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Uncertainties in Prediction of Wind Turbine Blade Flutter

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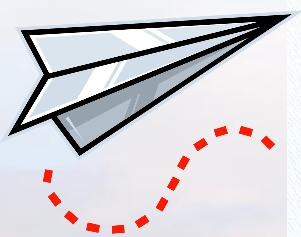
Wind Turbine Rotors Modeling and Simulation Motivation

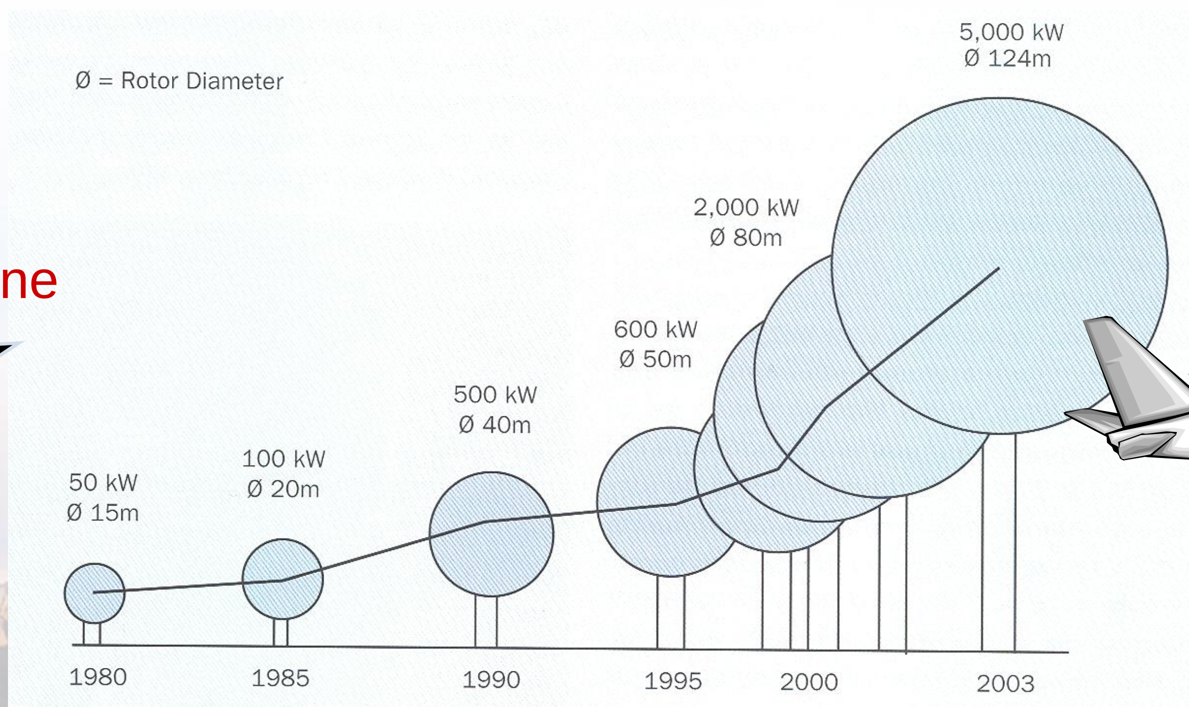
Smaller turbines → Larger turbines

$ → $$$

Build, Break, Redesign → Advanced Simulation

Paper airplane





Commercial Aircraft

Design Criteria Examples

Design Requirements

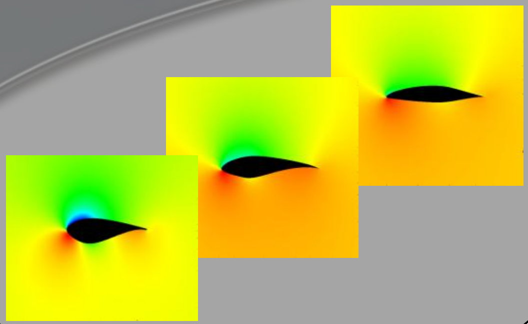
- **Conditions:**
  - 20 year minimum design life
  - Normal wind conditions
  - Extreme wind conditions
  - Wind defined by average wind speed and turbulence intensity
- **Loads**
  - Ultimate loads – can the system withstand the largest expected loads?
  - Fatigue – can it withstand the combination of all loads?
  - Functional requirements – deflections (tower clearance)

Example Load Cases

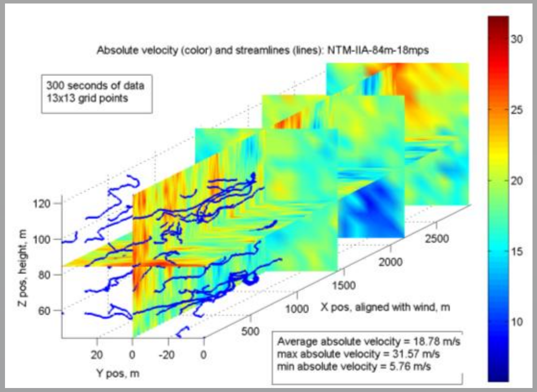
- **Normal production: Fatigue and/or ultimate loads due to**
  - Normal turbulence
  - Extreme turbulence
  - Extreme gust
    - Extreme wind speed
    - Extreme direction change
    - Extreme wind shear
  - Start up and shut down
- **Normal production with faults**
  - Yaw system fault
  - Pitch system fault
  - Loss of electrical load, etc.
- **Parked Turbine**
  - Extreme loads
  - Normal loads
- **Transportation loads**

System Analysis with Wind Turbine Aeroelastic Simulation

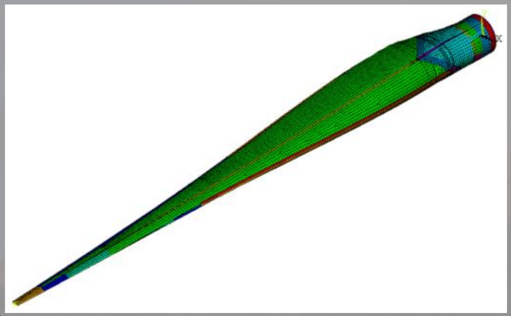
Aerodynamic Performance



Turbulent Wind Input



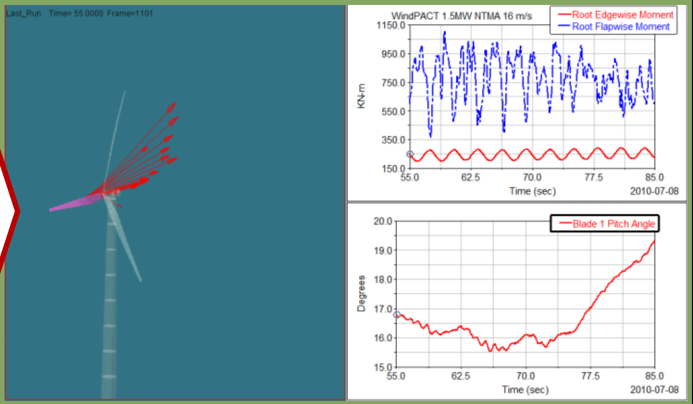
Structure and Materials



Aeroelastic System Dynamics Model

Includes Controls Implementation

System Response



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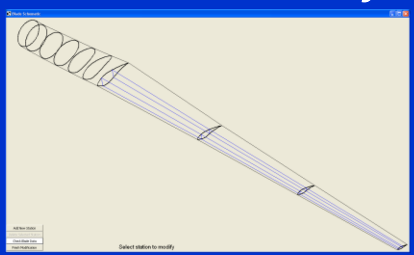
Blade Design with NuMAD

