SAND2011-1381C

SNL Structural Modeling Overview

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Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company,
for the United States Department of Energy's National Nuclear Security Administration
under contract DE-AC04-94AL85000.

Sandia National Laboratories

Outline

- Background of blade concepts at Sandia
- Blade structural design and analysis
- Wind turbine system analysis
- Experiments for blade and system model validation
- Improving models using experimental data
- List analysis tools used in the industry
- Topics for future modeling and simulation

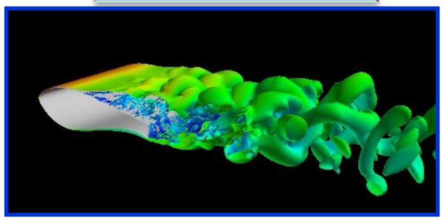
Innovative Blade Research: Major Focus

- **Innovations that lead to longer & lighter blades that reduce COE**

- **Working with industry, have designed, built & tested several blade prototypes to demonstrate a variety of innovations**

Rotor & Blade Innovation

Aerodynamics & Acoustics



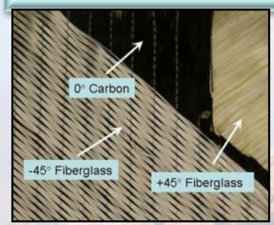
Concept Development

Testing & Sensors

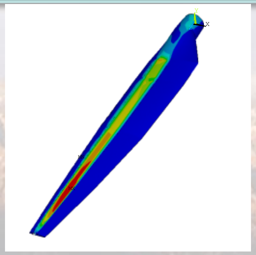
Industry Partners

Prototype Rotor

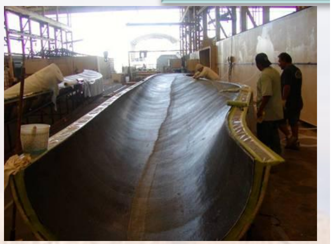
Materials

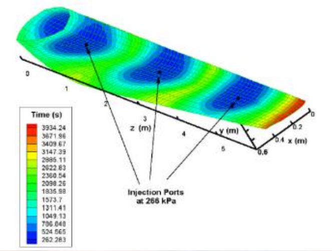


Design Tools



Manufacturing





Historical SNL Research Blades

<u>Research Goal</u>

Strategic use of carbon for weight reduction

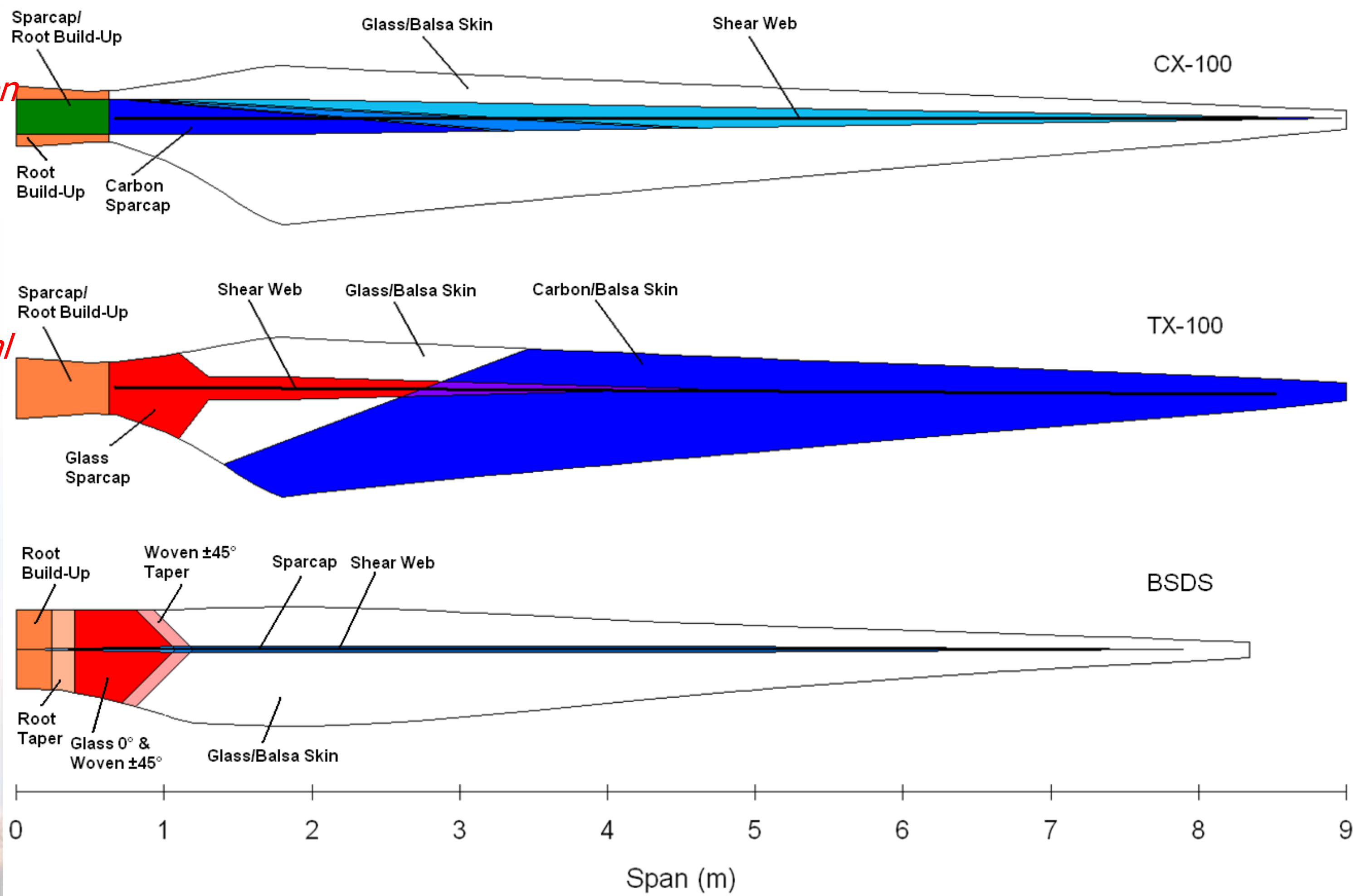
CX-100

Passive aero-structural load mitigation

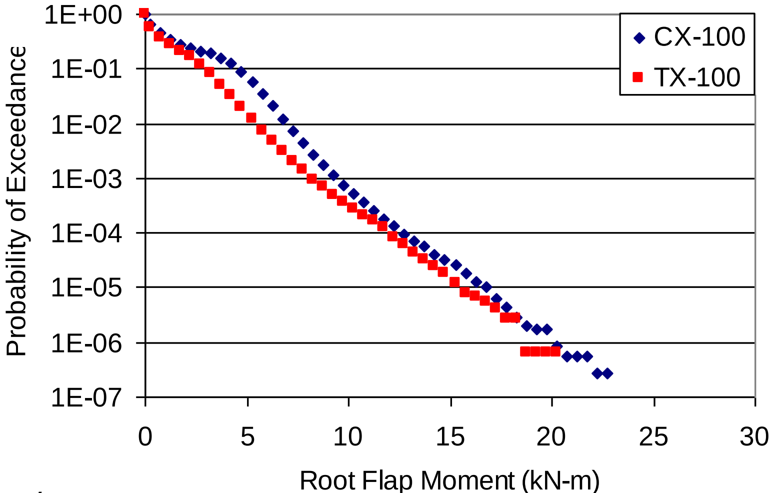
TX-100

Structural efficiency improvement

BSDS



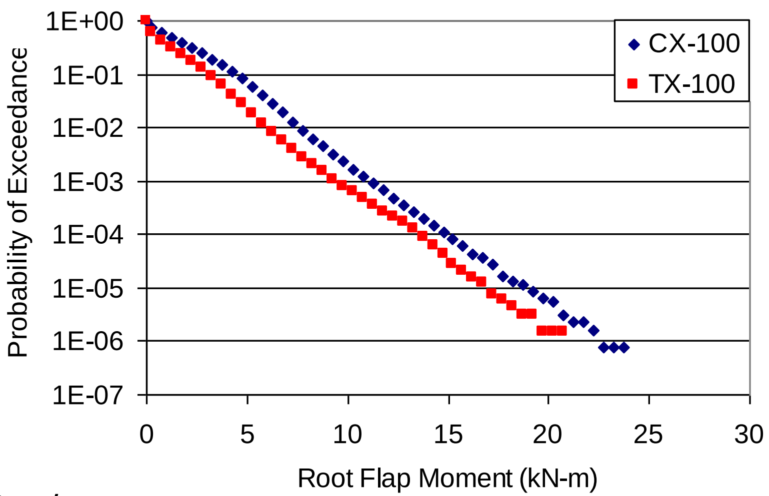
Fatigue Damage Reduction



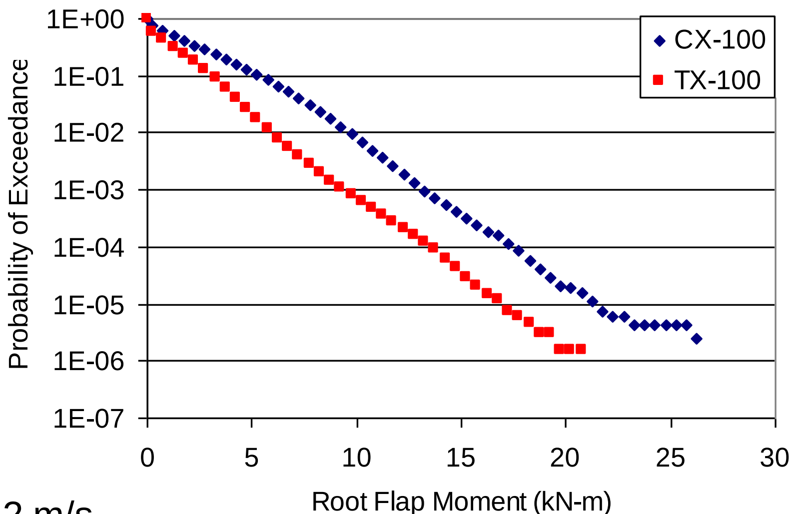
8 m/s

Wind Speed (m/s)	Relative Damage Rate (%)	Relative Damage Equivalent Load (%)
7-9	-53.8%	-7.4%
9-11	-69.1%	-11.1%
11-13	-93.6%	-24.0%

Fatigue Damage Summary (TX vs. CX)



10 m/s



12 m/s

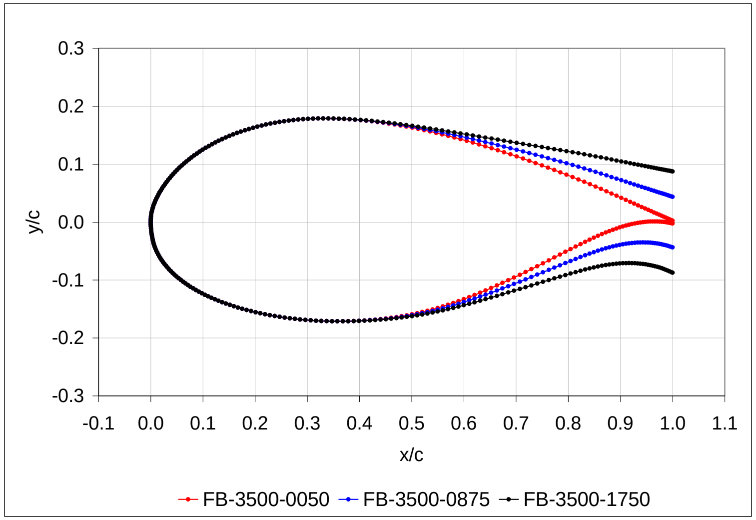
Structural Efficiency: Geometry

- **Flatback airfoils created by symmetric expansion about camber line**
- **Less soiling sensitivity than other thick foils**
- **Higher structural efficiency**
  - *Delayed Buckling ➔ better material usage at failure*

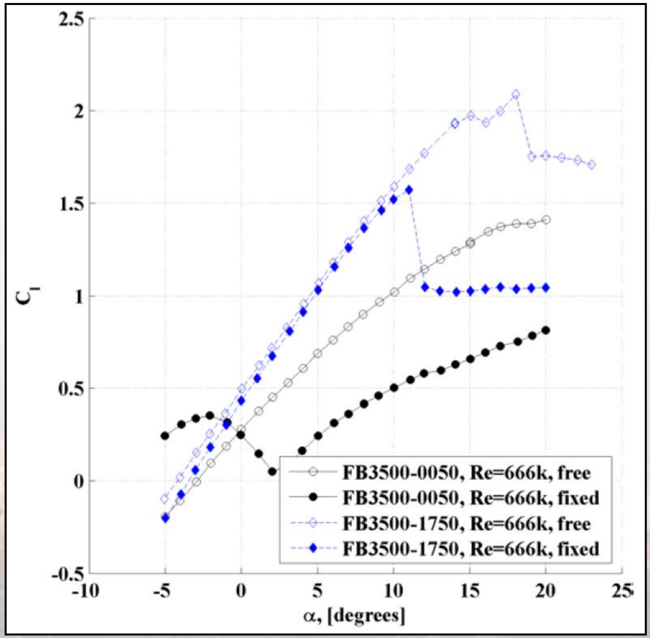
Structural Properties

Property	CX-100	TX-100	BSDS
Root Failure **Moment** (kN-m)	128.6	121.4	**203.9**
Max. Carbon Tensile **Strain at Failure** (%)	0.31%	0.59%	**0.81%**
Max. Carbon Compressive **Strain at Failure** (%)	0.30%	0.73%	**0.87%**

Flatback Airfoil Creation



Effect of Soiling



Knight & Carver STAR Blade

Cost-shared project "Sweep-Twist Adaptive Blade" began in November 2004

Goal – use geometric sweep to reduce loads through passive bend twist coupling

- Enables a larger rotor for a given design, leading to an overall increase in energy capture
    - 2.6 meter longer blade (24.5 → 27.1)
    - Predicted 5-8% increase in overall energy capture

Advanced Rotor Development: 100-m Sandia Blade Design

- **Goal:** Provide technology research to produce innovations and advanced design concepts to develop very large utility-grade blade and rotor designs for offshore and onshore (where possible).

