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Overview of Sandia Wind Turbine Blade Analysis

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Sandia Blade Workshop

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Outline

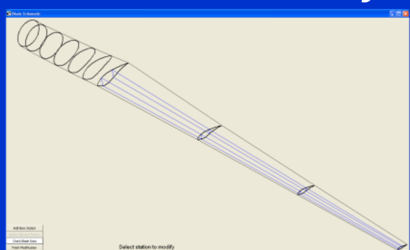
- Intro to NuMAD for detailed blade analysis
- Material properties
- Aero loads mapping from AeroDyn to ANSYS
- NuMAD output for CFD mesh
- Computation of beam properties for aeroelastic simulation
- Wind blade classical flutter analysis
- Sandia's integration of tools

Blade Design with NuMAD

NuMAD

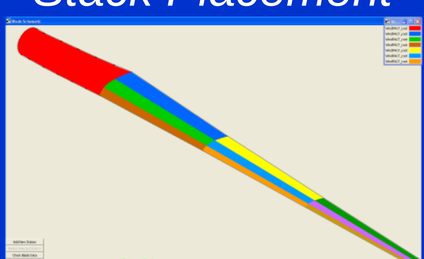
NuMAD:
Numerical Manufacturing
And Design Tool

Blade Geometry

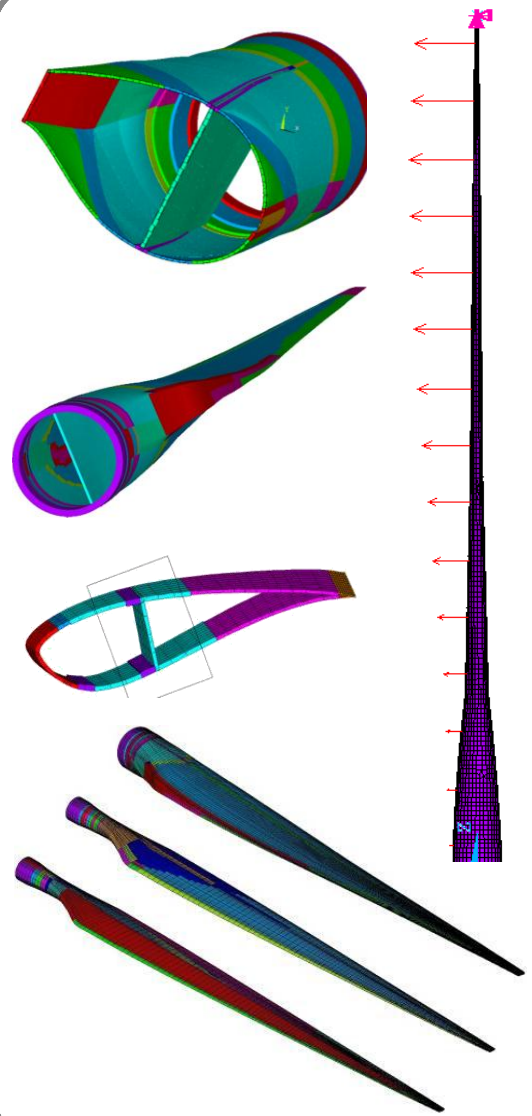


Materials & Layups

Stack Placement

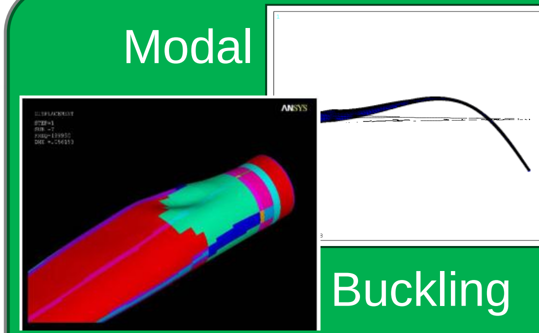


ANSYS FE Model



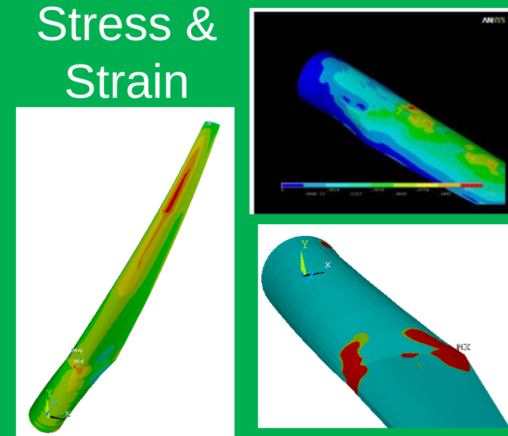
ANSYS Analysis

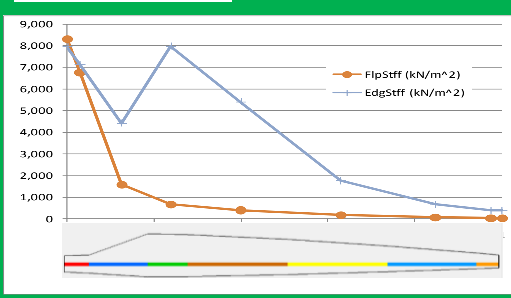
Modal



Buckling

Stress & Strain



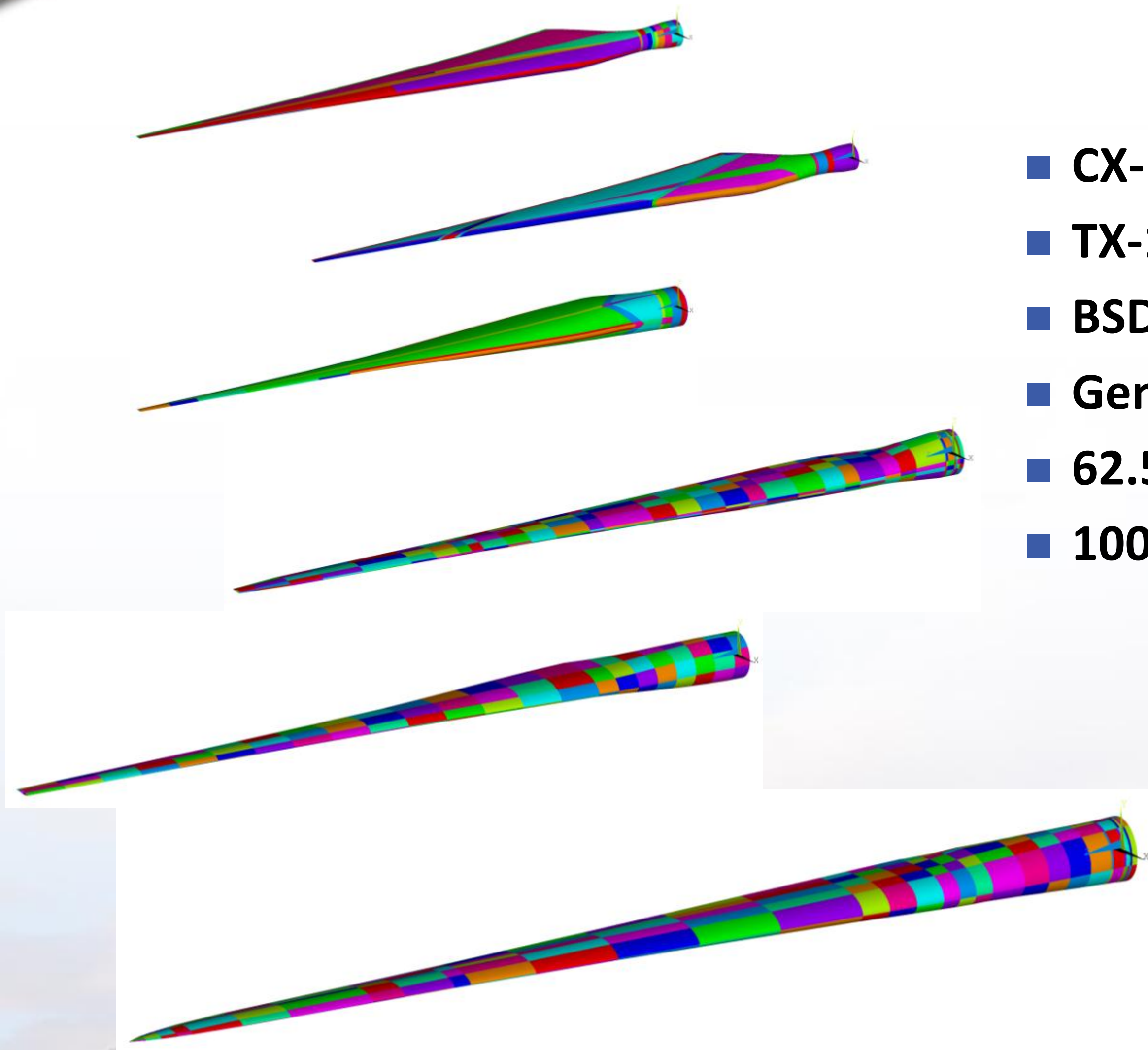


Beam Properties

NuMAD history

- **(Nu)merical (M)anufacturing (A)nd (D)esign tool for wind turbine blades**
- **Released initially in 2001 at Sandia by Daniel Laird; written in Tcl**
- **Experienced a few hurdles that led to lower usage by the research community:**
  - Concerns regarding offset node shell element formulations
    - Created motivation for development of tools such as PreVABS/VABS as well as PreComp-like approaches; some pursued blade models made of brick elements
  - Concerns regarding amount of time required to build and solve models
  - Concerns about an increasing number of bugs, likely associated with more modern operating systems
- **A NuMAD tutorial was held in July 2010 where it was decided to pursue a total update of the NuMAD tool for the benefit of Sandia users, as well as users in the research community at large**
- **The beginnings of a Matlab-based NuMAD was born in late 2010**