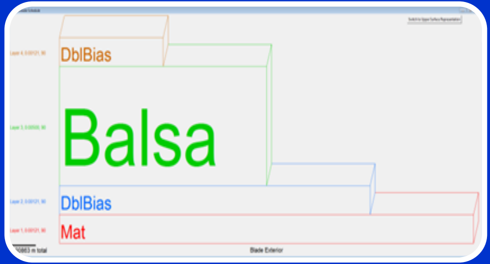
NuMAD

NuMAD:
Numerical Manufacturing
And Design Tool

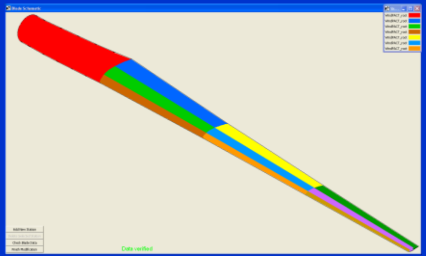
Blade Geometry



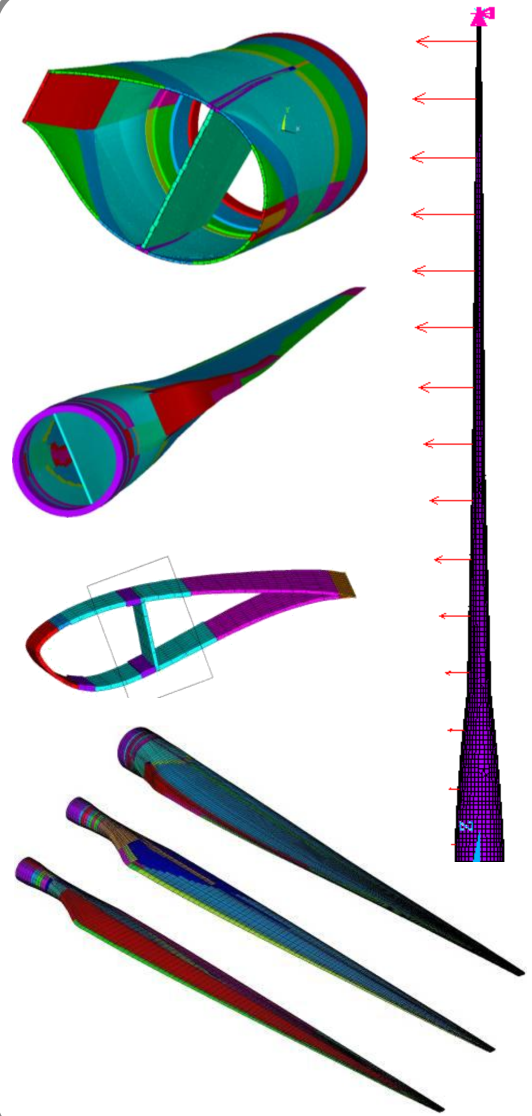
Materials & Layups



Stack Placement



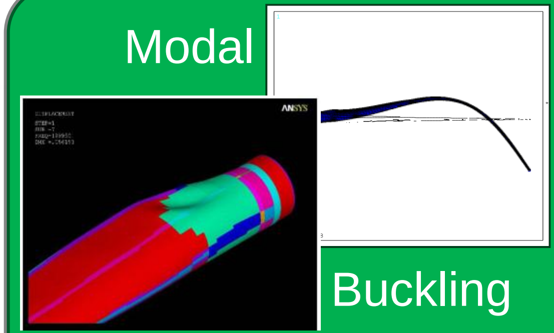
ANSYS FE Model



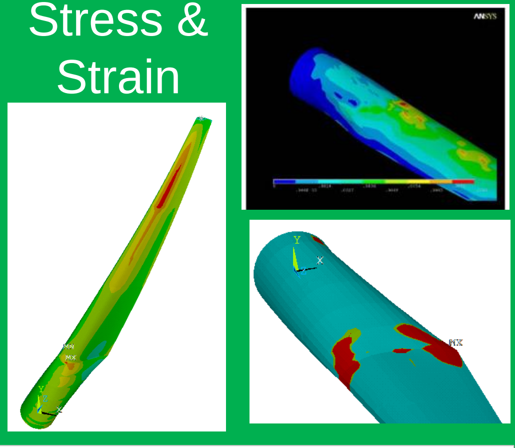
ANSYS Analysis

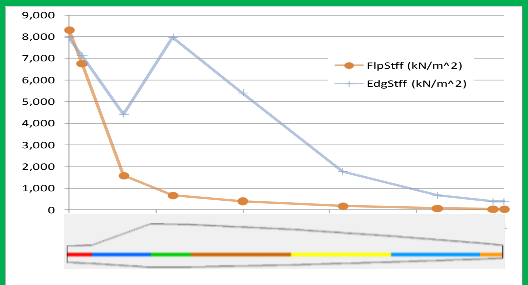
Modal

Buckling



Stress & Strain

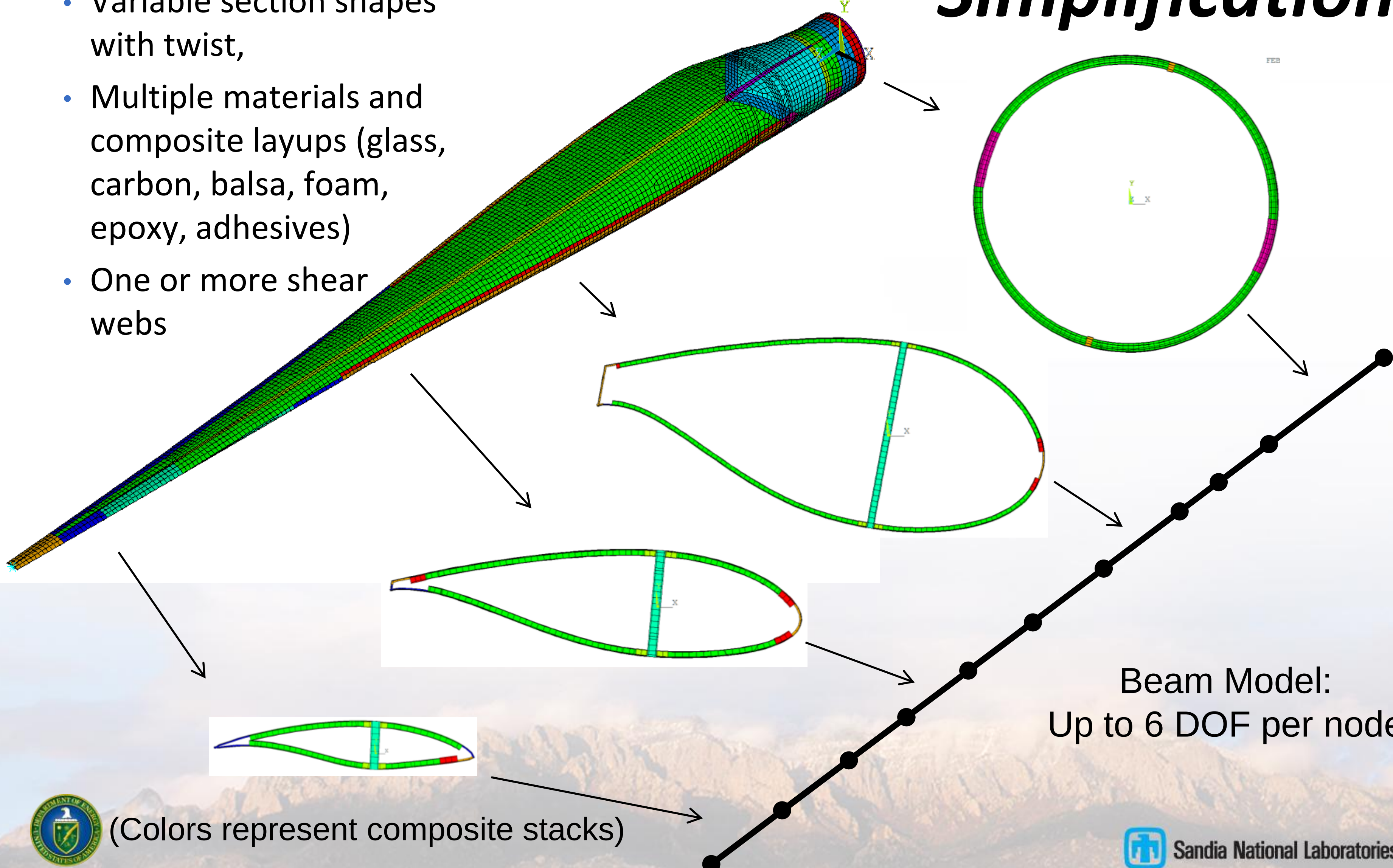




Beam Properties

Blade Structural Model Simplification

- **Wind turbine blades include**
  - Variable section shapes with twist,
  - Multiple materials and composite layups (glass, carbon, balsa, foam, epoxy, adhesives)
  - One or more shear webs



(Colors represent composite stacks)

Beam properties

- ***Motivation: Efficient aeroelastic analysis for design and certification***
  - Time marching system response simulation
  - Stability analyses

- ***Typical outputs consist of the following distributions***
  - Bending, torsion and axial stiffness
  - Coupled stiffness