- **Methodology:**
  - Develop and apply scaling laws to scale-up of 5 MW turbine system.
  - Create 13.2 MW Sandia Baseline (100 m long blade) with detailed composite laminates
  - Apply innovative concepts to baseline to reduce weight, and improve performance & cost effectiveness
- **Partners: European UpWind Program and NREL**

SNL Contacts: Tom Ashwill and D. Todd Griffith

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Challenges & Opportunities for Large Blade Development

Challenges:

Blade weight growth

Manufacturing & reliability issues

Material volumes & cost

Transportation

Opportunities:

Very thick airfoils for structural efficiency

Material lay-up & choices

Multidisciplinary design optimization

Blade joints

Load alleviation concepts (active & passive)

Other innovations

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- **Blade structural design and analysis**
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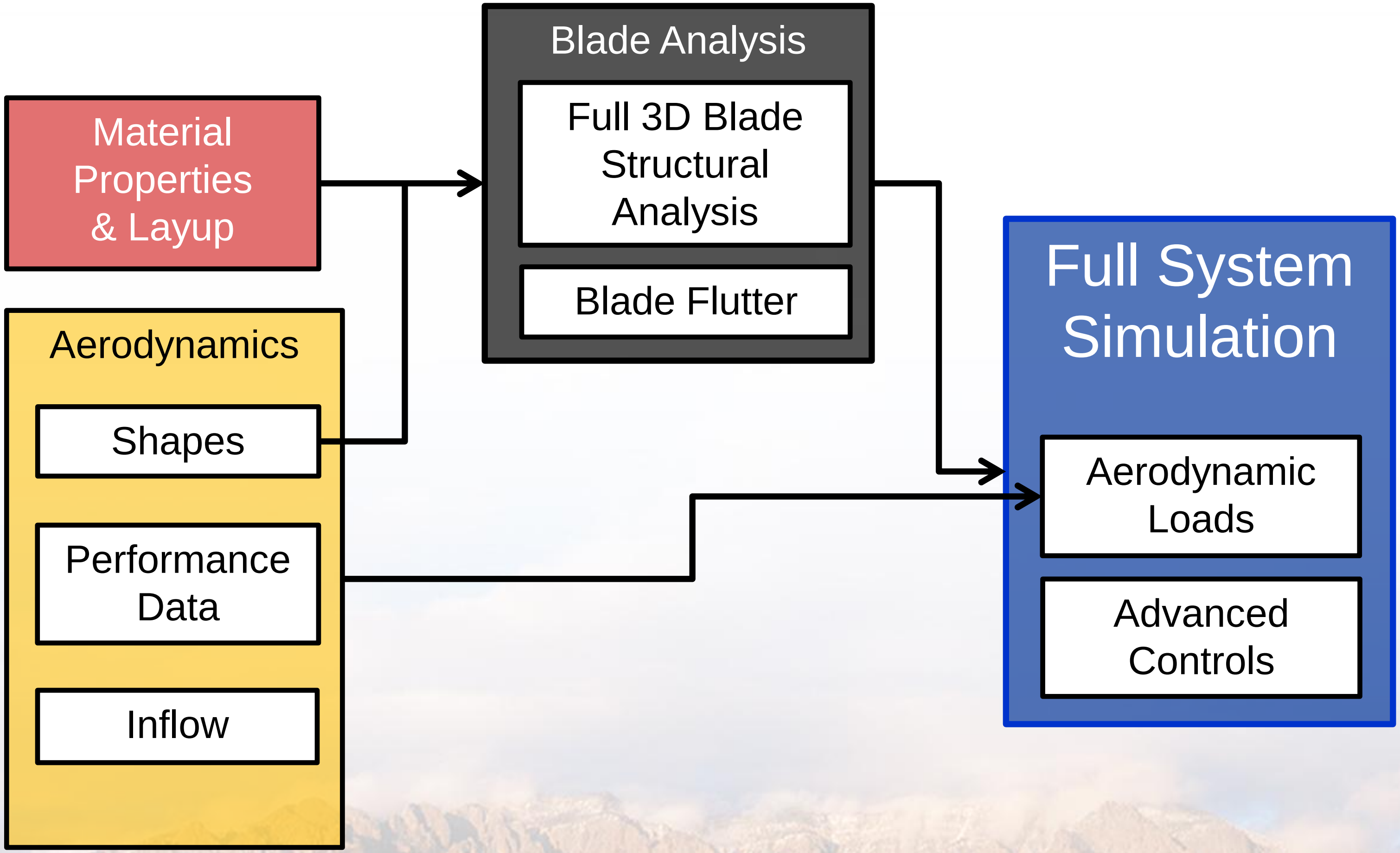
Wind Turbine Design/Analysis Elements

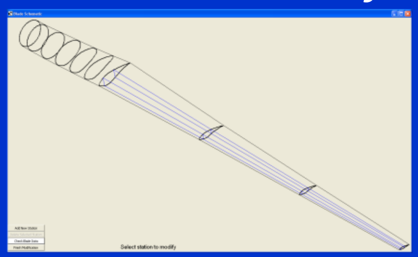


Blade Design with NuMAD

NuMAD

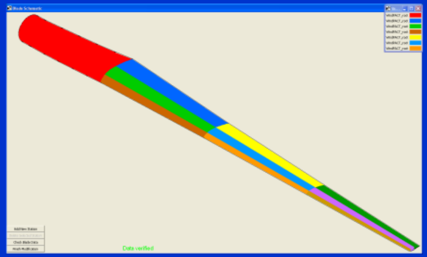
NuMAD:
Numerical Manufacturing
And Design Tool

Blade Geometry

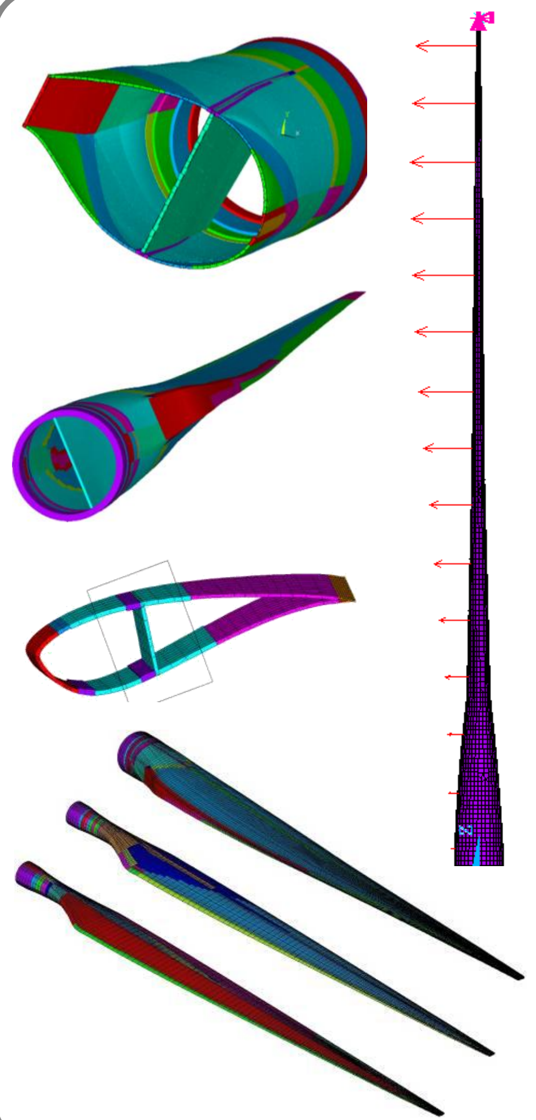


Materials & Layups

Stack Placement

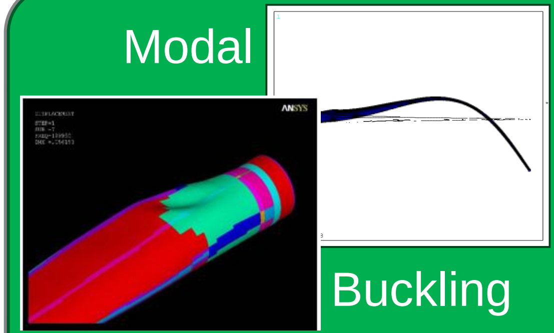


ANSYS FE Model



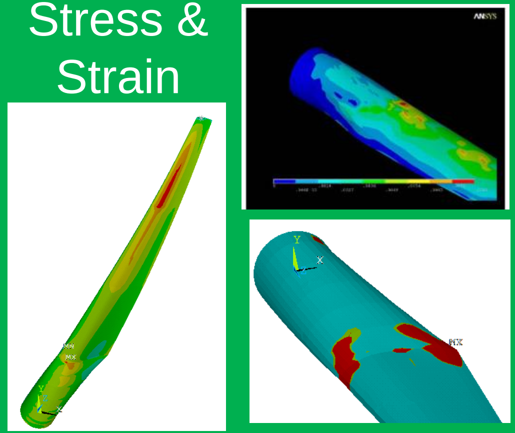
ANSYS Analysis

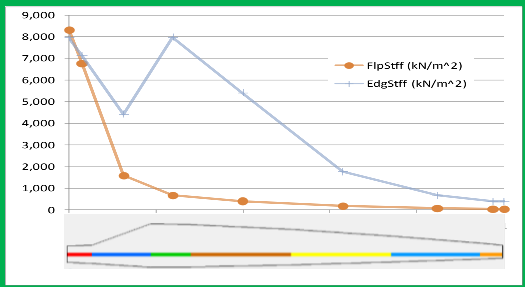
Modal



Buckling

Stress & Strain

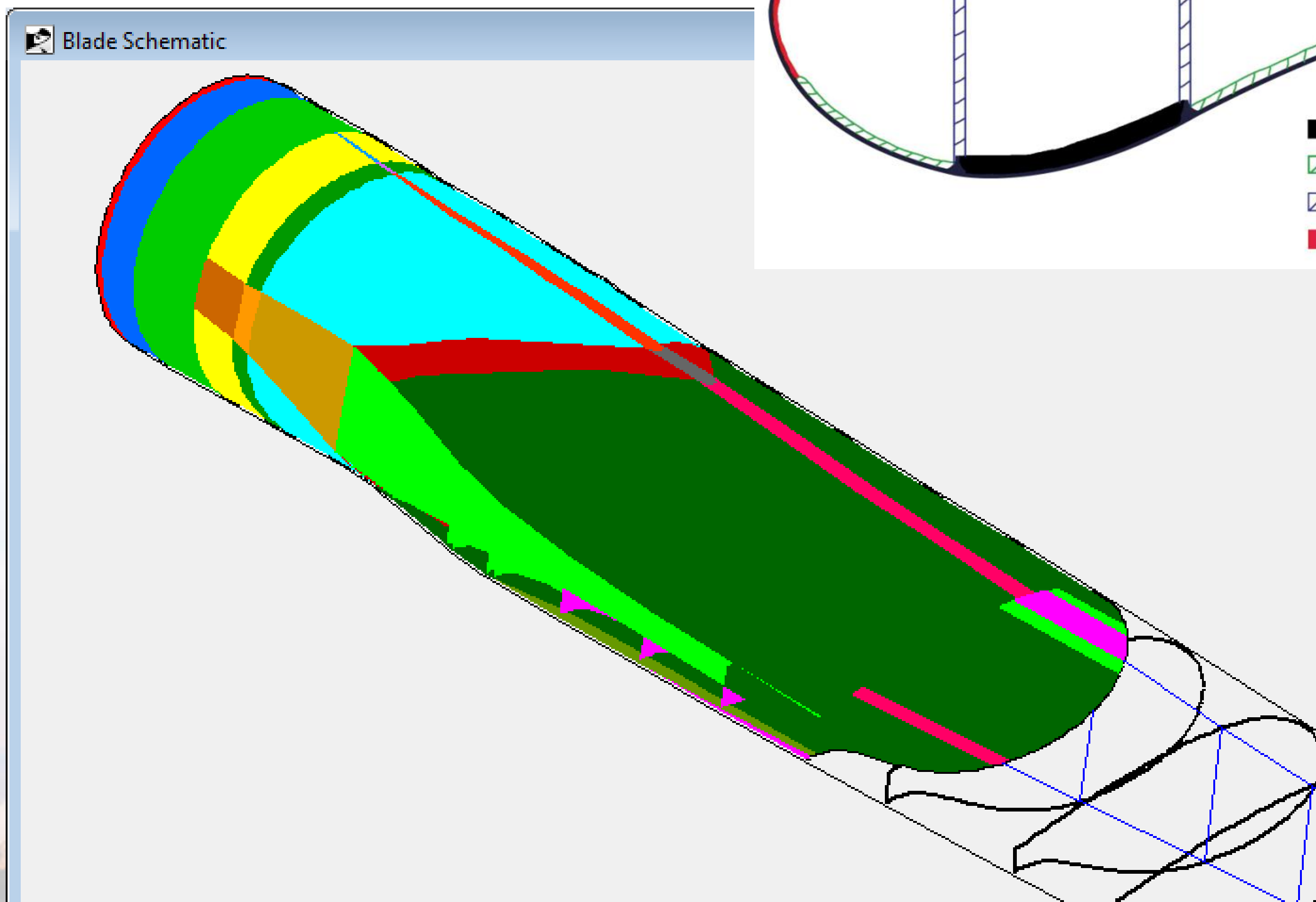


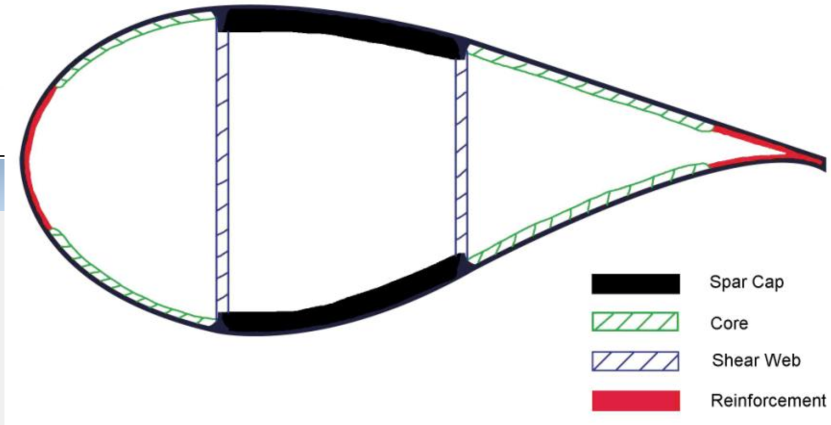


Beam Properties

NuMAD Geometry and Materials

- **A complicated example:**





Use of Offset-Thickness Shell Nodes

- **Offset-thickness nodes are most desirable for wind turbine blade FE models because the outer blade surface is the specified surface**

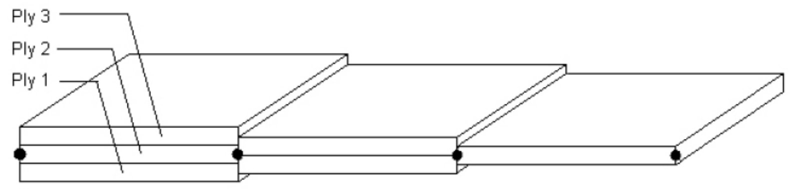


Figure 2. Schematic of physical representation of layered shell elements with nodes positioned at the mid-thickness.

