



Review of Structural Analysis Work at SNL

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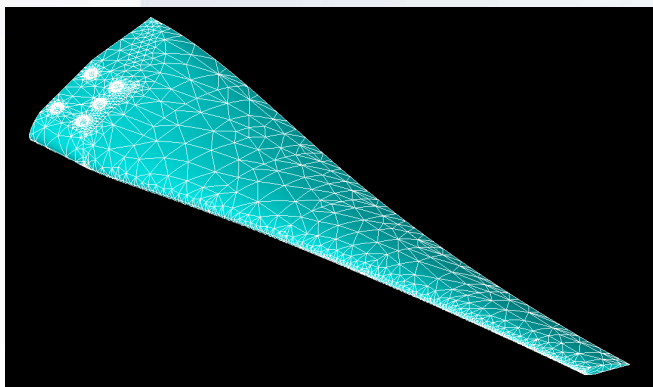
Verdant Blade FEA Analysis

- Geometry defined from IGES file created from Verdant model
- Material properties
 - $E = 10,300$ ksi
 - $\nu = 0.33$
 - $\rho = 0.0947$ lb/in³
- Model fixed at bolt locations
- Static analysis performed with and verified against measured loads from NREL test
- Modal analysis of first 10 modes

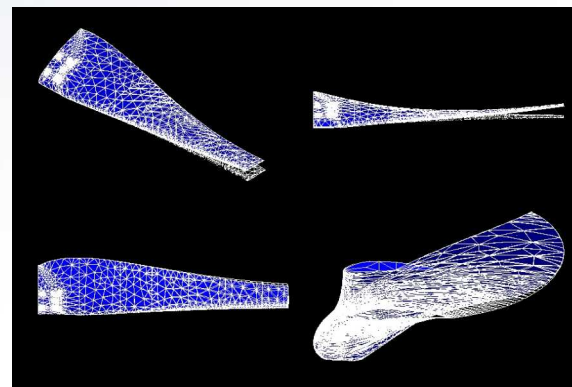
Property	Measured	FEA
Weight (lb)	374	378
CG_x, CG_y, CG_z (in)	-	3.407, 1.301, 32.548
I_{xx}, I_{yy}, I_{zz} (lb-in ²) (about rotor center)	-	$5.766 \times 10^5, 5.866 \times 10^5, 1.542 \times 10^4$
I_{xx}, I_{yy}, I_{zz} (lb-in ²) (about mass center)	-	$1.757 \times 10^5, 1.819 \times 10^5, 1.039 \times 10^4$

Span (in)	Strain ($\mu\epsilon$)	
	Measured	FEA
19.6	26	26
35.1	41	39
47.1	55	57
60.9	81	87
74.7	110	120
88.5	76	100

Tip Displacement (in)		
Measured	FEA	FEA (corrected)
0.135	0.093	0.135



Verdant ANSYS FEA Model



First Flap Mode at 32 Hz





Hydrodynamic and Structural Design

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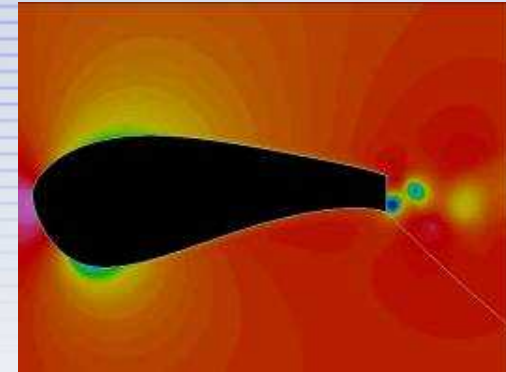
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Department Activities

■ Blade Technology

- Materials and Manufacturing
- Structural, Aerodynamic, and Full System Modeling
- Sensors and Structural Health Monitoring
- Advanced Blade Concepts
- Lab - Field Testing and Data Acquisition