  - Shear center coordinates
  - Tension center coordinates
  - Inertial properties: masses and center of mass

Outline

- Background and motivation for blade model simplification
- **Background on PreComp, BPE, VABS**
- **Comparison of tools on a uniform cross section**
- **Comparison of tools on an actual wind turbine blade**
- **Background on a classical flutter analysis approach for wind turbine blades**
- **Demonstration of computed flutter speed sensitivity with respect to computed beam properties**

PreComp

- Includes a modified classic laminate theory with a shear-flow approach to compute necessary properties and axis locations
- Computes blade torsion stiffness and cross-stiffness properties
- Assumes that the blade is straight and that shear webs are normal to the chord
- Assumes that transverse shearing is negligible and that the blade section is free to warp
- Computes Euler-Bernoulli beam stiffnesses
- Computationally efficient and publicly available

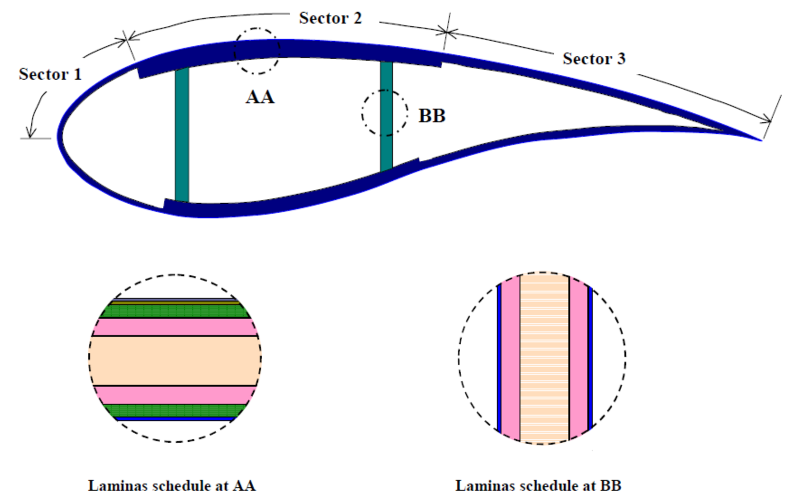
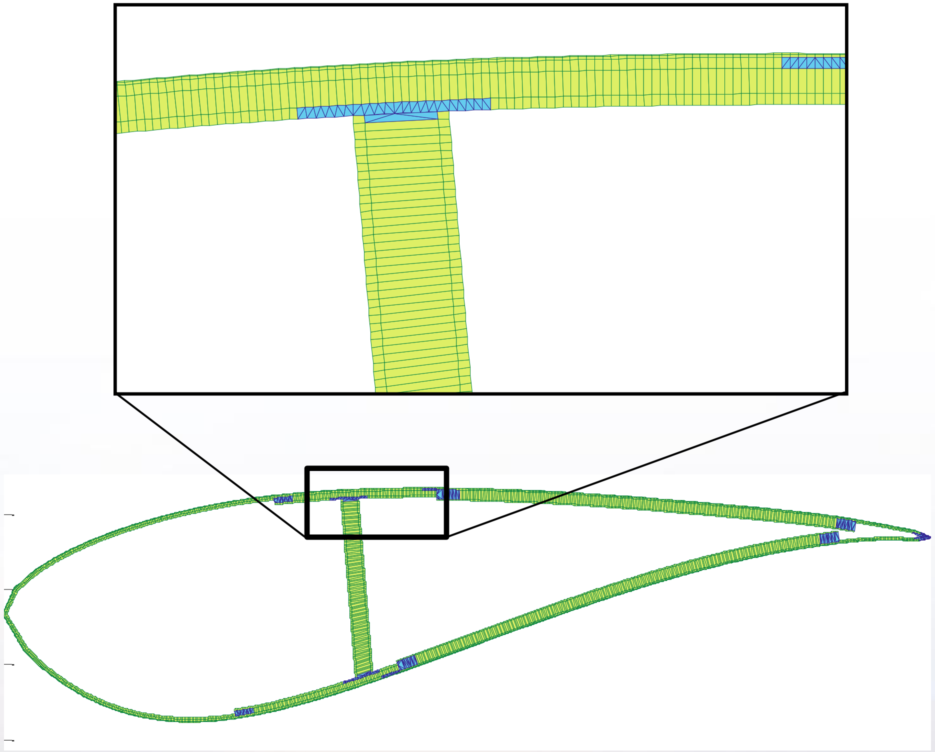


