Integrated Design and System Analysis at Sandia

2010 Sandia Wind Turbine Blade Workshop

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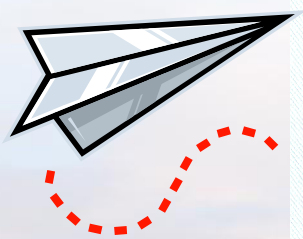
Modeling and Simulation Motivation

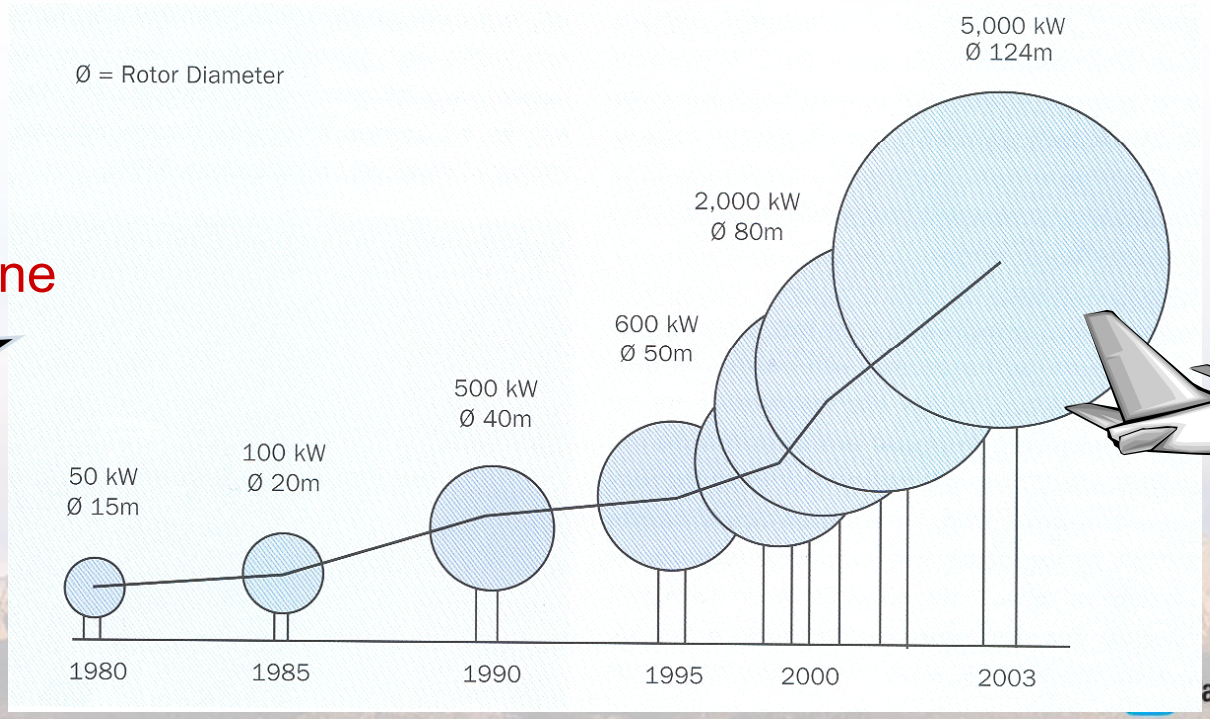
Smaller turbines → Larger turbines

$ → $$$

Build, Break, Redesign → Advanced Simulation

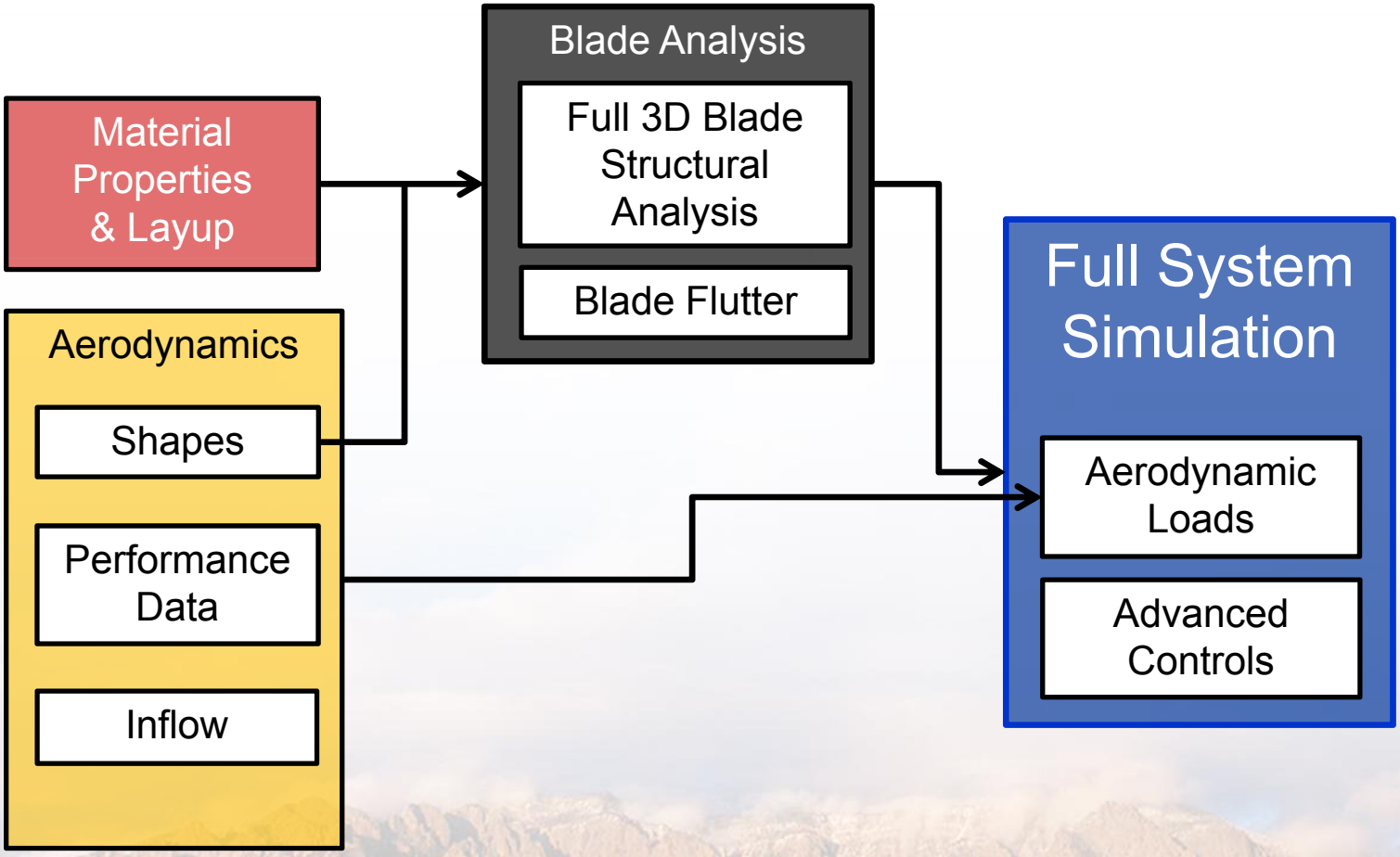
Paper airplane





Commercial Aircraft

Wind Turbine Design Elements

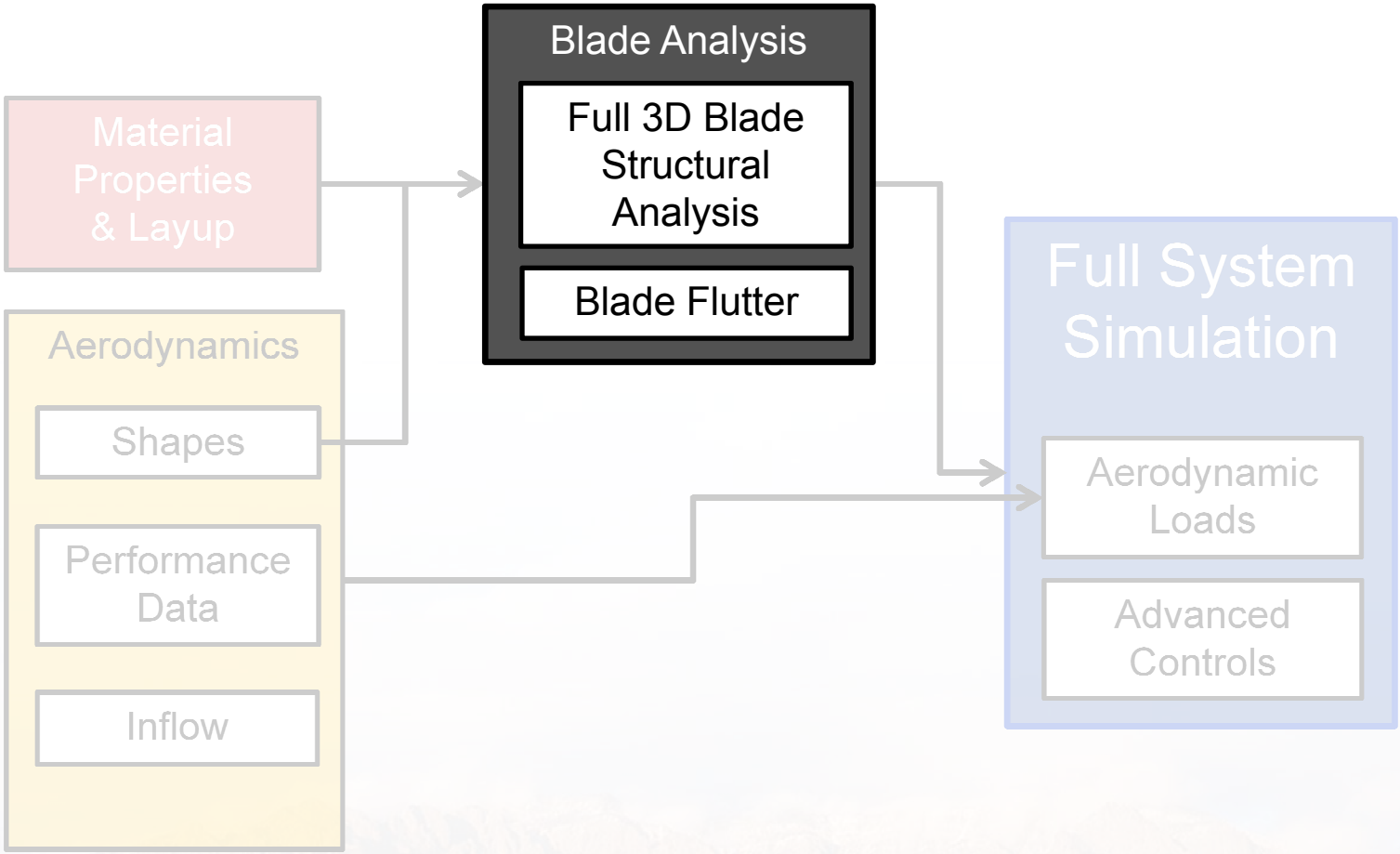


Recently Supported Research Projects

The use of design tools at Sandia provides a bridge between research and application by supporting our projects:

- **SMART rotor technology**
  - System simulations with active reduction of loads
  - System simulations and blade analysis to support SMART Blade design
- **CX-100 sensor blade activities**
  - Blade test definitions