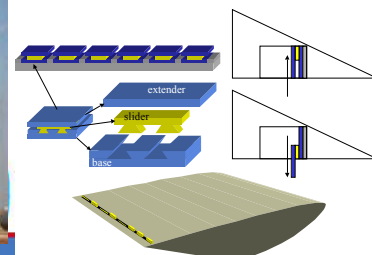
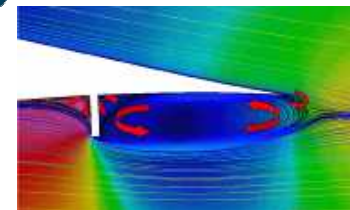
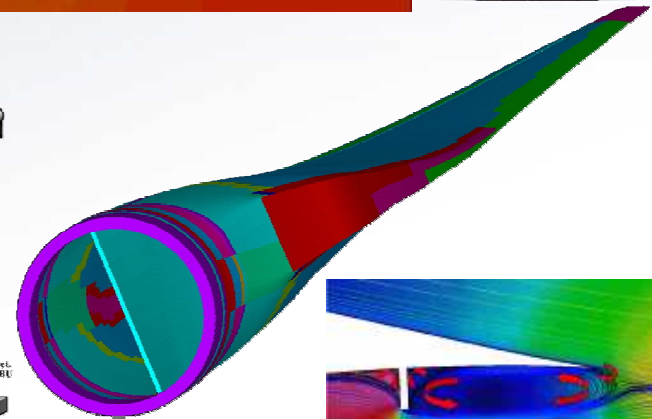
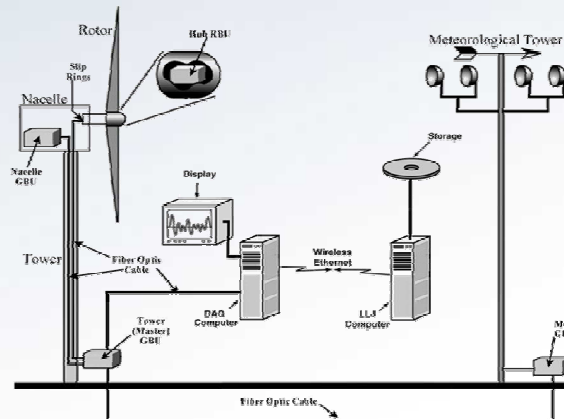


■ System Reliability

- Industry Data Collection
- Improve reliability of the existing technology and future designs

■ System Integration & Outreach

- Integration Studies & TEAM
- Wind/Radar



SNL CRADA Tasks

- **Task 1: Design Requirements (NREL/SNL/Verdant)**
 - Role: Participate in the development of design requirements document for Verdant Power rotor.
 - Allocation: 15k
 - Team: Paquette, Veers
- **Task 2: Baseline Fatigue Testing (NREL/SNL/Verdant)**
 - Role: Provide testing and analysis assistance.
 - Allocation: 10k
 - Team: Paquette, Johnson
- **Task 3: Blade/Rotor Performance Modeling (NREL/Verdant)**
- **Task 4: Hydrofoil Survey and Selection (NREL/SNL)**
 - Role: Provide consultation for hydrofoil selection and produce hydrofoil performance data.
 - Allocation: 20k
 - Team: Paquette, Barone, van Dam
- **Task 5: Load Estimation (NREL/Verdant)**
- **Task 6: FEA Structural Design (NREL/SNL/Verdant)**
 - Role: Develop laminate specification to meet strength and stiffness requirements.
 - Allocation: 80k
 - Team: Paquette, Resor
- **Task 7: Develop Candidate Designs (NREL/SNL/Verdant)**
 - Role: Contribute to development plan for one or two design concepts.
 - Allocation: 25k
 - Team: Paquette, Veers, Barone, Resor



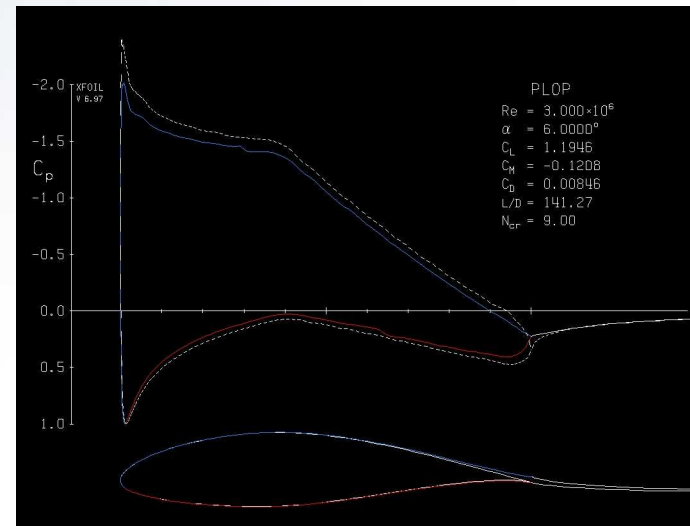
Computational Airfoil Analysis

Automated Airfoil Analysis Tools

- Automatic mesh generator with geometry modifications
- Automated batch script generator for parametric studies
- NASA ARC2D code generates CFD solutions