Figure 2: Example of spar-cap-type layup of composites at a blade section

Figure courtesy of NREL, PreComp Users Manual

VABS and PreVABS

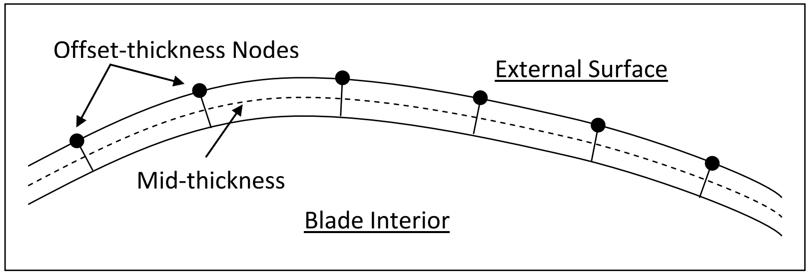
- Computes sectional properties of curved and pre-twisted anisotropic blades
- Recovers the pointwise distribution of the 3D displacement/stress/strain field
- VABS can only provide accurate 3D fields away from beam boundaries, concentrated loads and sudden changes in the cross-sectional geometry along the span
- Requires a finite element discretization of the cross-section
- PreVABS, has been developed for generating VABS inputs
- Model setup effort similar to that of PreComp

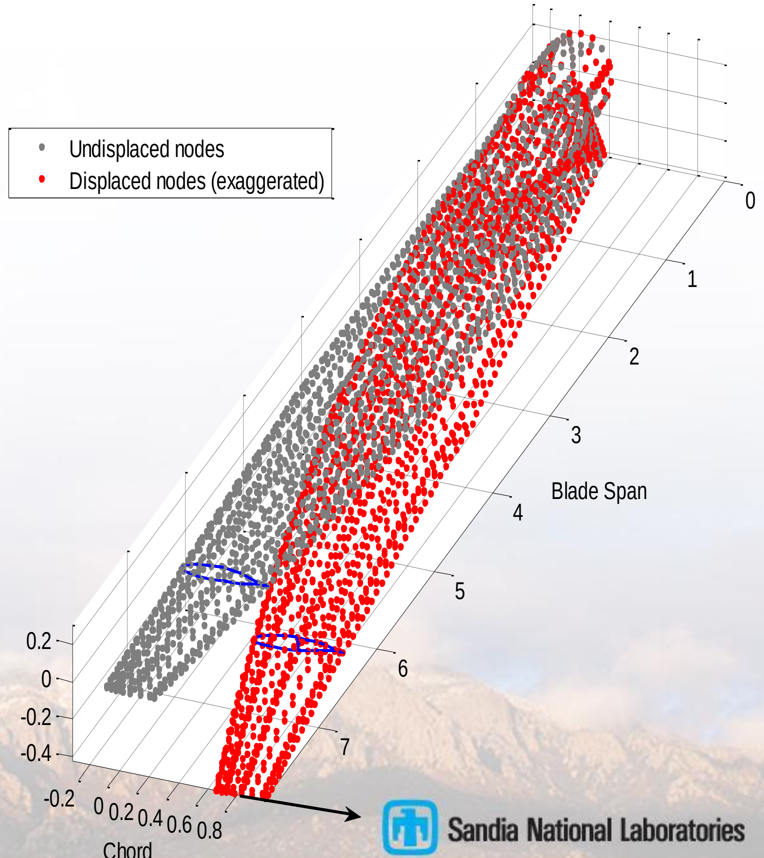


PreVABS Output: VAB mesh of an outboard section of wind turbine blade

Beam Property Extraction (BPE)

- **Captures 3D effects: shear and out-of-plane warping**
- **Accommodates blades with curvature, i.e. precurve and/or presweep; captures coupling**
- **Locates the center of mass, elastic center, principal directions, and shear center**
- **The process:**
  - Apply loads at tip of FE model (3 forces and 3 moments)
  - Fit planes to disp/rot at defined sections
  - Compute 6 × 6 Timoshenko stiffness matrices for equivalent beam elements
  - Compute property distributions for wind blade codes
- **Also requires:**
  - ANSYS commercial finite element analysis package
  - NuMAD wind turbine blade model preprocessor for ANSYS (available upon request from Sandia)
    - Management of materials, layups and geometry of wind turbine blade models
    - Creates shell element models in ANSYS



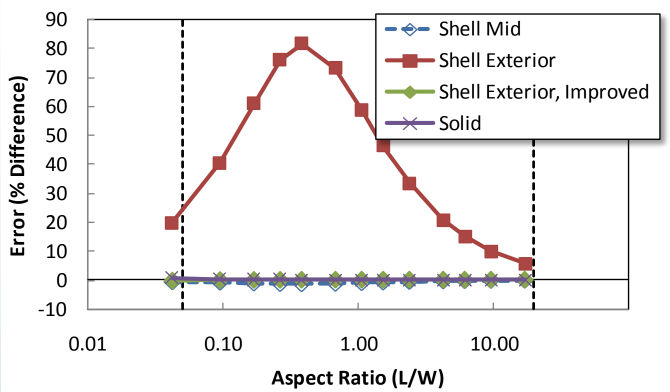


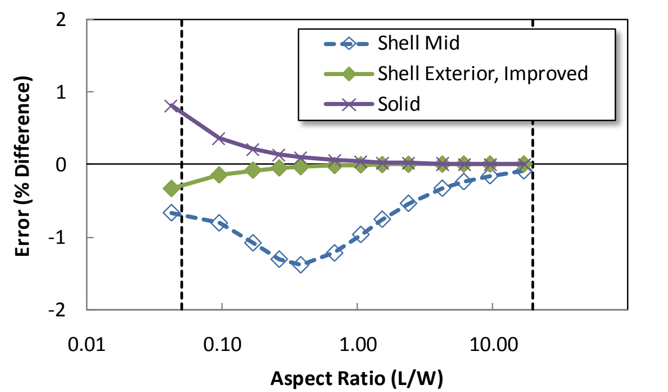
BPE Challenges

- **Three problems with BPE:**
  - 1 - The application of the unit forces/moments must ensure that the boundary layer effects are minimized
  - 2 - The difficulty in selecting the right set of nodes to determine the sectional displacement is a problem.
  - 3 - The sectional properties will depend on the size of the blade segment one chooses to perform the FEA
- **Responses:**
  - 1 – This matters most at the blade tip; these outboard properties have lesser effect on the dominant wind turbine design load cases
  - 2 – Ensure that BPE nodes are located at defined blade sections
  - 3 - BPE nodes convergence study is performed as part of this paper

An Improved Shell Formulation

- Laird's AIAA-ASM 2005 Conference paper highlighted some serious issues with prediction of shear stress and torsional stiffness for FEA models that use offset node shell elements
- New shell formulations have since been released; an example is the ANSYS R12, Shell281
  - The current paper shows results of computations described by Laird using the new shell formulation
  - Recent results are very much improved





