon_{\max allowable}$$

Previous Work: *HARP_Opt*

Coupled Aerodynamic-Structural Optimization

- maximize energy production & minimize blade mass
- genetic algorithm identifies set of Pareto-efficient designs



Moving Forward: Structural Design

Develop a tool capable of modeling realistic composite blades

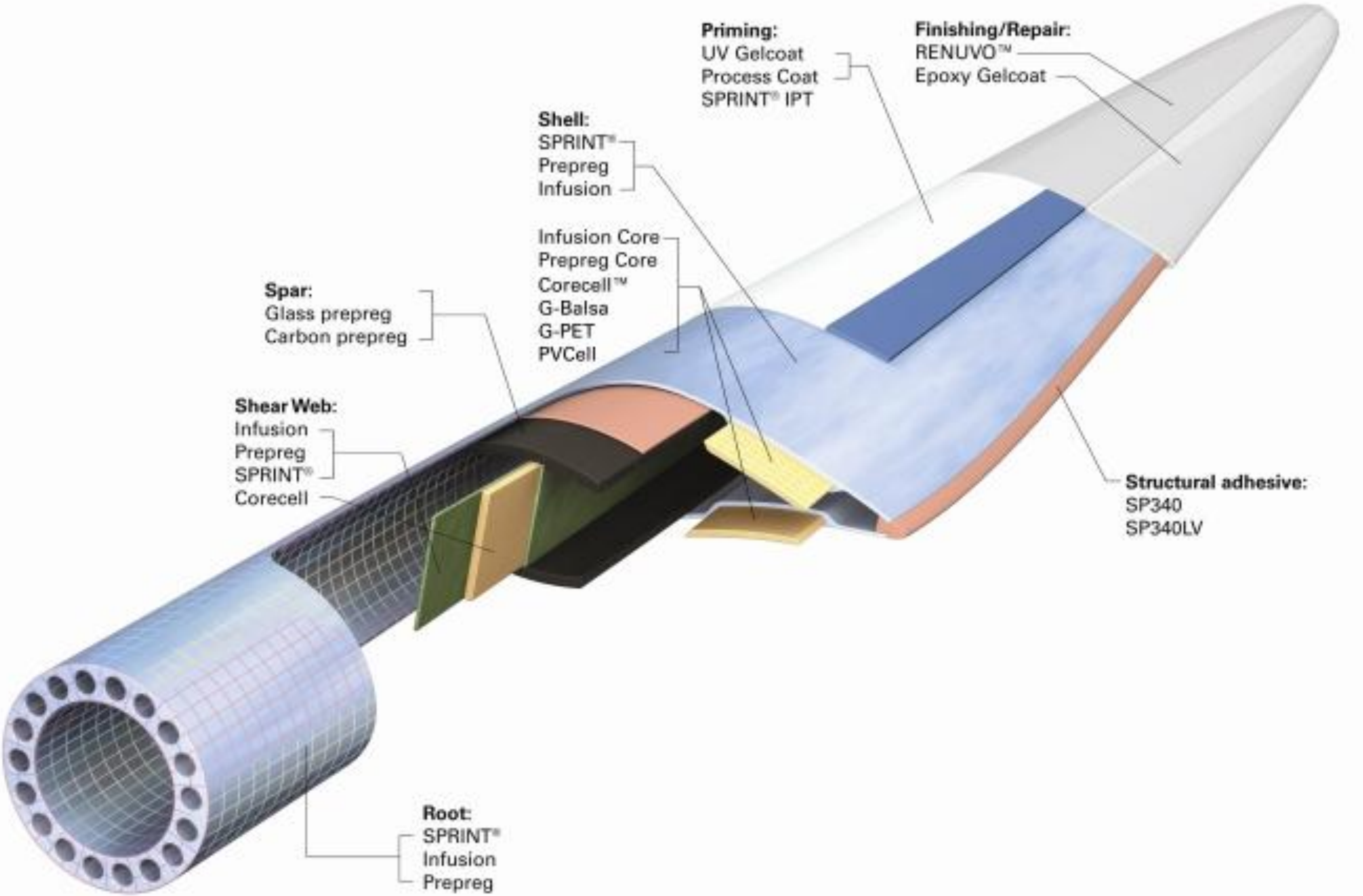


Image: *www.Gurit.com*

Overview of *CoBlade* software

Structural Analysis and Design of Composite Blades

- **realistic modeling of composite blades**
  - arbitrary topology & material properties
- **computes structural properties**
  - stiffnesses: bending, torsional, axial
  - inertias: mass, mass moments of inertia
  - principal axes: inertial/centroidal/elastic principal axes
  - offsets: center-of-mass, tension-center, shear-center
- **structural analysis tool**
  - arbitrary applied loads & body forces
  - recovery of 2D lamina-level strains & stresses
  - blade deflection & modal analysis
  - linear buckling analysis
- **optimization of composite layup**