XFOIL Panel Code

- Quick turnaround airfoil analysis
- Simple shape changes
- Shape design mode



Flatback Airfoils

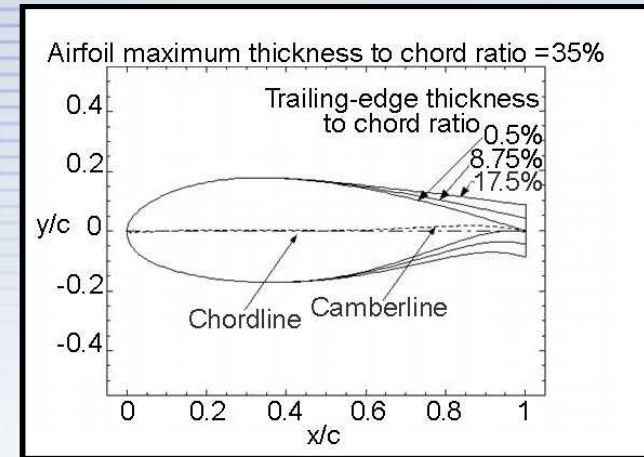
Possible Use in Kinetic Hydropower

■ Advantages

- Structural benefit of larger sectional area for given chord and thickness.
- Hydrodynamic benefit of decreased sensitivity to blade soiling.
- Possible suction surface cavitation benefits

■ Disadvantages

- Increased drag
- Possible risk of cavitation in turbulent wake
- Noise?



Flatback Creation



Sandia BSDS Blade

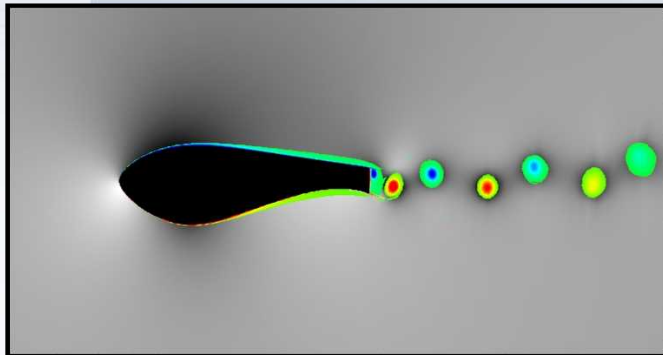


Wind Tunnel Flatback Model

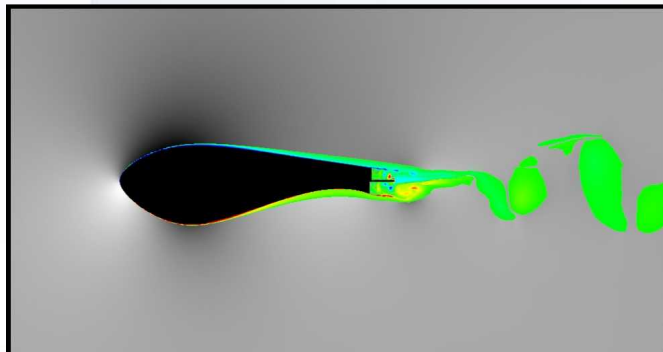
Flatback Airfoil CFD Modeling

Unsteady 2D CFD Simulation of Flatback Airfoil Wake

Flatback Airfoil

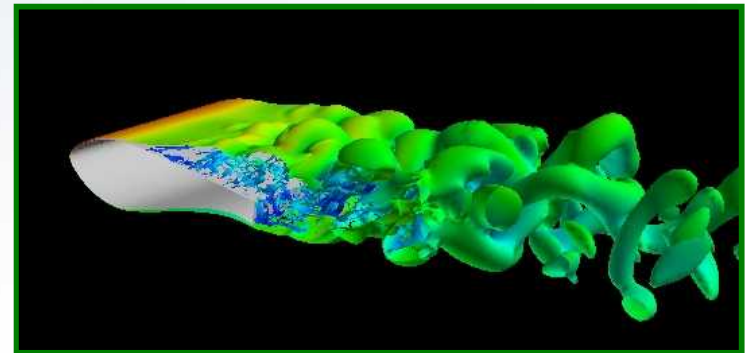


Flatback Airfoil with Splitter Plate Attachment



Unsteady CFD Simulation of 3D Flatback Airfoil Wake

- More accurate drag prediction than 2D computation.
- Provides prediction of unsteady forces due to turbulent wake.
- Provides a means to assess cavitation risks.