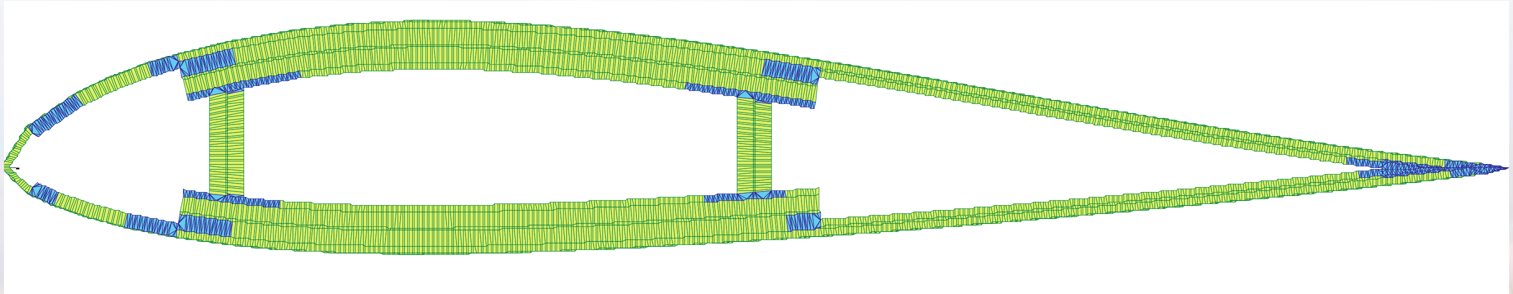
# of Elements	19200
Radius/ Thickness	10
Length/ Diameter	10

- As a result, stiffness predictions by BPE are now much more accurate
  - Last year's SDM paper shows how well it works

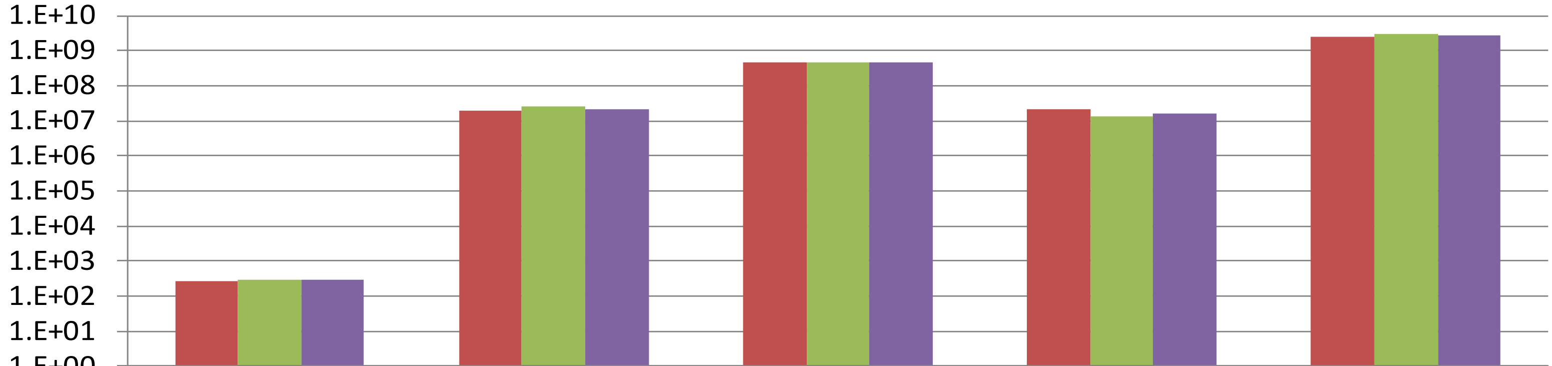
Uniform Cross Section

Section is defined in detail in Chen, et.al, 2009 Wind Energy Journal article:

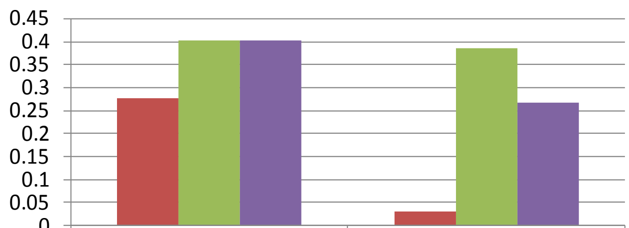
- **Materials**
  - Unidirectional FRP, double bias FRP, Gelcoat, Nexus and Balsa
- **Two shear webs**
- **MH 104 Airfoil**
  - http://www.ae.illinois.edu/m-selig/ads/coord-database.html



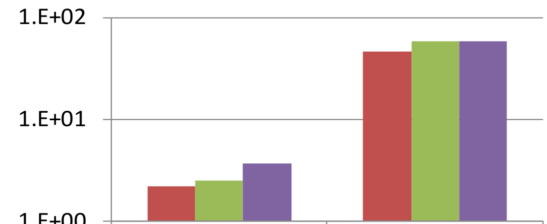
Analysis Results



	MassDens (kg/m)	FlpStff (N m^2)	EdgStff (N m^2)	GJStff (N m^2)	EAStff (N)
VABS (Ref.13)	258.053	1.916E+07	4.398E+08	2.167E+07	2.387E+09
PreComp, Mod.	288.3	2.521E+07	4.672E+08	1.389E+07	2.939E+09
BPE	284.687	2.212E+07	4.468E+08	1.572E+07	2.755E+09



	EdgcgOf (ChFract wrt LE)	EdgEAOf (ChFract wrt LE)
VABS (Ref.13)	0.278	0.031
PreComp, Mod.	0.402	0.386
BPE	0.403	0.267



	FlpIner (kg m)	EdgIner (kg m)
VABS (Ref.13)	2.172	46.418
PreComp, Mod.	2.474	58.04
BPE	3.633	57.956