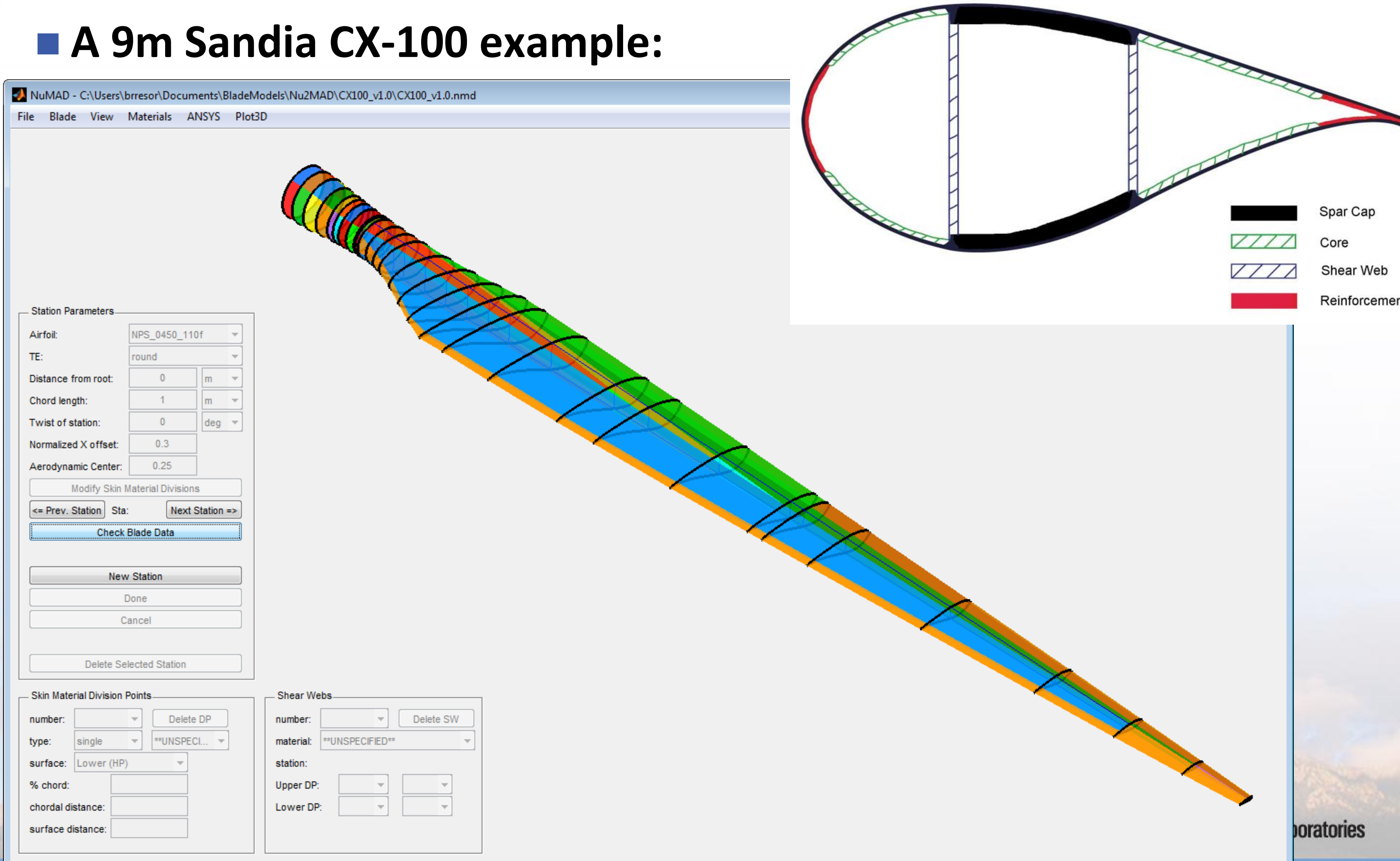
Sandia Blade Models



- CX-100 9m
- TX-100 9m
- BSDS 9m
- Generic WindPACT 33.25m
- 62.5m
- 100m

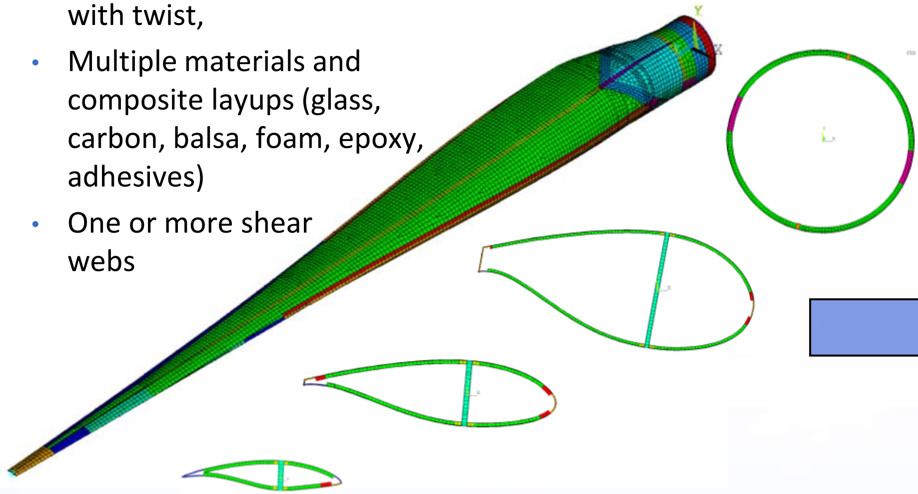
NuMAD Geometry and Materials

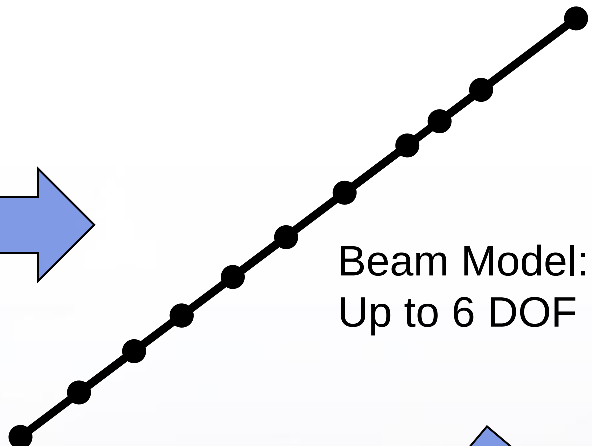
- **A 9m Sandia CX-100 example:**



The Wind Blade Design & Analysis Cycle

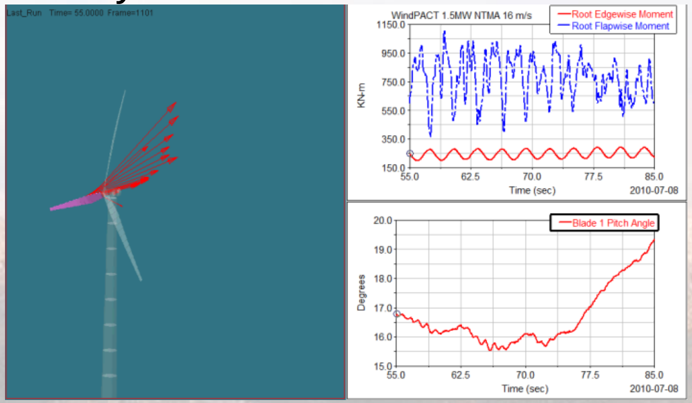
- **Wind turbine blades include**
  - Variable section shapes with twist,
  - Multiple materials and composite layups (glass, carbon, balsa, foam, epoxy, adhesives)
  - One or more shear webs





Beam Model:
Up to 6 DOF per node

Full system aeroelastic simulation



Aerodynamic and structural dynamic loads applied to the model

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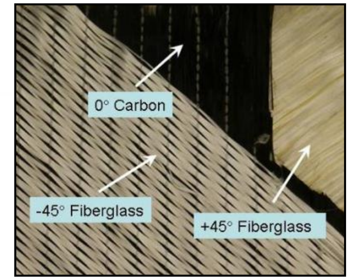