Rotor CFD

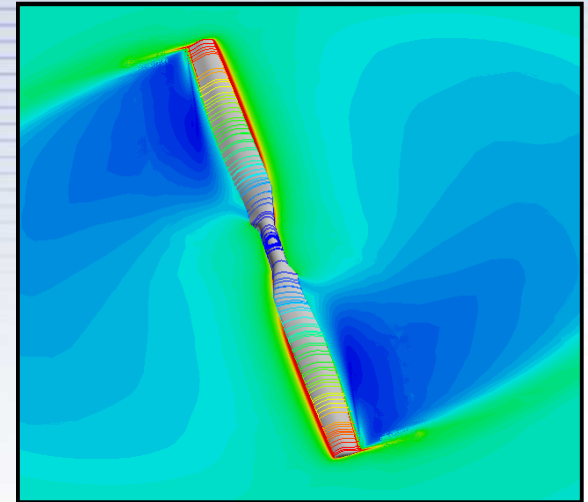
Full Rotor CFD Capability (with Case Van Dam, UC Davis)

- OVERFLOW 2 Code developed at NASA Langley
- Uses sliding overset meshes to compute the flow about rotating geometries
- Validated against existing wind turbine aerodynamic data
- Computationally intensive

Application to Water Turbines

- No code modifications required
- Can be used to:
 - Verify hydrodynamic performance of a design
 - Compare hydrodynamic performance of several designs
 - Explore tower-rotor interactions

Simulated Flow about the
NREL Phase VI Rotor



Sandia's 53 TeraFlop Thunderbird
Computing Cluster



NuMAD

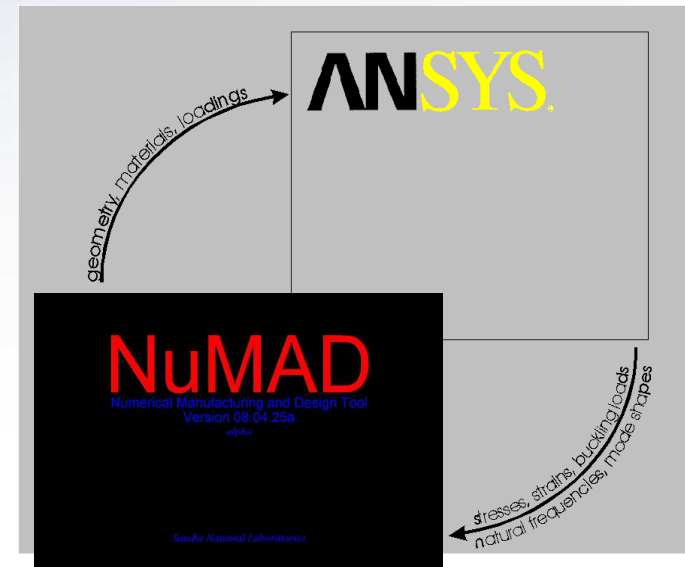
Blade Structural Design Tool

■ NuMAD Objective

- Promote utilization of FEA in addition to spreadsheet-based beam models
- Significantly decrease model generation time for 3-D, FE models of wind turbine blades