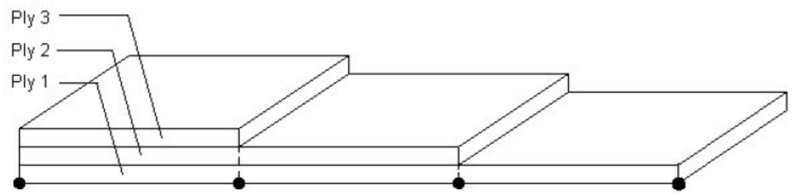


Figure 3. Schematic of physical representation of layered shell elements with nodes offset to the bottom surface.[1]

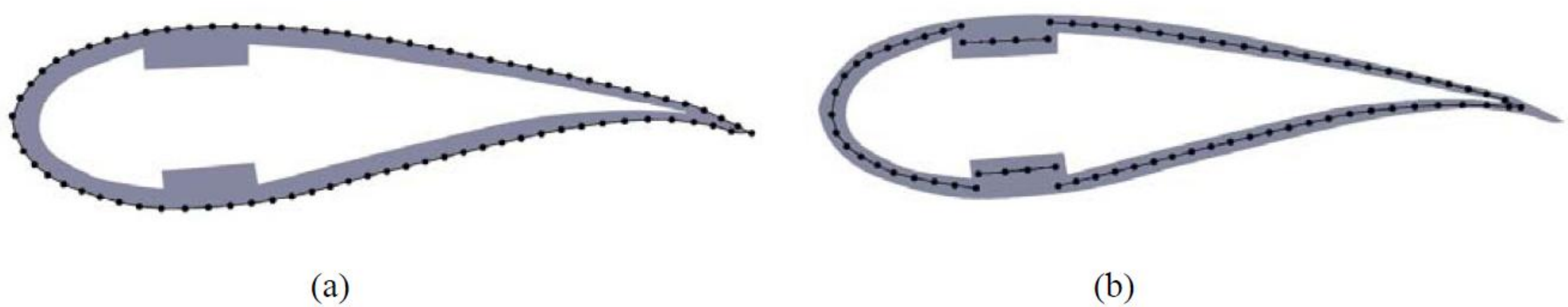
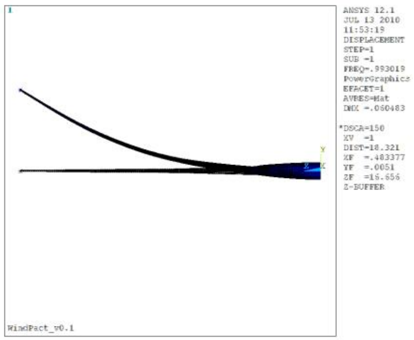
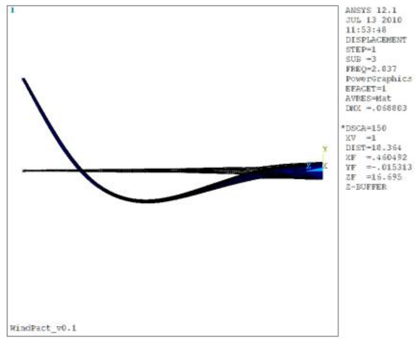


Figure 4. Blade cross-sections with nodes located at the exterior surface (a) and the mid-thickness (b).

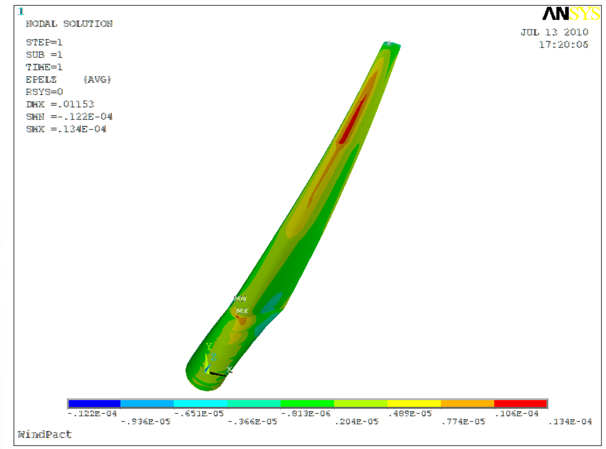
Example ANSYS Analyses

- **Modal**

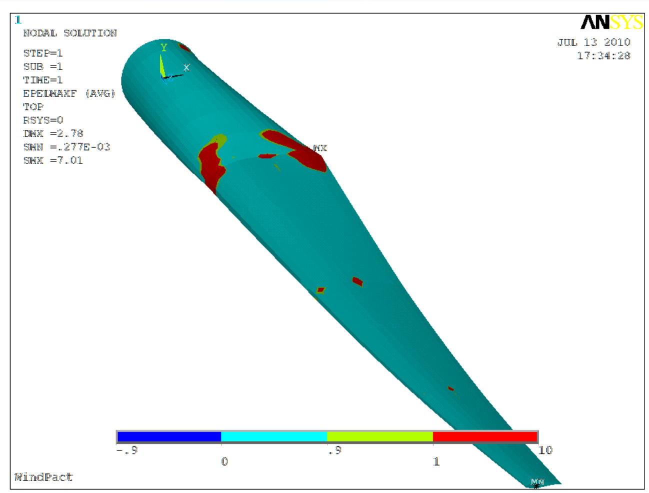




- **Strains**

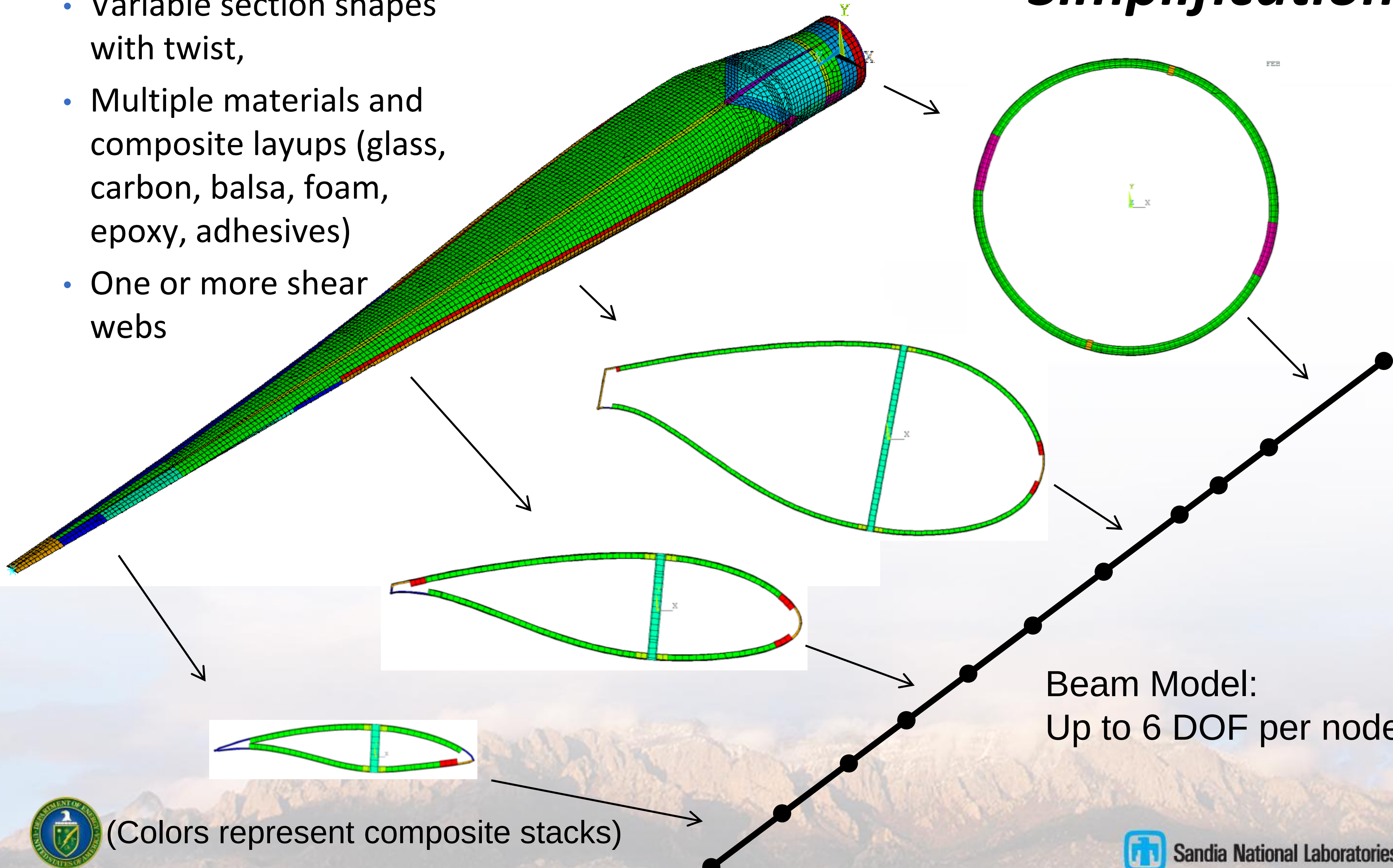


- **View material failure**
  - Ultimate
  - Fatigue

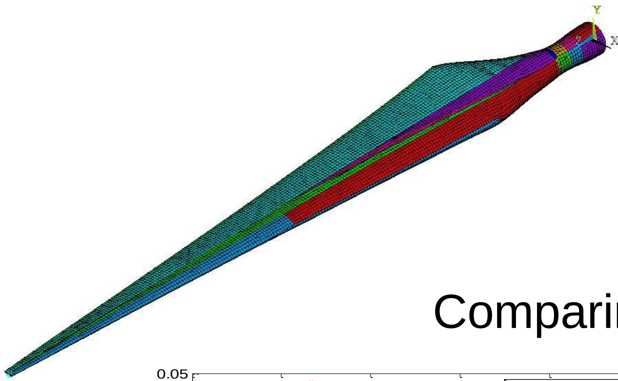


Blade Structural Model Simplification

- **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

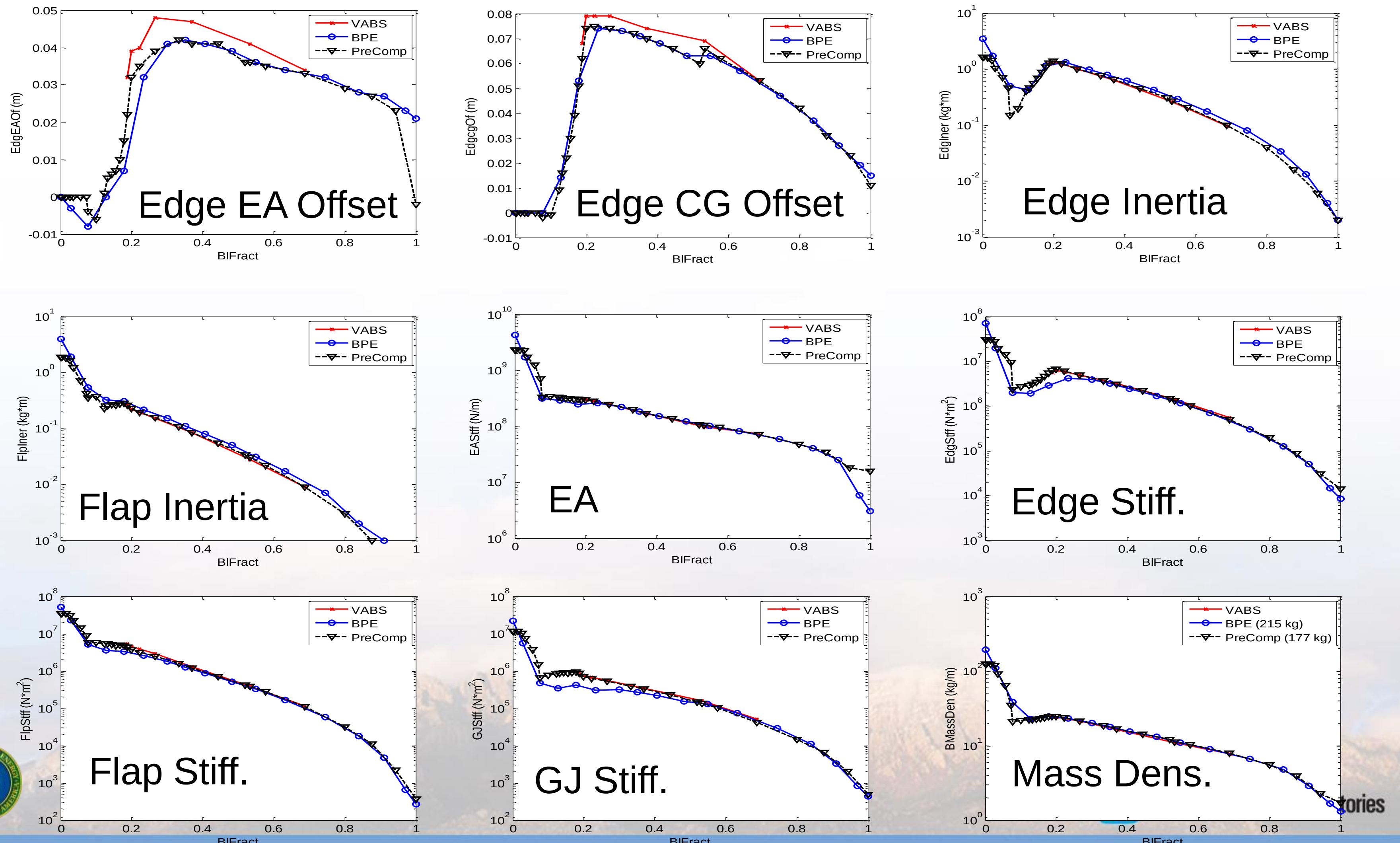


(Colors represent composite stacks)

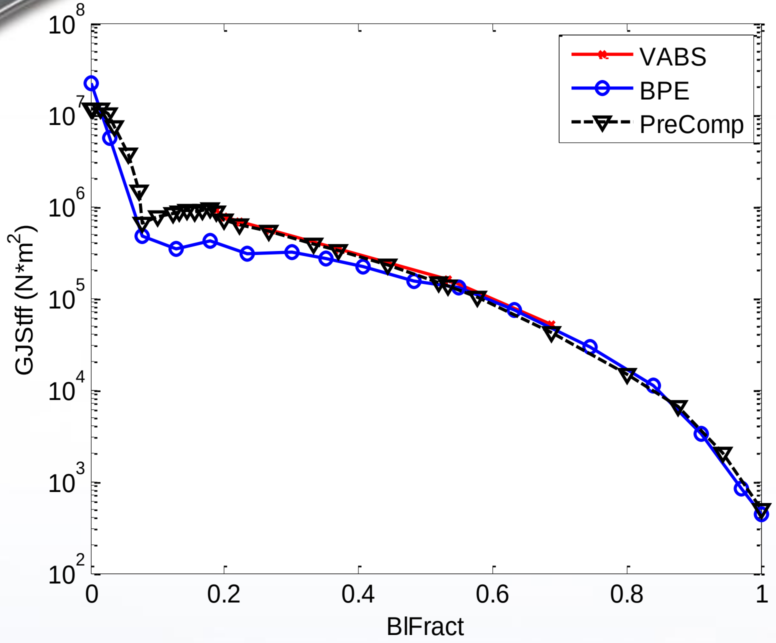


Calculate Beam Properties

Comparing three techniques: BPE, 2D Section & VABS



Torsional Stiffness and Flutter



How sensitive is flutter speed to torsional stiffness?