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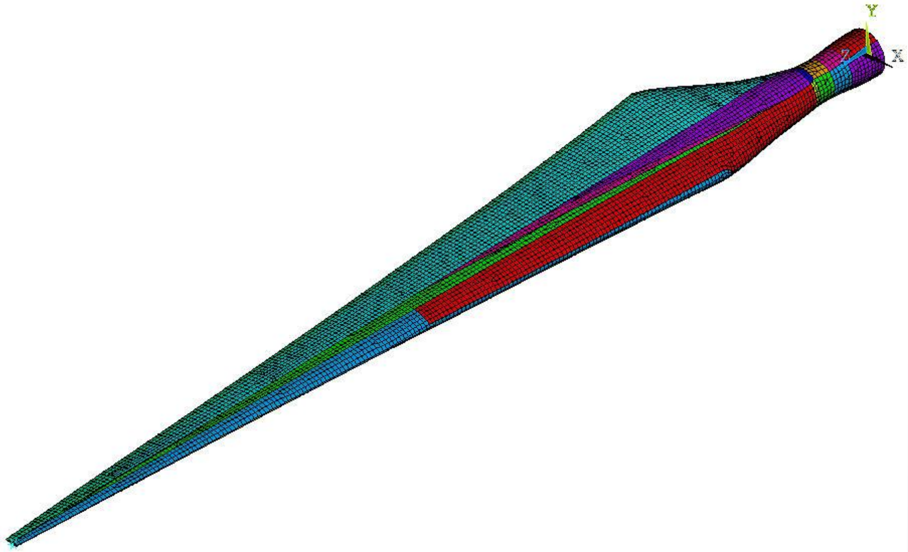
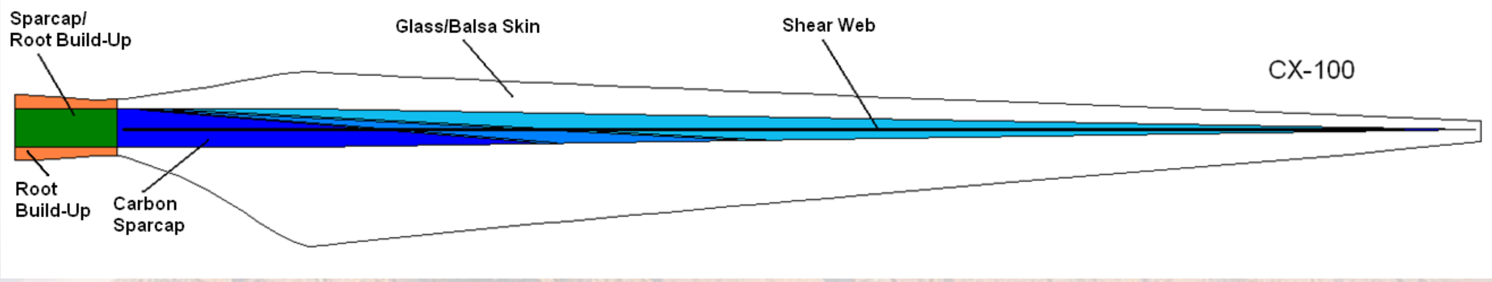
CX-100 Blade Introduction