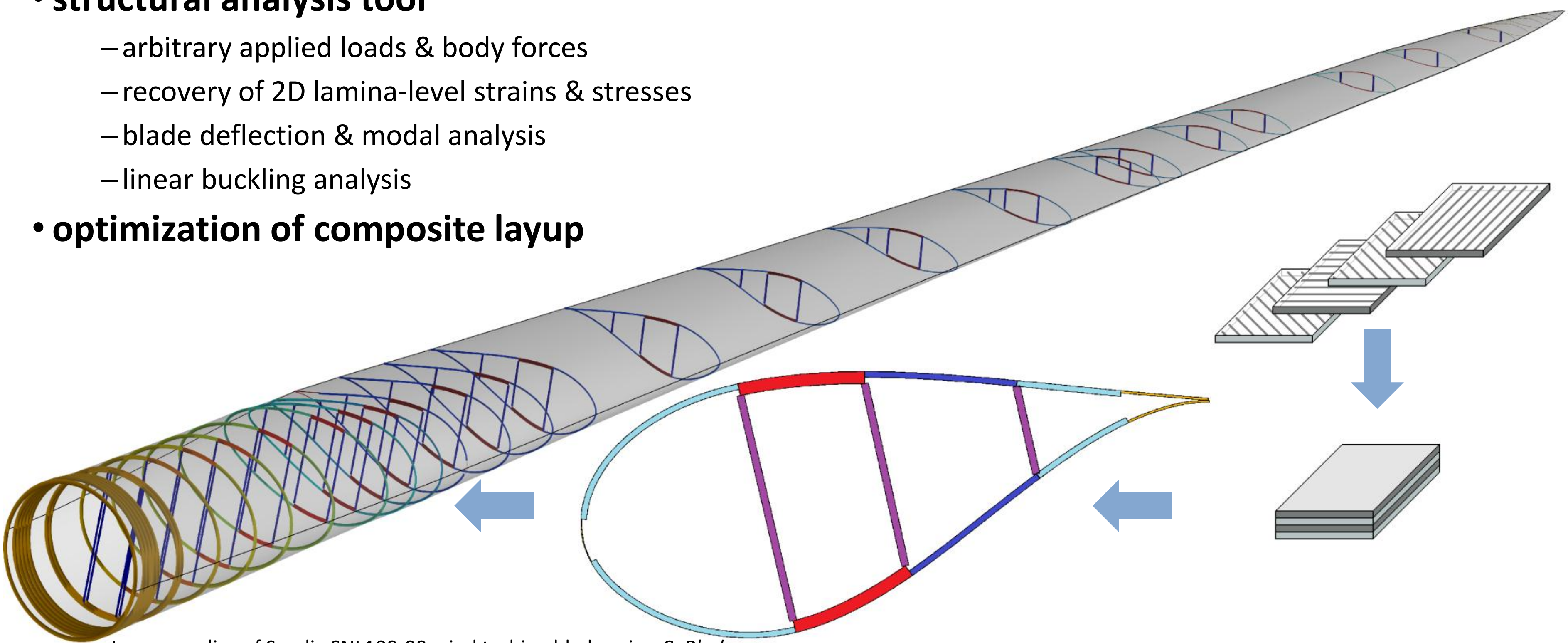
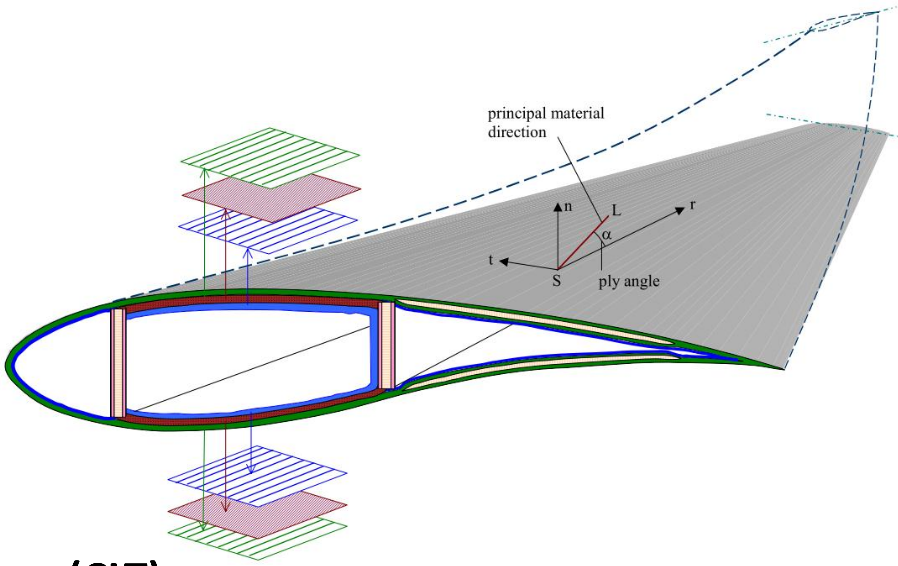


Image: replica of Sandia SNL100-00 wind turbine blade using *CoBlade*

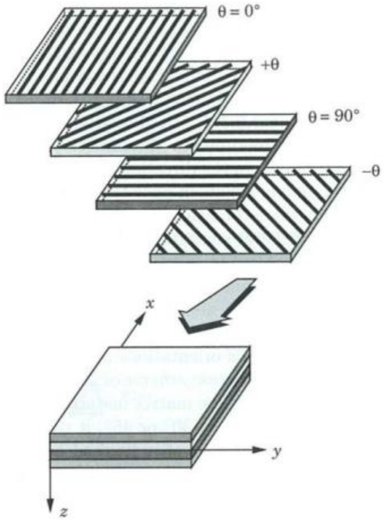
Methodology

Classical Lamination Theory + Euler-Bernoulli beam model + shear flow



Classical Lamination Theory (CLT)

- describes mechanical response of laminated plates



$$A_{ij} = \sum_{k=1}^{N} (C_{ij}^*)_k (z_k - z_{k-1})$$ extensional stiffness

$$D_{ij} = \frac{1}{3}\sum_{k=1}^{N} (C_{ij}^*)_k (z_k^3 - z_{k-1}^3)$$ bending stiffness

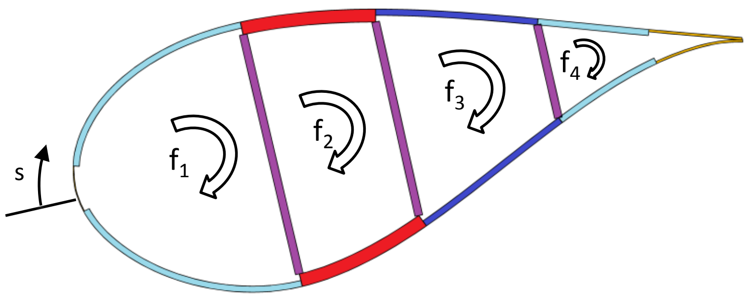
$$B_{ij} = \frac{1}{2}\sum_{k=1}^{N} (C_{ij}^*)_k (z_k^2 - z_{k-1}^2)$$ coupling stiffness

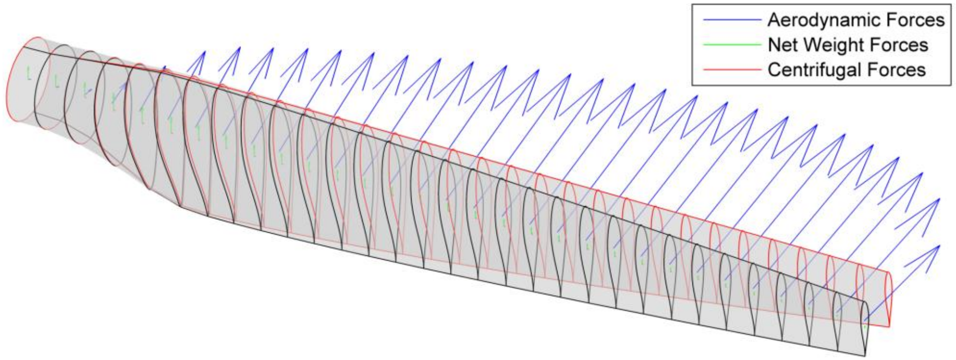
Image: G.S. Bir. “PreComp User’ Guide”

Methodology

Composite Euler-Bernoulli Beam and shear flow approach

- describes global mechanical behavior of composite beam



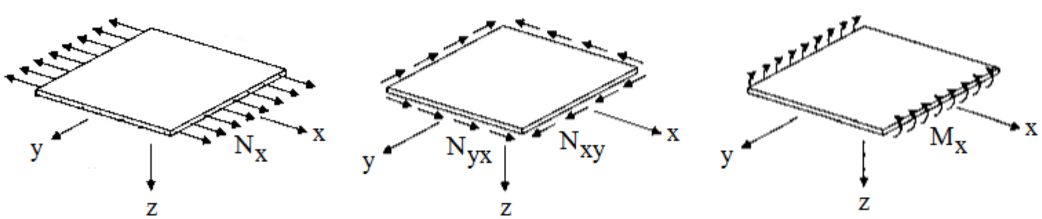


$$\sigma_{zz} = E_{ref}\left[\frac{V_z}{S^*} - \left(\frac{M_y H_x^* + M_x H_{xy}^*}{H_x^* H_y^* - {H_{xy}^*}^2}\right)x + \left(\frac{M_x H_y^* + M_y H_{xy}^*}{H_x^* H_y^* - {H_{xy}^*}^2}\right)y\right]$$

$$\frac{df_o}{ds}(s) = -t\frac{\partial \sigma_{zz}}{\partial z} \qquad \tau_{zs}(s) = \frac{f}{t}$$