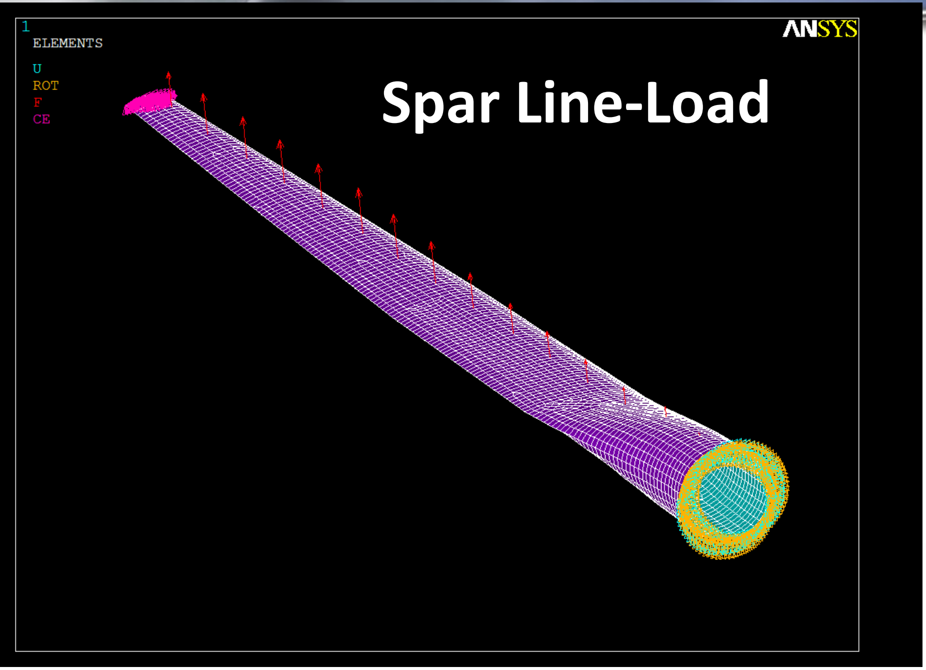
Materials Research

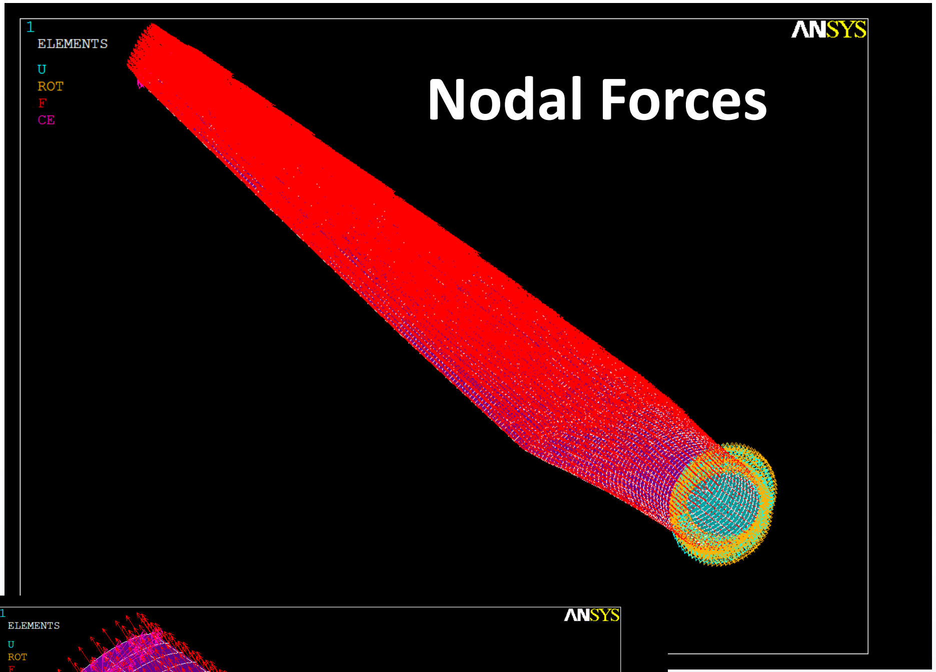
- **Goal:** Advance the state of composite materials for use in large-scale wind turbine blades.
- **Methodology:**
  - Determine composite fatigue & strength properties
    - New materials & forms
    - Ply drops, adhesives, core, alternate materials
  - Engineer materials to reduce weight & increase reliability of blades
  - Build up SNL/MSU Fatigue Database
    - Material properties (10000+ tests for 175 materials)
  - Develop design improvements
    - Structurally more efficient airfoils
    - Composite hybrids
- **Partners:** Montana State and multiple industry members; PPG, Owens-Corning, Reichold, Arkema, GE, Clipper, many others