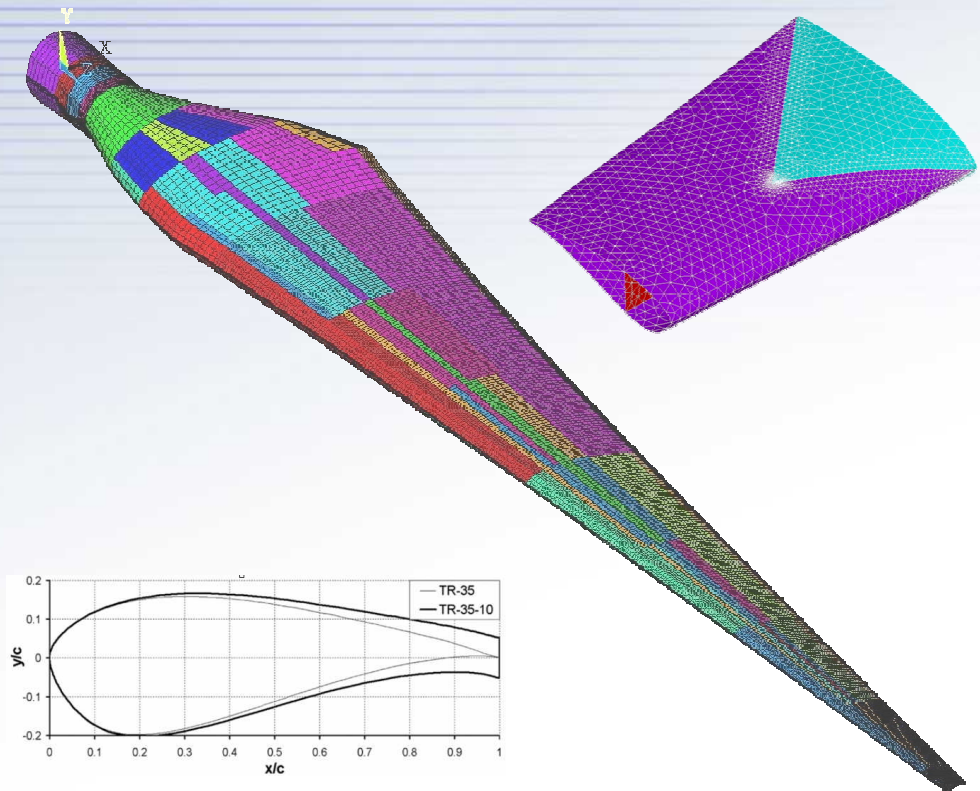
■ Approach

- GUI pre-processor for ANSYS®
- Tailored to analyze wind blades
- Quickly generate 3-D structural models
- Flexibility/Expandability
 - materials database
 - airfoils database
- Standard MS Windows® application
- Analysis used to find weak spots in blades
- Development guided by industry input
- Beam Property Extraction (BPE) capability



Recent NuMAD Upgrades

- Redesigned GUI
- Transitional meshing
- Multiple element options
 - Layered shells
 - Layered bricks
- Precise skin material definition
- Inboard/outboard skin material tapering
- Triangular skin material areas
- Flatback airfoil capability
- Airfoil definition-independent



NuMAD Model Definition Process

Define Materials

NuMAD v.B8.10.28 Jobname: C:\Documents and Settings\japaque\Desktop\New NuMAD BSDS\New_NuMAD_BSDS Units: m/kg/s
Rotor Rotation: cw Mesh Density: 0 Target Element Size: 0.05

File Units Materials Blade Boundary_Conditions Elements Output Generate_Model

Currently defined materials

Add	Modify/Duplicate	Delete	OK
Isotropic			
Aluminum2014T6			
fill_epoxy			
gel_coat			
SteelA36			
Orthotropic Layer			
C520			
C520_NPS			
C520_NPS_TX_Root			
C520_ab			
CDB340 / Epoxy			
CDB340_vf_05			
CX100_hybrid_triak			
D092[0]0iv45CoRezyn634V-051			
D155[0]6iv45CoRezyn634V-051			
Composite			
BC1_spar_low_Tip_10			
BC1_spar_up_25_05			
BC1_spar_up_25_10			
BC1_spar_up_50_05			
BC1_spar_up_50_10			
BC1_spar_up_75_05			
BC1_spar_up_75_10			
BC1_spar_up_Tip_05			
BC1_spar_up_Tip_10			

C520

Ex: 3.730e+010 Pa
Ey: 7.600e+009 Pa
Ez: 7.600e+009 Pa
Gxy: 6.890e+009 Pa
Gyz: 6.890e+009 Pa
Gxz: 6.890e+009 Pa
pν_{xy}: .31
pν_{yz}: .31
pν_{zx}: .31
Mass Density: 1874.00 kg/m³
JP: Same as C520_NPS