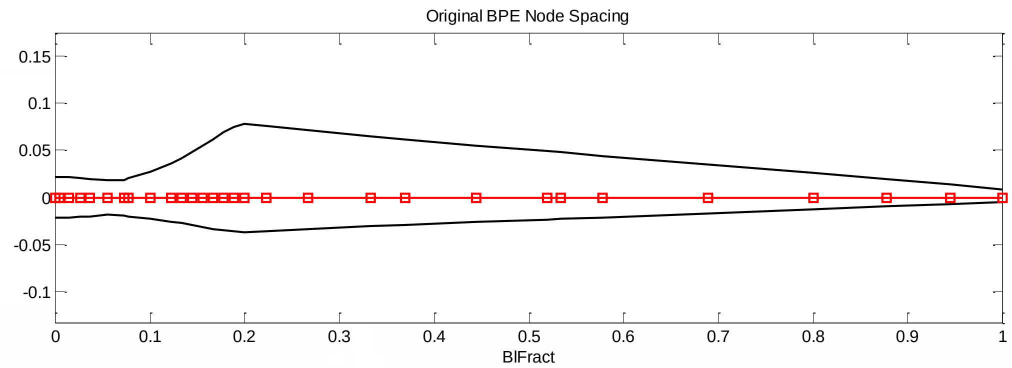
Micon turbine with 9m CX-100 blades



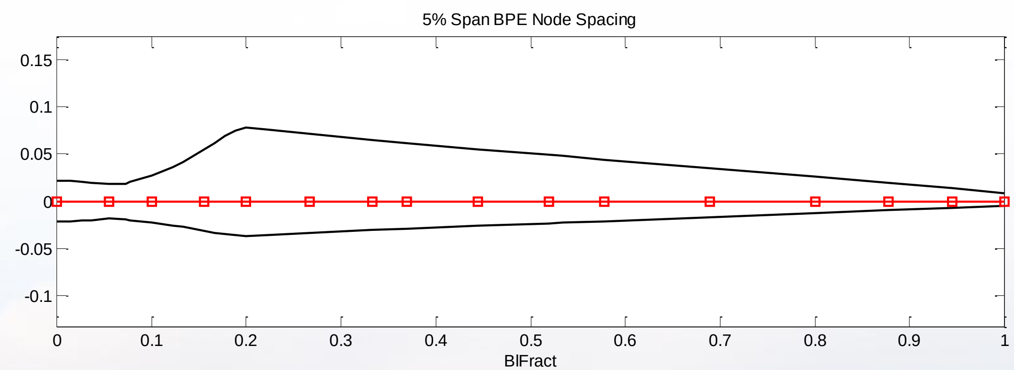


BPE Node Spacing Study

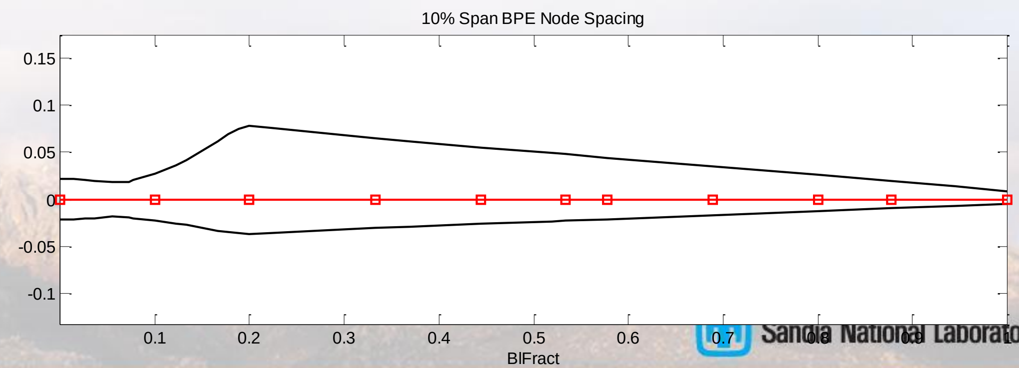
- Nodes located at each station



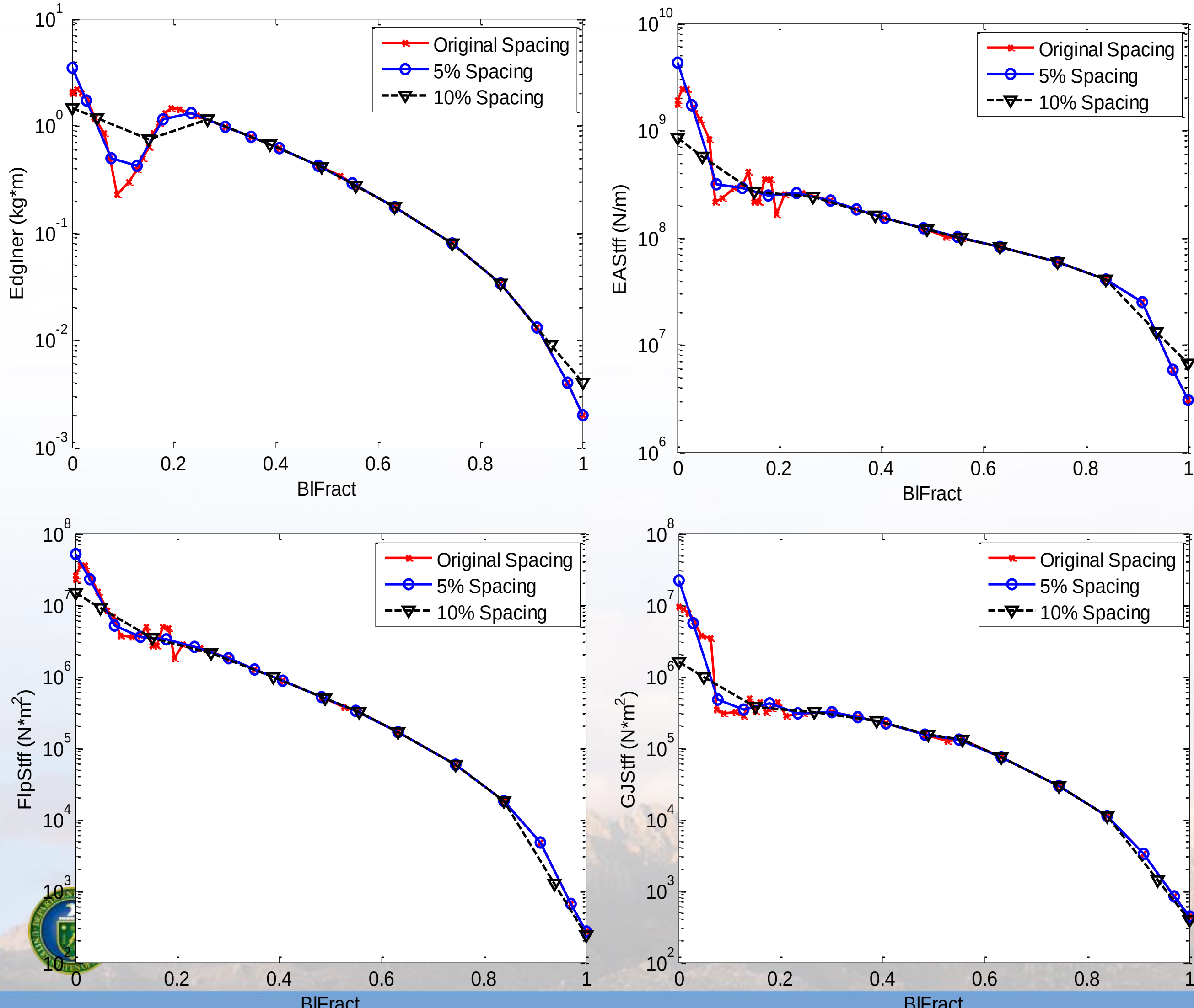
- 5% span spacing



- 10% span spacing



Node Spacing Results



- **Recommendation:**
  - 5% span spacing is close to optimal

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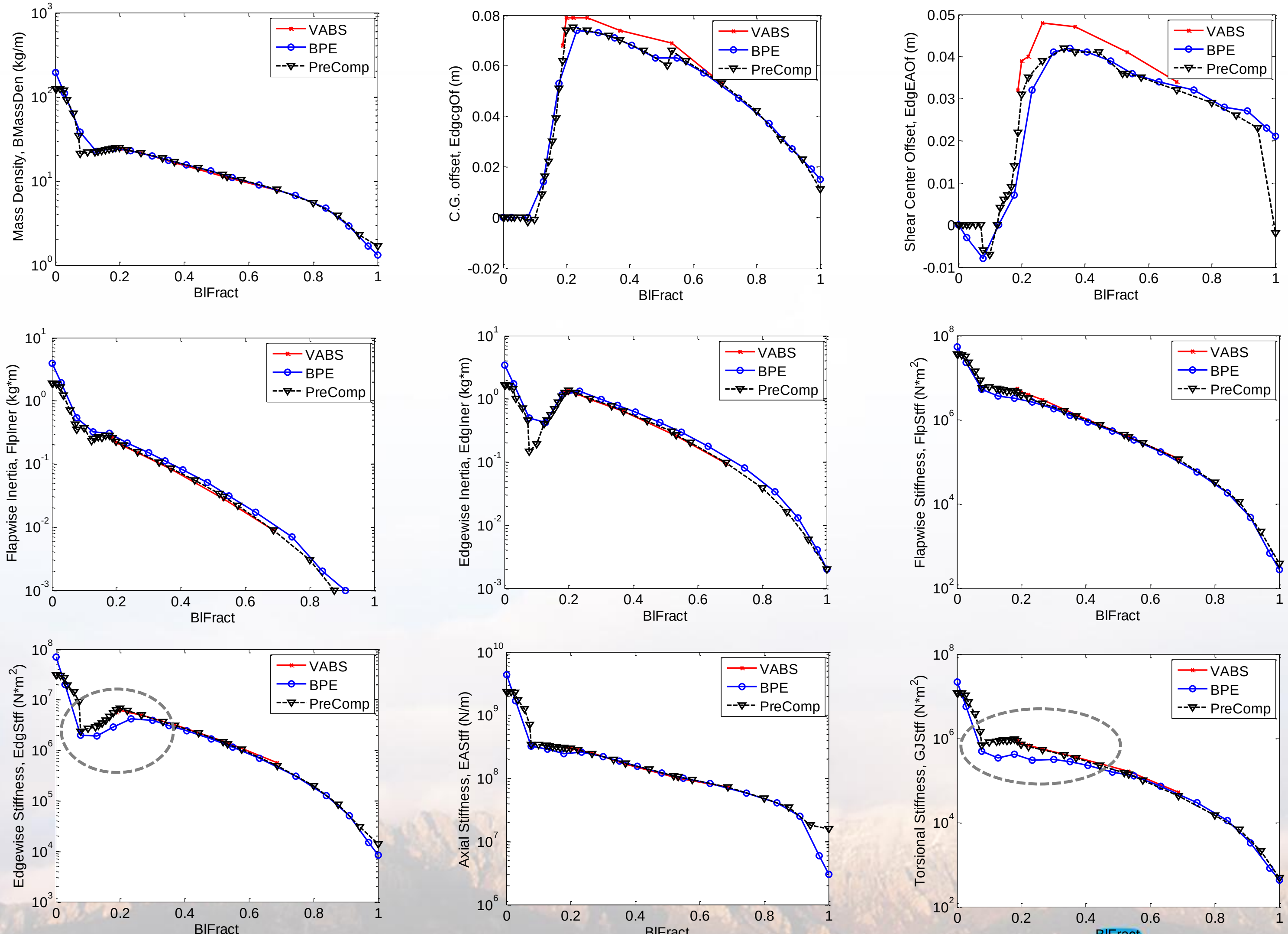
Computed CX-100 Properties