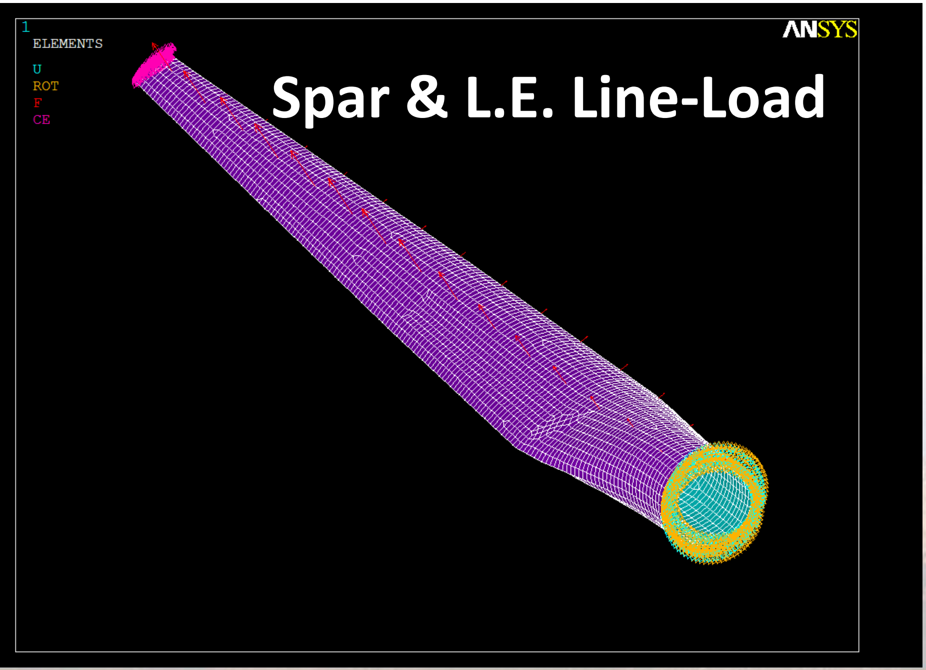


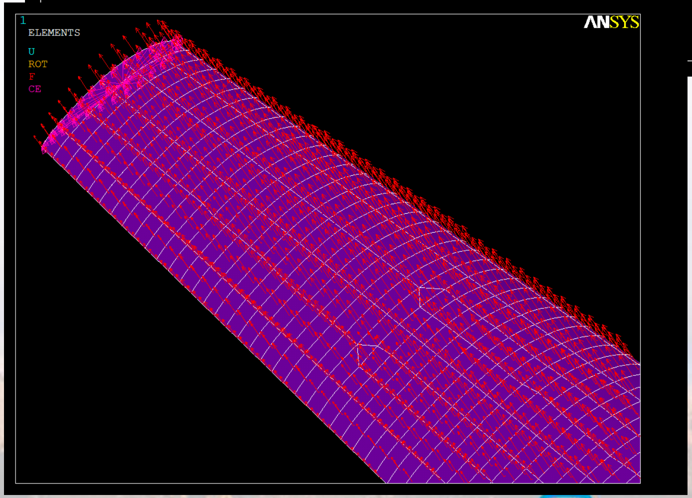
SNL Contact: Josh Paquette

Loading Approaches









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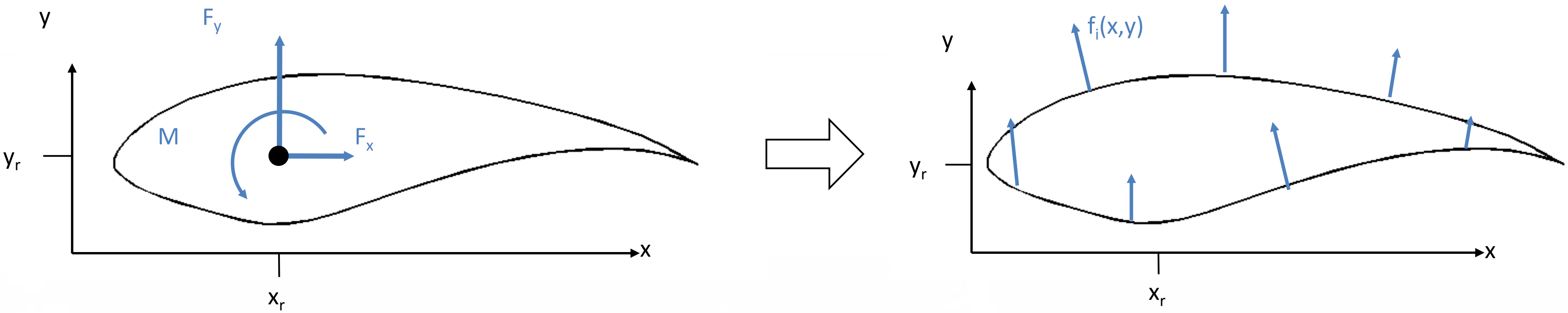
Load Mapping



We require static equivalence:

$$F_x = \sum_{i=1}^{N} f_{x,i} \qquad F_y = \sum_{i=1}^{N} f_{y,i}$$

~~$$M = \sum_{i=1}^{N} (x_i - x_r) \cdot f_{y,i} - (y_i - y_r) \cdot f_{x,i}$$~~

We assume linear spatial distribution:

$$f_{x,i} = a_x (y_i - y_r) + b_x$$

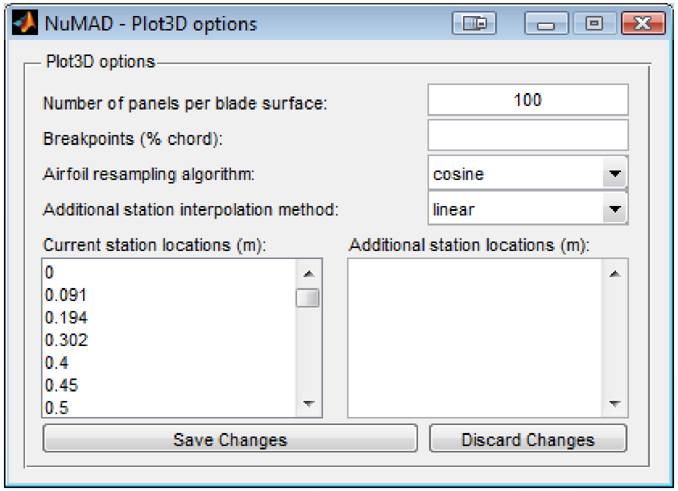
$$f_{y,i} = a_y (x_i - x_r) + b_y$$

$$M = \sum_{i=1}^{N} (x_i - x_r) \cdot f_{y,i} \qquad 0 = \sum_{i=1}^{N} -(y_i - y_r) \cdot f_{x,i}$$

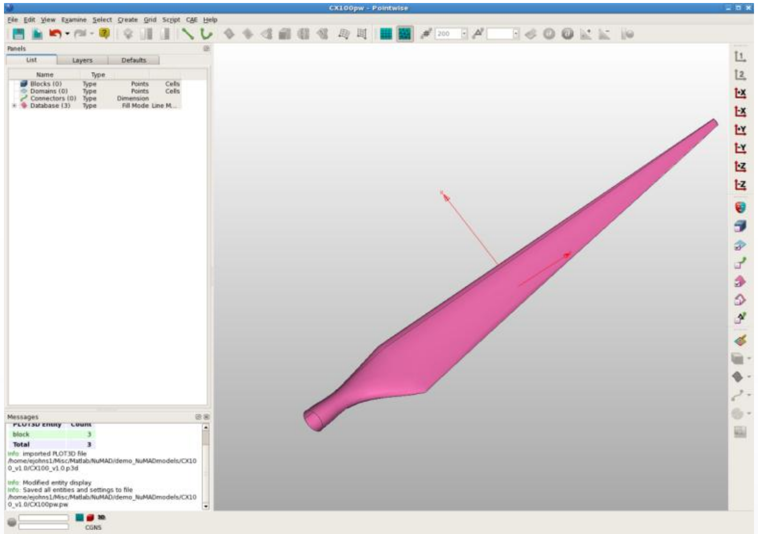
Berg, J. C. et. al. "Mapping of 1D Beam Loads to the 3D Wind Blade for Buckling Analysis." AIAA SDM, 2011.