Convert Beam Stresses into Equivalent Plate Loads

- recover 2D strains & stress at lamina level



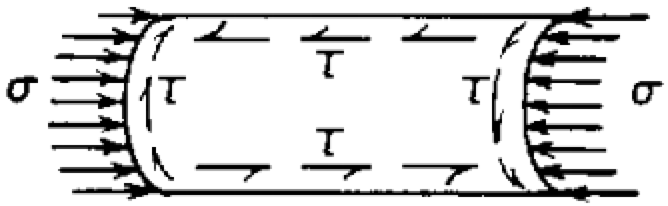
$$\begin{Bmatrix} N_x \\ N_y \\ N_{xy} \\ M_x \\ M_y \\ M_{xy} \end{Bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{16} & B_{11} & B_{12} & B_{16} \\ A_{12} & A_{22} & A_{26} & B_{12} & B_{22} & B_{26} \\ A_{16} & A_{26} & A_{66} & B_{16} & B_{26} & B_{66} \\ B_{11} & B_{12} & B_{16} & D_{11} & D_{12} & D_{26} \\ B_{12} & B_{22} & B_{26} & D_{12} & D_{22} & D_{26} \\ B_{16} & B_{26} & B_{66} & D_{16} & D_{26} & D_{66} \end{bmatrix} \begin{Bmatrix} \varepsilon_{x0} \\ \varepsilon_{y0} \\ \gamma_{xy0} \\ \kappa_x \\ \kappa_y \\ \kappa_{xy} \end{Bmatrix}$$

Methodology

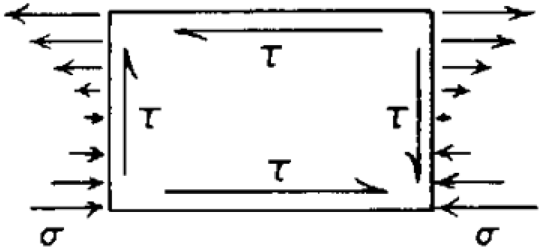
Linear Buckling Analysis

- pinned boundary conditions (conservative)
- contributions from panel stiffness, curvature, thickness, & width

top/bottom surface panels

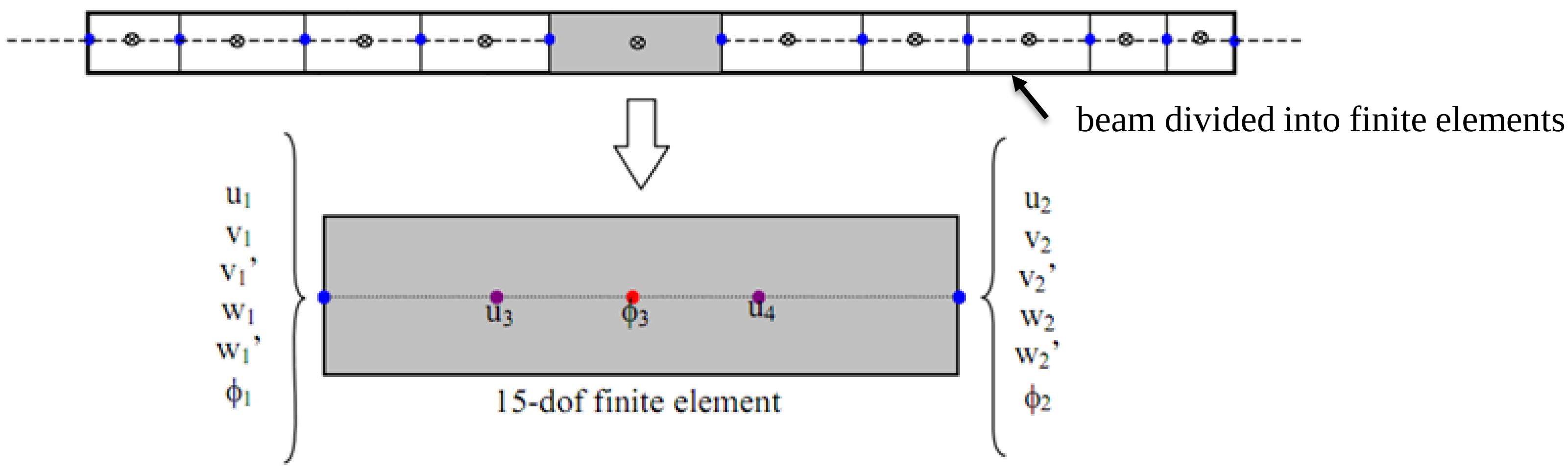


shear web panels



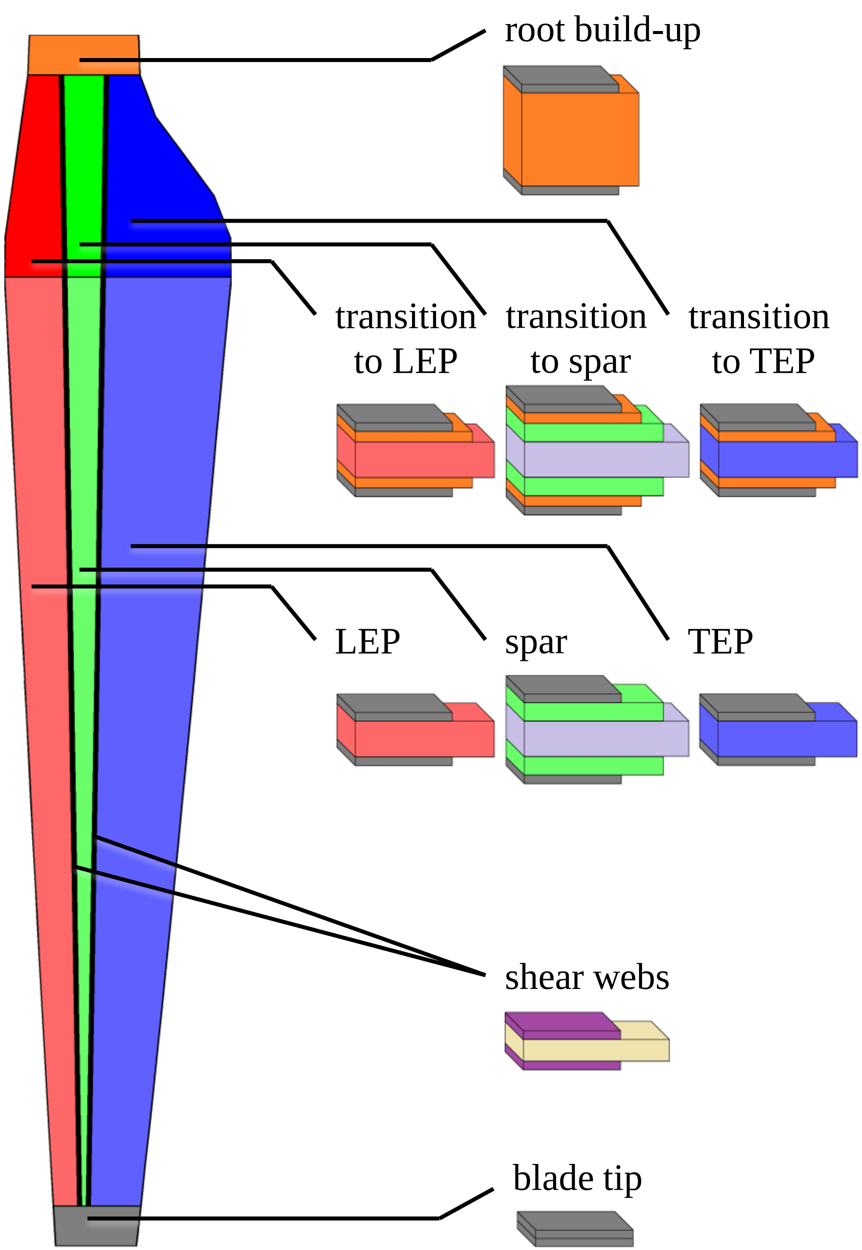
Modal Analysis

- ***BModes***: Rotating Beam Coupled Modes (NREL code)