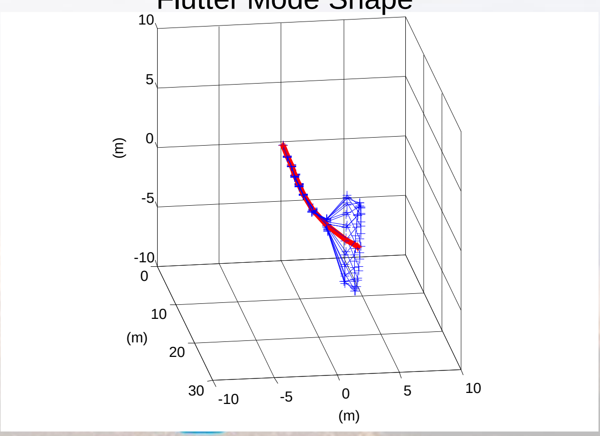
Sandia Classical Flutter Capability for HAWTs

- **Current capability utilizes the tool described by Lobitz (Aeroelastic Stability Predictions for a MW-sized Blade, *Wind Energy,* 2004)**
  - Matlab and Fortran routines for easy problem set up in Nastran. Inputs:
    - LCS, lift curve slope, and pitch axis location
    - AeroDyn input information
    - FAST blade structure information
    - MSC. Nastran formulates initial structural matrices
    - Lobitz's tool determines necessary mass, stiffness, and damping matrix additions due to aerodynamic effects (Theodorsen forcing)
    - MSC.Nastran solves the complex eigenvalue problem

$$[M + M_a(\Omega)]\{\ddot{u}\} + [C_C(\Omega) + C_a(\omega,\Omega)]\{\dot{u}\} + [K(u_0,\Omega) + K_{tc} + K_{cs}(\Omega) + K_a(\omega,\Omega)]\{u\} = 0$$

Matrix	Description
M, C, K	Conventional matrices (with centrifugal stiffening)
$M_a(\Omega)$, $C_a(\omega, \Omega)$, $K_a(\omega, \Omega)$	Aeroelastic matrices
$C_C(\Omega)$	Coriolis
$K_{cs}(\Omega)$	Centrifugal softening
K_{tc}	Bend-twist coupling

Flutter Mode Shape



Flutter Analysis Process

Increase rotor speed

Set rotor speed and estimate frequency of flutter mode

Form mass, stiffness and damping matrices and perform complex eigen solve

Verify that flutter mode frequency estimate was correct: Yes/No

Yes

Record damping ratio

No

Iterate on frequency

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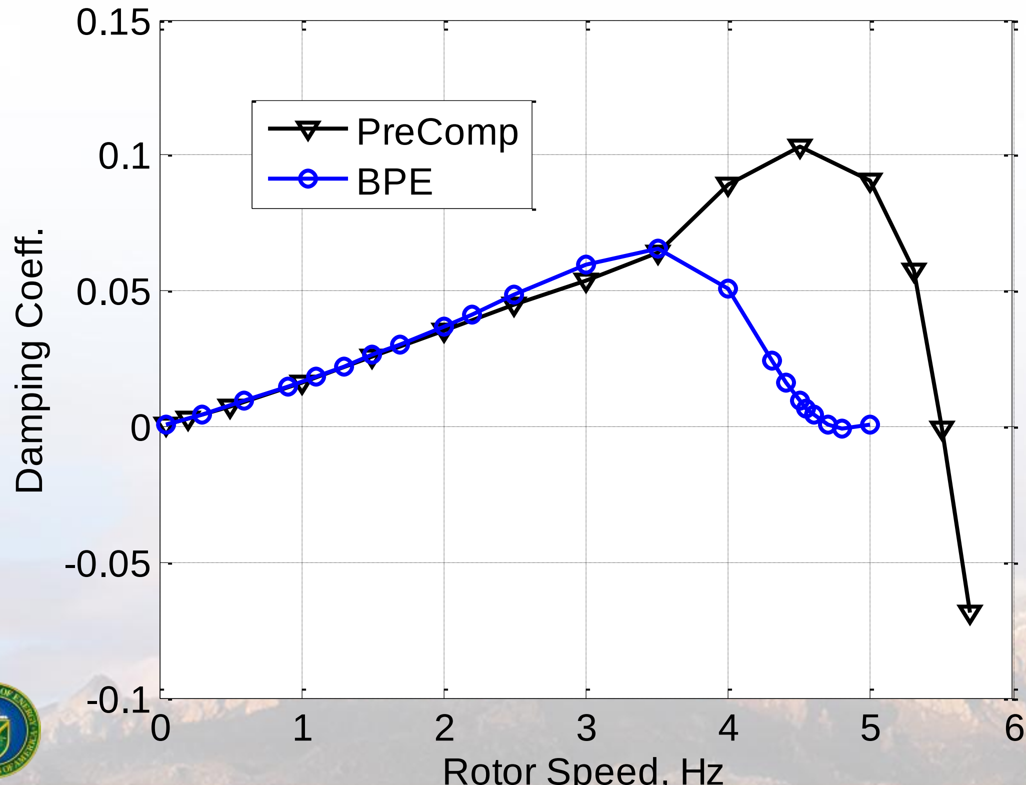
Computed Flutter Speeds

Analysis input parameters	Unstable blade rotation speed, Hz
PreComp properties	5.50
BPE properties	4.74



- **Variation in beam model parameters accounts for a 14% decrease in computed flutter speed**

Conclusions and Recommendations

Beam Properties

- **PreComp, VABS, and BPE compute roughly equivalent beam properties for a uniform section**
  - Discrepancies may be related to the way each code discretizes the airfoil shape
  - Discrepancies are probably less than what is expected due to uncertainty in manufacturing processes
- **Discrepancies in computed beam properties for a realistic blade were noted**
  - PreComp and VABS compute similar beam property distributions
  - BPE properties indicate a more flexible beam
  - PreComp and VABS disagree with BPE in the way they represent three dimensional effects that are applicable in the inner 30% of a CX-100 blade span
- **Future work should pursue high quality experiments on structures that can validate the results of these codes**

Effects on Flutter

- **Computed flutter speed was 14% lower as a result of the torsional flexibility of a beam made with BPE.**
- **Flutter not an issue today, but expect that it will be for very large blades**
- **Accurate tools and techniques for blade structural analysis and aeroelastic stability analysis will be needed for effective design of these future systems**

Acknowledgements

- **Hui Chen, Utah State University, PreVABS creator**
  - Thanks for assistance with PreVABS
- **Wenbin Yu, Utah State University, VABS creator**
  - Thanks for making the latest version of VABS (v3.4) available for this work
- **Gunjit Bir, NREL, PreComp creator**
- **David Malcolm, GEC, BPE creator**
- **Jonathan Berg, Sandia Laboratories**
  - Improvements to PreComp source code
- **Joshua Paquette, Sandia Laboratories, coauthor**
  - CX-100 FEA Model Creator

Sandia Wind Turbine Field Test Site – Bushland, Texas. *Photo by J.White*

A Blade Design Process