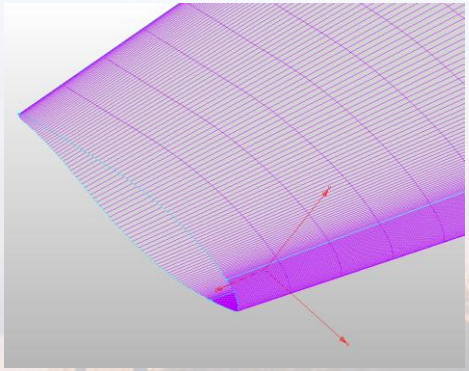
Plot3D output for CFD mesh

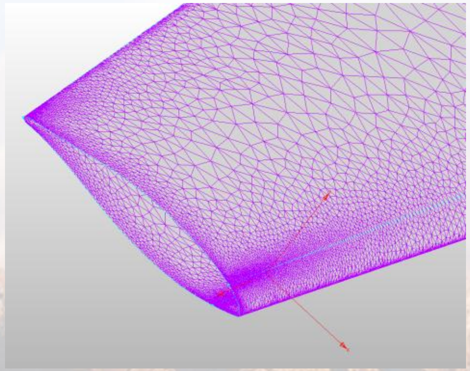
- **NuMAD -> Plot3D data format**

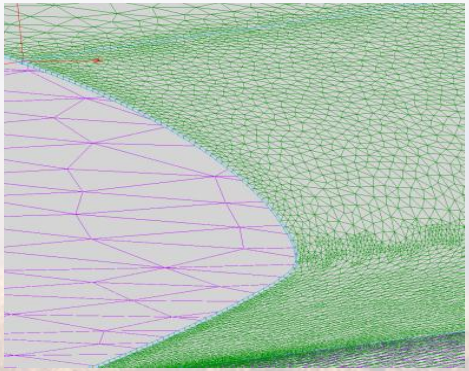


CX-100 Blade Surface in Pointwise®









Property Distribution Computations

Two-Dimensional Approach

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

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

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

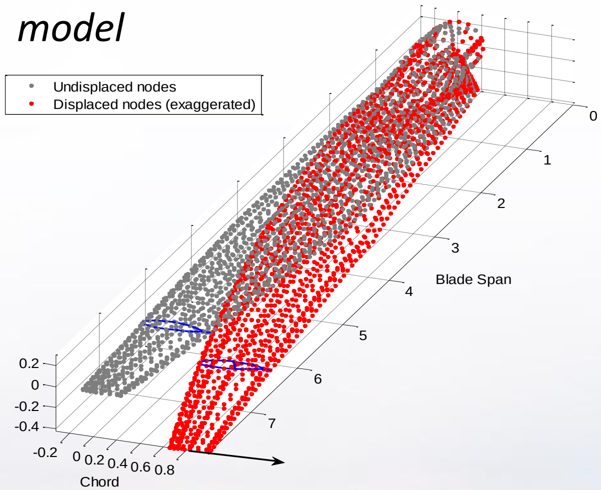
$$GJ = \iint G(x,y)(x^2+y^2)dxdy \text{ and}$$

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

- ***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/DNV*
  - *Distributed with NuMAD (D.Laird, Sandia Labs)*

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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

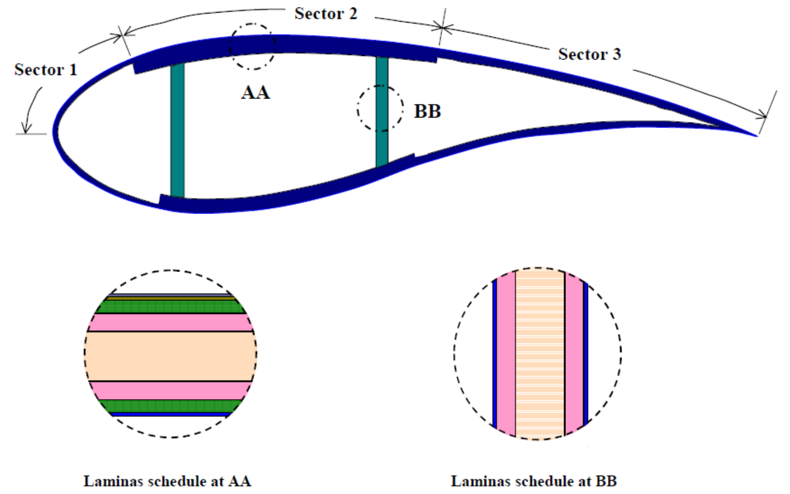
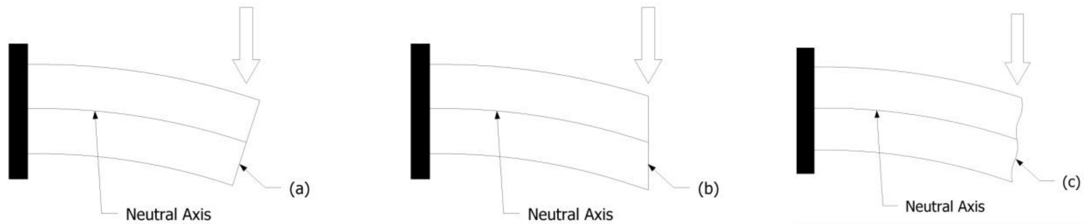


Figure 2: Example of spar-cap-type layup of composites at a blade section

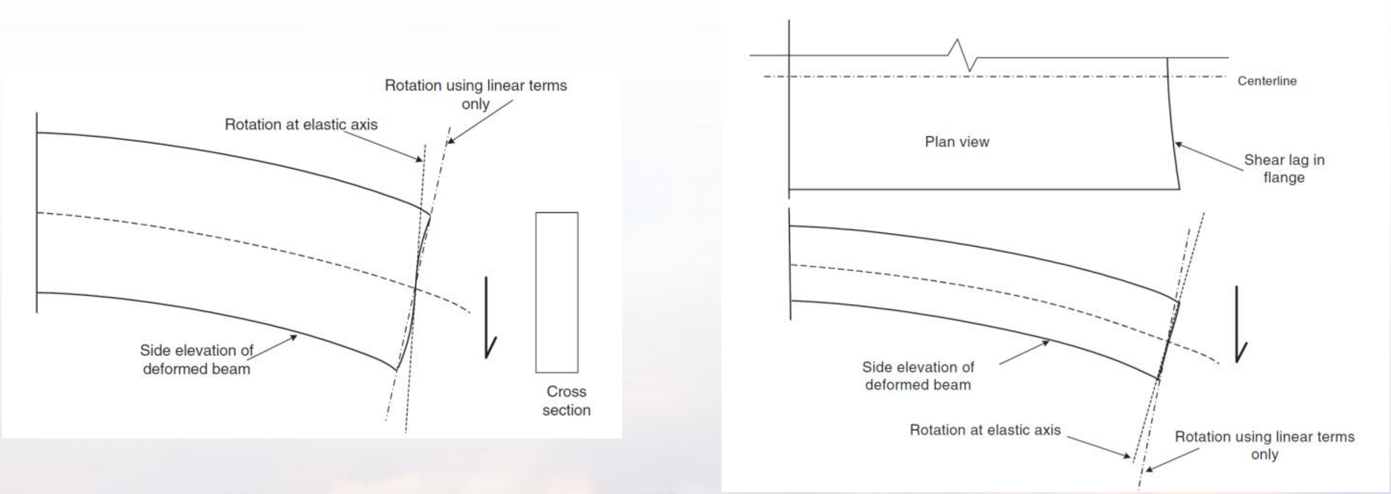
Figure courtesy of NREL, PreComp Users Manual

Cross section deformations

- **Goal: Assess the degree to which these out-of-plane effects are present in a real wind turbine blade structure.**