User Specified Material

Please enter characteristics of this ORTHOTROPIC material

Material Name: C520 ☐ new material

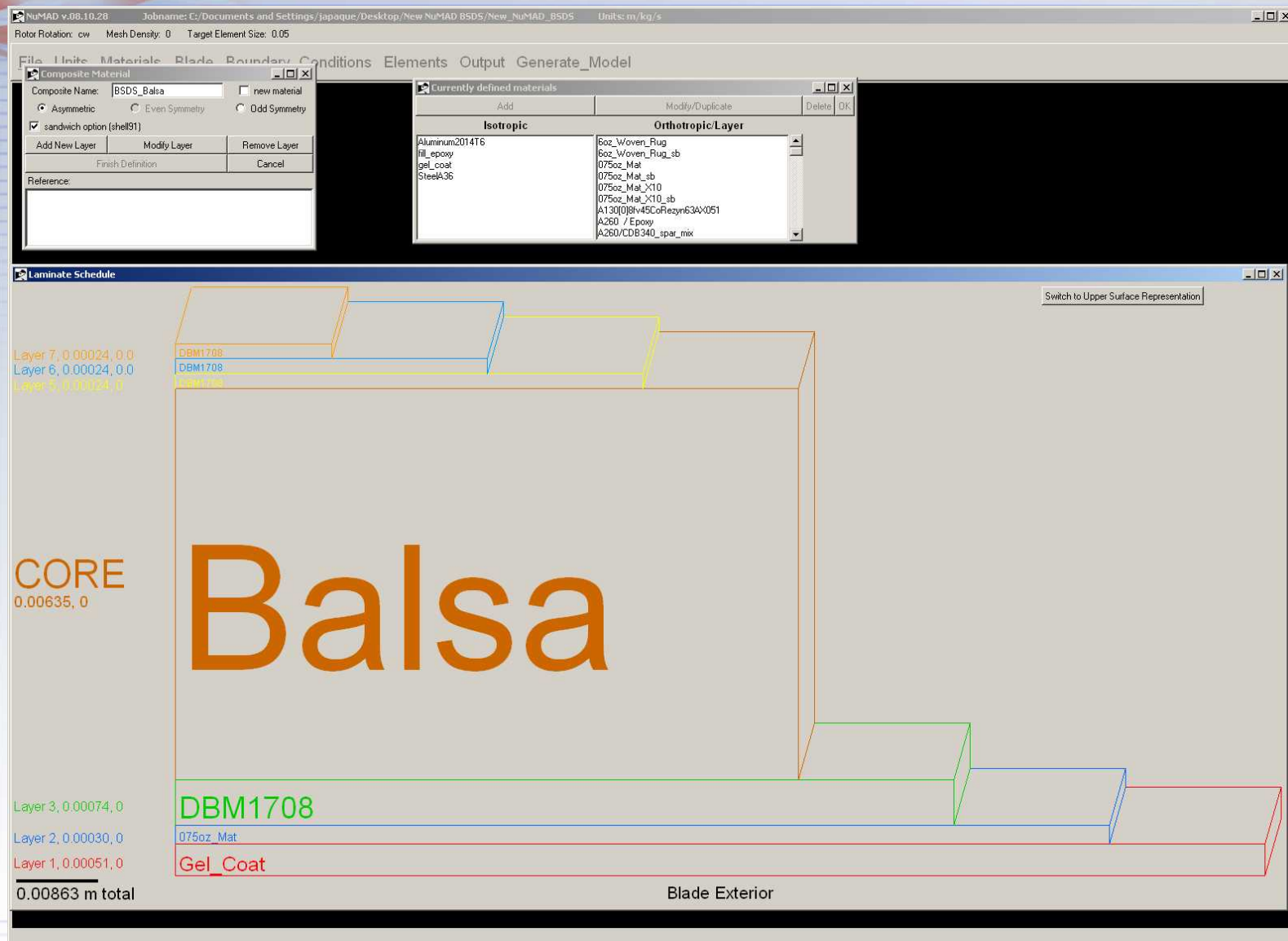
Young's Modulus (Ex): 3.730e+010 Pa 779025420.0 psf 5409917.4 psi
Young's Modulus (Ey): 7.600e+009 Pa 158729040.0 psf 1102288.8 psi
Young's Modulus (Ez): 7.600e+009 Pa 158729040.0 psf 1102288.8 psi
Shear Modulus (Gxy): 6.890e+009 Pa 143900406.0 psf 999311.82 psi
Shear Modulus (Gyz): 6.890e+009 Pa 143900406.0 psf 999311.82 psi
Shear Modulus (Gxz): 6.890e+009 Pa 143900406.0 psf 999311.82 psi
Major Poisson's Ratio (ν_{xy}): .31 .31 .31
Major Poisson's Ratio (ν_{yz}): .31 .31 .31
Major Poisson's Ratio (ν_{zx}): .31 .31 .31
Mass Density: 1874.00 kg/m³ 3.63615902035 slug/ft³ 0.000175353800456 lb-cz²/in⁴
JP: Same as C520_NPS
Reference:

Selected Composite Materials

BSDS_2_Strip
BSDS_Balsa
BSDS_Balsa_Strip
BSDS_No_Balsa_No_Strip
BSDS_Root000
BSDS_Root000_Spar
BSDS_Root000_Strip
BSDS_Root350
BSDS_Root350_Spar
BSDS_Root350_Strip
BSDS_Root394
BSDS_Root394_Spar