Inputs used in classical flutter prediction

Parameter	Description
EI_flap	Flapwise bending stiffness
EI_edge	Edgewise bending stiffness
GJ	Torsional stiffness
Twist	Blade pretwist
Tiner	Torsional inertia
LCS	Lift curve slope
Elastax	Distance along the chord the elastic axis is aft of the pitch axis
Aerocntr	Fraction of the chord that the aerodynamic center is aft of the leading edge.
Masscntr	Distance the mass center is aft of the elastic axis
Chord	Section chord length

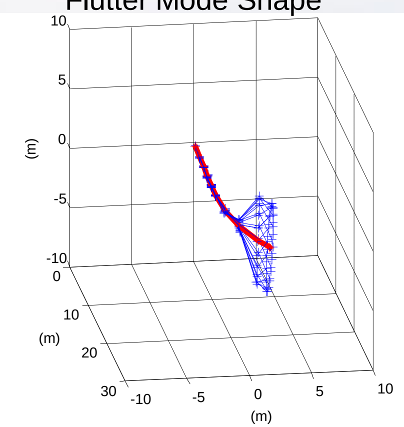
Sandia Classical Flutter Capability

- **Current capability utilizes:**
  - MSC.Nastran 2005
  - FAST2NAST.m (Matlab routine)
    - Required inputs: lift curve slope and pitch axis location along with information taken from ad.IPT and blade.DAT files utilized by FAST
  - Fortran executable
    - Determines necessary mass, stiffness, and damping matrix additions due to aerodynamic effects (Theodorsen)
    - Generates additional Nastran decks for the **complex eigenvalue solve**
- **Iterates on operating speed, following the complex modes, to find the flutter speed**

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

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



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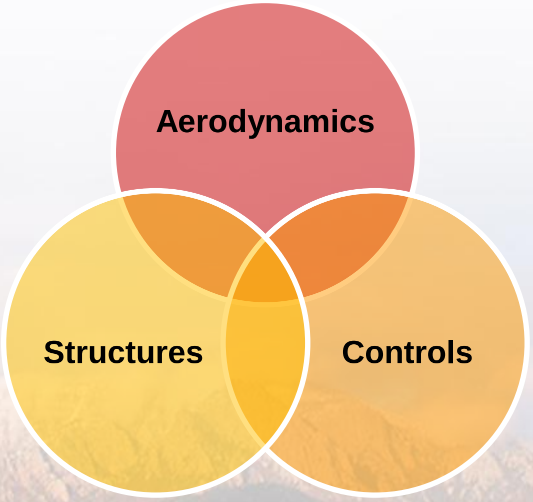
Importance of System Analysis

- **Full system analysis is required in order to evaluate the capability of the design to withstand loads prescribed by certification standards**

- **It is just as important to understand and report the cost of an innovation as well as the benefit; Common system costs include**
  - Increased forces and moments in the system
  - Increased complexity
  - Decreased energy capture

$$COE = \frac{FCR * ICC + (O\,\&\,M)}{AEP}$$



Design Criteria Examples

Design Requirements

- **Usually governed by IEC or GL Standards**
- **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**

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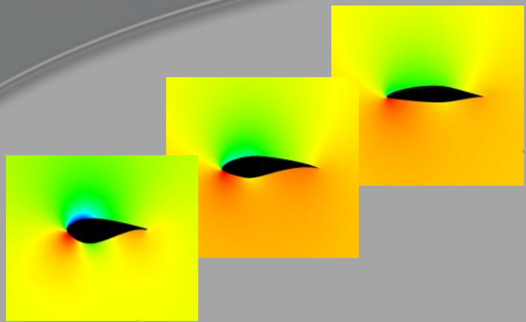
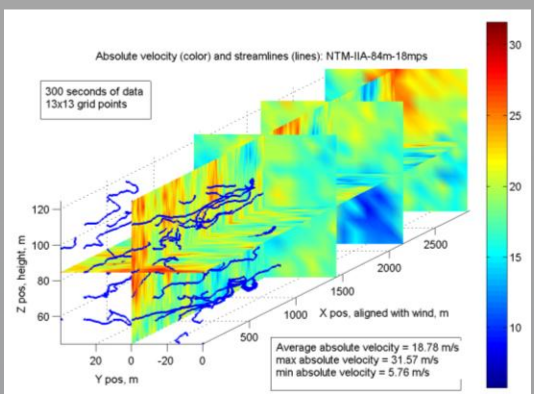
System Analysis with Wind Turbine Aeroelastic Simulation

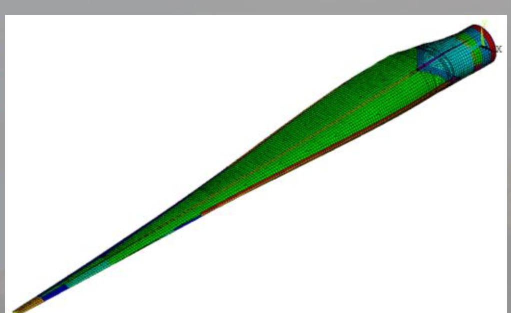
Aerodynamic Performance



Turbulent Wind Input



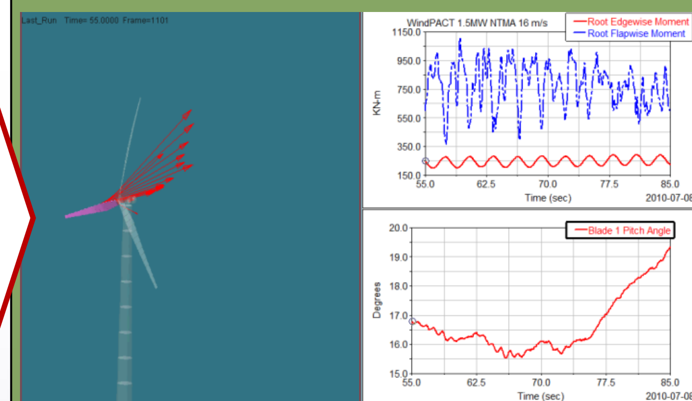
Structure and Materials



Aeroelastic System Dynamics Model

Includes Controls Implementation

System Response



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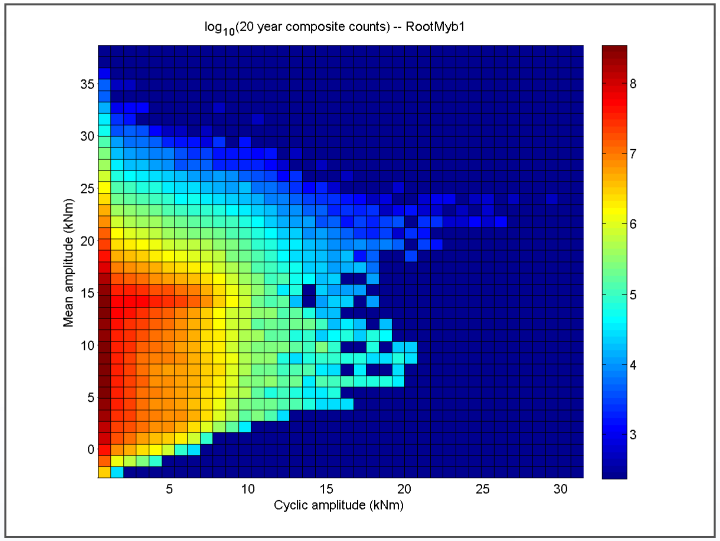
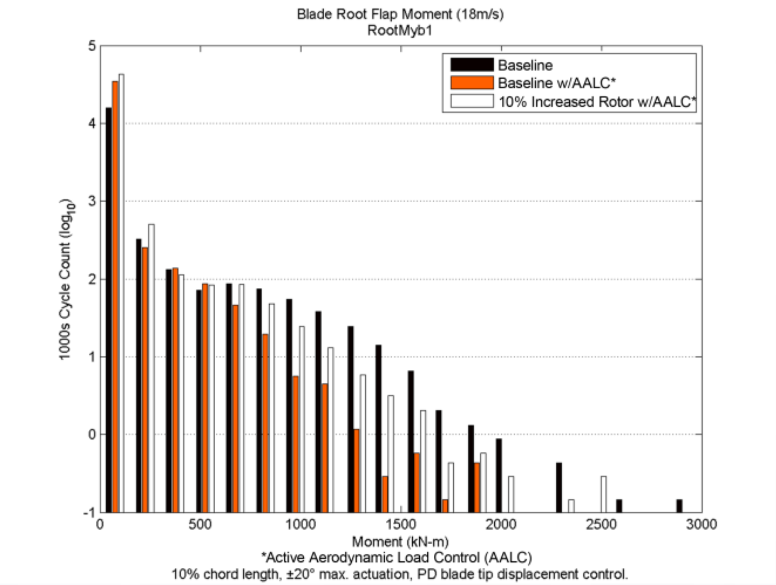
Analyze System Response w.r.t Fatigue

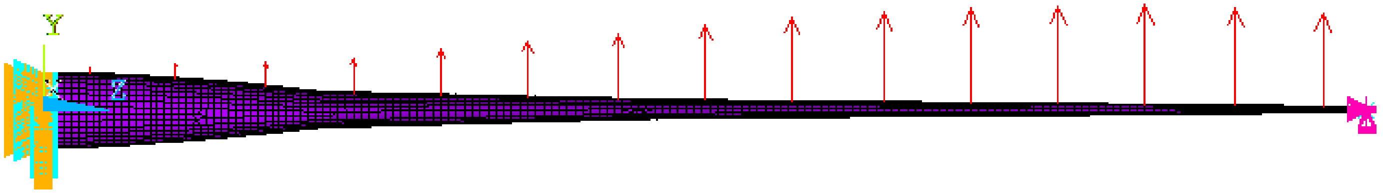




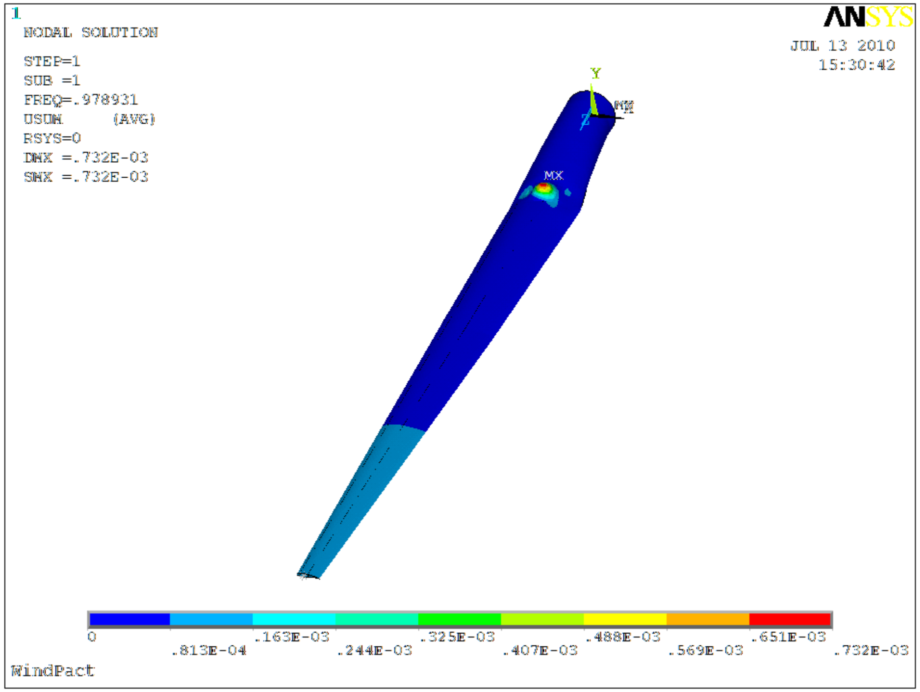
Percent Change in Equivalent Fatigue Load	9 m/s	11 m/s	18 m/s	Avg.Wind 5.5m/s	Avg.Wind 7m/s
Low Speed Shaft Torque	-1.7	-4.9	-33.5	-3.1	-7.3
Blade Root Edge Moment	1.7	1.9	-2.5	0.8	0.8
Blade Root Flap Moment	-31.2	-27.1	-30.4	-23.1	-26.3
Tower Base Side-Side Moment	-0.1	-8	-7.2	-0.9	-2.9
Tower Base Fore-Aft Moment	-18.6	-16.5	-13.8	-5	-8
Tower Top Yaw Moment	-53.2	-42.9	-43.4	-25.1	-32.2

Buckling in ANSYS

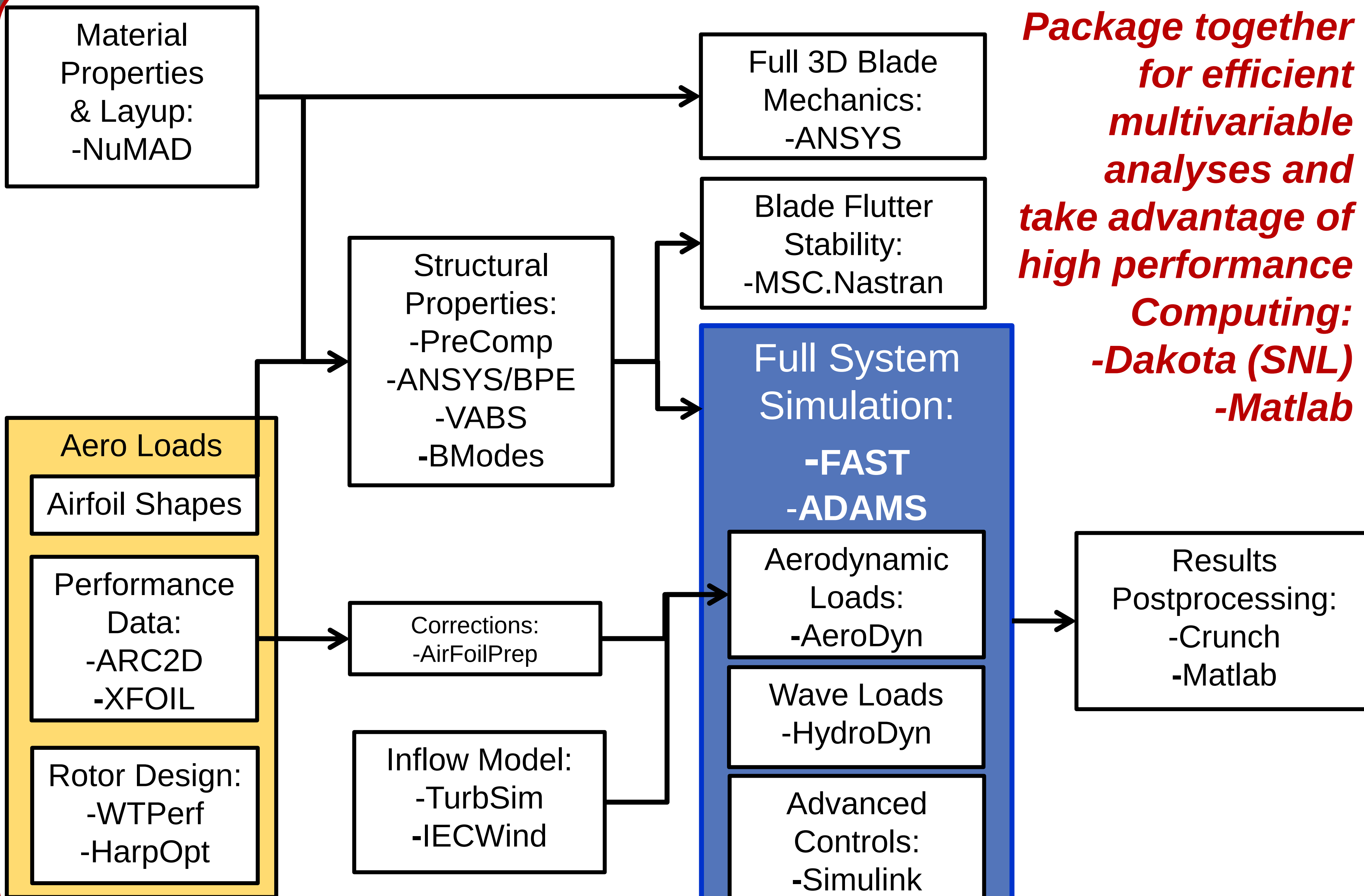
- **Apply forces to nodes using aeroelastic simulation data**



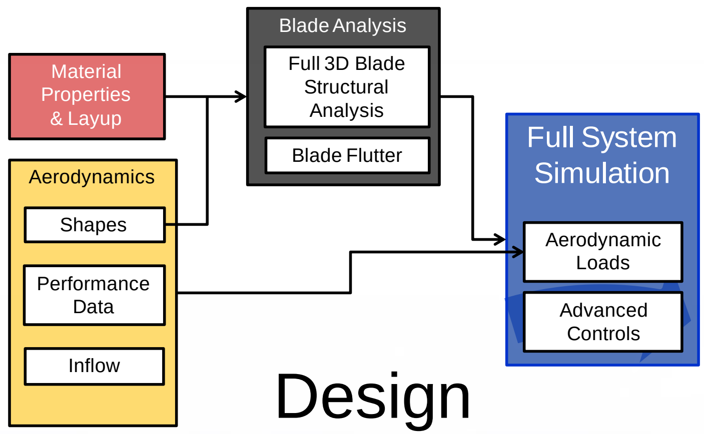
- **Buckles at 0.9789 x Applied load**
  - Design iteration required!