  - Sensor placements
- **"Certification" of the 100m blade design concept**
- **Blade fatigue failure modeling**

Wind Turbine Design Elements

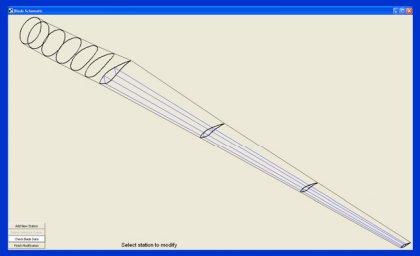


Blade Design with NuMAD

NuMAD

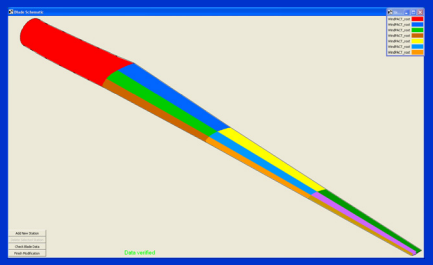
NuMAD:
Numerical Manufacturing
And Design Tool

Blade Geometry

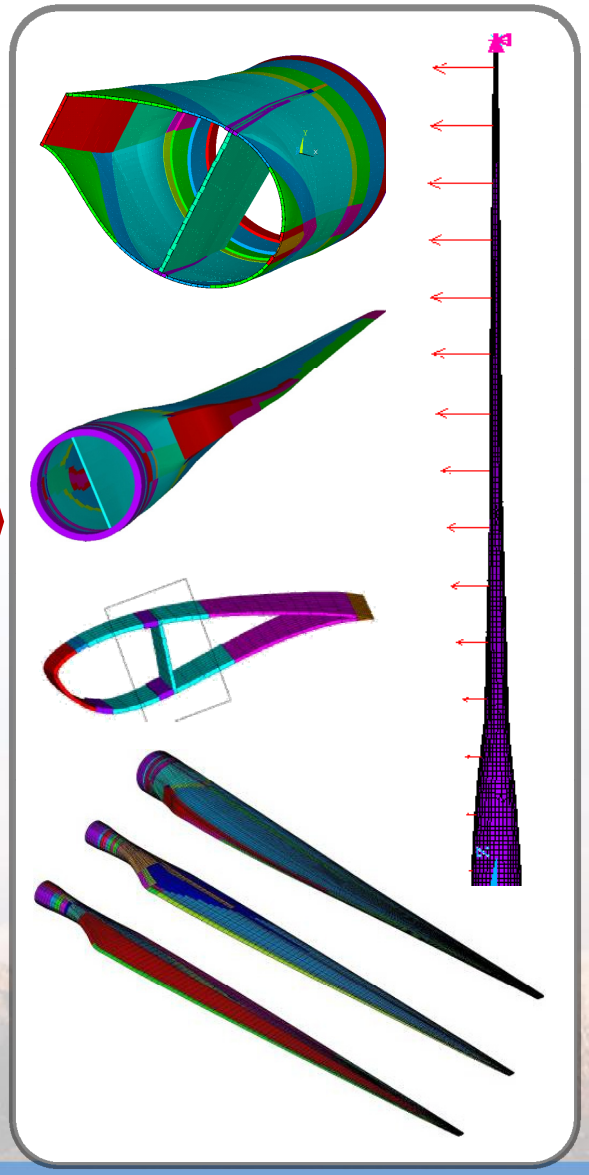


Materials & Layups

Stack Placement

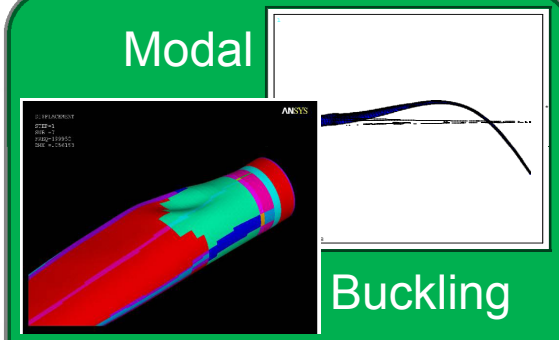


ANSYS FE Model



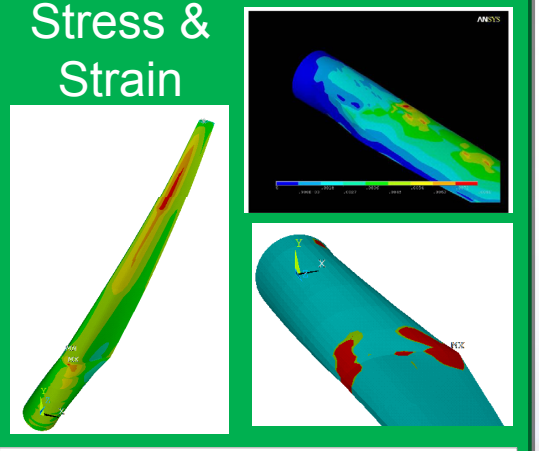
ANSYS Analysis

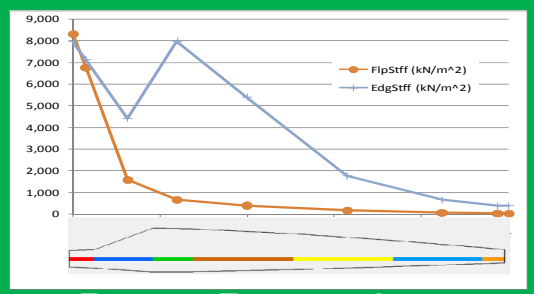
Modal



Buckling

Stress & Strain





Beam Properties

Use of Offset-Thickness Shell Nodes

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

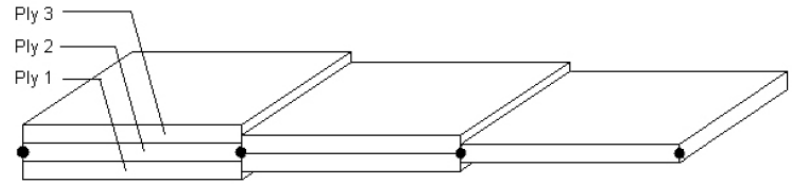


Figure 2. Schematic of physical representation of layered shell elements with nodes positioned at the mid-thickness.