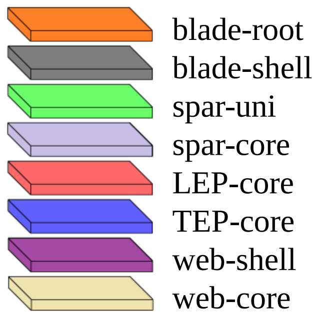


[1] G.S. Bir, 2005. "User's Guide to BModes: Software for Computing Rotating Beam Coupled Modes," NREL TP-500-38976, Golden, CO: National Renewable Energy Laboratory.

Optimization: Composite Layup



Material Legend:



Material Properties:

E_{11}
E_{22}
G_{12}
ν_{12}
ρ

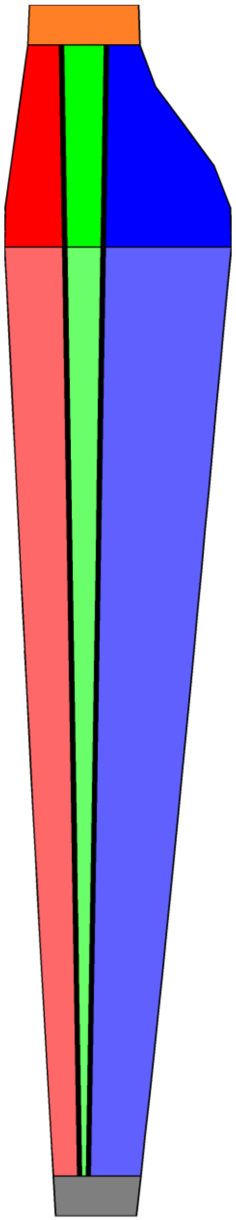
Failure Stresses:

$\sigma_{11,fT}$
$\sigma_{11,fC}$
$\sigma_{22,yT}$
$\sigma_{22,yC}$
$\tau_{12,y}$

Composite Layup

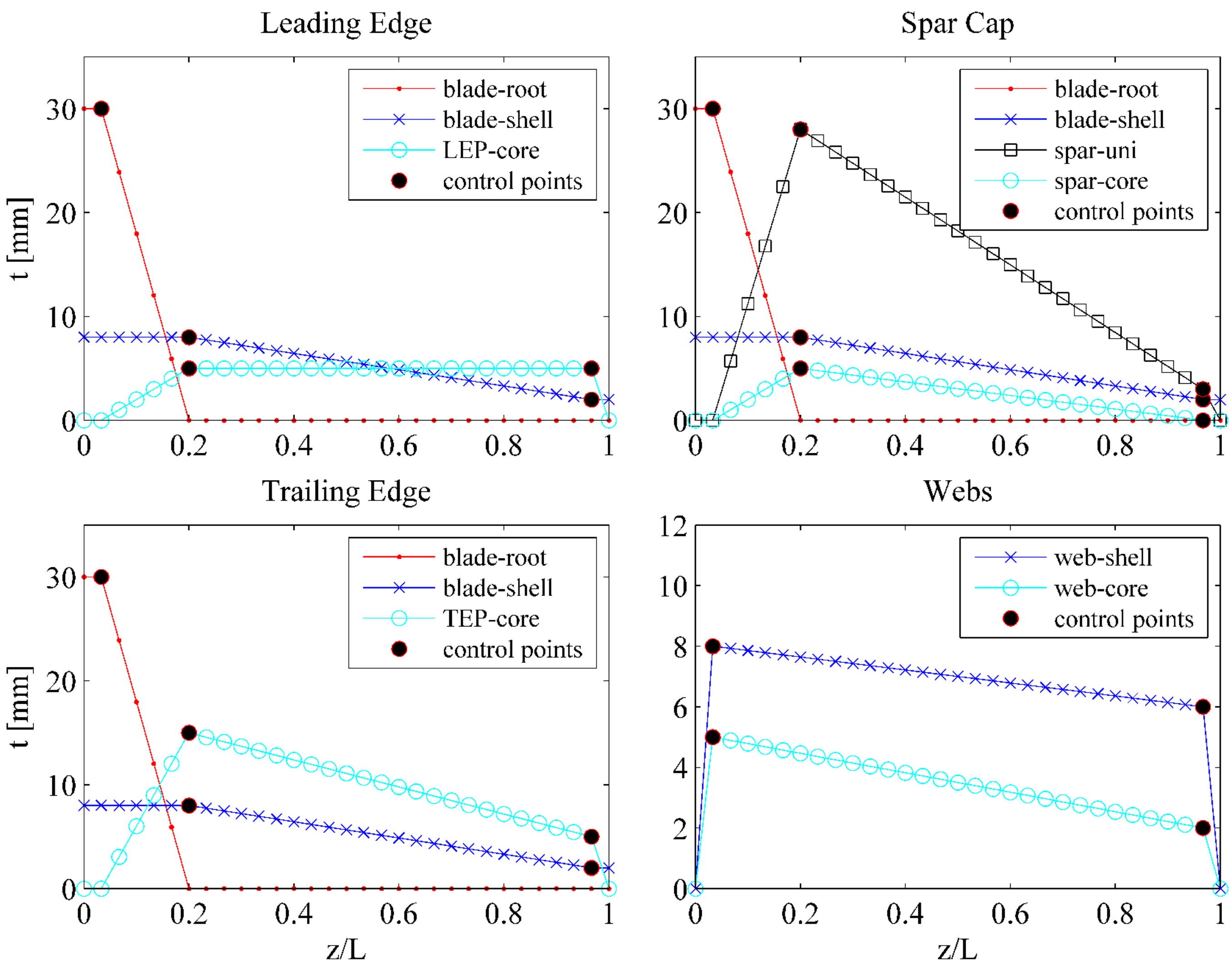
- all laminates balanced & symmetric
- high & low pressure surfaces symmetric
- identical shear web laminates

Optimization: Design Variables



Design Variables

- spar-cap width at inboard & outboard stations
- lamina thicknesses along blade length