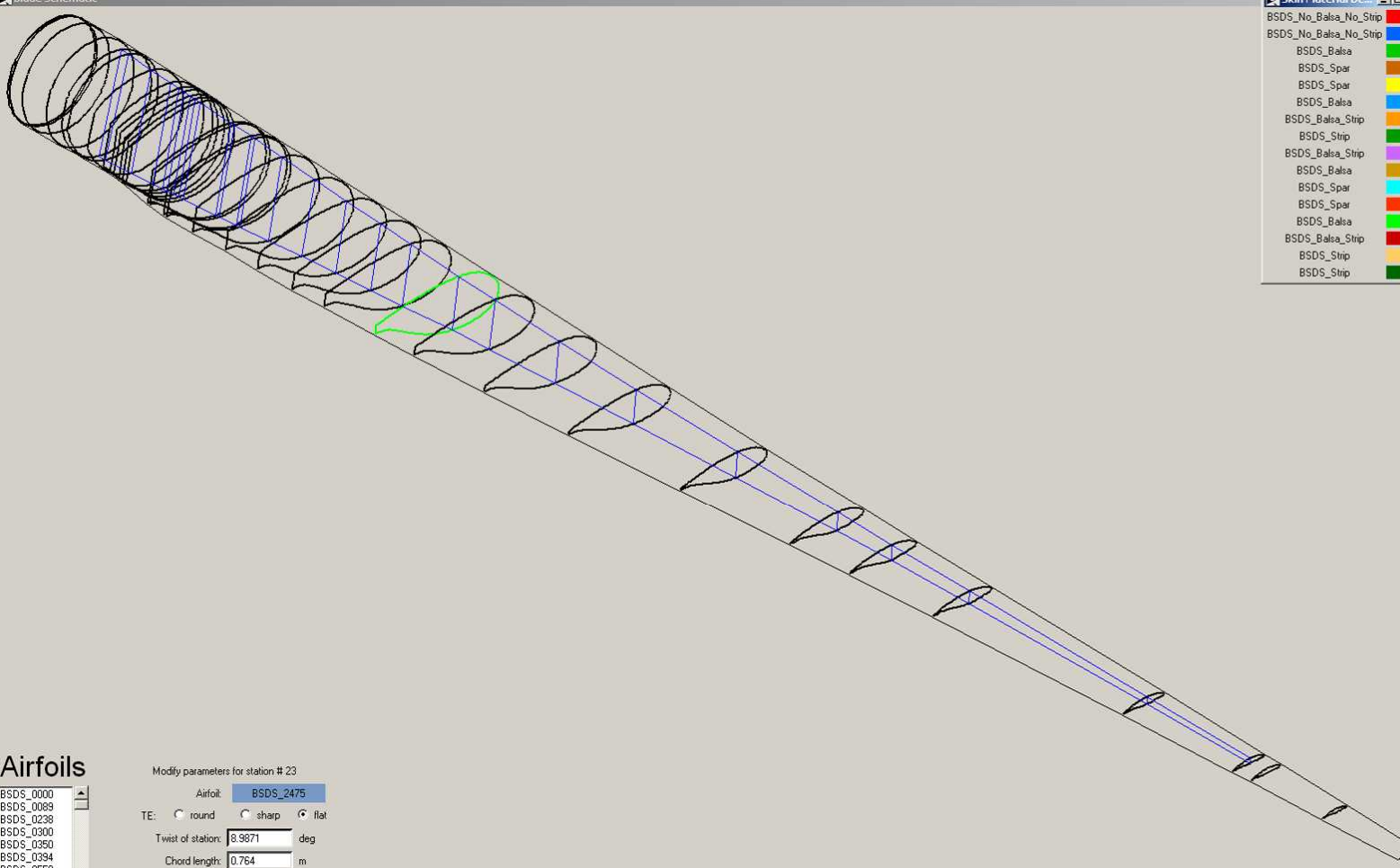
NuMAD Model Definition Process

Define Laminates



NuMAD Model Definition Process

Define Geometry



The main window displays a 3D wireframe model of a propeller blade. The blade is composed of multiple airfoil cross-sections along its length. A specific section of the blade is highlighted with a green wireframe, indicating the current station being modified.