Beam section deformation: (a) Bernoulli, (b) Timoshenko and (c) out-of-plane warping effects



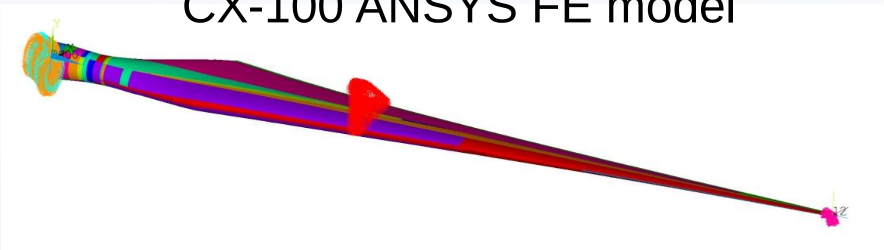
Deformation due to loading of rectangular section along (a) minor axis and (b) major axis Ref.[2]

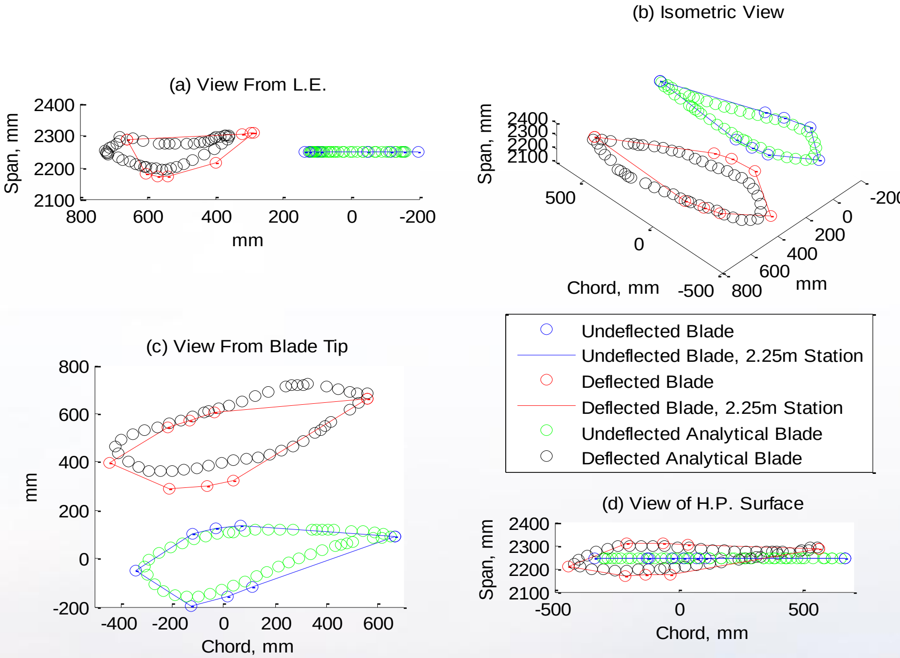
- **Ref.[2] - Malcolm, D. J. and Laird, D. L. "Extraction of Equivalent Beam Properties from Blade Models," *Wind Energy*, 2007, Vol. 10, pp. 135-137.**

Comparison to static test measurements

API Omnitrac laser

CX-100 ANSYS FE model





Deflected displacements are magnified 50x

- ***Scott Hughes and team, "Sandia CX-100 Property Test Report." 110504. Blade tests performed October/November 2010.***

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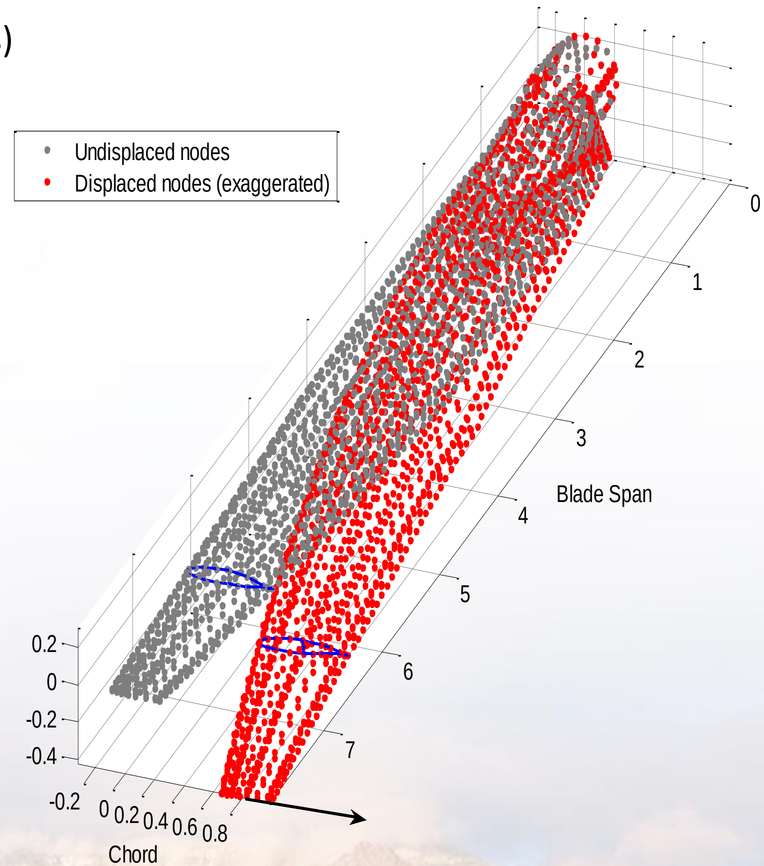
Beam Property Extraction (BPE)

- **Developed by GEC/DNV for Sandia**
- **The process:**
  - Apply loads at tip of shell FE model (3 forces and 3 moments)
  - Fit planes to displacement/rotations at defined sections
  - Compute 6 × 6 Timoshenko stiffness matrices for equivalent beam elements in an inverse manner
  - Compute property distributions for wind blade codes
- **Captures 3D effects: shear and out-of-plane warping**
- **Accommodates blades with curvature, i.e. precurve and/or presweep; captures coupling**
- **Requires:**
  - ANSYS commercial finite element analysis package
  - NuMAD wind turbine blade model preprocessor for ANSYS (available upon request from Sandia)



- **Malcolm, D. J. "Extraction of Equivalent Beam Properties from Blade Models." Wind Energy, 2007**