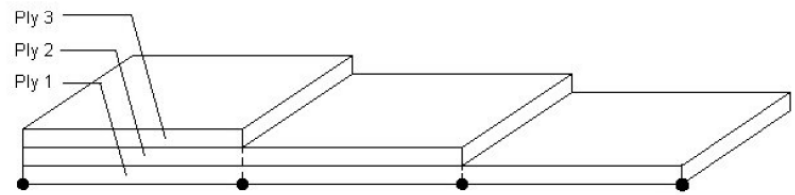


Figure 3. Schematic of physical representation of layered shell elements with nodes offset to the bottom surface.[1]

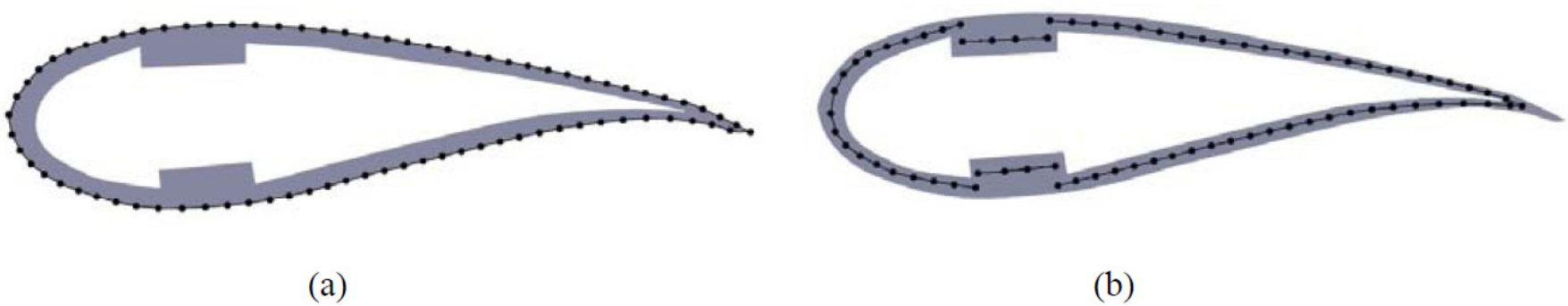
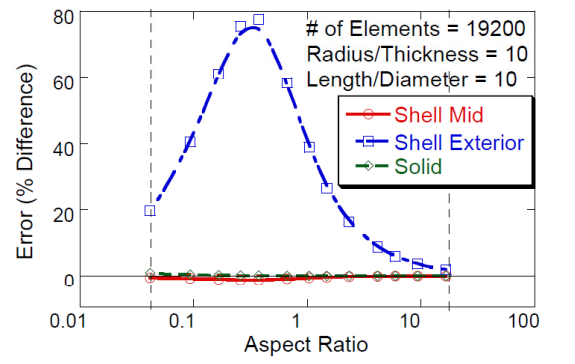
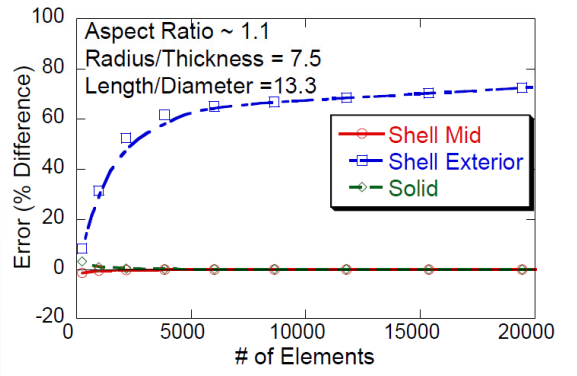


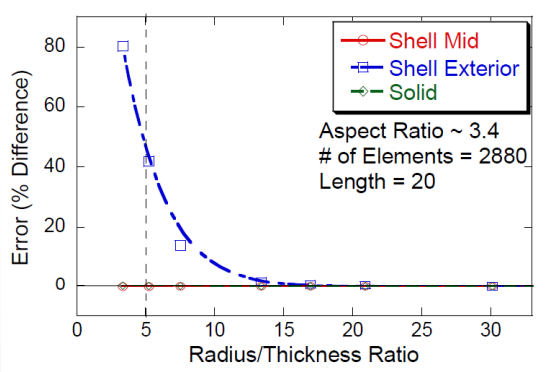
Figure 4. Blade cross-sections with nodes located at the exterior surface (a) and the mid-thickness (b).

Offset Node Shell Element Problems

- **Work by Daniel Laird, and others, documented in 2005 uncovered significant problems with the use of offset-node shell elements**







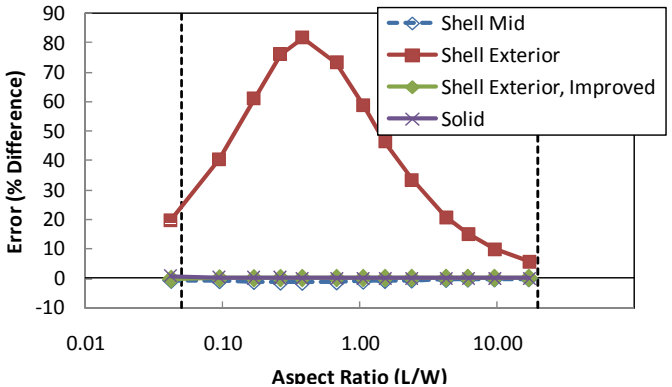
- **The wind industry sought other solutions for blade models:**
  - Restrictions to mid-thickness node shell elements
  - Entire wind turbine blades modeled with solid elements
  - High fidelity cross sectional analysis, such as VABS

New shell formulation in ANSYS 12.0

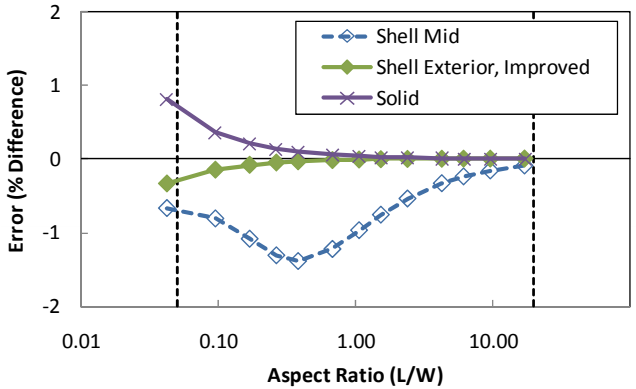
Very good news!

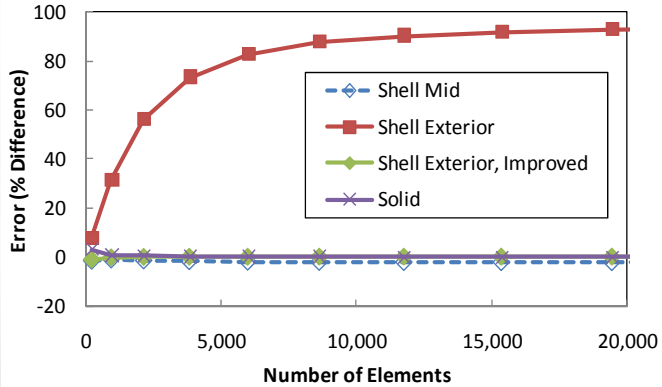
- **Redo the AIAA 2005 investigations using new formulation: SHELL281**
- **Shear:**
  - Element aspect ratio
  - Number of Elements