Optimization: Objectives & Constraints

minimize: $f(\vec{x})$ = *BladeMass* * $\prod_{n=1}^{N} \max\{1,\ p_n\}^2$

$$p_1 = \frac{\sigma_{11,max}}{\sigma_{11,fT}}$$

$$p_2 = \frac{\sigma_{11,min}}{\sigma_{11,fC}}$$

$$p_3 = \frac{\sigma_{22,max}}{\sigma_{22,yT}}$$

$$p_4 = \frac{\sigma_{22,min}}{\sigma_{22,yC}}$$

$$p_5 = \frac{\tau_{12,max}}{\tau_{12,y}}$$

penalty factors for maximum stress

$$p_6 = \left(\frac{\sigma}{\sigma_{buckle}}\right)^{\alpha} + \left(\frac{\tau}{\tau_{buckle}}\right)^{\beta}$$

penalty factors for buckling under compression & shear

$$p_7 = \frac{\delta_{tip}}{\delta_{allow}}$$

penalty factor for tip deflection

$$p_8 = \max\left\{\frac{\Delta\omega_{separation}}{|\omega_m - \omega_{rotor}|}\right\}, m = 1, \ldots M_{modes}$$

penalty factor for separation of blade freqs. & rotor freq.

subject to: $\overrightarrow{x_{LB}} \leq \vec{x} \leq \overrightarrow{x_{UB}}$

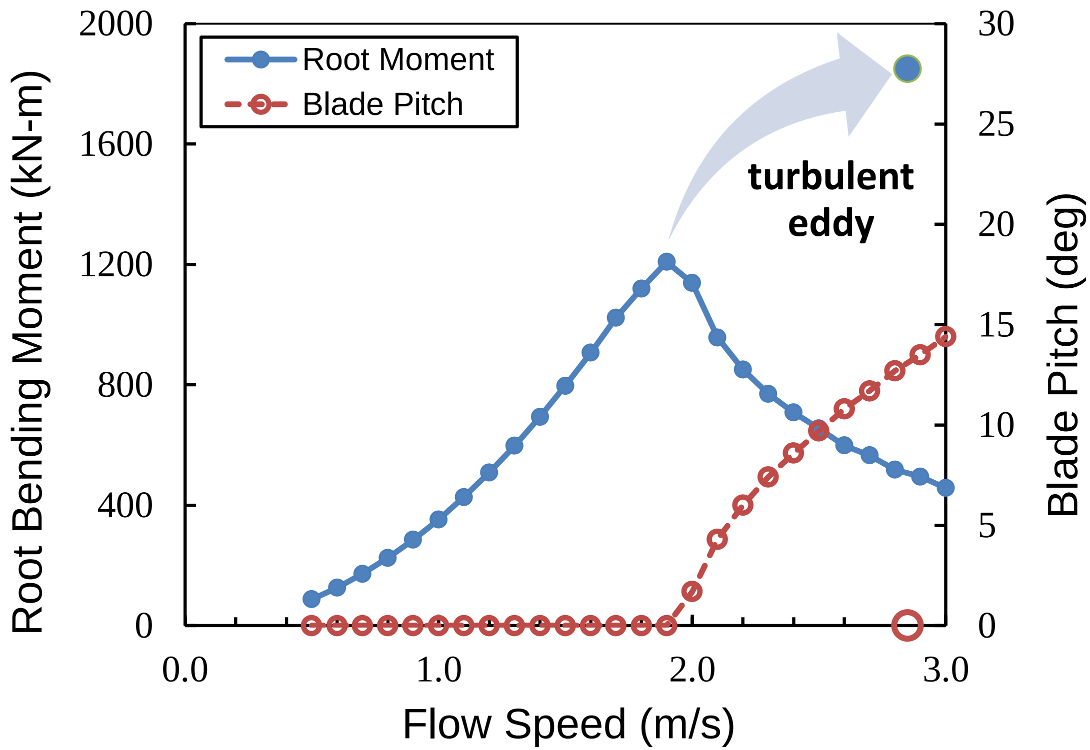
$A\vec{x} \leq \vec{b}$

constraints ensure feasible geometry

Optimization: Example Design

Composite Blade Design for Tidal Turbine

- hydrodynamic design: Department of Energy Reference Tidal Current Turbine, ref. [1]
- design loads: extreme operating conditions in Puget Sound, WA., ref. [2]



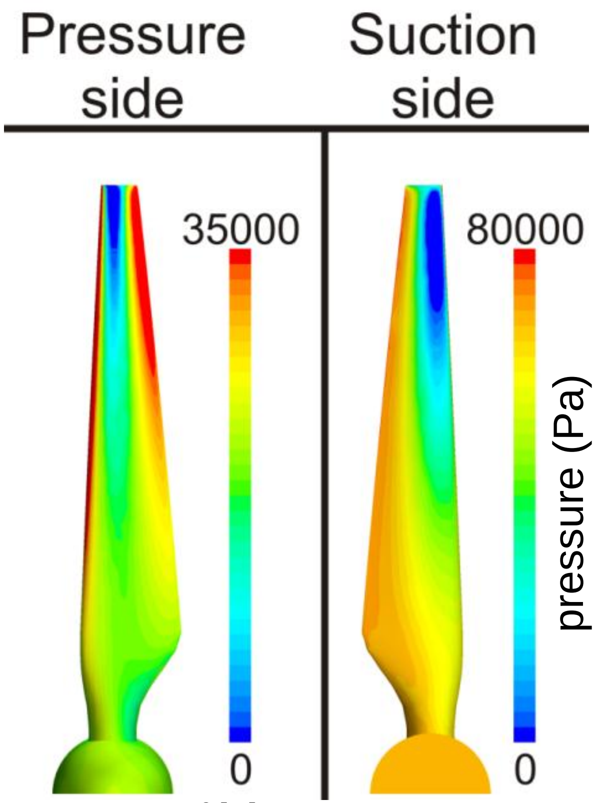
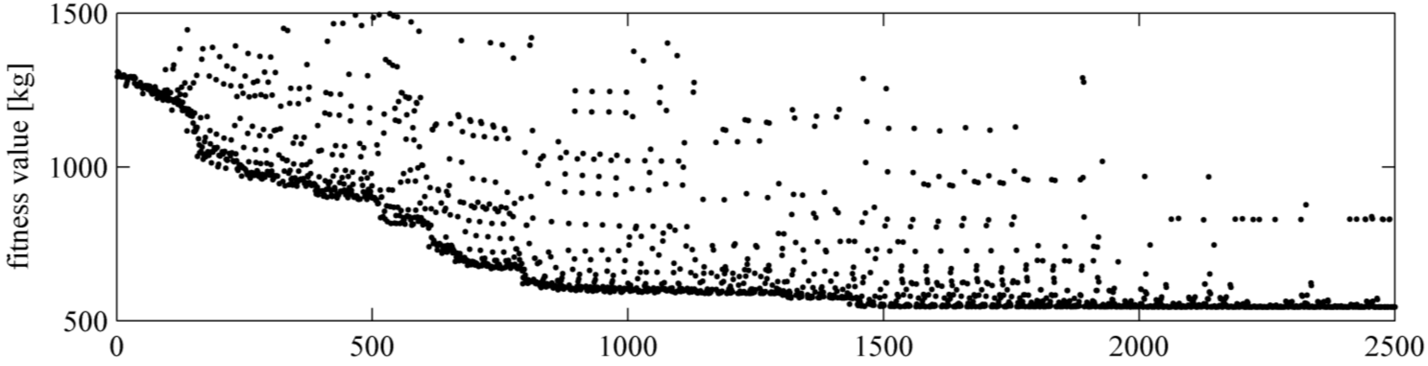


Image: ref [2]