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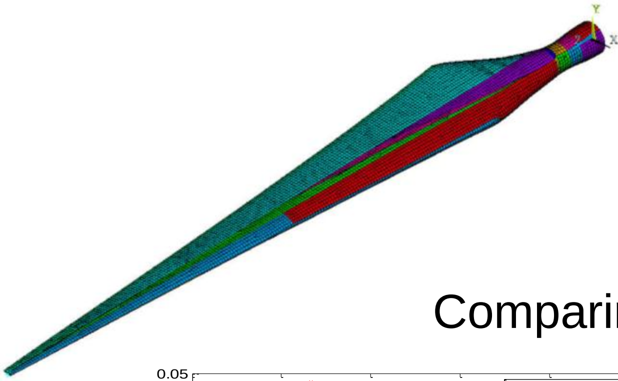
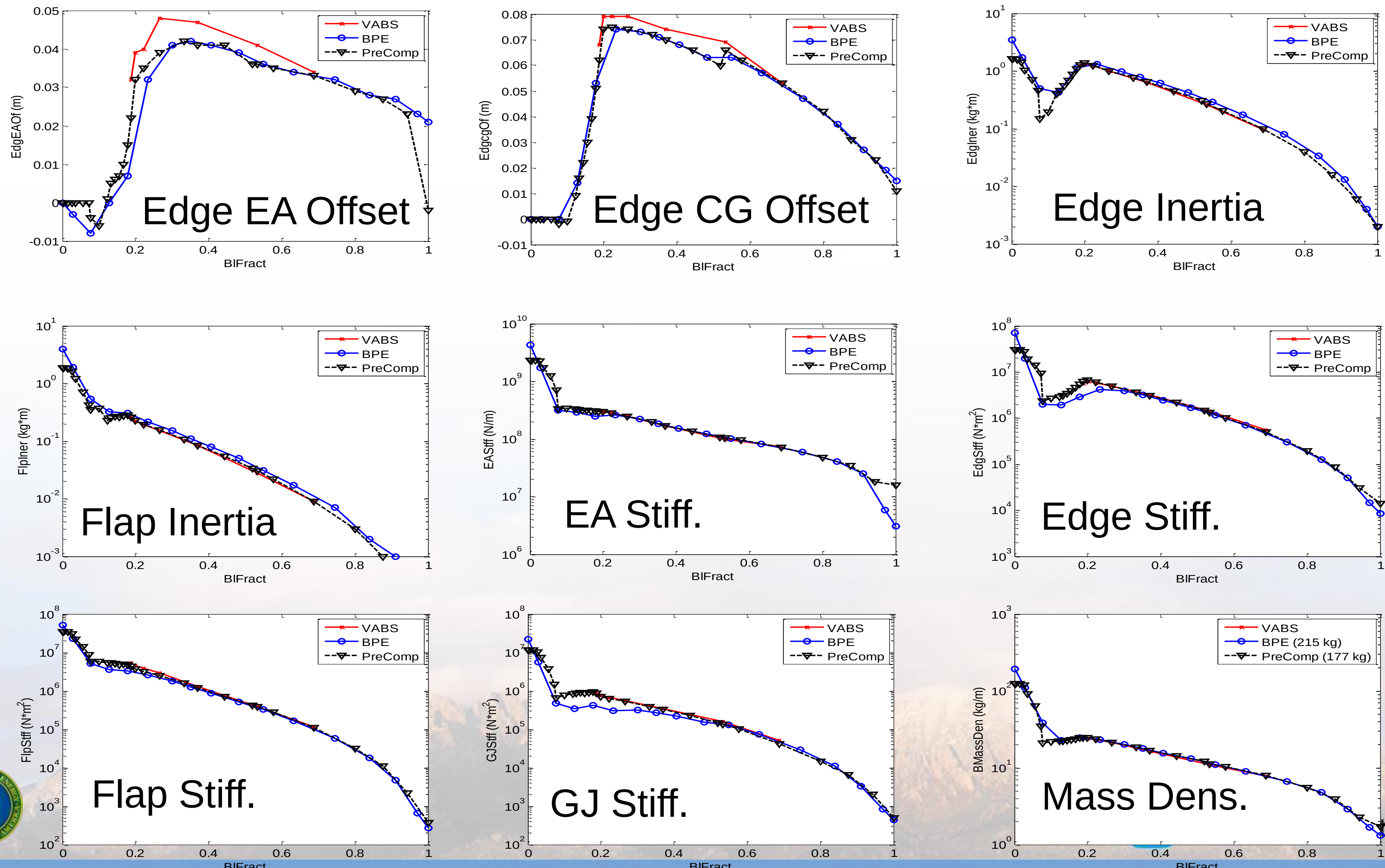


Calculate Beam Properties

Resor,B. "Uncertainties in Prediction of Wind Turbine Blade Flutter." AIAA SDM 2011
Resor,B. "An Evaluation of Wind Turbine Blade Cross Section Analysis Techniques." AIAA SDM 2010

Comparing three techniques: BPE, 2D Section & VABS



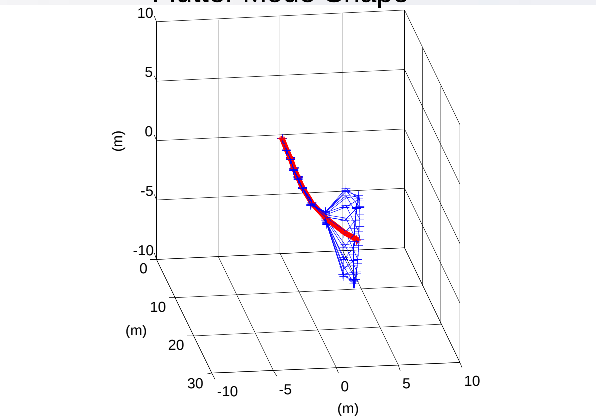
Sandia Classical Flutter Capability

- **SNL legacy capability (Lobitz, Wind Energy 2007) utilized MSC.Nastran and Fortran to set up and solve the classical flutter problem.**
  - Required numerous manual iterations on operating speed and flutter frequencies to find the flutter speed
- **A new Matlab based tool has been developed in 2012; B.Owens, Texas A&M Grad Student**
  - Starting point: Emulate all assumptions of the legacy Lobitz tool
    - Theodorsen harmonic forcing, arbitrary elastic axes, mass centers, aerodynamic centers
    - Gathers information from FAST blade, AeroDyn and NuMAD input files
  - Continued development
    - Automatic iterations to locate flutter modes
    - Higher fidelity representation of aerodynamic and elastic parameters; addition of a dedicated beam model
    - Thorough verifications of flutter characteristics

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

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

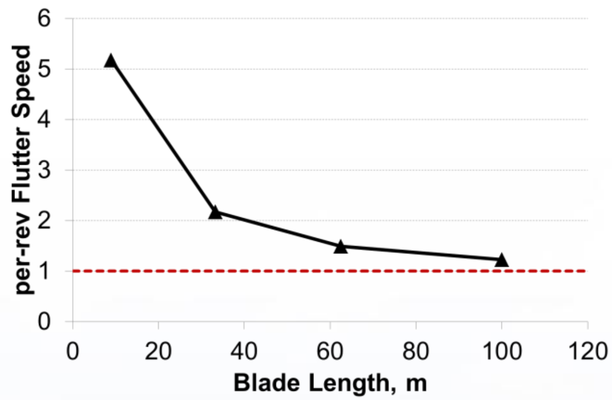


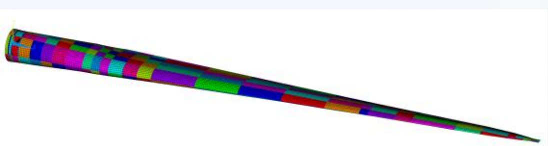
100m Blade Flutter Parameter Study

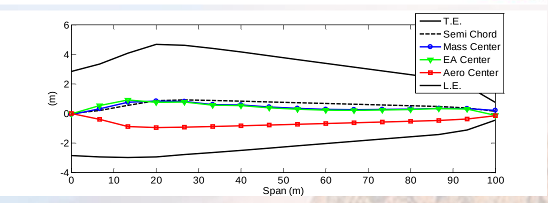
- **Resor and Griffith. "Aeroelastic Instability of Very Large Wind Turbine Blades." Scientific Poster. EWEA Copenhagen, 2012.**

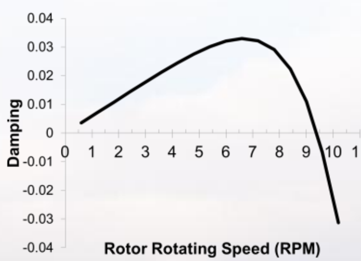
Data shown are from classical flutter analyses of various wind blade sizes:

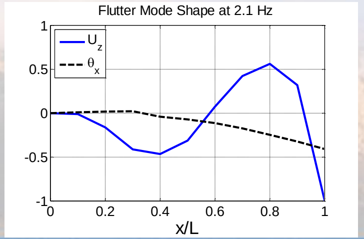
- SNL 9-meter CX-100 experimental blade [Resor, 2011]
- WindPact 33.25-meter 1.5MW concept blade [Lobitz, 2007]
- SNL 62.5-meter blade (preliminary design)
- SNL 100-meter blade concept