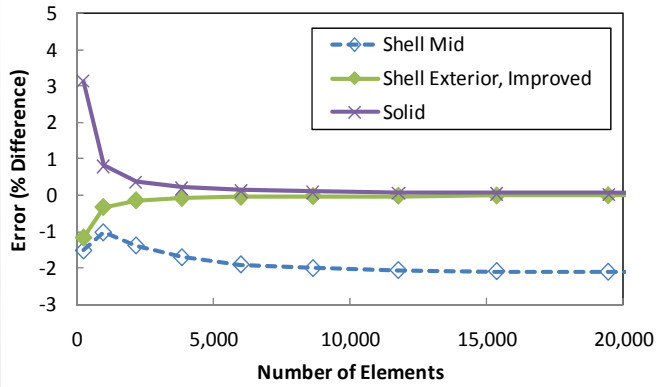
Results including old formulation



Results not including old formulation







Error as high as 80-90%

Error mostly below 1%

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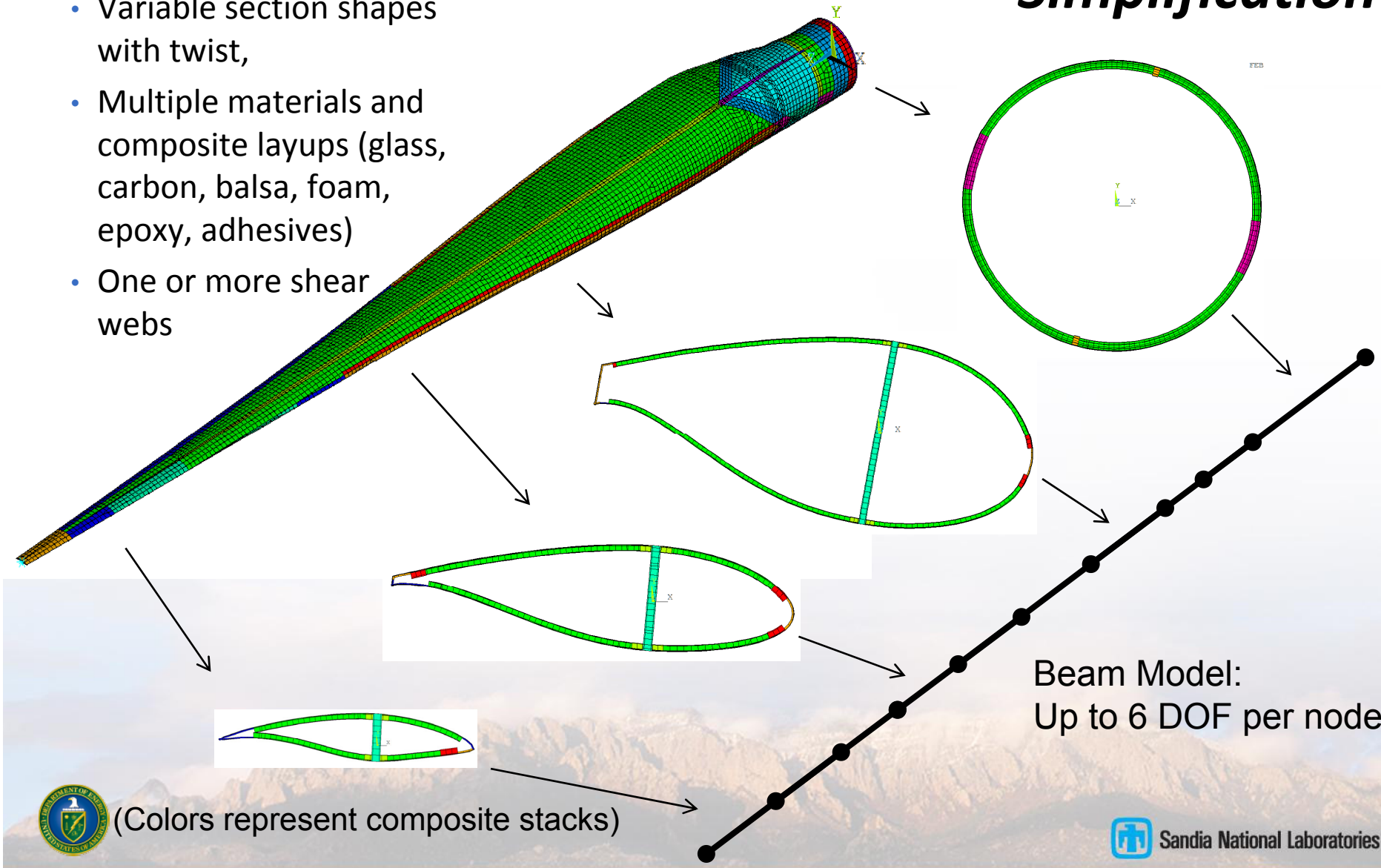
Blade Structural Model Simplification

- **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
  - Blade test design and setup

- ***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

Property Distribution Computations

Two-Dimensional Approach

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

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

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

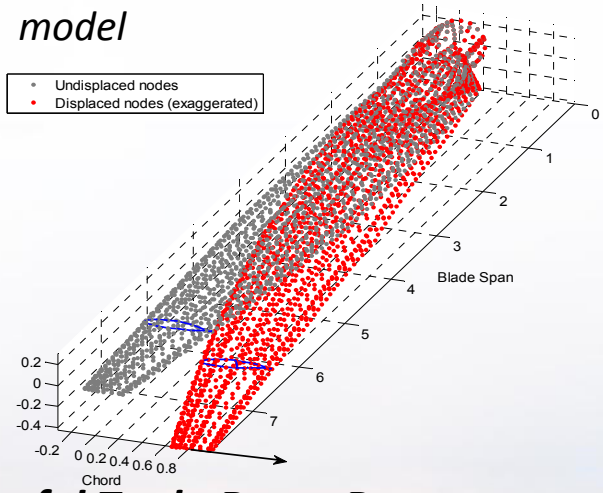
$$GJ = \iint G(x,y)(x^2+y^2)dxdy \text{ and}$$

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

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

Three-Dimensional Approach

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



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

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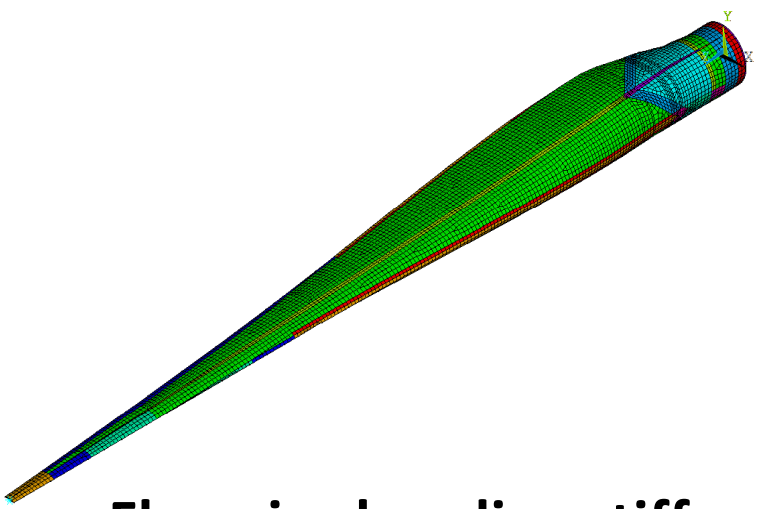
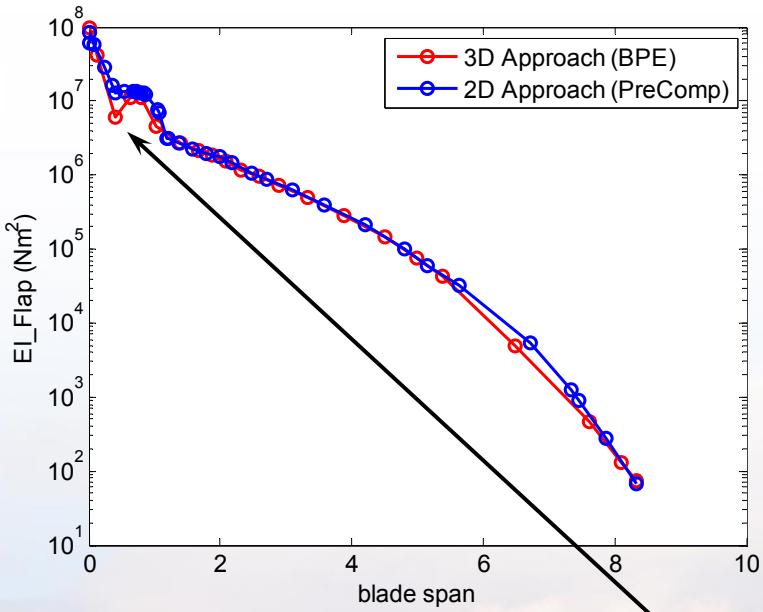
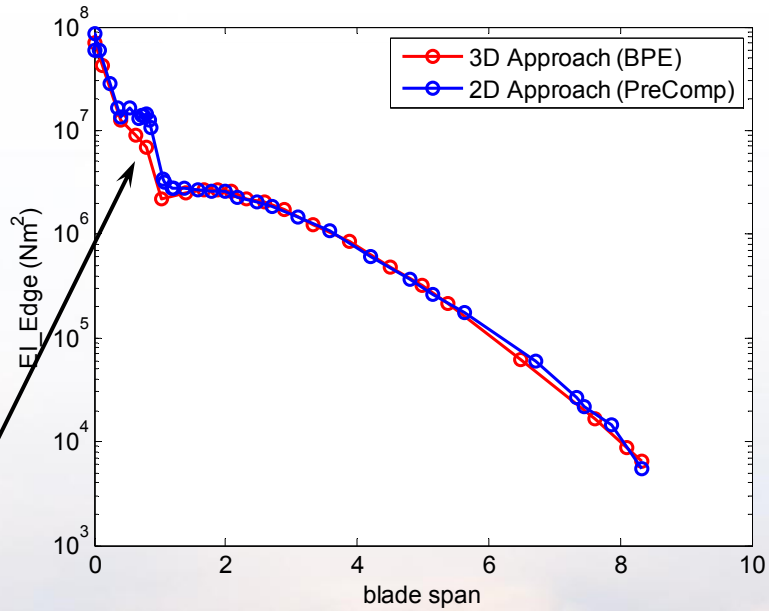


BSDS Model
2D & 3D beam properties

Flapwise bending stiffness



Edgewise bending stiffness*



BPE Property ~50% of PreComp

**Note: bugs were identified and resolved in PreComp as a result of this work. See Resor 2010 AIAA-SDM paper for details.*