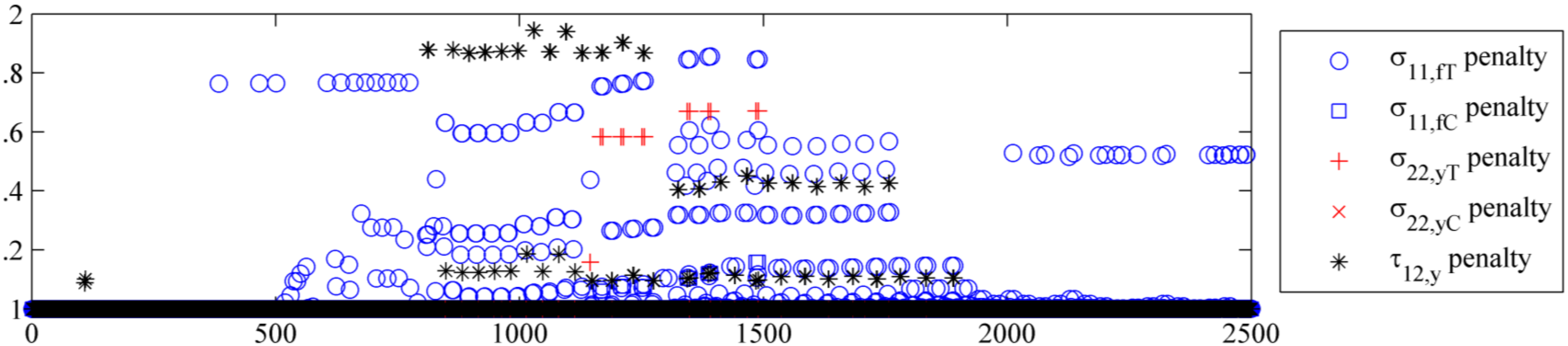
[1] M.J. Lawson, Y. Li, and D.C. Sale, 2011. “Development and Verification of a Computational Fluid Dynamics Model of a Horizontal Axis Tidal Current Turbine.” The 30th International Conference on Ocean, Offshore and Arctic Engineering.

[2] G.S. Bir, M.J. Lawson, and Y. Li, 2011. “Structural Design of a Horizontal-Axis Tidal Current Turbine Composite Blade.” The 30th International Conference on Ocean, Offshore and Arctic Engineering.

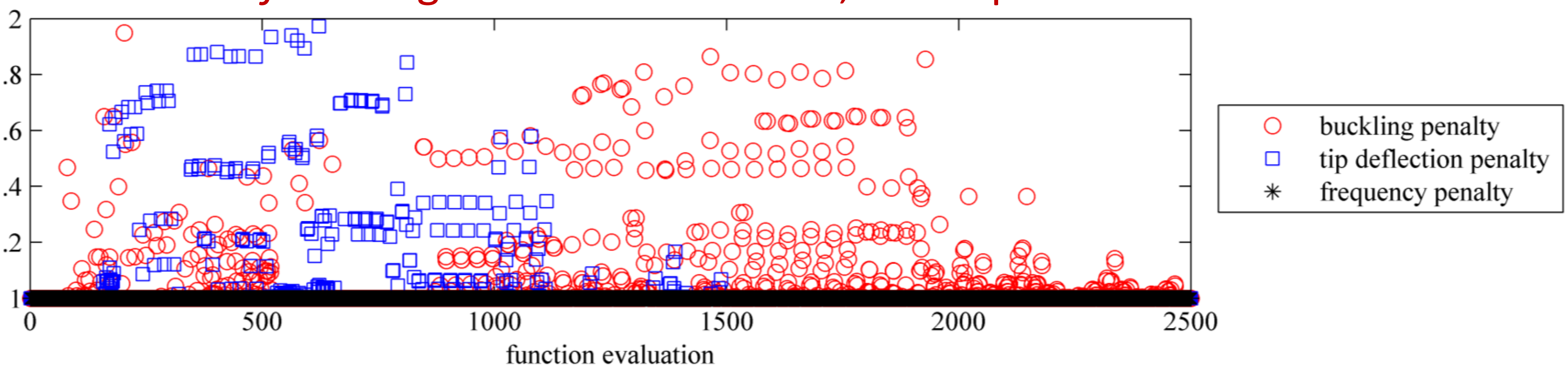
Optimization: Results



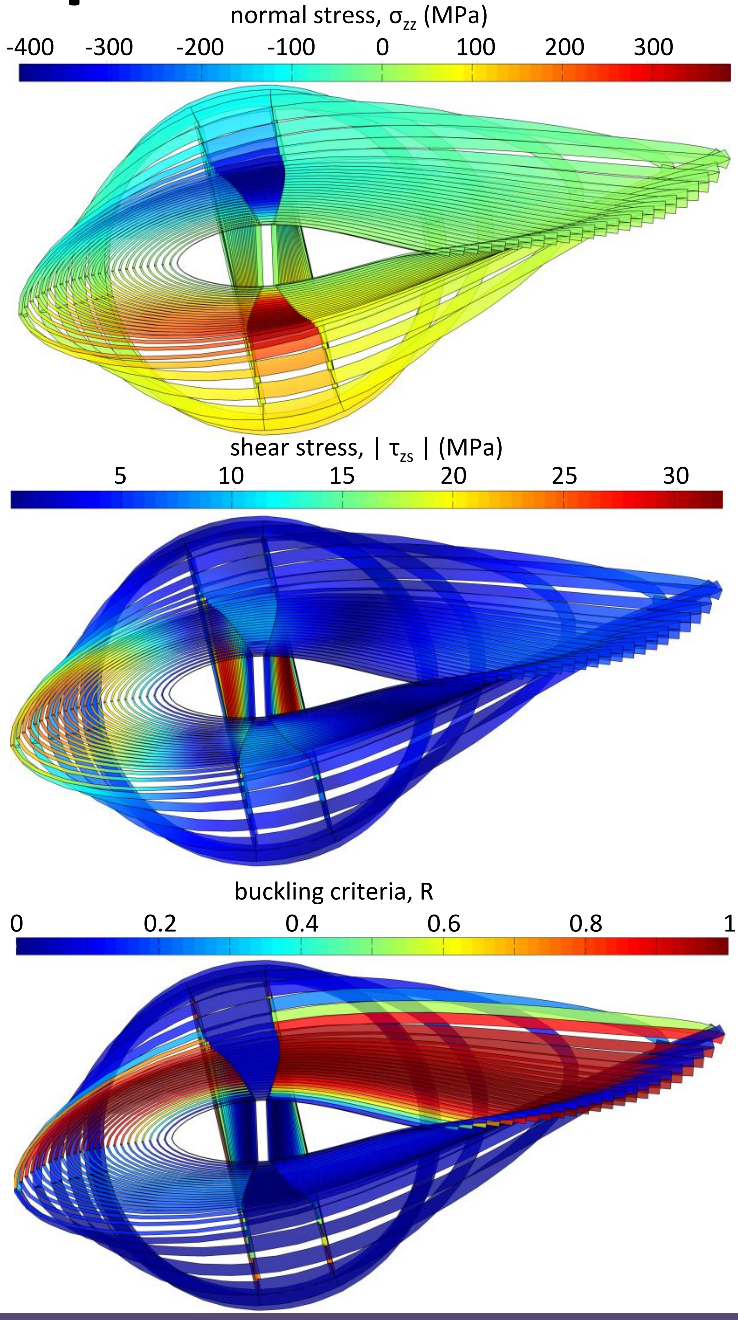
Blade mass is minimized, final iteration satisfies all constraints (no penalties)