Wind Turbine Design Tools in Use at Sandia



Design & Test Loop at SNL



Design

Simulate

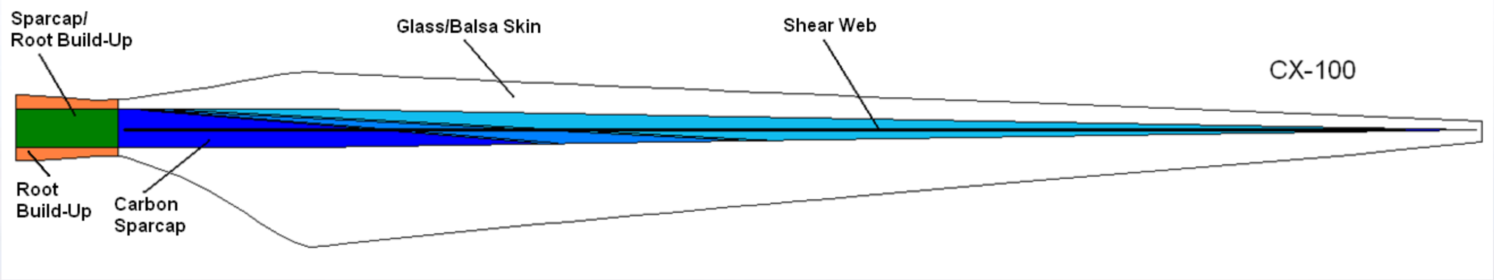
Calibrate the model
or
Include missing physics

Measure

Test

Example 1

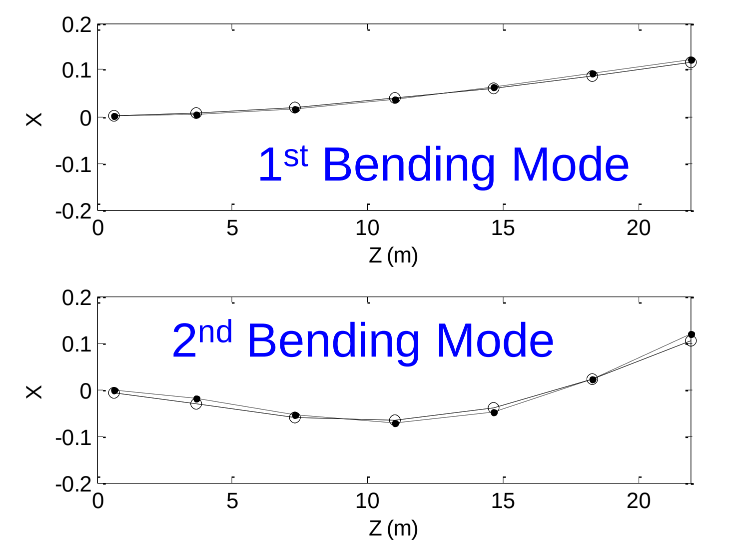
Micon turbine with 9m CX-100 blades



Micon Tower Modal Analysis

- Simmermacher et al. (1999) Performed Impact Test of Tower “C”

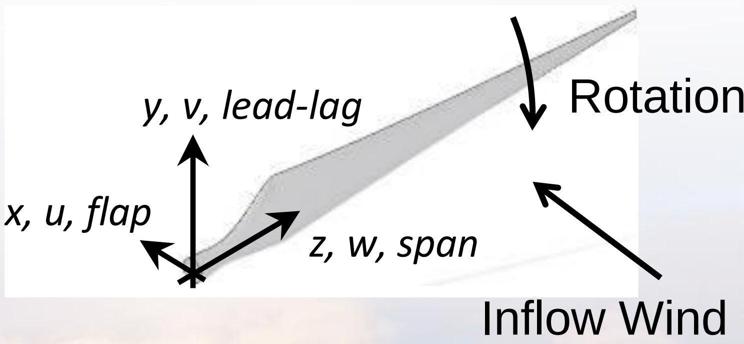
Mode	Experimetnal Frequency (Hz)	Analytical Beam Frequency (Hz)	Difference	Description
1	3.3	3.13	-4.9%	1st Fore-Aft Bending
2	3.3	3.13	-5.4%	1st Side-Side Bending
3	15.3	16.31	6.8%	2nd Fore-Aft Bending
4	15.8	16.31	3.5%	2nd Side-Side Bending



CX-100 Modal Analysis

- Impact Test of Free-free CX-100 Sensored Rotor Blade

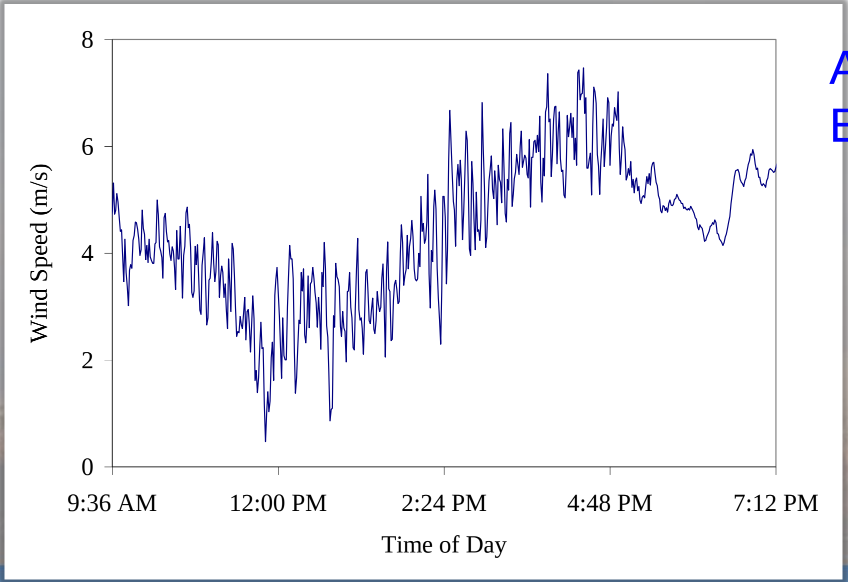
Mode	Experimetnal Frequency (Hz)	Analytical Beam Frequency (Hz)	Difference	Description
1	8.2	8.30	1.0%	1st Flap Bending
2	16.8	17.17	2.3%	1st Edge Bending
3	20.3	18.96	-6.5%	2nd Flap Bending
4	33.8	34.22	1.1%	3rd Flap Bending
5	42.2	42.19	0.0%	2nd Edge Bending
6	52.2	56.77	8.8%	4th Flap Bending



Micon 65/13M Wind Turbine Modal Analysis

- Impact Test of Micon 65/13M Wind Turbine at Rest

- Wind Speed Profile During Test



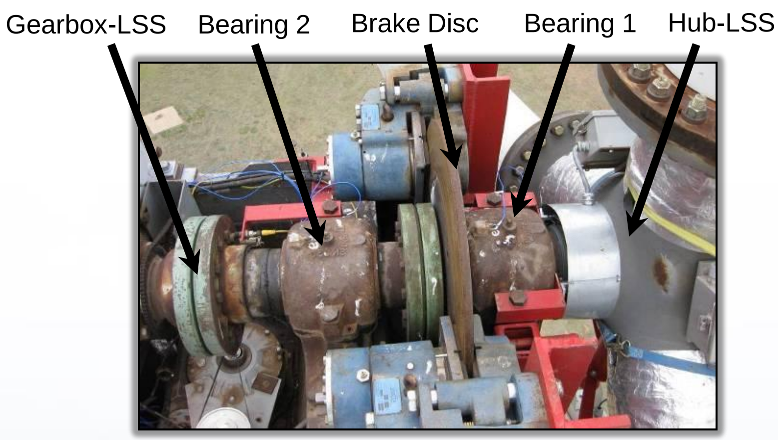
Ambient Excitation Makes Experimental Testing Difficult

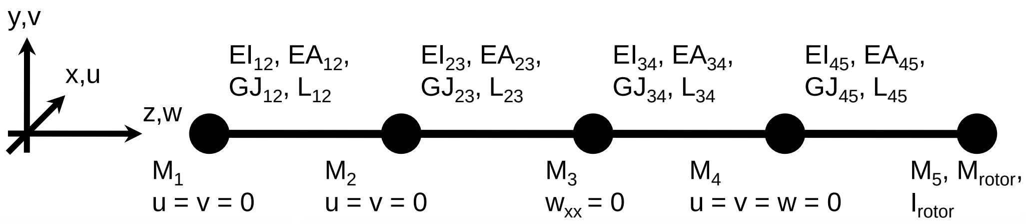
Micon 65/13M Model Comparison

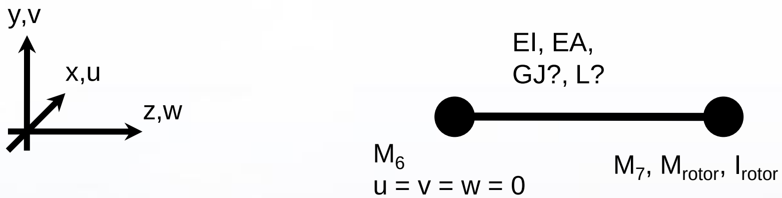
Mode	Experimental Frequency (Hz)	Rigid LSS Frequency (Hz)	% Diff.	Description
1	1.30	1.33	2.3%	1st Side-Side Tower
2	1.34	1.35	0.7%	1st Fore-Aft Tower
3	3.19	3.31	4.0%	1st Rotor Torsion
4	3.26	3.61	10.8%	1st Flap Antisymmetric (about vertical axis)
5	3.45	4.21	22.2%	1st Flap Antisymmetric (about horizontal axis)
6	4.51	4.29	-4.9%	1st Flap Symmetric
7	5.35	5.86	9.6%	1st Edge Symmetric, In-phase
8	5.51	6.00	8.9%	1st Edge Symmetric, Out-phase
9	6.57	6.52	-0.7%	2nd Flap Antisymmetric (about vertical axis), Tower In-phase
10	7.17	10.13	41.2%	2nd Flap Antisymmetric (about horizontal axis), Tower In-phase
11	10.01	11.35	13.4%	2nd Flap Antisymmetric (about horizontal axis), Tower Out-phase
12	10.34	10.96	6.0%	2nd Flap Antisymmetric (about vertical axis), Tower Out-phase
13	11.49	10.90	-5.1%	2nd Flap Symmetric
14	15.41	14.85	-3.6%	2nd Rotor Torsion
		Average	7.48%	
		1 Std. Dev.	12.39%	

System Model Additions

- Develop Single Element Flexible LSS Model

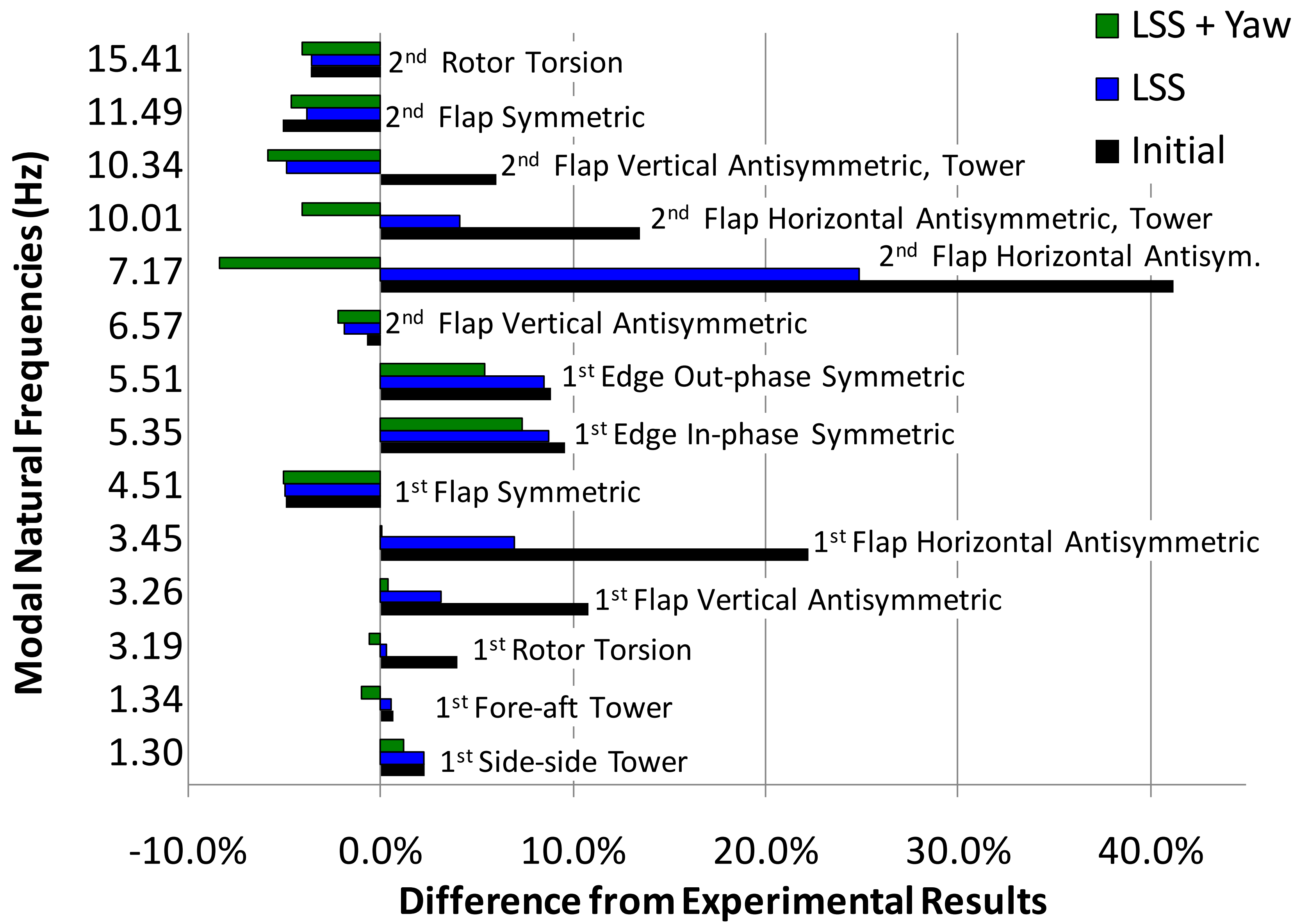






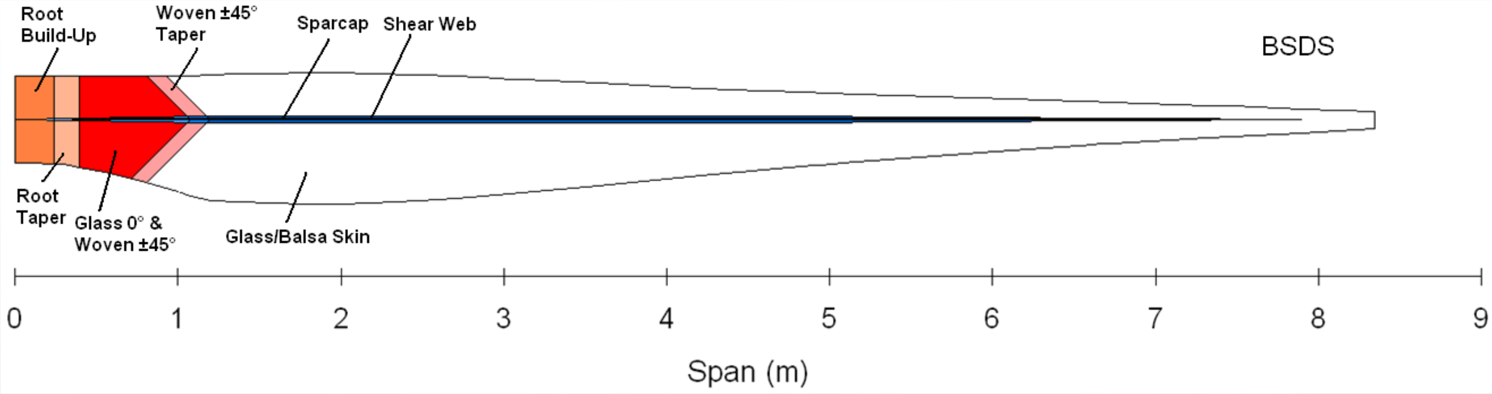
- Yaw Bearing and Brake Bending Flexibility was Un-modeled