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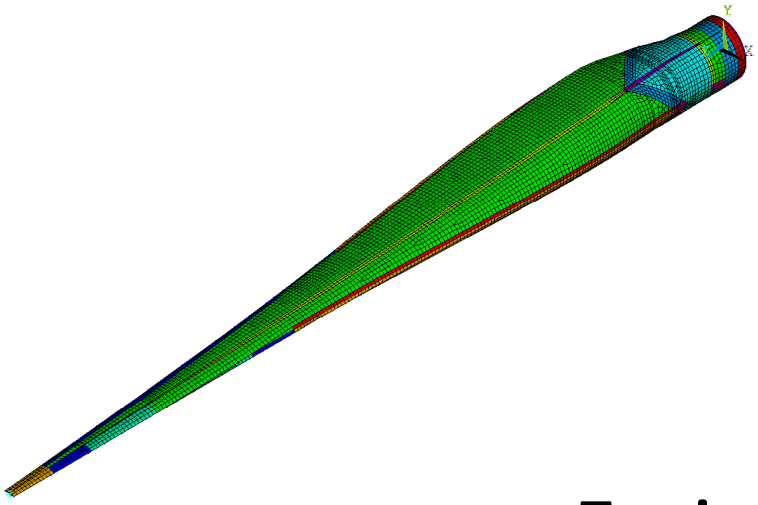
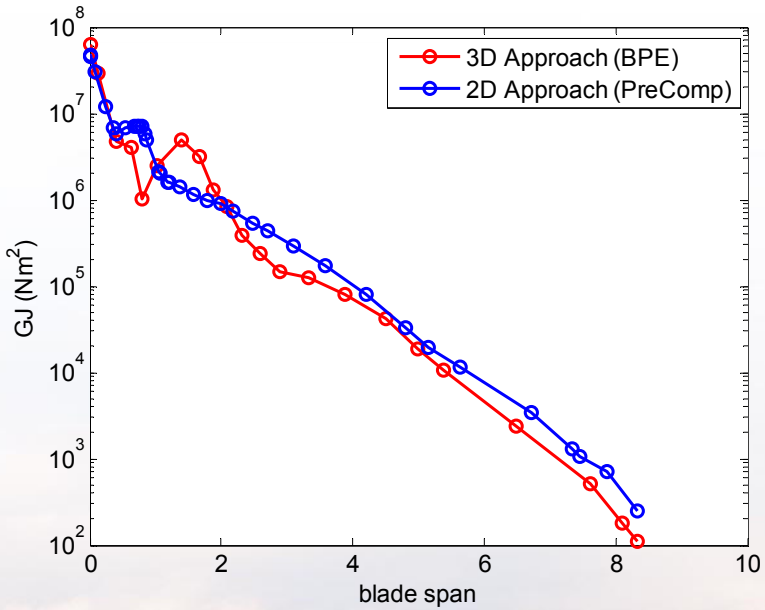


BSDS Model
2D & 3D beam properties

Torsional stiffness



Note discrepancies along entire span

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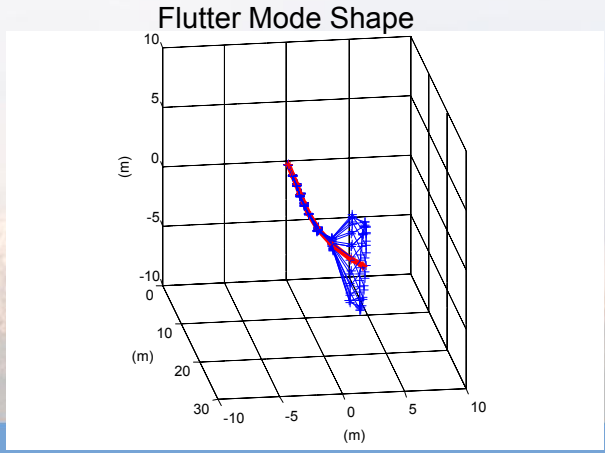
Current Sandia Classical Flutter Capability

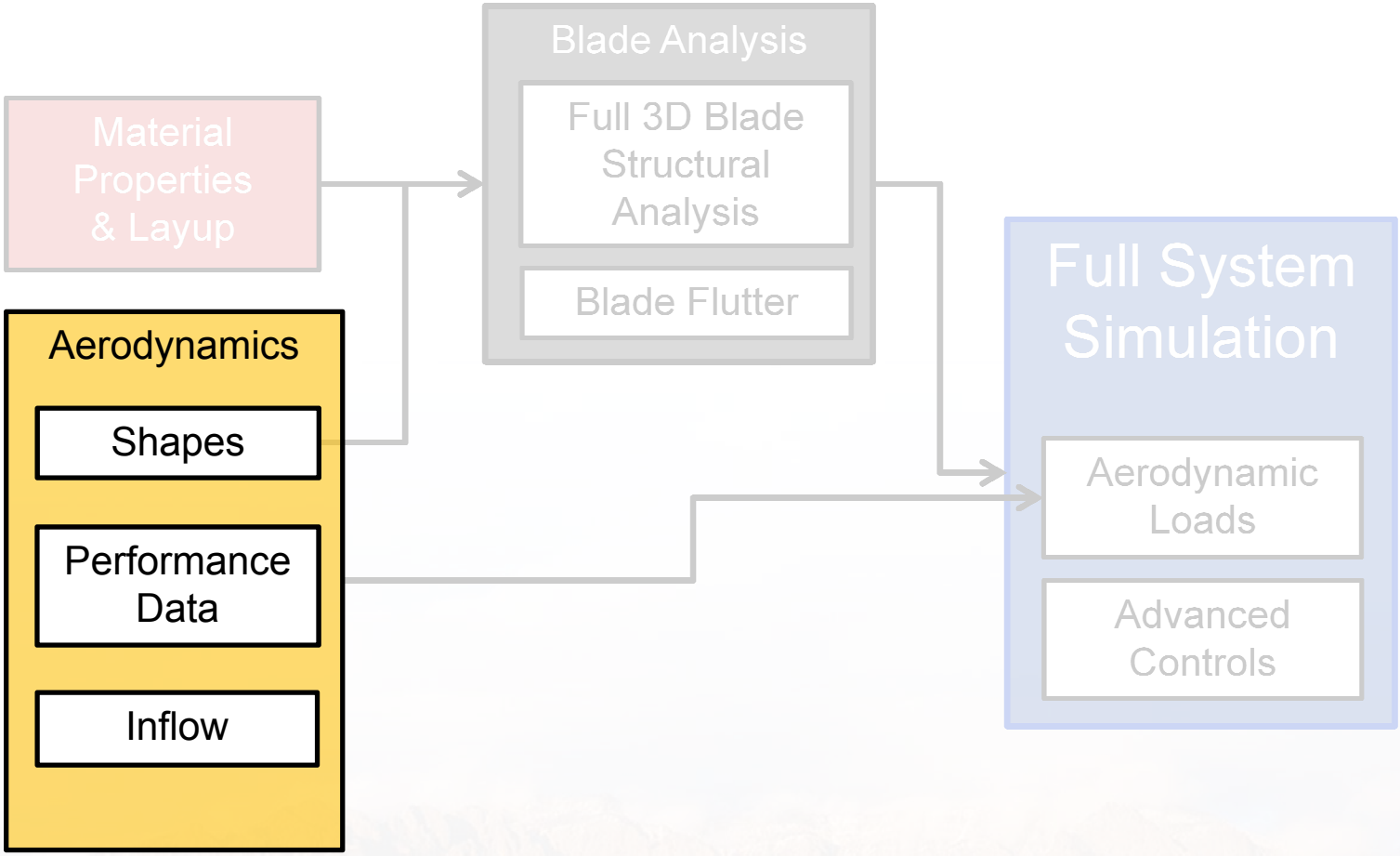
- **Current capability utilizes:**
  - MSC.Nastran 2005
  - FAST2NAST.m (Matlab routine)
    - Required inputs: lift curve slope and pitch axis location along with information taken from ad.IPT and blade.DAT files utilized by FAST
  - Fortran executable
    - Determines necessary mass, stiffness, and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