Airfoils

BSDS_0000
BSDS_0069
BSDS_0238
BSDS_0300
BSDS_0350
BSDS_0394
BSDS_0550
BSDS_0675
BSDS_0700
BSDS_0730

Modify parameters for station # 23

Airfoil: **BSDS_2475**

TE: ☐ round ☐ sharp ☒ flat

Twist of station: 8.9871 deg

Chord length: 0.764 m

Normalized X offset: 0.3550

Distance from root: 2.4750 m

Buttons:

- Add New Station
- Delete Selected Station
- Check Blade Data
- Finish Modification
- Add/Modify Skin Material Division
- Remove Skin Material Division
- Add/Modify Shear Web
- Remove Shear Web
- Previous Station
- Next Station
- Update Display
- Cancel

Click to modify station

Skin Material Definition

Material Name	Color
BSDS_No_Balsa_No_Strip	Red
BSDS_No_Balsa_No_Strip	Blue
BSDS_Balsa	Green
BSDS_Spar	Brown
BSDS_Spar	Yellow
BSDS_Balsa	Blue
BSDS_Balsa_Strip	Orange
BSDS_Strip	Green
BSDS_Balsa_Strip	Purple
BSDS_Balsa	Brown
BSDS_Spar	Cyan
BSDS_Spar	Red
BSDS_Balsa	Green
BSDS_Balsa_Strip	Red
BSDS_Strip	Yellow
BSDS_Strip	Green

NuMAD Model Definition Process

Define Laminate Sections

The image displays the NuMAD software interface for defining laminate sections. The main workspace shows a schematic of a blade with three airfoil sections. Each section is divided into colored regions representing different laminate materials. The top section is primarily red and orange, the middle is green and blue, and the bottom is blue and green. A legend on the right, titled 'Skin Material De...', lists various material types with corresponding color swatches: BSDS_No_Balsa_No_Strip (red), BSDS_No_Balsa_No_Strip (blue), BSDS_Balsa (green), BSDS_Spar (orange), BSDS_Balsa (blue), BSDS_Balsa_Strip (orange), BSDS_Strip (green), BSDS_Balsa_Strip (purple), BSDS_Balsa (yellow), BSDS_Spar (cyan), BSDS_Spar (red), BSDS_Balsa (green), BSDS_Balsa_Strip (red), BSDS_Strip (yellow), and BSDS_Strip (dark green).

Airfoils

Modify parameters for station # 23

Airfoil: **BSDS_2475**

TE: ☐ round ☐ sharp ☒ flat

Twist of station: deg

Chord length: m

Normalized X offset:

Distance from root: m

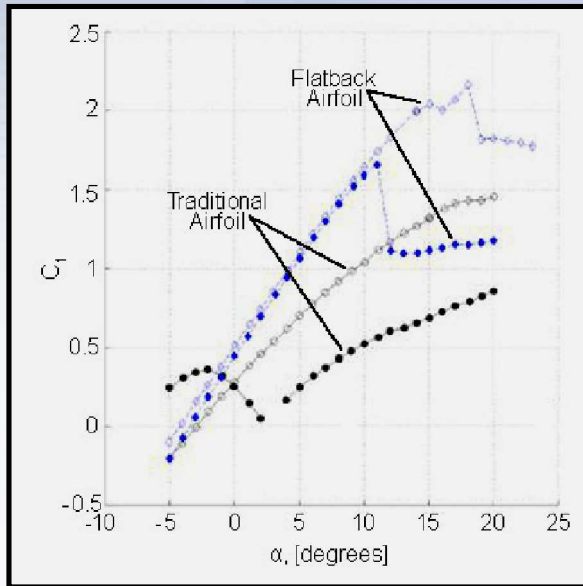
Buttons: Add New Station, Delete Selected Station, Check Blade Data, Finish Modification, Add/Modify Skin Material Division, Remove Skin Material Division, Add/Modify Shear Web, Remove Shear Web, Previous Station, Next Station, Update Display, Cancel

Slide 8 of 9

Level

Larger Smaller

Potential Challenges



■ Hydrofoil Selection and CFD Modeling

- Tower-rotor interactions
- Soiling effects
- Modeling of cavitation and effect on structure over lifetime

■ Structural Modeling

- NuMAD and other codes were developed to analyze thin shell structures (i.e. wind turbine blades)
- Kinetic hydropower blades will likely be thick structures
- Severe event modeling impact from floating debris

■ Manufacturing (AWPP)

- Coatings (material protection, soiling reduction)
- Molds
- Materials