Model Update Results



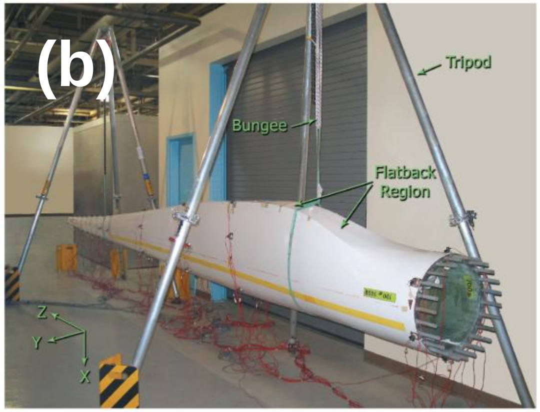
Example 2

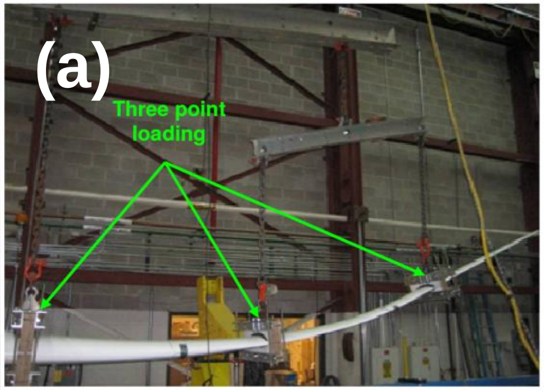
BSDS Blade



BSDS Experimentally Determined Properties

- **Flap-wise stiffness distribution determined using three approaches**
  - (a) Static load-deflection testing
  - (b) Free boundary condition modal test
  - (c) Root boundary condition modal test: seismic mass on airbags
- **Mass properties were measured directly from sliced sections of a BSDS blade which had been tested to failure**

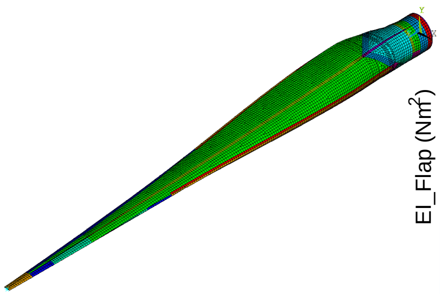


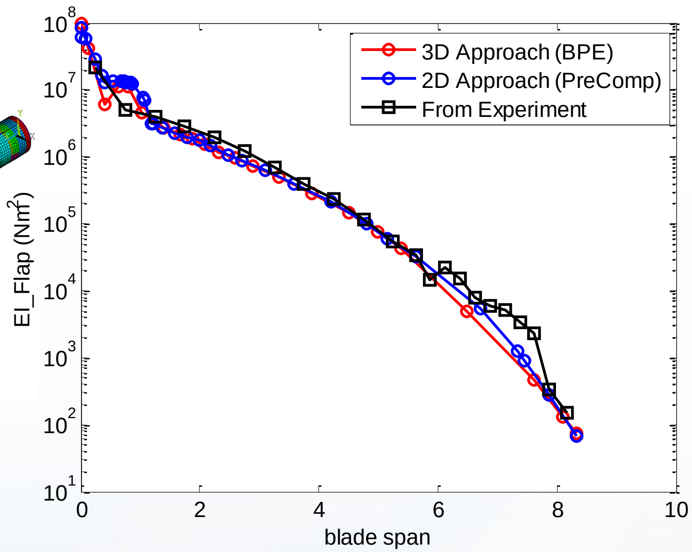


D.T.Griffith, et.al., SNL

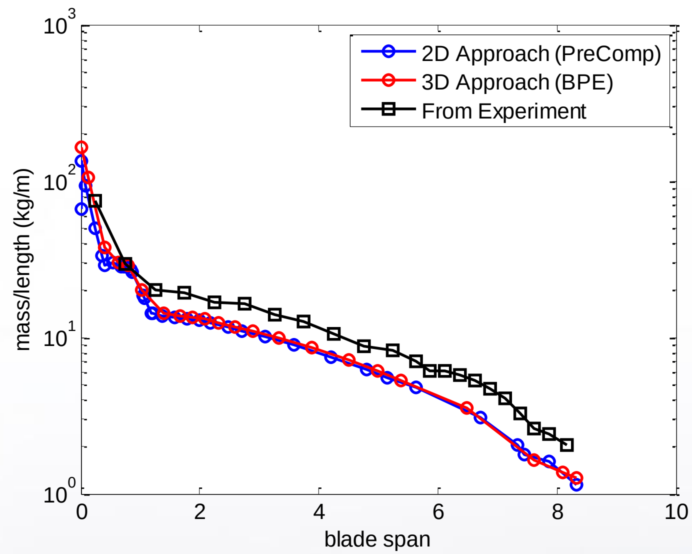
Compare Analysis and Experiment

Flapwise bending stiffness





Mass Distribution



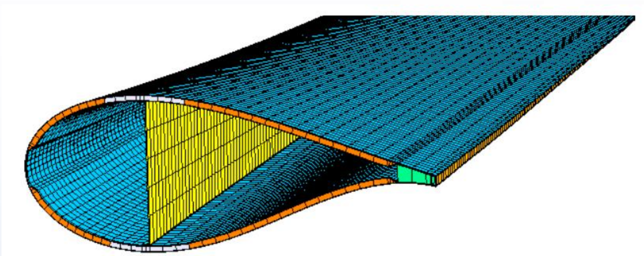
Free-Free Beam Model	BSDS Hardware (Actual)	BPE	BPE/Hardware % Difference
Mass (kg)	127	105.6	-16.8%
1st Flap (Hz)	5.25	5.43	3.4%
2nd Flap (Hz)	13.5	12.9	-4.4%
1st Edge (Hz)	17.2	14.0	-18.6%
3rd Flap (Hz)	24.5	23.8	-3.1%

Outline

- Background of blade concepts at Sandia
- Blade structural design and analysis
- Wind turbine system analysis
- Experiments for blade and system model validation
- Improving models using experimental data
- **List analysis tools used in the industry**
- Topics for future modeling and simulation

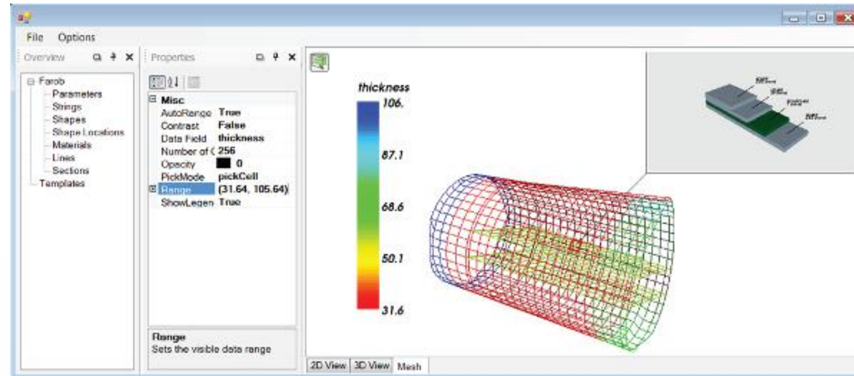
Blade Modeling Tools - Worldwide

- **Focus6**
  - Commercially available in modules from Knowledge Centre WMC & ECN, The Netherlands
- **ANSYS and ANSYS ACP**
- **Abaqus**

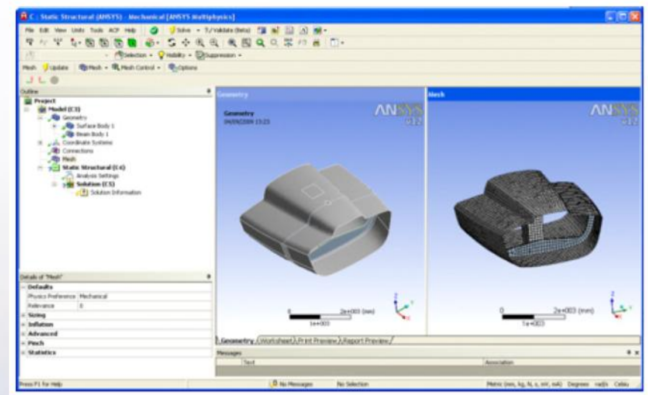


- **VABS**
  - There are several different efforts to look at design environments that take advantage of VABS

Focus6



ANSYS ACP



Aeroelastic Simulation Tools - Worldwide

- **Bladed, Garrad Hassan, UK**
  - Mainstream tool
- **Focus 6, WMC/ECN, The Netherlands**
  - Mainstream tool
- **HAWC2, Riso National Lab, Denmark**
- **Flex5, DTU**
- **FAST and AeroDyn, NWTC-NREL, United States**
  - Very popular in the research community
- **MSC.ADAMS and AeroDyn**
  - Used in some of the more challenging/innovative projects
- **Full Blade FE Model coupled with multibody dynamics (and possibly CFD)**
- **DU_SWAMP, TU-Delft, The Netherlands**
  - Simulink-based multibody dynamics for advanced controls simulation
  - A very young code

SNL Structural Tools
Activities Moving Forward

In order of completion; near-term first

- **Application of blade loads from aeroelastic simulation to the NuMAD/ANSYS finite element blade model**
- **Implementation of NuMAD in Matlab: Experiencing increased usage by industry and researchers**
- **Creation of a parametric wind turbine system analysis toolbox in Matlab: For highly effective setup, execution and analysis of a very large numbers of simulations**
- **Detailed structural models from NuMAD: i.e. Brick elements**

Future research areas

- **Passive and active fatigue load mitigation concepts**
- **Damage and defect modeling**
- **Full system aeroelastic stability**

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

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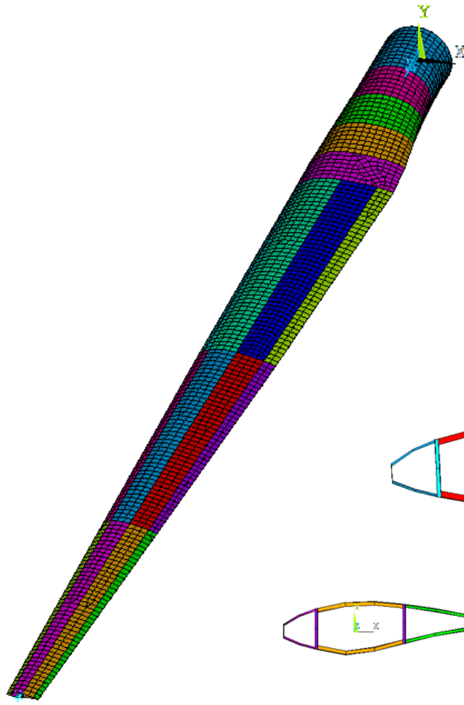
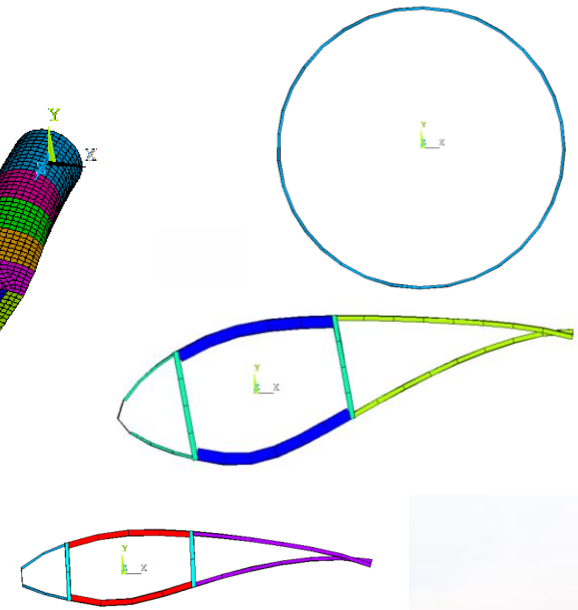
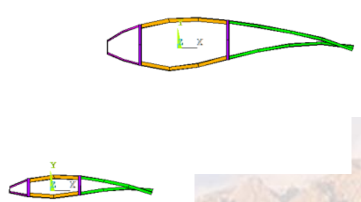
Additional Slides

A Generic 1.5MW Blade Model

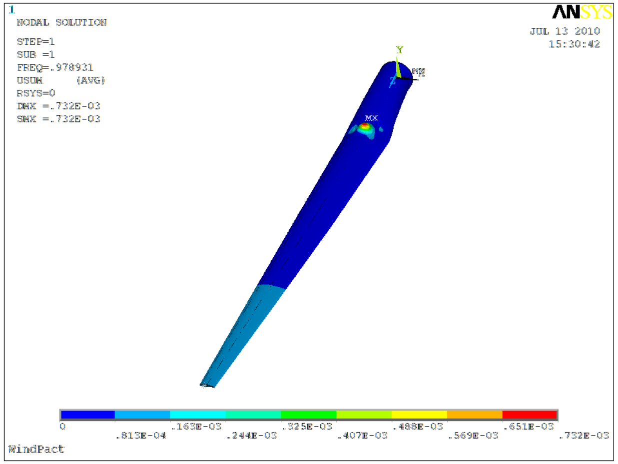
Created using information found in public reports from the WindPact study.

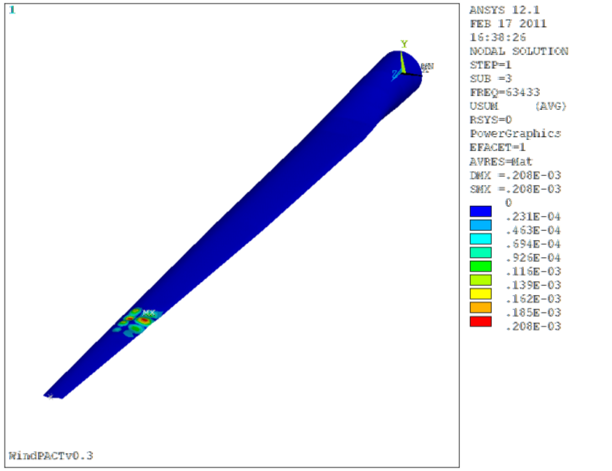






Only issue was that the basic design buckled under normal operational loads. Modifications were made to make the max-chord region more robust.