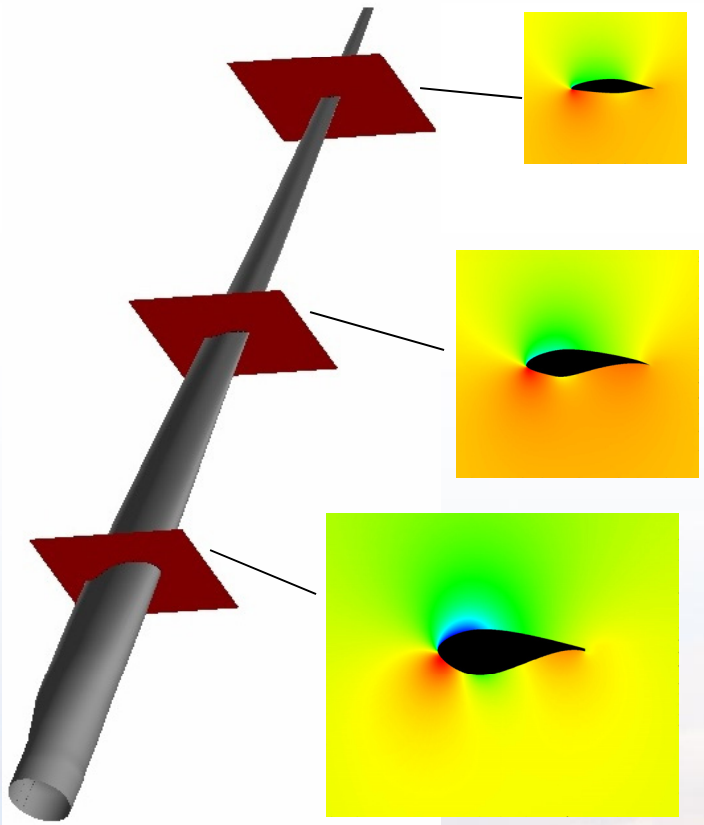


Wind Turbine Design Elements



Blade Aerodynamics Modeling

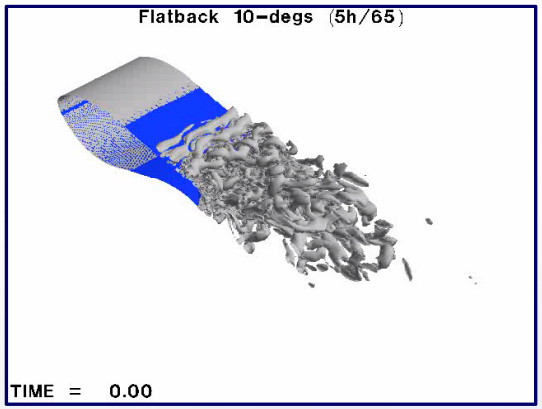
Blade Aerodynamic Model



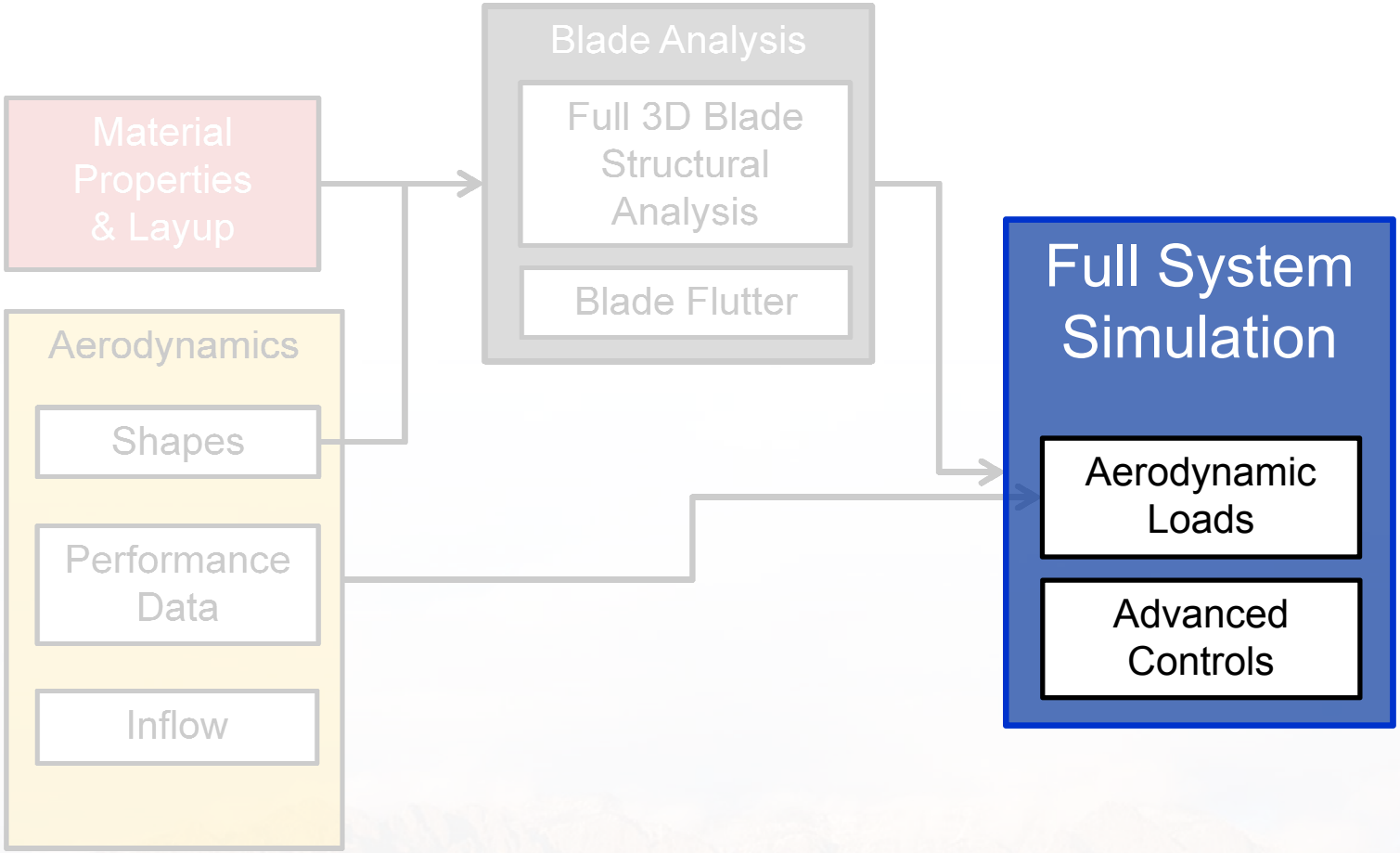
- Blade aerodynamic model requires computational models of airfoil performance
- Many (hundreds) of solutions typically required

SNL Thunderbird Computing Cluster

Advanced 3D Airfoil Simulation

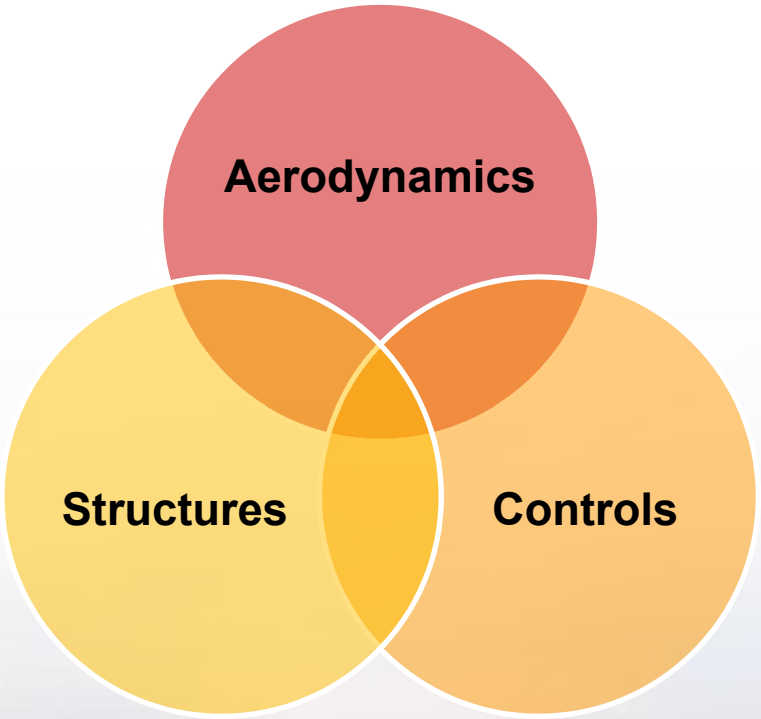


Wind Turbine Design Elements



Wind Turbine System Modeling

- All disciplines come together to enable assessment of system effects
- Changes to component technology affect system behavior resulting in both costs and benefits



Design Criteria Examples

Design Requirements

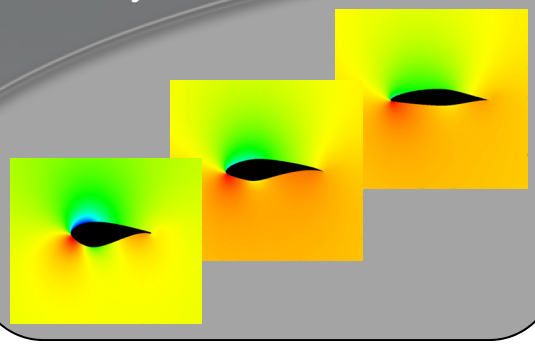
- **Conditions:**
  - 20 year minimum design life
  - Normal wind conditions
  - Extreme wind conditions
  - Wind defined by average wind speed and turbulence intensity
- **Loads**
  - Ultimate loads – can the system withstand the largest expected loads?
  - Fatigue – can it withstand the combination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