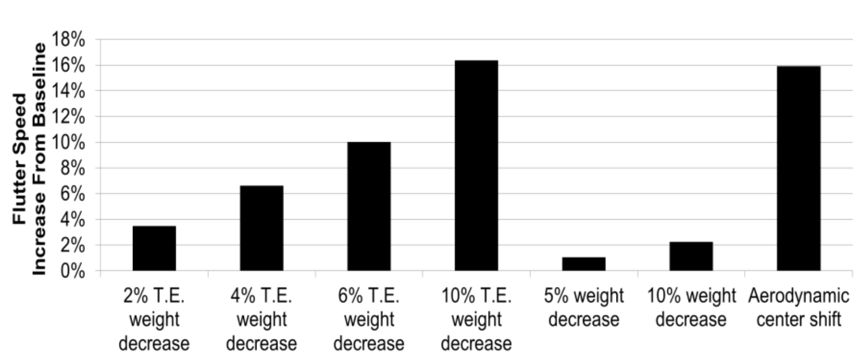












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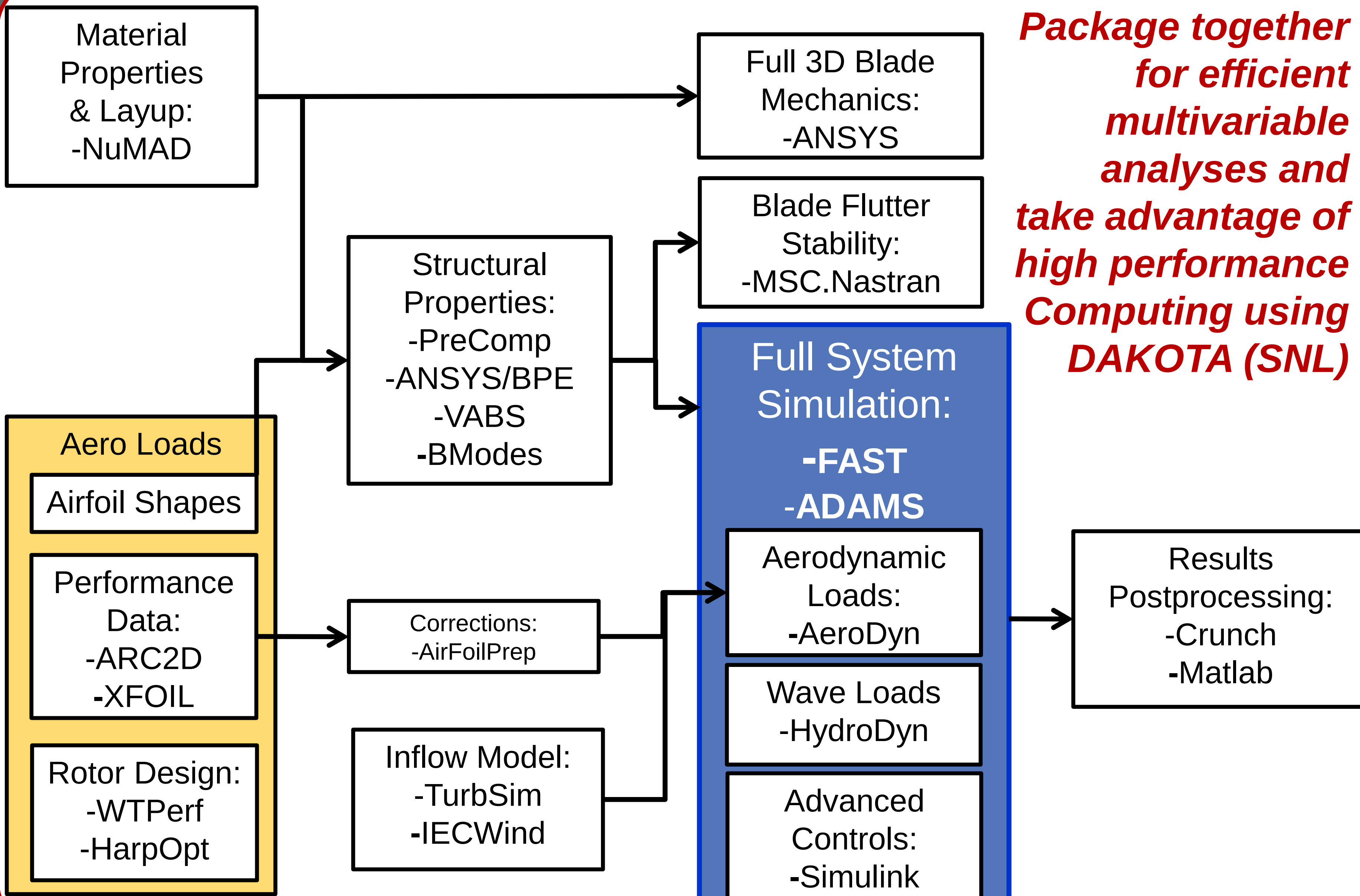
Wind Turbine Design Tools in Use at Sandia

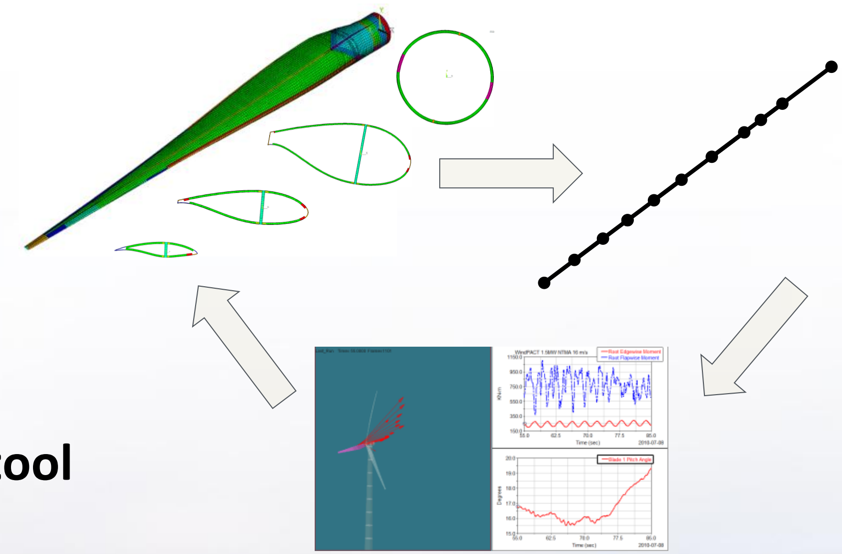


Package together for efficient multivariable analyses and take advantage of high performance Computing using DAKOTA (SNL)

Future work in blade modeling

Good ideas for future research:

- **Perform blade beam property validations**
  - Torsion matters: Passive load alleviation via bend twist coupling or blade geometry
    - Flexible, nonlinear blades
    - Large deflection blades
- **Blade materials response characterization**
- **Accurate determination of blade loads**
  - Especially extreme loads
- **Continued aeroelastic instability (flutter) tool development and validation**
  - Will be required for very large blade concepts



NuMAD future

- ***Acknowledgement***
  - *Thanks to Jonathon Berg of Sandia for the dedication and meticulousness required to perform the complete overhaul and upgrade of NuMAD!*
- **FY12**
  - Conduct a NuMAD workshop to get user feedback on beta version prior to the SNL Wind Blade Workshop on May 29
  - Copyright and review and approval process prior to full public release
  - Package and release NuMAD (source and compiled), supporting tools and example blade models
- **FY13**
  - Ongoing maintenance TBD based on level of interest from users
  - Future NuMAD developments to be driven and funded directly by projects based on specific needs