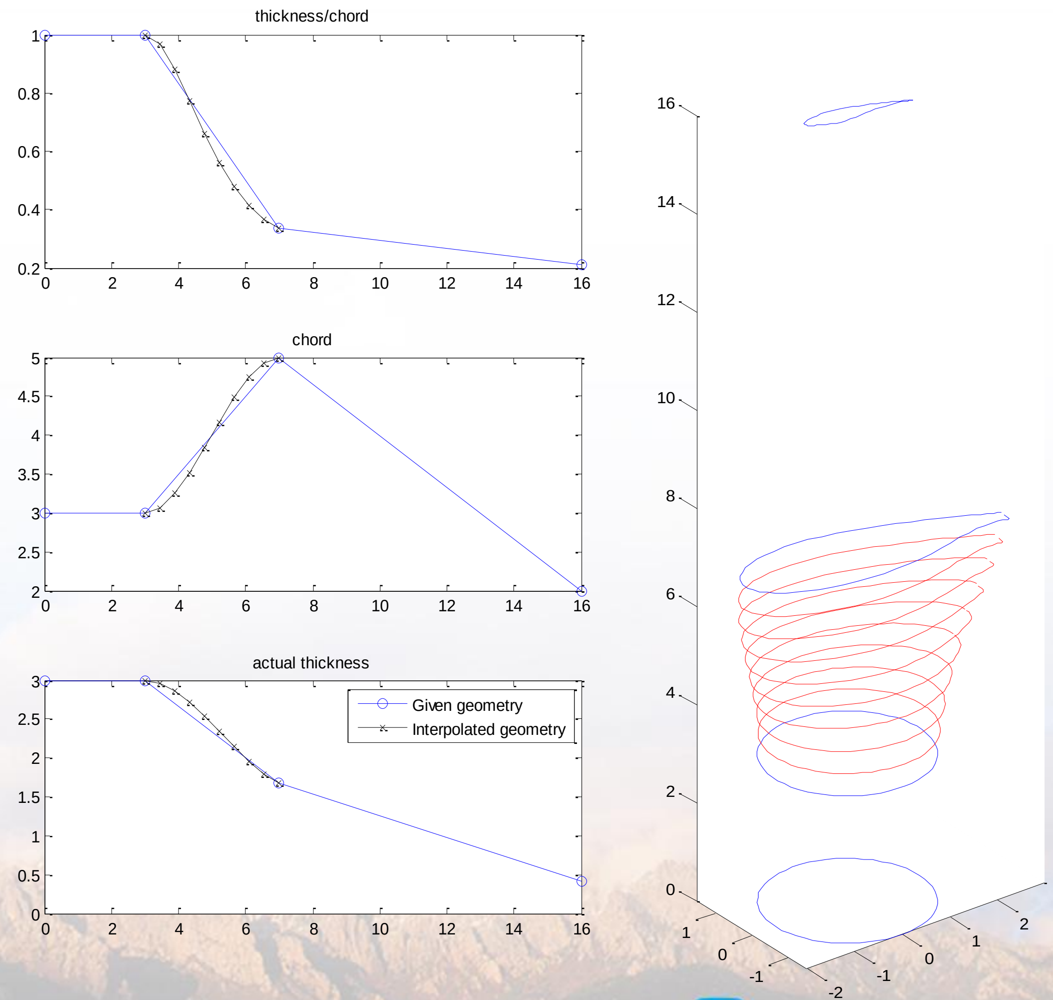




Determine intermediate shapes

- Blades can be defined initially with only a handful of shapes along the blade span

- Developed a technique that preserves **blade camber** and ensures a *smooth transition* of airfoil **thickness** and **chord**



Property Distribution Computations

Two-Dimensional Approach

- ***Pros***
  - *Readily and freely available*
  - *Computationally efficient*
- ***Cons***
  - *Limited to 2D analysis*
  - *Simple examples below:*

$$EI\_flap = \iint E(x,y)x^2 dxdy \,,$$

$$EI\_edge = \iint E(x,y)y^2 dxdy \,,$$

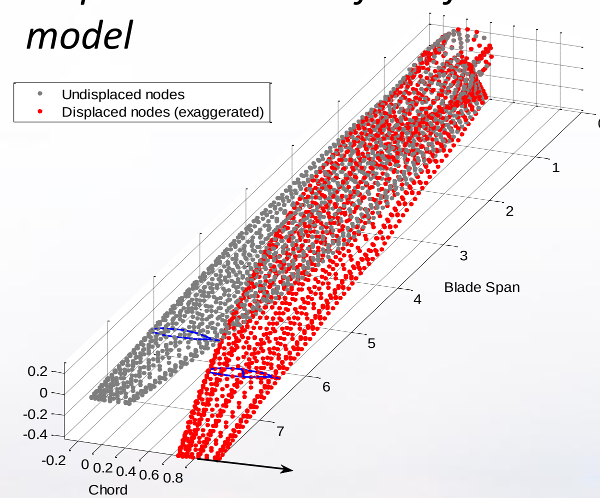
$$GJ = \iint G(x,y)(x^2 + y^2) dxdy \text{ and}$$

$$EA = \iint E(x,y) dxdy$$

- ***Chosen Tool: PreComp***
  - *Created by Gunjit Bir, NREL*

Three-Dimensional Approach

- ***Pros***
  - *Includes three dimensional effects*
- ***Cons***
  - *Requires creation of the finite element model*



- ***Chosen Tool: Beam Property Extraction (BPE)***
  - *Created by David Malcolm, GEC*
  - *Distributed with NuMAD (D.Laird, Sandia Labs)*

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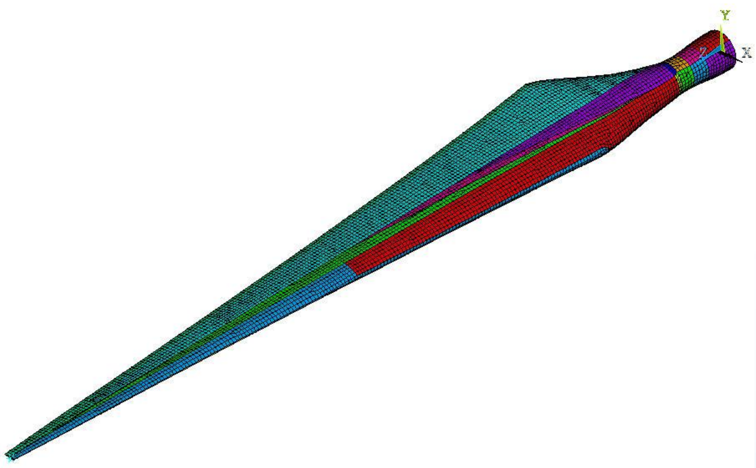
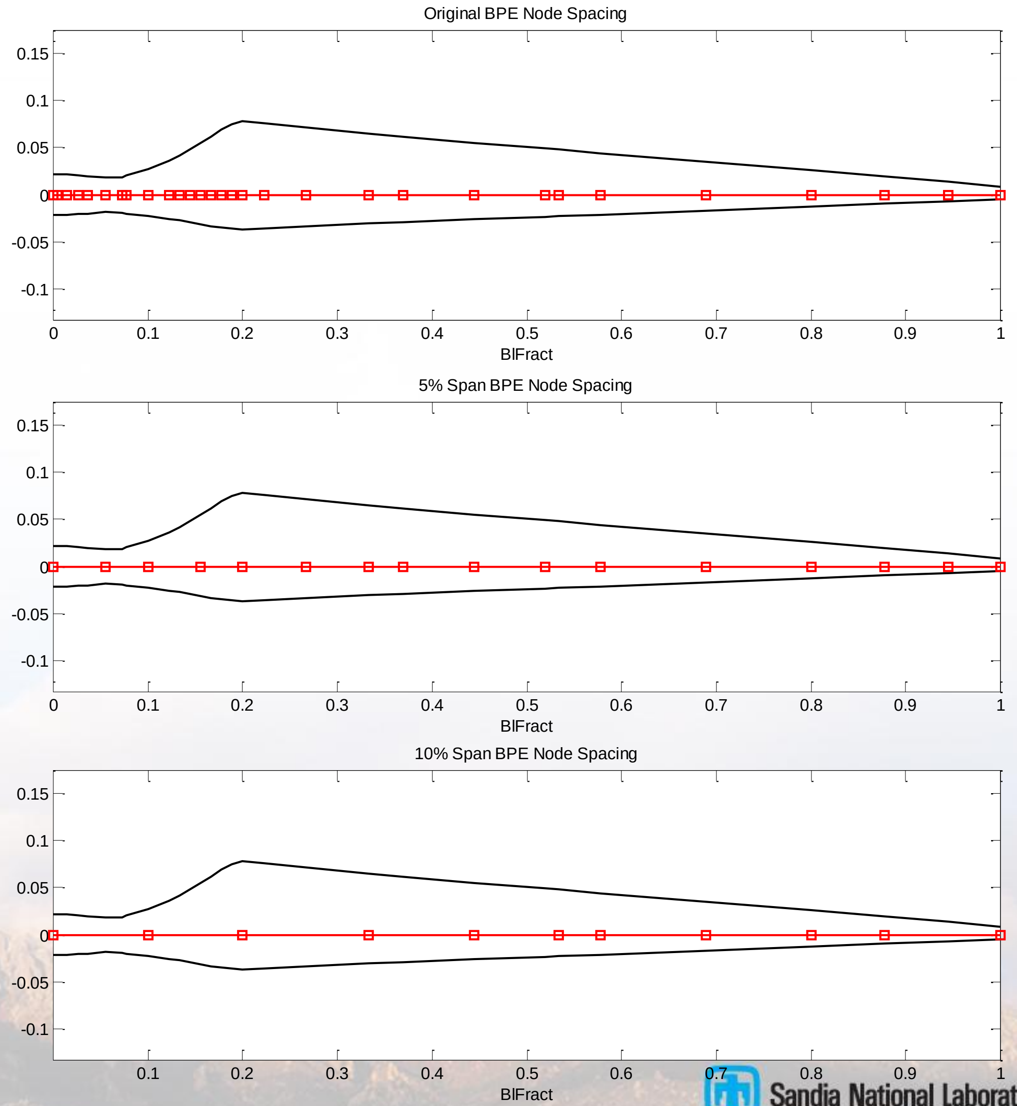
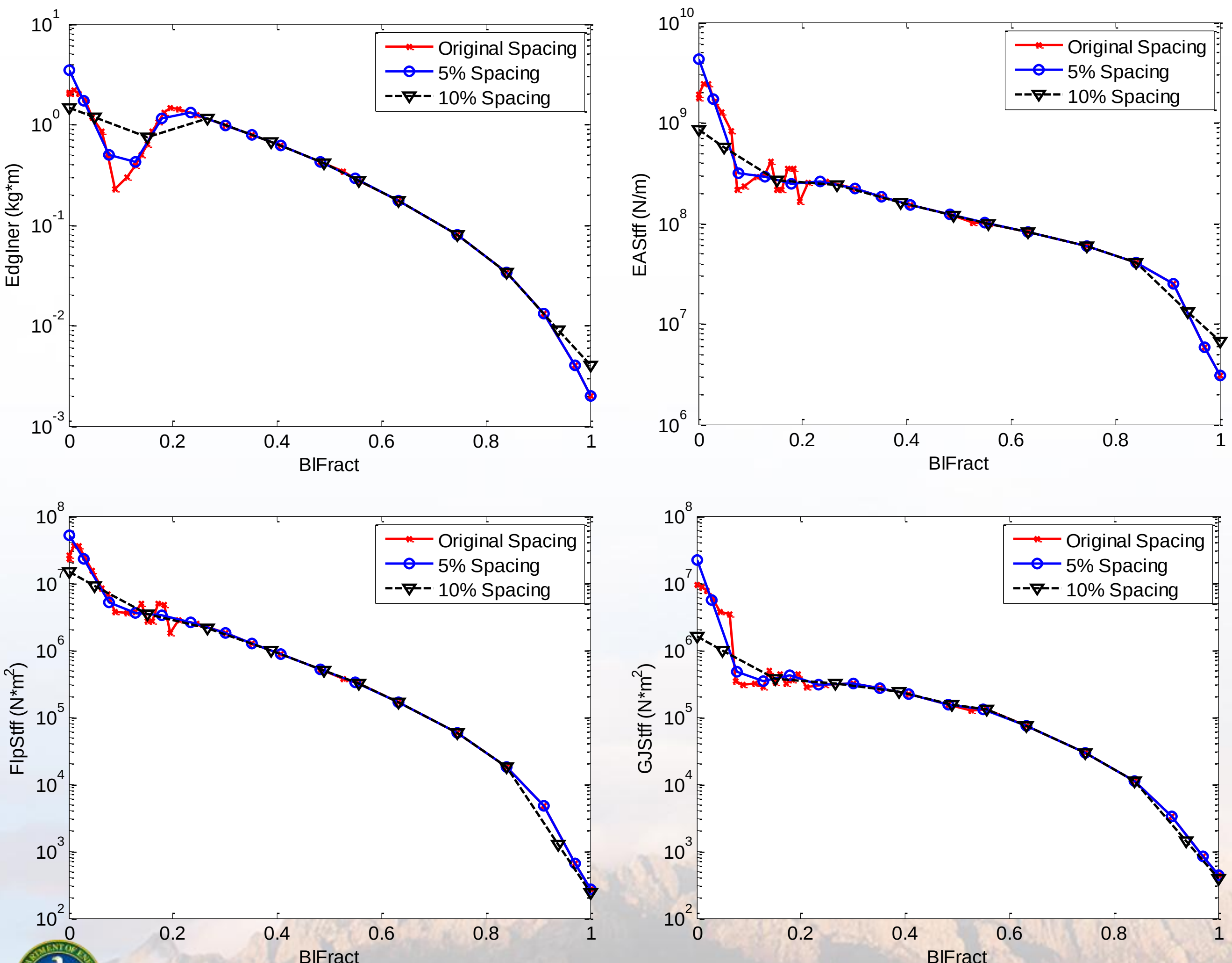
BPE Node Spacing Study





BPE Node Spacing Recommendation



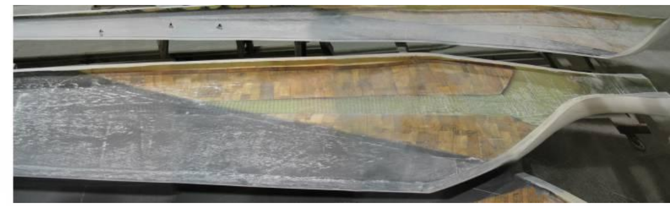
Node spacing guideline: ~5% span increments