Example Load Cases

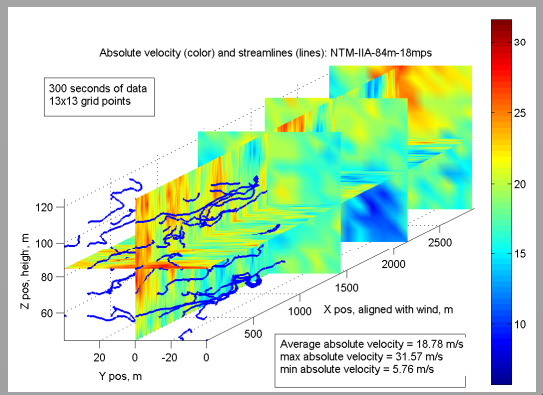
- **Normal production: Fatigue and/or ultimate loads due to**
  - Normal turbulence
  - Extreme turbulence
  - Extreme gust
    - Extreme wind speed
    - Extreme direction change
    - Extreme wind shear
  - Start up and shut down
- **Normal production with faults**
  - Yaw system fault
  - Pitch system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

System Analysis with Wind Turbine Aeroelastic Simulation

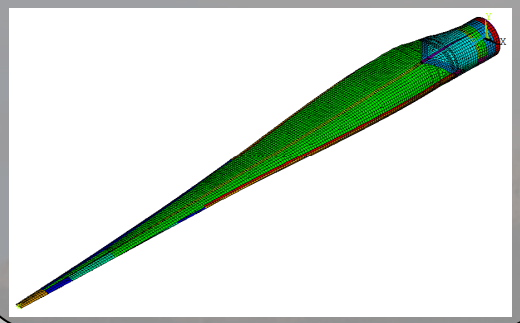
Aerodynamic Performance



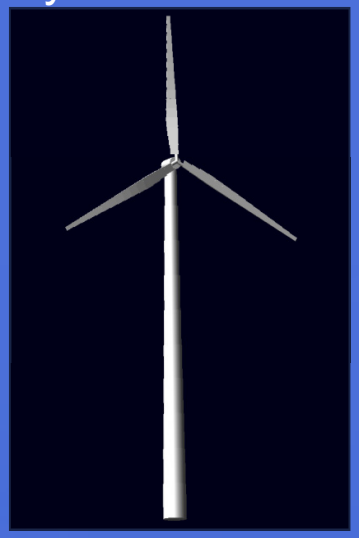
Turbulent Wind Input



Structure and Materials

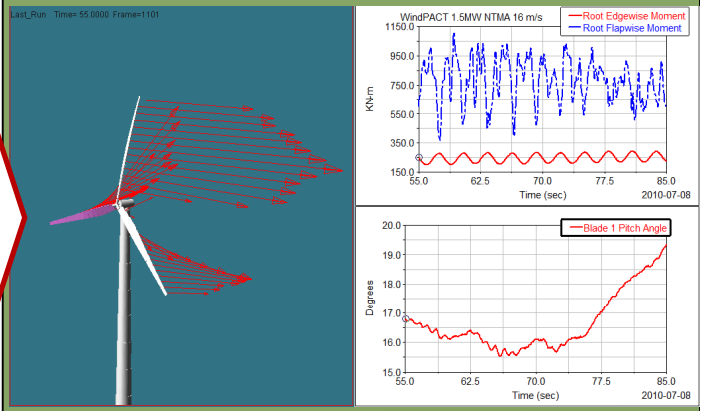


Aeroelastic System Dynamics Model



Includes Controls Implementation

System Response



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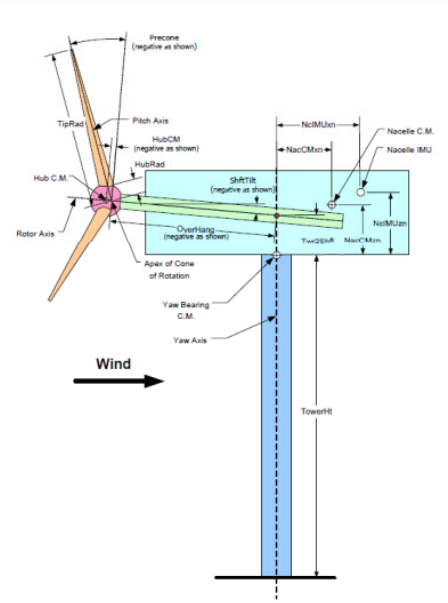
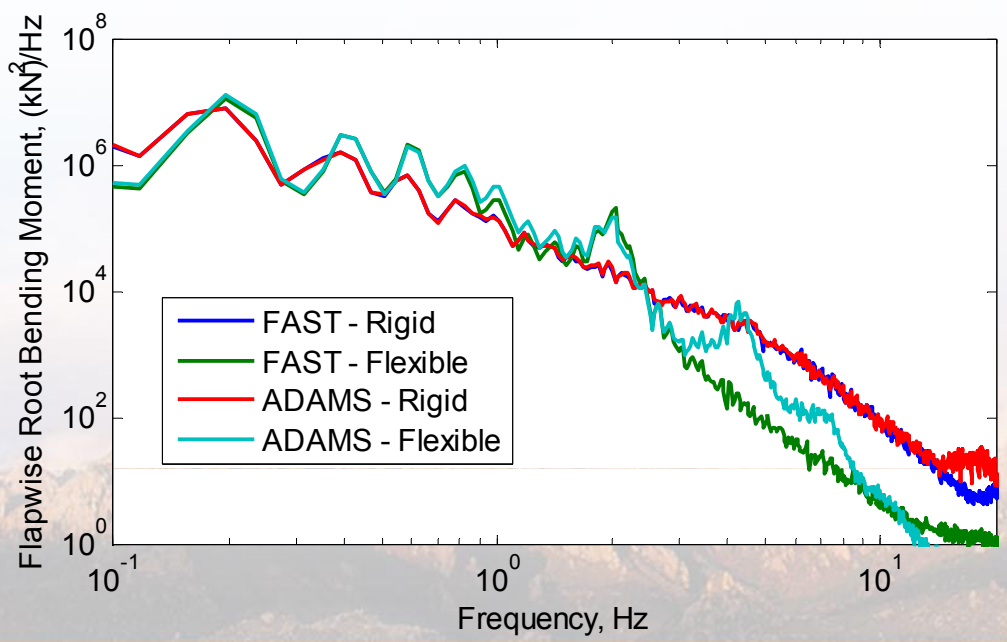
Tools: FAST and ADAMS

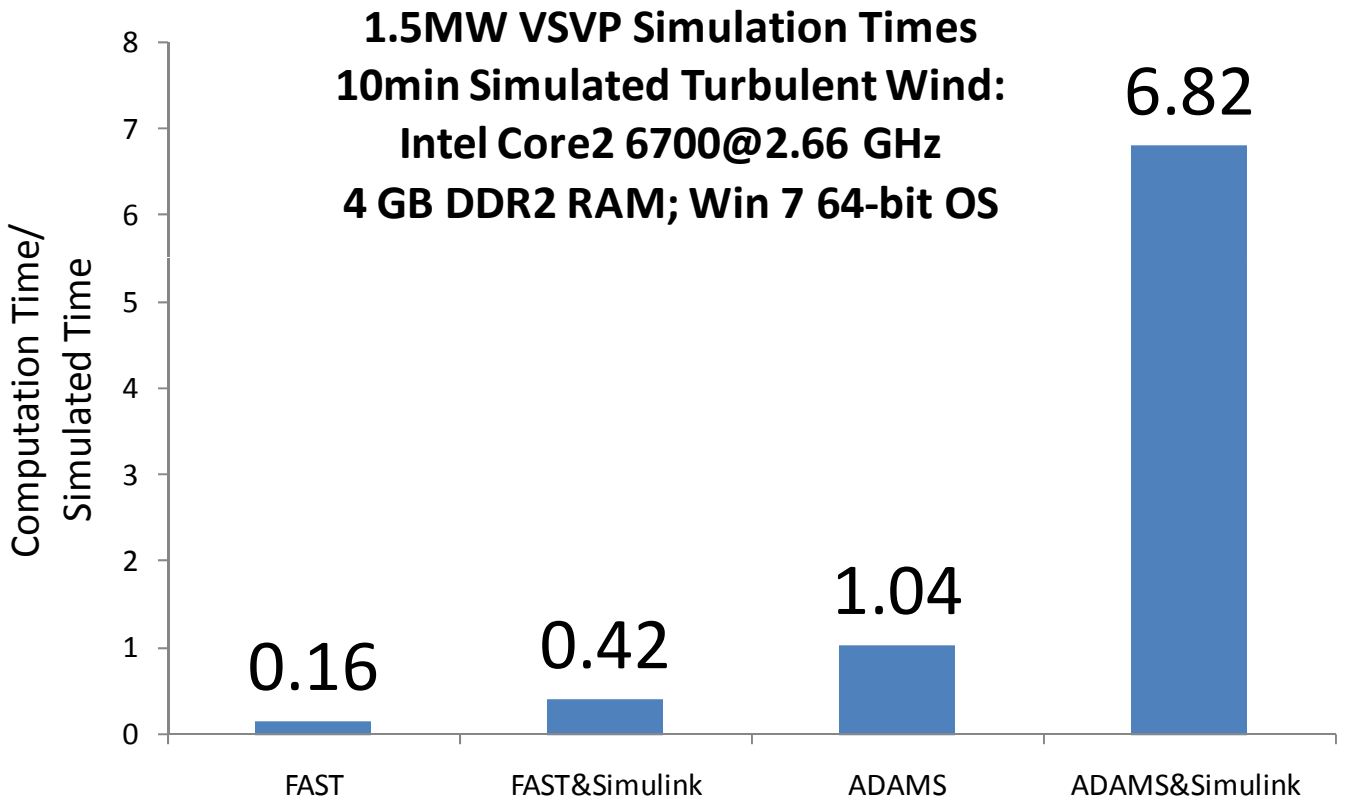
	FAST	ADAMS
Available from	NREL	MSC Corporation
Structural modes included	Up to 2 each of blade flap/edge and tower F-A/S-S	Unlimited; depends on discretization
Aerodynamic forces	AeroDyn	AeroDyn
Uses	Very fast computations; Adequate for most work, especially certification	Code verification; Simulations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