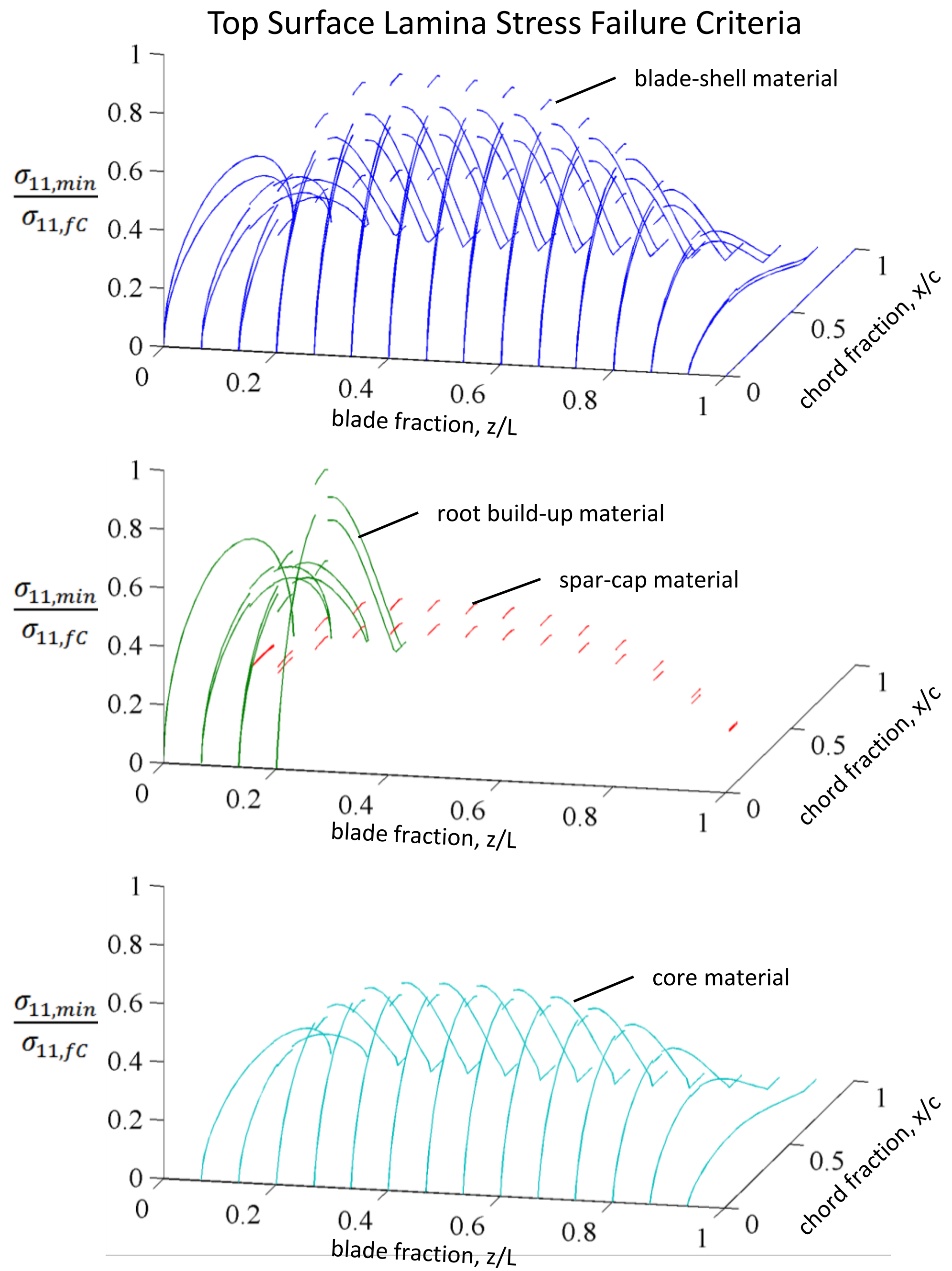


CoBlade is *fast:* single evaluation: ~1 sec, total optimization: ~40 min

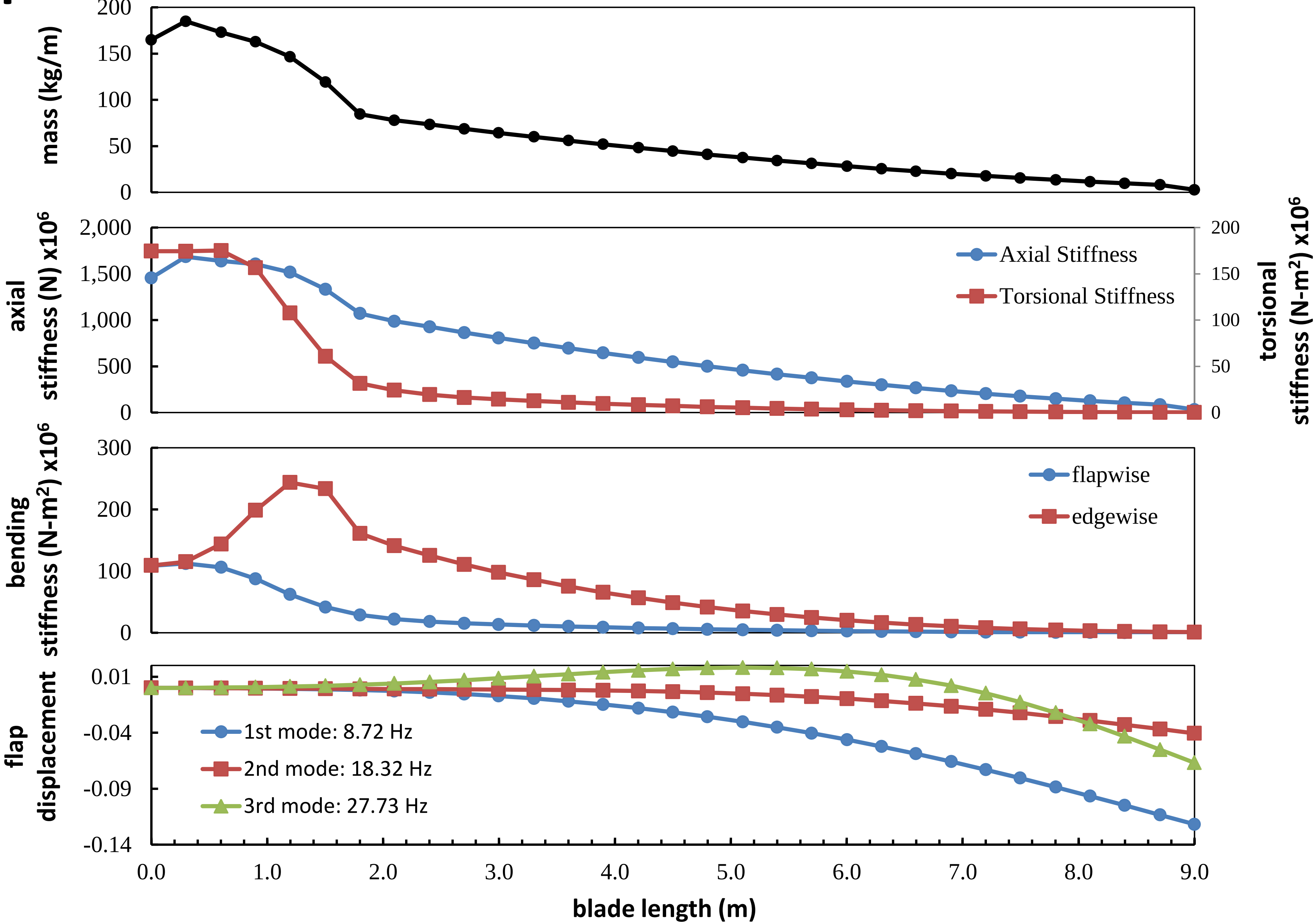


Optimization: Results





Optimization: Results

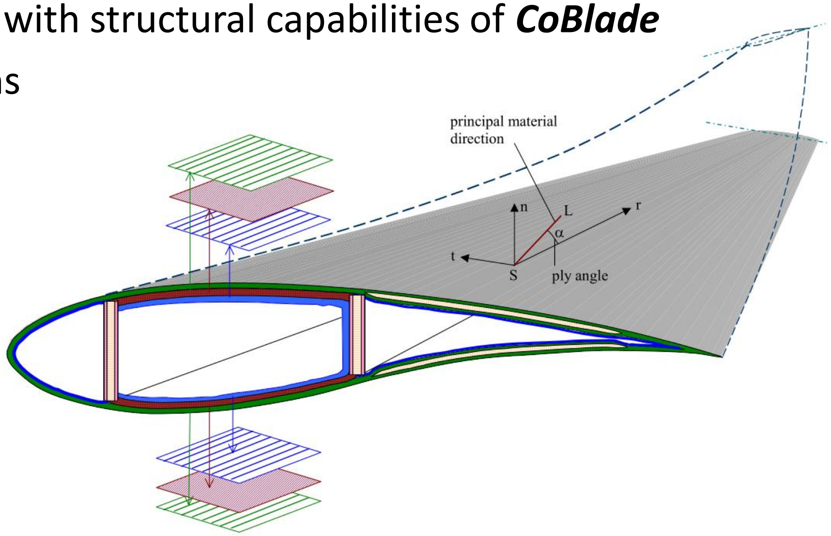


Conclusions

- Capable structural design tool, modeling of complex layups possible with ***CoBlade***
- ***NOT*** a replacement for higher-fidelity FEM, but very effective for preliminary design work
- Limited validation studies
  - –excellent agreement for analytically obtainable results
  - –good agreement with ANSYS FEM model of tapered composite beam (collaboration w/ Penn. State)

Future Work

- Preliminary results seem reasonable, but require further validation
  - –anisotropic layups
  - –buckling
  - –lamina-level strains/stresses