Innovative Blade Developments

Recent History

BMI 2000-02 ERS-100

Carbon-Hybrid Blade Developments
2003-05 CX-100, TX-100



WindPACT (2001-05) BSDS

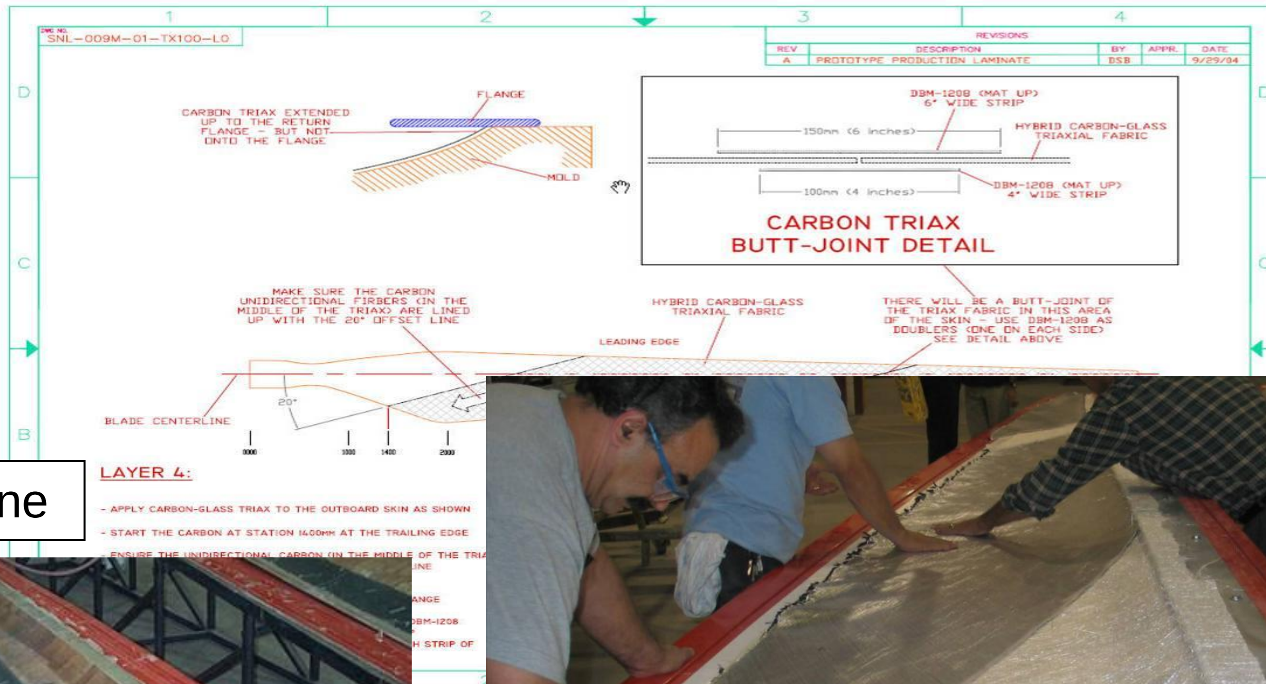
STAR 27m Swept Blade (2005-09)

Sensor Blade I/II (2008-10)

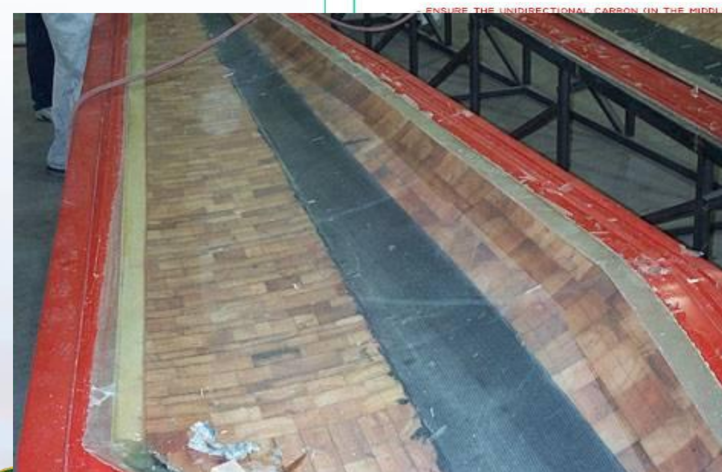
2011 - CX-100 with Flap for Active Control

TX-100 9-Meter Blade

Twist-Coupling Using Off-Axis Fibers



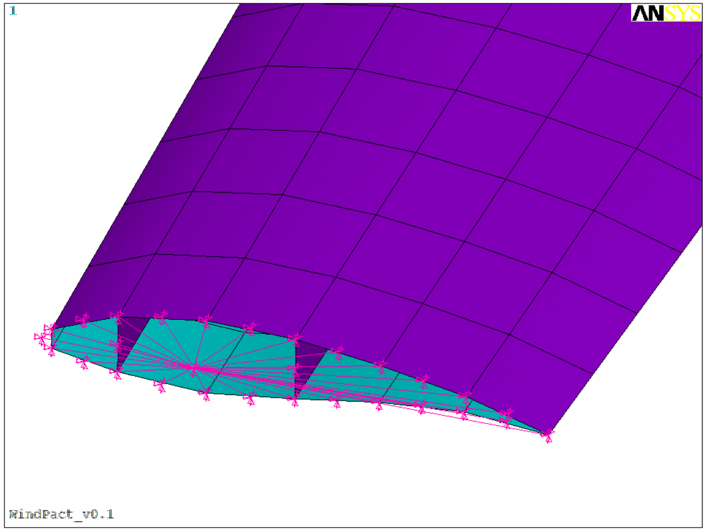
CX-100 baseline



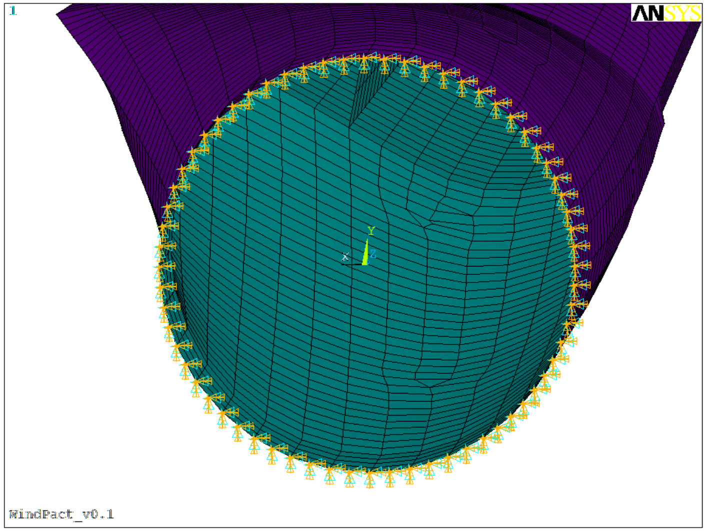
TX-100 with off-axis carbon fiber

Generate FE Model in ANSYS; Apply Boundary Conditions

- Create master node at blade tip

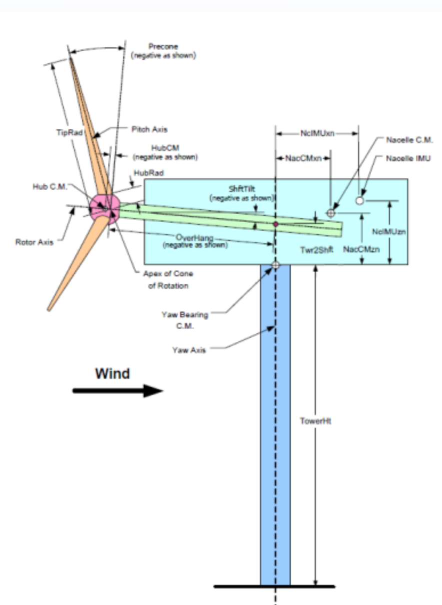


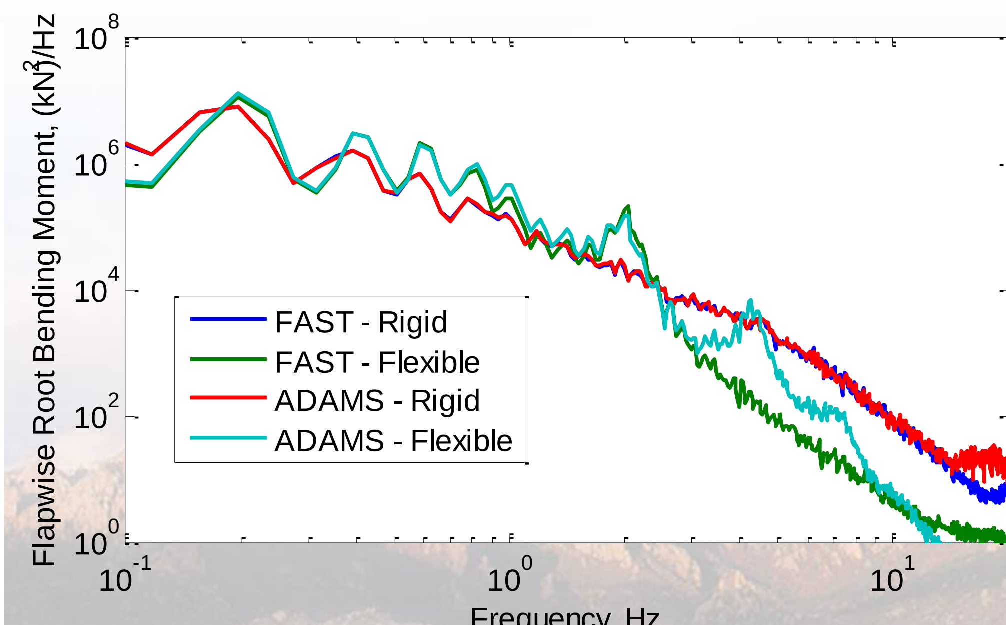
- Enforce boundary condition at root
  - Cantilevered: all DOF fixed at root or
  - Free-free: no constraints



Tools: FAST and ADAMS

	FAST	ADAMS
Available from	NREL	MSC Corporation
Structural modes included	Up to 2 each of blade flap/edge and tower F-A/S-S	Unlimited; depends on discretization
Aerodynamic forces	AeroDyn	AeroDyn
Uses	Very fast computations; Adequate for most work, especially certification	Code verification; Simulations requiring several dynamic structural modes





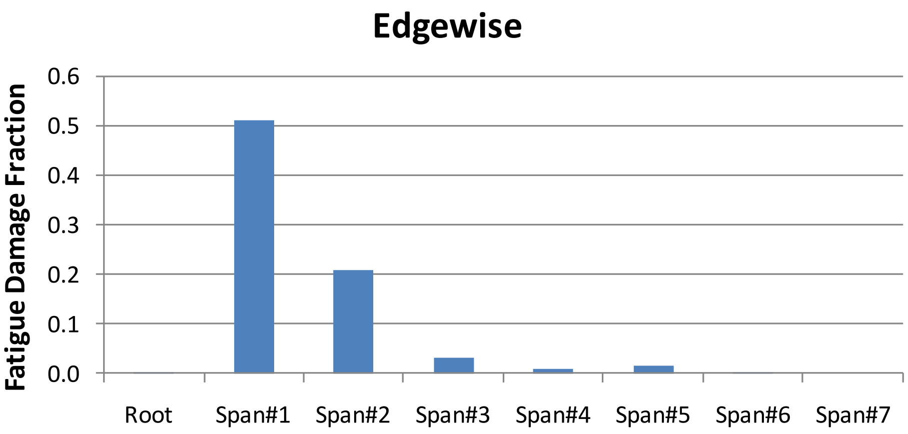
Fatigue Analysis Example

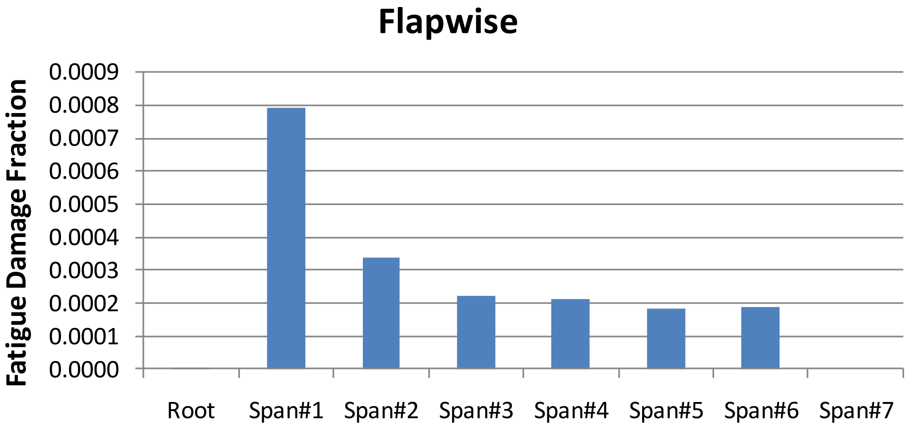
- **Very Large Rotor; Squared-Cubed Conundrum:**
  - Mass grows by length cubed
  - Power grows by length squared
- **Total Damage Fraction from Miner's Rule:**

$$C = \sum_{i=1}^{k} \frac{n_i}{N_i}$$

  - n_i=number of cycles at stress level, i
  - N_i=number of cycles to failure at stress level, i
  - k=total number of stress cycles
  - C=damage fraction;
    assume failure at C=1.0
  - Safety factor (1.6335) included
- **Edge loads dominate at large scales**

20-year life Fatigue Analysis





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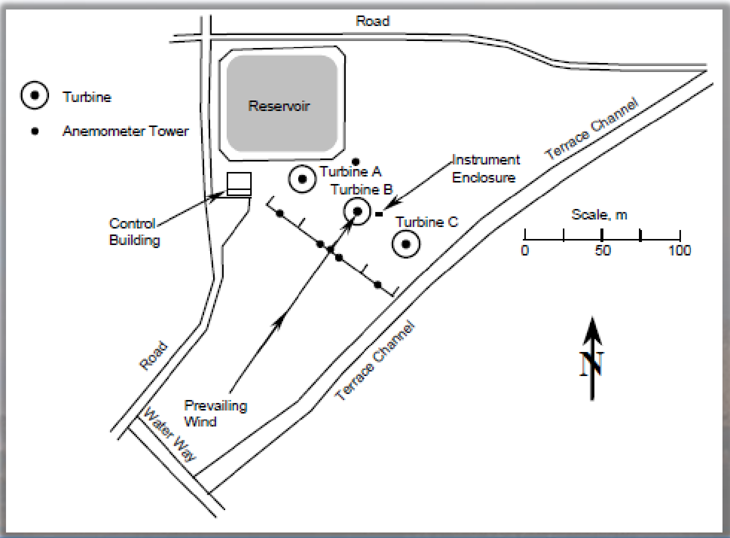
Codes Acknowledgement

- **Many of the individual codes used by Sandia have been developed, tested, documented, and made available by NREL. These codes are extremely valuable to the research community:**
  - FAST/AeroDyn
  - ADAMS coupling
  - AirfoilPrep
  - TurbSim
  - PreComp (Sandia modified)
  - BModes
  - HydroDyn
  - WTPerf
  - HydroDyn
  - Crunch
  - More information at: http://www.nrel.gov/wind/model_analysis.html

- **The following tools are made available by Sandia:**
  - NuMAD
  - BPE

SNL / USDA-ARS Research Turbines

- Micon 65/13M Wind Turbine to be Modeled



Micon 65/13M	
Speed Regulation	fixed 55 rpm
Rotor Pitch Regulation	fixed 0 deg.
Generator Type	asynchronous
Generator Speed	1200 rpm
Generator Voltage	480 V, 3-phase
Generator Rated Power	115 kW
Tower Height	22 m
Tower Mass	6575 kg
Nacelle Mass	3889 kg
Nacelle Inertia	4137 kg m^2
Hub Height	23 m
Hub Radius	0.61 m
Hub Mass	572 kg
Tilt Angle	4 deg.
Coning Angle	-4 deg.

Certification Standards

- **Industry must adhere much more closely to all aspects of certification standards such as IEC or GL**
- **The nearly 400 page GL document covers details regarding:**
  - Safety systems and monitoring devices
  - Manufacturing quality management
  - Load assumptions
  - Strength analyses: metallics, concrete, composites
  - Structures: blades, connections, tower, foundation
  - Machinery: actuators, bearings, drivetrain
  - Electrical

Stability Analysis - Worldwide

- **Eigenvalue approach:**
  - HAWCStab, Riso National Lab, Denmark

- **Time Marching:**
  - The following codes have been used to demonstrate onset of instability:
  - HAWC2 (Buhl, 2009)
  - ADAMS/AeroDyn (Lobitz, 2004)