Aeroelastic Tool Computation Times

- **Project goals dictate the system dynamics tool used**

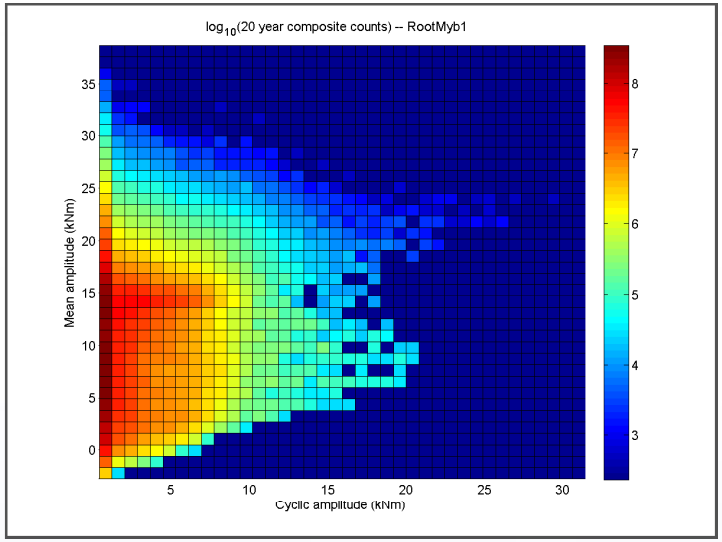


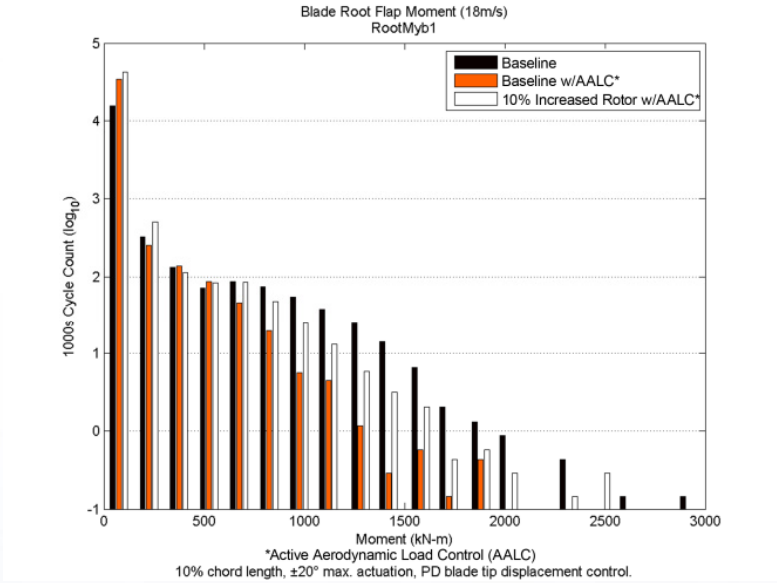
Typical System Certification

Structurally Tailored Blades/Tower

Nonlinear Controls Research

Example: Fatigue Analysis of System Response Data





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

Importance of System Analysis

- **Return at this point to the original motivation:**

  Bridging research and application

- **A philosophy that seems to always apply for modifications to *properly designed* wind turbine systems:**

  There are no free handouts from Mother nature

- **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 elsewhere in the system
  - Increased complexity
  - Decreased energy capture

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

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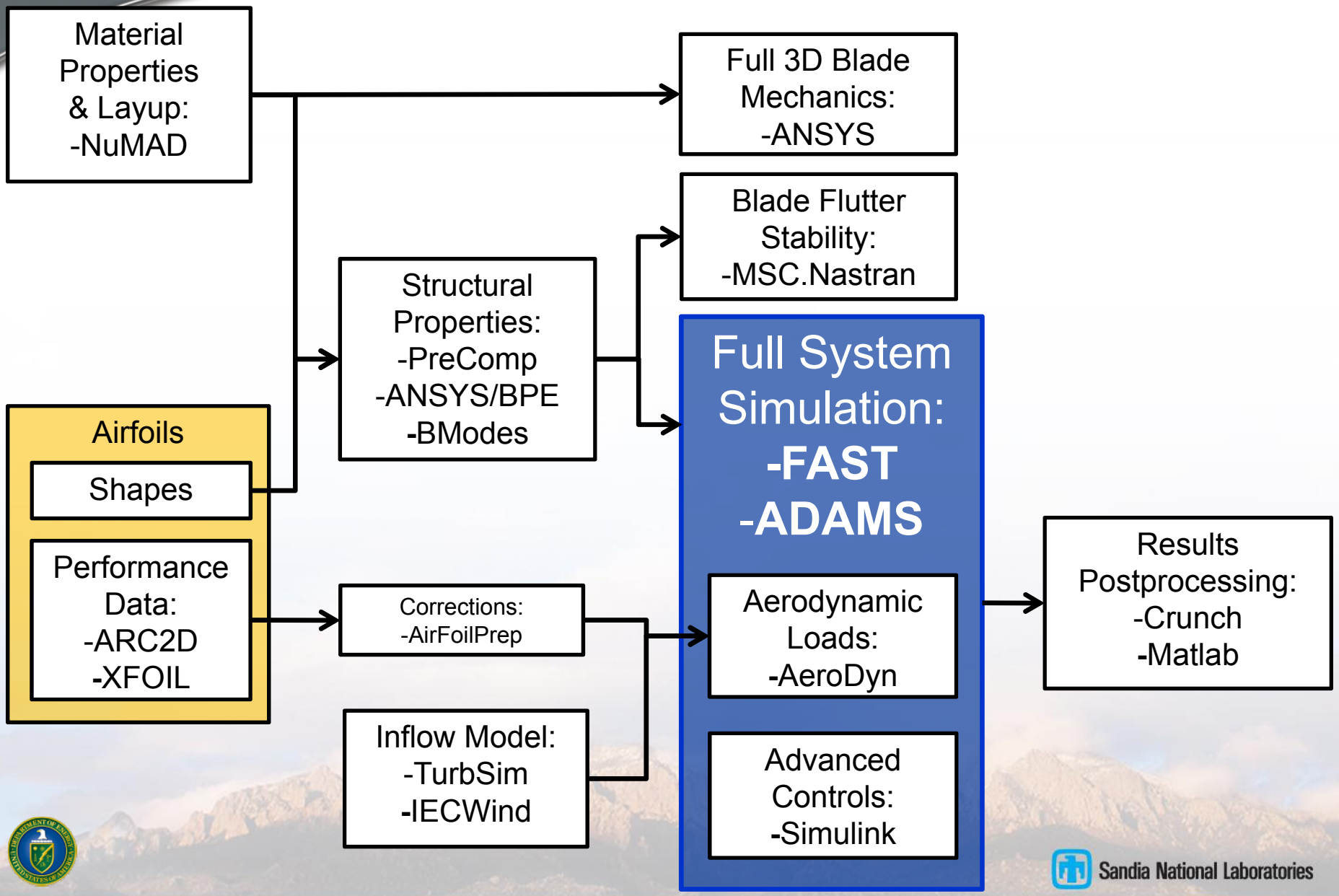
Wind Turbine Design Tools in Use at Sandia



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Summary

- **Blade design tools have been shown**
- **Success with new shell element formulations has been shown**
- **Full aeroelastic models are critical for assessment of system effects of innovations on overall response and on the cost of electricity**

- **Thank you!**