- Repeat coupled aero-structural optimization (***HARP_Opt***) with structural capabilities of ***CoBlade***
- Include cross-coupled terms from CLT into beam equations
- Public release of ***CoBlade*** code & documentation



Thank you! Questions?

Acknowledgements

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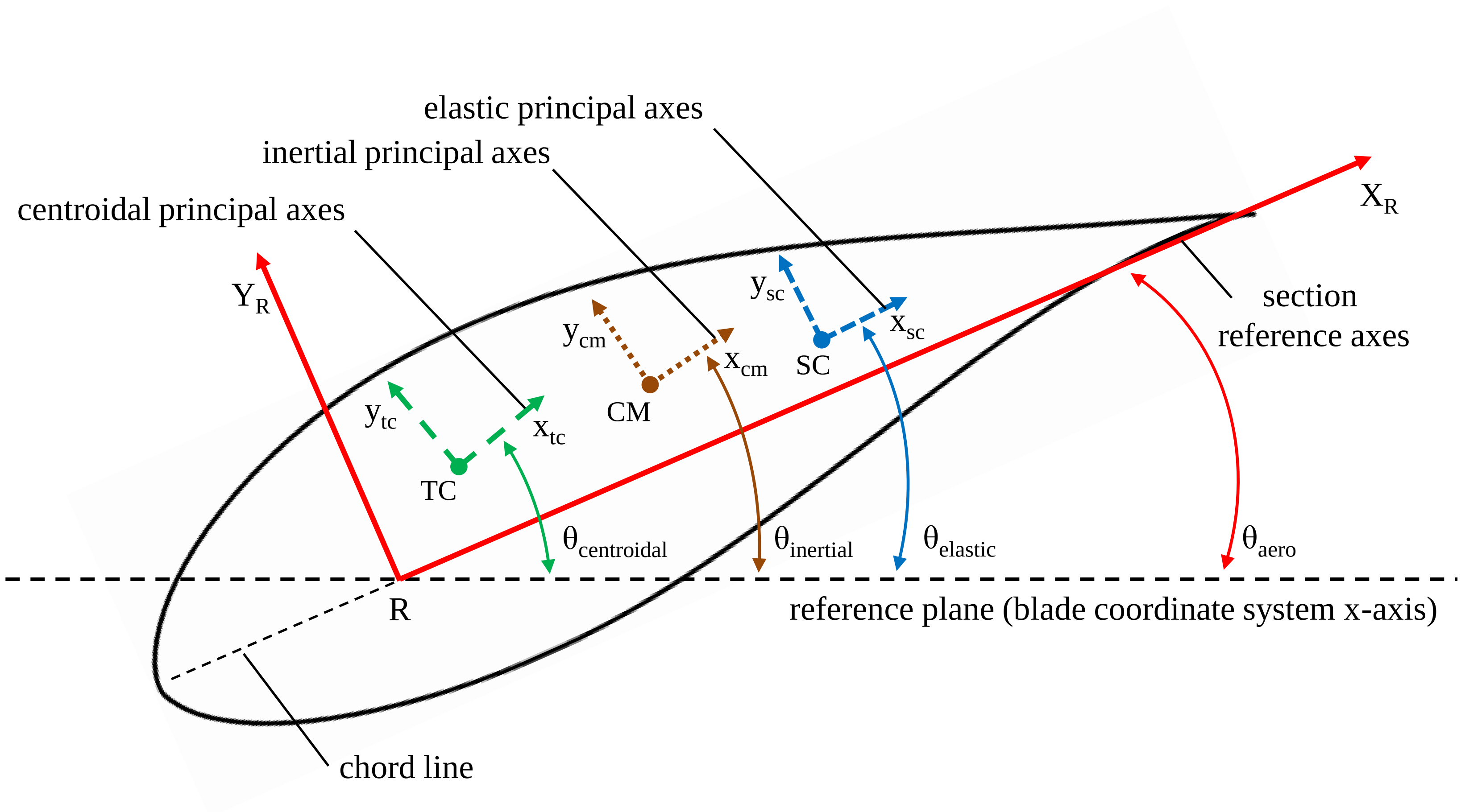
- Department of Energy, National Renewable Energy Laboratory
- University of Washington, Northwest National Marine Renewable Energy Center

Extra


elastic principal axes
inertial principal axes
centroidal principal axes
X_R
Y_R
y_{sc}
x_{sc}
SC
y_{cm}
x_{cm}
CM
y_{tc}
x_{tc}
TC
section reference axes
$\theta_{centroidal}$
$\theta_{inertial}$
$\theta_{elastic}$
θ_{aero}
R
reference plane (blade coordinate system x-axis)
chord line